Quantifying the Effect of Helmet Fit on Performance

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SCHOLARLY ABSTRACT

Fit is often pointed to as the most important factor to consider when selecting a helmet. However, there is no published biomechanical evidence suggesting that of helmet fit effects concussion risk. The objectives of this study were to quantify helmet fit on a headform and to determine the effect fit has on helmet performance. An impact pendulum was used to strike a helmeted NOCSAE headform mounted on a Hybrid III neck. Helmets were impacted at 4 locations at 3 energies representing a range of concussive to sub-concussive impacts. The fit conditions evaluated in this study represent fitting scenarios in which an athlete is provided a helmet that is properly or improperly sized and cases in which a properly sized helmet is too loose, too tight, or properly adjusted. A custom pressure sensor was developed and used to characterize helmet fit in each condition with a quantitative fit metric representative of a variation from zero pressure on the headform. All helmets produced significant differences in both peak linear and peak angular acceleration due to fit. Differences were generally small with some exceptions. Furthermore, air bladder inflation generated significant differences in both peak linear and peak angular acceleration, but these were generally small in magnitude. While fit associated with size and air bladder inflation significantly affected linear and rotational head acceleration for most impact conditions, the best fit condition did not always generate the lowest accelerations. Differences can be attributed to varying helmet characteristics between and within helmet models.

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PUBLIC ABSTRACT

Fit is often pointed to as the most important factor to consider when selecting a helmet. However, there is no published biomechanical evidence suggesting that of helmet fit effects concussion risk. The objectives of this study were to quantify helmet fit on a headform and to determine the effect fit has on helmet performance. An impact pendulum was used to strike a helmeted biofidelic head-neck assembly in a multitude of impact velocities and locations in order to simulate a range of on-field head impacts in a laboratory setting. The fit conditions evaluated in this study represent fitting scenarios in which an athlete is provided a helmet that is properly or improperly sized and cases in which a properly sized helmet is too loose, too tight, or properly adjusted. A custom pressure sensor was developed and used to characterize helmet fit in each condition with a quantitative fit metric representative of a variation from zero pressure on the headform. Linear and rotational acceleration were evaluated to characterize concussion risk as they have been found to be the best correlate for concussion risk in previous work. In this study, the effects of helmet fit and helmet air bladder inflation on peak linear and rotational head acceleration were evaluated. In general, the effects of both fit and air bladder inflation were small, but there were cases of substantial differences. However, the best fit condition did not always result in the lowest head acceleration. Differences can be attributed to varying helmet characteristics between and within helmet models. This data can be used to progress helmet safety through improving helmet performance evaluation, which will increase consumer awareness.

DEDICATION

I would like to thank my advisor Dr. Steve Rowson. Your mentorship and guidance has helped shape me both as an engineer and as a man. I am so grateful for the opportunity you gave me to work in the helmet lab. I would also like to thank my committee members Dr. Duma and Dr. Brolinson.

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Let’s Go… Hokies!!!

Table of Contents

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: OPENING REMARKS

Concussion in Sports

In recent years, the issue of concussion in sports has been thrust into the public spotlight through lawsuits, print, and even the film industry. A concussion, a form of mild traumatic brain injury, can be caused by a direct impact to the head or other region of the body causing a force to be exerted on the brain. These forces cause stresses and strains on the brain resulting in damage. Concussion symptoms, while inconsistent on a case-by-case basis, include headaches, dizziness, nausea, impaired motor skills, etc.[1] Of greater concern, are the long-term impacts concussion might have on the human brain such as depression, memory-deficit, and a neurodegenerative disease known as chronic traumatic encephalopathy (CTE). CTE is a condition characterized by atrophy of the cerebral hemispheres, medial temporal lobe, thalamus, mammillary bodies, and brainstem, with ventricular dilatation and a fenestrated cavum septum pellucidum.[2] While the exact cause of CTE is unknown, there have been multiple studies linking the disease to participation in contact sports.[2-7]

Research Objectives

Helmet fit is often pointed to as the most important factor to be considered when choosing a helmet. However, there is no published evidence supporting these claims. Helmet manufacturers provide fitting directions for players, coaches, and athletic trainers, but there is no scientific evidence to supporting their definition of fit and the biomechanical effect it has on helmet performance. Each helmet manufacturer has their own method of adjusting fit, whether that be through inflatable air bladders or adjustable harnesses, but the effects of these different fitting mechanisms has yet to be studied.

This study aims to develop a quantitative fit metric, and apply it to different fit conditions to analyze the effect of fit on helmet performance through laboratory testing. Four different fit conditions will be evaluated in this study. These fit conditions represent fitting scenarios in which an athlete is provided a helmet that is properly or improperly sized and cases in which a properly sized helmet is too loose, too tight, or properly adjusted according to the manufacturer recommendations. These tests will also cover a broad spectrum of impact conditions.

This research will provide athletic directors, athletic trainers, coaches, parents, athletes, and anyone else who might purchase or fit helmets for athletes, valuable information on fit conditions along with helmet properties that might be affected by those conditions. In addition to the effect this will have on the football population, this research can expand to various helmeted sports such as hockey, lacrosse, baseball, and cycling along with sports like soccer that are starting to implement head protection. However, this research is not limited to the sports world. There are multiple professions such as construction and military that require the use of helmets, of which fit might affect performance.

CHAPTER 2: QUANTIFYING THE EFFECT OF HELMET FIT ON PERFORMANCE

Introduction

An estimated 1.6 to 3.8 million Americans suffer a sports-related concussion each year.[8] Between 2005 and 2012, concussion rates in high school football doubled.[9] However, this increase is likely due to the increased awareness to concussion in football, which has been thrust into the public spotlight in recent years through lawsuits, print, and even the film industry. As a result, people are reporting more concussions rather than sustaining more. Of all sports, football accounts for the highest incidence of concussion in the United States due to the large number of participants in the sport.[10] It is well supported that concussion incidence can be reduced through rule changes and modified practice methods,[11] but equipment also plays a role in minimizing the risk associated with the collision filled sport. It has been shown that newer helmets using improved energy management technology can reduce concussion risk, but this testing occurs under generalized helmet conditions.[12-14] Helmet fit is often pointed to as the most important factor to be considered when choosing a helmet. While there have been no biomechanical studies assessing the effect of helmet fit on helmet performance to date, there have been multiple studies that have analyzed the risk qualitatively.

McGuine et al. conducted a study documenting helmet fitting errors in 33 Wisconsin high school football teams. Twelve certified athletic trainers evaluated helmet fit based on helmet manufacturer's fitting criteria. They found 3403 fitting errors in 1671 evaluated helmets (2.04 ± 1.40 per helmet). In addition, 61.9% of the helmets evaluated had 2 or more errors. It was concluded that many of the errors were associated with inadequate air bladder inflation, but usually, the recommended air bladder inflation resulted in players complaining that their helmet was too tight. Because of this, many players would adjust their helmets to make them looser, which highlighted the need for in-season helmet rechecks. The researchers also found that the helmet fitting errors could be generalized into 2 groups: helmets with 1 or 2 errors and helmets with 4 or more errors. In cases where the helmets had 1 or 2 errors, the cause was typically easily fixed by tightening the chinstrap, replacing jaw pads, or adjusting inflation. However, cases where there were 4 or more errors were typically associated with the shell being too large, highlighting the need for more helmets to accommodate differing size requirements.[15] Greenhill et al. reported that athletes with improperly fit helmets had greater rates of drowsiness, hyperexcitability, and sensitivity to noise.[16] These helmet fitting errors, however, were subjectively determined by different athletic trainers. Although the focus of this study is football helmets, helmet fitting issues exist beyond the sport of football.

Parkinson et al. reported that only 4% of children or their parents were able to correctly fit a bicycle helmet.[17] In addition, Rivera et al. collected data from children admitted to the hospital due to action sports-related injuries. It was found that the difference between helmet width and head width might be the most important factor contributing to poor fit. They hypothesized that the increased distance between the head and the helmet might allow the head to accelerate during a crash before it comes into contact with the padding, and helmets that are too large in any dimension might be more likely to move out of the correct position during a crash, leaving portions of the head unprotected.[18] While the latter is most likely the case, that most likely does not apply for helmets that have a larger coverage of the skull such as football. Even though fitting error frequency and type has been evaluated and documented, documentation of the effect of fit of protective headwear, such as helmet size and adjustment of internal fitting mechanisms, is scarce and incomplete.[19]

There is no published evidence supporting the claims of helmet fit effecting concussion risk and helmet performance. Helmet manufacturers provide fitting directions for players, coaches, and athletic trainers, but there is no scientific evidence to support their definition of fit and whether or not it provides optimum protection to the athlete. Each helmet manufacturer has their own method of adjusting fit, whether that be through inflatable air bladders or adjustable harnesses, but the effect of these different fitting mechanisms has yet to be studied. The objectives of this study are to define helmet fit on a headform and to determine the effect fit has on helmet performance.

Methods

An impact pendulum was used to simulate head impacts in football.[20] The length of the pendulum arm from the center of its pivot point to the center of its impacting mass is 190.5 cm. The pendulum arm has a total mass of 36.3 kg and a moment of inertia of 72 kg m^2 with an impacting mass of 16.3 kg. The nylon impactor face has a diameter of 12.7 cm, which is flat and rigid. The pendulum impacts a helmeted medium NOCSAE headform mounted on a Hybrid III 50th percentile neck. The NOCSAE headform was chosen because it provides the most realistic fit between the headform and helmet.[21] The headform-neck assembly is mounted to a linear slide table (Biokinetics, Ottawa, Ontario, Canada) with 5 degrees of freedom (DOF). A custom adaptor plate was used to allow the mounting of the NOCSAE headform to the Hybrid III neck while maintaining the relative locations of the center of gravity (CG) of the headform and the occipital condyle pin when compared to the Hybrid III head and neck assembly.[22] The headform was instrumented with a 6 DOF sensor package consisting of 3 linear accelerometers (Endevco 7264B-2000, Meggitt Sensing Systems, Irvine, CA) and 3 angular rate sensors (ARS3 PRO-18K, DTS, Seal Beach, CA).

The headform was impacted in variety of impact conditions to represent a range of impact conditions experienced by players in on-field scenarios.[13, 22-35] Four impact locations, equally spaced around the transverse plane of one side of the headform, were selected for testing: front, front boss, rear, and rear boss (Fig. 1, Table 1). The front and rear locations represented centric impacts, where the direction of force is aligned with the CG of the headform, and the front boss and rear boss impacts were considered non-centric. The pendulum impacted the headform at 3 different energies to observe a range of sub-concussive to concussive impacts. For these tests, the pendulum arm was raised to angles of 40°, 65°, and 90° from vertical resulting in impact velocities of 3.0, 4.6, and 6.1 m/s, respectively.

Figure 1: Pendulum impactor impacting helmet in (left to right) front, front boss, rear, and rear boss impact locations.

Table 1: NOCSAE headform locations and rotations on the 5 DOF linear slide table. A centered upright headform facing the pendulum impactor would have measurements of Y = 0 cm, Z = 0 cm, R_y = 0°, and R_z = 0°.

Location	Y (cm)	Z (cm)	R_y (°)	R_y (°)
Front	0	4.3	-30	0
Front Boss	2	3.8	-10	-60
Rear	-2	5.3	5	-120
Rear Boss	0	4.3	0	-180

Three different helmets were evaluated: Riddell Speed, Schutt Air XP Pro VTD, and Xenith Epic (Fig. 2). The Speed's liner system is comprised of vinyl nitrile padding encased in an inflatable air bladder used for fitting. The Air XP Pro VTD's liner system is comprised of an external thermoplastic urethane cushion with an internal inflatable air bladder. Finally, the Xenith Epic's liner system is comprised of dashpot style shock absorbers attached to a suspension system. The Epic's fitting system is an adjustable harness controlled by the chinstraps.

Figure 2: Medium NOCSAE headform with (left to right) Riddell Speed, Schutt Air XP Pro VTD, and Xenith Epic.

A custom pressure sensor array (Pressure Profile Systems, Los Angeles, CA) was developed and used to create pressure profiles for helmets fitted to a headform (Fig. 3). The pressure sensor array consists of 502 capacitive pressure sensors integrated into a skull cap that is worn on top of the headform and underneath the helmet.

Figure 3: Medium NOCSAE headform with custom pressure sensor array. The pressure sensor array consists of 502 capacitive pressure sensors.

The pressure sensor array was used to create pressure profiles of each helmet under 4 different fit conditions: minimum, loose, best, and tight (Table 2). The minimum fit condition is as a size extra-large, unadjusted helmet. This fit condition represents a fitting case in which the athlete was provided a helmet that is too large and was not adjusted to fit his/her head. The minimum fit condition generated the least amount of pressure on the head achievable in the laboratory setting. The loose fit condition is a size large, uninflated helmet. This fit condition characterizes a fitting scenario in which the athlete might have been properly sized for a helmet, but no adjustments were made to fit the specific athlete. The best fit condition is a size large helmet adjusted to the manufacturer recommendation. This fit condition represents a fitting scenario in which the athlete was administered a helmet that was both properly sized and fit to the specific athlete according the manufacturer's fitting instructions. Finally, the tight fit condition is a large helmet, inflated to twice the manufacturer recommended pad pressure. This fit condition represents a snug fit that is tighter than recommended by the manufacturer but not too tight to incur extreme discomfort.

Table 2: Helmet fit conditions and their respective helmet size and inflation level. These fit conditions represent fitting scenarios in which an athlete is administered a helmet that is both properly and improperly sized and cases in which the helmet is too loose, too tight, and properly adjusted according to the manufacturer recommendations.

Fit Condition	Helmet Size	Inflation Level/Adjustment
Minimum	XL	Uninflated/unadjusted
Loose	L	Uninflated
Best	L	Manufacturer Recommended
Tight	L	2x Manufacturer Recommended

Using preliminary data from the pressure sensor array, a rank-order analysis was performed to determine a metric for use in this study (Eqn. 1). The goal for the metric was to take average pressure into account, while weighting points of higher pressure to account for comfort. It was determined that variation from zero pressure on the headform best discriminated between fit conditions. To model this, each pressure sensor value (P_i) was squared, summed, divided by the total amount of sensors (n = 502), and raised to the one-half power.

$$fit = \sqrt{\frac{\sum_{i=1}^{n} {P_i}^2}{n}} \qquad (1)$$

A total of 360 impact tests were conducted to evaluate the effects of fit on helmet performance. Two sets of fit conditions were compared. The minimum and best fit conditions were selected to compare a fitting scenario in which an athlete was administered an improperly sized and unadjusted helmet versus a fitting scenario in which the athlete is administered a properly sized helmet and was properly fitted to the manufacturer-defined ideal fit. All 3 helmets were tested at the 4 locations, 3 impact energies, 3 times each for a total of 216 tests. The loose and tight fit conditions were compared to quantify the effect of air bladder inflation on helmet performance. These fit conditions were selected to compare a fitting scenario in which an athlete is administered a properly sized but unadjusted helmet versus a fitting scenario in which the athlete is administered a properly sized helmet that is over-inflated and too tight. For the tight fit condition, the air bladders were inflated to twice the padding pressure of the manufacturer recommended fit. A maximum inflation was not analyzed because the goal was to examine a realistic tight fitting scenario. The Xenith helmet was not tested for this analysis since its adjustment system is a harness that is not inflatable. The Speed and Air XP Pro VTD were tested at the 4 locations, 3 impact energies, 3 times each for a total of 144 tests.

Linear acceleration and angular rate data were collected at a sampling rate of 20,000 Hz using TDAS data acquisition software (DTS, Seal Beach, CA). These data were processed using MATLAB R2014b. Data were filtered using a 4-pole Butterworth low pass filter with a cutoff frequency of CFC 1650 Hz (CFC 1000) for linear acceleration and a cutoff frequency of 256 Hz (CFC 155) for angular rate data. Angular acceleration was calculated by differentiating the angular rate data. All data were transformed to the CG of the headform. Peak linear and peak angular accelerations from these tests were analyzed and compared within helmet and impact velocity. A two-way ANOVA and Tukey HSD were performed using statistical software (JMP, version 11, SAS Institute Inc., Cary, NC) to analyze the factors of fit and location within helmets and impact energies ($p < 0.05$).

Results

Pressure Profiles

Helmet fit on the headform varied within helmet models (Fig. 4). The Riddell Speed's average fit metric ranged from 5.3 ± 0.1 to 15.4 ± 0.9 kPa. The Schutt Air XP Pro VTD average fit metric ranged from 5.8 ± 0.8 to 14.0 ± 0.6 kPa. Finally, the Xenith Epic's average fit metric ranged from 6.7 ± 2.8 to 13.4 ± 2.5 kPa.

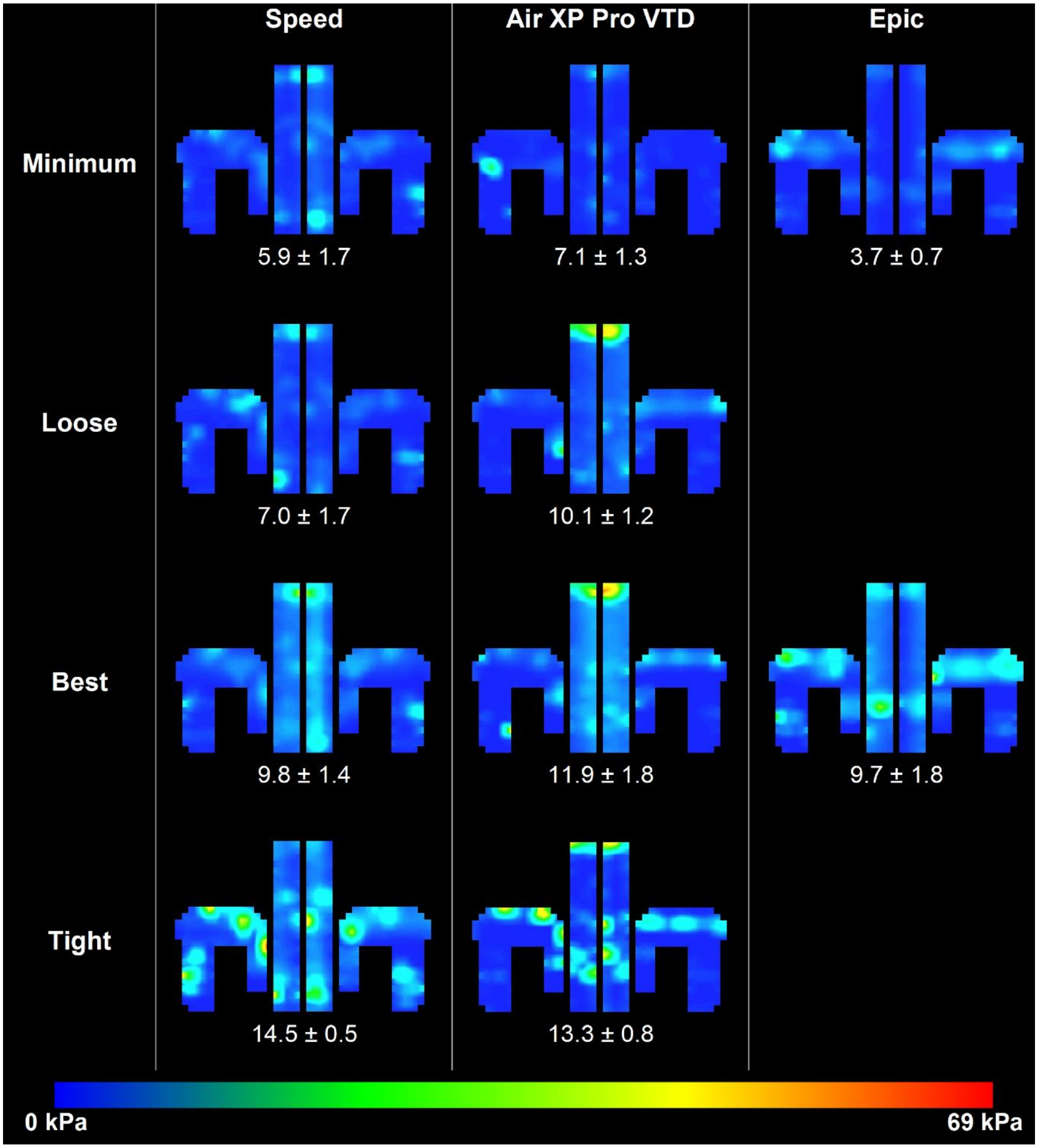

Figure 4: Pressure profiles and associated average fit metrics for each helmet within each fit condition. Fit metric increases with fit condition, but the increase differs in magnitude and variation by helmet. The Xenith Epic was not tested in the loose or tight fit conditions because its fitting mechanism is an adjustable harness and not an inflatable air bladder.

Effect of Fit

All 3 helmets generated significant differences associated with fit (Table 3). Differences between fit conditions varied by impact location and impact energies within helmet models (Fig. 5). The average difference across all helmets, impact locations, and impact velocities was 5 g and 48 rad/s^2. The Riddell Speed had an average difference of -6 g and 170 rad/s^2 across all impact energies and locations. The Speed generated significant differences in peak linear acceleration due to fit within all three impact energies, but only generated significant differences in peak angular acceleration due to fit in the 4.6 m/s impact velocity. The Schutt Air XP Pro VTD had an average difference of 16 g and -20 rad/s^2 across all impact energies and locations. The Air XP Pro generated significant differences in both peak linear and peak angular acceleration due to fit within all 3 impact energies. The Xenith Epic had an average difference of 4 g and -4 rad/s^2 across all impact energies and locations. The Epic generated significant differences in peak linear acceleration due to fit in both the 4.6 and 6.1 m/s impact tests but generated no significant differences in peak angular acceleration due to fit within any of the impact energies. Finally, all 3 helmets generated significant differences in both peak linear and peak angular acceleration due to location and the interaction of fit and location within all 3 impact energies.

Table 3: Statistical significance of peak linear acceleration and peak angular acceleration due to fit, positive difference denotes the best fit condition performed better.

Helmet	Impact Velocity (m/s)	Peak Linear Acceleration		Peak Angular Acceleration	
		Average Difference (g)	p-value	Average Difference (rad/s^2)	p-value
Speed	3.0	-4	0.0005*	100	0.2165
	4.6	-4	0.0002*	239	0.0204*
	6.1	-9	<0.0001*	170	0.1567
Air XP Pro VTD	3.0	6	0.0002*	267	0.0020*
	4.6	18	<0.0001*	357	0.0221*
	6.1	25	<0.0001*	-686	0.0005*
Epic	3.0	0	0.8979	-5	0.9572
	4.6	4	0.0038*	-10	0.9200
	6.1	9	0.0019*	1	0.9930

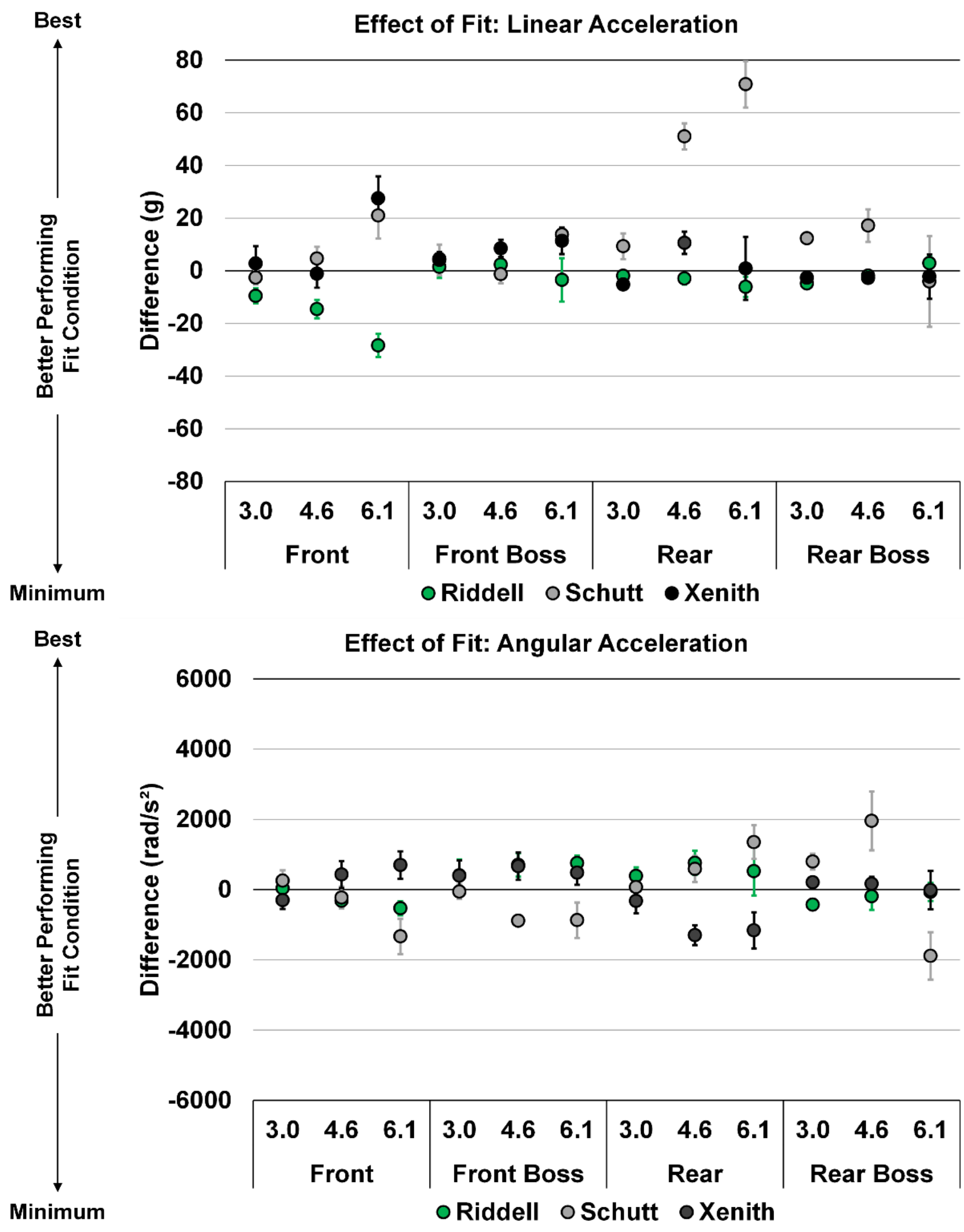

Figure 5: Difference in peak linear and peak angular acceleration between best and minimum fit conditions. Significant differences in peak linear and/or peak angular acceleration due to fit were found in each helmet. Helmet fit affected performance differently between helmets, locations, and velocities. The superior performing fit condition varied within helmets, the highest variation occurring in the Air XP Pro VTD.

Effect of Air Bladder Inflation

Both helmets generated significant differences associated with air bladder inflation (Table 4). Differences between fit conditions varied by impact location and impact energies within helmet models (Fig. 6). The average difference across all helmets, impact locations, and impact velocities was -1 g and -254 rad/s^2. The Riddell Speed had an average difference of 3 g and -127 rad/s^2 across all impact energies and locations. The Speed generated significant differences in peak linear acceleration due to air bladder inflation within both the 3.0 and 4.6 m/s impacts and generated a significant differences in peak angular acceleration due to air bladder inflation in both the 4.6 and 6.1 m/s impact tests. The Schutt Air XP Pro VTD had an average difference of -5 g and -380 rad/s^2 across all impact energies and locations. The Air XP Pro VTD generated significant differences in peak linear acceleration due to air bladder inflation within all 3 impact energies and generated significant differences in peak angular acceleration due to air bladder inflation within the 3.0 and 6.1 m/s impact tests. Both helmets generated significant differences in both peak linear and angular acceleration due to location within all 3 impact energies.

Table 4: Statistical significance of peak linear acceleration and peak angular acceleration due to air bladder inflation, positive difference denotes the tight fit condition performed better.

Helmet	Impact Velocity (m/s)	Peak Linear Acceleration		Peak Angular Acceleration	
		Average Difference (g)	p-value	Average Difference (rad/s^2)	p-value
Speed	3.0	4	<0.0001*	79	0.2758
	4.6	4	<0.0001*	-192	<0.0001*
	6.1	2	0.1046	-269	0.0028*
Air XP Pro VTD	3.0	2	0.0046*	202	0.0323*
	4.6	-1	0.0027*	-99	0.1748
	6.1	-15	0.0027*	-1242	<0.0001*

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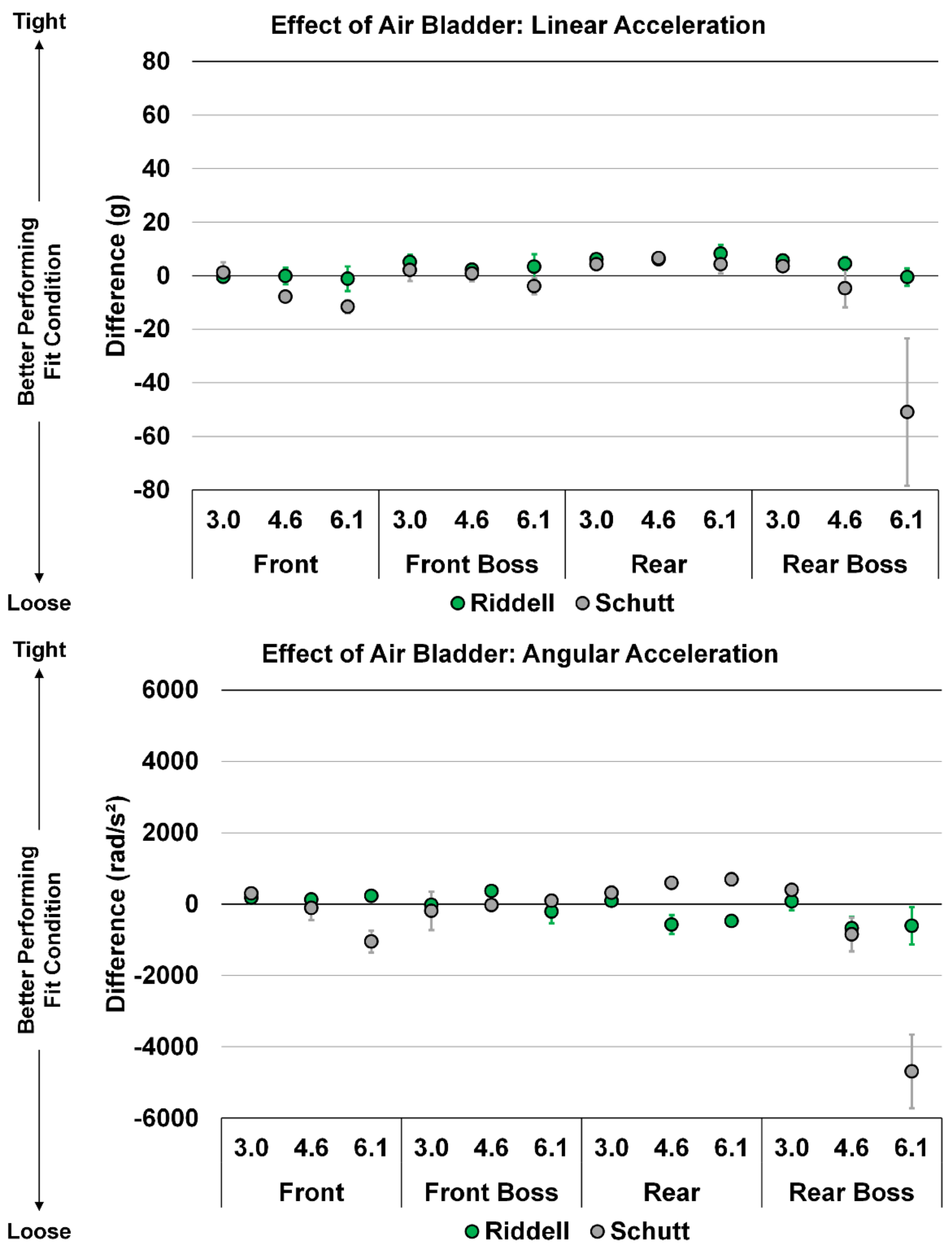

Figure 6: Difference in peak linear and peak angular acceleration between tight and loose fit conditions. Significant differences in peak linear and/or peak angular acceleration due to air bladder inflation were found in both helmets. With the exception of the 6.1 m/s impact to the rear boss of the Schutt Air XP Pro VTD, there were small differences in peak linear and peak angular acceleration associated with air bladder inflation.

Discussion

While each helmet's fit metric generally increased with fit condition, there was a noticeable difference in the variation between and within fit conditions for each helmet (Fig. 7). The Riddell Speed's pressure profiles in the minimum, loose, and best fit conditions were similar with some overlap in their standard deviations, but pressure increased substantially in the tight fit condition. In the Schutt Air XP Pro VTD, there was a more consistent increase in pressure from the minimum to the tight fit condition. The Xenith Epic had a distinct difference in pressure between fit conditions. Generally, variance was similar between helmets and fit conditions.

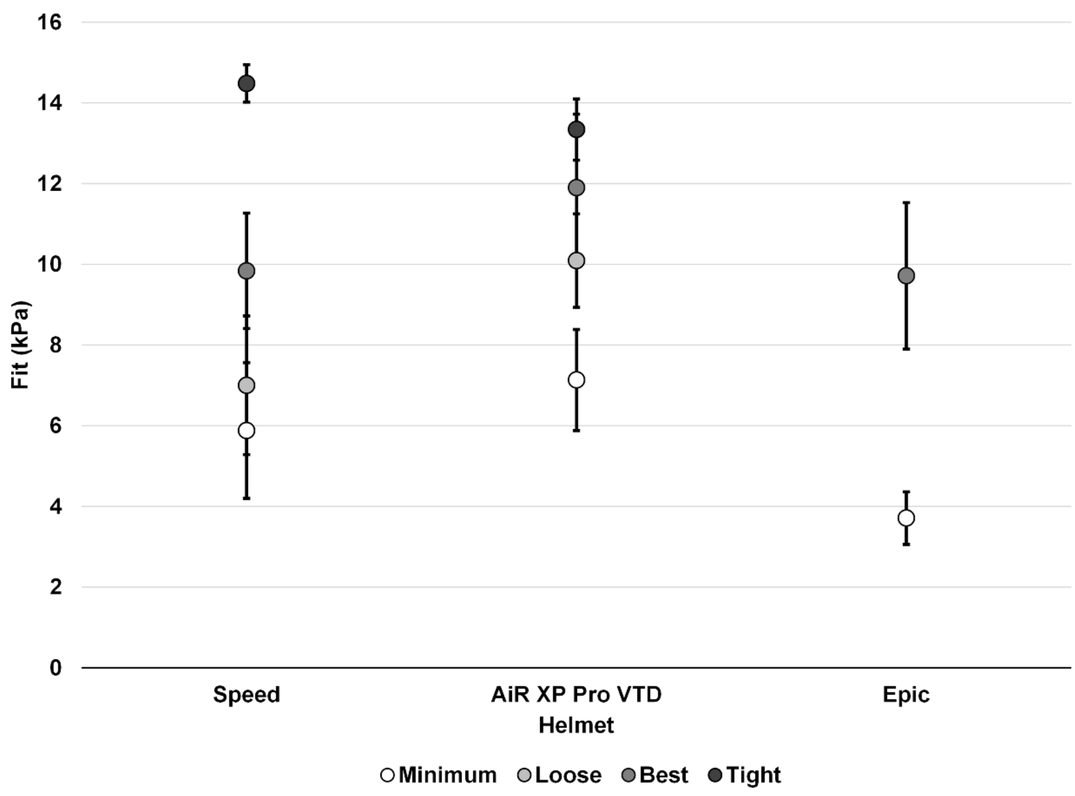

Figure 7: Comparison of fit metrics between fit conditions divided into helmets. The Speed's fit metric in the minimum, loose, and best conditions were similar but increased substantially for the tight condition. Conversely, the Air XP Pro VTD and Epic's fit metrics increased more uniformly with fit condition.

Helmet fit was found to effect the biomechanical performance of the helmets tested. There are a number of possible explanations for these differences. Helmet manufacturers have differing approaches to the way the helmet's padding interacts with the head and the rest of the helmet, such as having a single layer of padding versus multiple layers. Another possible factor could be air bladder inflation. For instance, the best fit condition has air bladder inflation whereas the minimum fit condition does not. Finally, there could be differences in padding within helmet models between helmet sizes.

Of the significant differences found due to fit, the largest differences associated with the Schutt Air XP Pro VTD. For most tests, the best fit condition outperformed the minimum fit condition. With the exception of the 6.1 m/s impact in the rear boss location, there were generally small differences with respect to air bladder inflation. Upon inspection of the padding, it was found that the padding in the size extra-large Air XP Pro VTD was 12 to 30 percent thinner than the size large Air XP Pro VTD. The increased padding thickness is most likely the cause of the improved energy modulation in the size large helmet. The outlier of these data is the 6.1 m/s impact in the rear boss location. It is believed that this outlier could be caused by pre-compression or padding shifting out of place during impact. These tests were further evaluated with repeat testing but generated the same results. The Riddell Speed produced small differences due to air bladder inflation. However, in the fit tests, the minimum fit condition outperformed the best fit condition. The improved performance in the front impact location of the extra-large helmet can likely be attributed to the increased padding thickness. The size extra-large Speed had a 37 percent thicker frontal pad than did the size large Speed, but the other pads were similar between sizes. The Xenith Epic best fit condition outperformed the minimum fit condition in the front, 6.1 m/s impact. Again, this improved performance in the front can likely be attributed to the frontal pads in the size extra-large Epic being 17 percent thinner than in the size large Epic.

The fit conditions used in this study represent fitting scenarios in which an athlete is administered a helmet that is both properly and improperly sized and cases in which the helmet is too loose, too tight, and properly adjusted according to the manufacturer recommendations. Unfortunately, these data do not allow for the determination of which fit condition provides optimum protection to athletes. Determination of the ideal fit condition is likely helmet and person specific, but this study demonstrates that helmet fit is an important factor in helmet performance.

This study was limited in a number of ways. First, these tests were restricted to the use of a single head shape in the form of the medium NOCSAE headform. In order to fully evaluate the effect of fit, a representative distribution of human head shapes is needed to account for variation between head shapes. Second, the helmet sample was limited to 3 helmets. To completely analyze the effect of fit on helmet performance, every helmet available to consumers should be evaluated. Finally, this study was unable to determine which fit condition was ideal due to a combination of the previous limitations.

Conclusions

This study presents biomechanical data showing that helmet fit plays a role in the performance of football helmets. While the effect of air bladder inflation is small, proper helmet sizing is vital to the reduction of concussion risk. In addition, this study produced a method of quantifying helmet fit. Overall, there were small differences associated with helmet fit and air bladder inflation with a few exceptions. While helmet fit affects helmet performance, differences due to helmet performance might be greater than the effects of poor fit. When choosing a helmet to purchase, consumers should select a helmet that both performs and fits well.

CHAPTER 3: CONCLUDING REMARKS

Research Summary

This study demonstrated that helmet fit does effect helmet performance, but that effect varies between helmets. While the manufacturer defined fit condition outperformed improperly fit helmets in some impact scenarios, it was outperformed in others. Even though the effect of air bladder inflation is negligible, proper helmet sizing is important to the reduction of concussion risk. These data should be considered by helmet manufacturers and standards committees when developing and evaluating helmets of varying sizes.

Future Work

There is much more work to be done in order to understand the full effect of different helmet fit conditions, their effects on helmet performance, and how it relates to concussion risk as a whole. However, for the first time ever, there are biomechanical data showing that helmet fit plays a role in the performance of football helmets. To maximize the reduction of concussion risk in the human population, these data should be used to expand this research to other sports and other helmeted professions in which concussion is prevalent.

Publication Outline

Chapter 2 of this thesis is planned to be submitted to the Journal of Sports Engineering and Technology.

APPENDIX

Figure 8: Pendulum impactor used to test helmets. The impactor face at the end of the pendulum arm impacts a helmet on a NOCSAE headform mounted to a Hybrid III neck. The headform-neck assembly is mounted to a 5 DOF linear slide table.

Table 5: Average linear acceleration values for the Riddell Speed in the fit tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Linear Acceleration (g)	Standard Deviation (g)
Best	Front	3.0	54	2
		4.6	87	0
		6.1	126	3
	Front Boss	3.0	43	3
		4.6	80	4
		6.1	118	7
	Rear	3.0	35	1
		4.6	67	1
		6.1	100	1
	Rear Boss	3.0	41	1
		4.6	74	1
		6.1	110	2
Minimum	Front	3.0	44	2
		4.6	72	3
		6.1	97	3
	Front Boss	3.0	44	3
		4.6	82	1
		6.1	115	4
	Rear	3.0	33	2
		4.6	64	2
		6.1	94	4
	Rear Boss	3.0	36	2
		4.6	72	2
		6.1	113	2

Table 6: Average linear acceleration values for the Schutt AiR XP Pro VTD in the fit tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Linear Acceleration (g)	Standard Deviation (g)
Loose	Front	3.0	42	1
		4.6	70	3
		6.1	85	4
	Front Boss	3.0	31	6
		4.6	63	3
		6.1	75	1
	Rear	3.0	38	0
		4.6	62	4
		6.1	83	4
	Rear Boss	3.0	30	1
		4.6	60	1
		6.1	123	13
Tight	Front	3.0	39	3
		4.6	75	3
		6.1	106	8
	Front Boss	3.0	35	2
		4.6	61	2
		6.1	89	1
	Rear	3.0	47	5
		4.6	113	3
		6.1	154	8
	Rear Boss	3.0	42	2
		4.6	77	6
		6.1	118	12

Table 7: Average linear acceleration values for the Xenith Epic in the fit tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Linear Acceleration (g)	Standard Deviation (g)
Loose	Front	3.0	29	7
		4.6	58	2
		6.1	76	5
	Front Boss	3.0	41	2
		4.6	72	0
		6.1	108	4
	Rear	3.0	47	1
		4.6	87	4
		6.1	129	10
	Rear Boss	3.0	39	0
		4.6	83	1
		6.1	128	5
Tight	Front	3.0	31	1
		4.6	57	5
		6.1	103	6
	Front Boss	3.0	46	1
		4.6	81	3
		6.1	119	3
	Rear	3.0	42	1
		4.6	98	2
		6.1	130	7
	Rear Boss	3.0	37	1
		4.6	80	2
		6.1	125	7

Table 8: Average angular acceleration values for the Riddell Speed in the fit tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Angular Acceleration (rad/s^2)	Standard Deviation (rad/s^2)
Loose	Front	3.0	1963	89
		4.6	3369	103
		6.1	4269	109
	Front Boss	3.0	3093	302
		4.6	5909	300
		6.1	8279	138
	Rear	3.0	2390	94
		4.6	3934	343
		6.1	5286	551
	Rear Boss	3.0	2549	58
		4.6	4412	213
		6.1	7124	96
Tight	Front	3.0	2000	60
		4.6	3049	139
		6.1	3738	166
	Front Boss	3.0	3498	339
		4.6	6615	158
		6.1	9033	168
	Rear	3.0	2778	225
		4.6	4694	51
		6.1	5810	416
	Rear Boss	3.0	2118	83
		4.6	4221	322
		6.1	7059	240

Table 9: Average angular acceleration values for the Schutt AiR XP Pro VTD in the fit tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Angular Acceleration (rad/s^2)	Standard Deviation (rad/s^2)
Loose	Front	3.0	1771	151
		4.6	3250	49
		6.1	4820	481
	Front Boss	3.0	1964	201
		4.6	5253	78
		6.1	6968	321
	Rear	3.0	2254	113
		4.6	4206	25
		6.1	4807	97
	Rear Boss	3.0	2203	198
		4.6	3923	198
		6.1	9401	538
Tight	Front	3.0	2027	251
		4.6	3020	311
		6.1	3486	154
	Front Boss	3.0	1905	57
		4.6	4368	72
		6.1	6096	392
	Rear	3.0	2327	244
		4.6	4792	372
		6.1	6159	471
	Rear Boss	3.0	3001	109
		4.6	5879	815
		6.1	7513	404

Table 10: Average angular acceleration values for the Xenith Epic in the fit tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Angular Acceleration (rad/s^2)	Standard Deviation (rad/s^2)
Loose	Front	3.0	1772	169
		4.6	2644	180
		6.1	3424	323
	Front Boss	3.0	2301	139
		4.6	5156	168
		6.1	6616	275
	Rear	3.0	2161	347
		4.6	5252	168
		6.1	6278	299
	Rear Boss	3.0	2272	73
		4.6	5231	187
		6.1	7886	451
Tight	Front	3.0	1470	182
		4.6	3074	341
		6.1	4123	225
	Front Boss	3.0	2696	410
		4.6	5822	353
		6.1	7096	206
	Rear	3.0	1839	67
		4.6	3953	228
		6.1	5117	421
	Rear Boss	3.0	2481	70
		4.6	5396	65
		6.1	7872	304

Table 11: Average linear acceleration values for the Riddell Speed in the air bladder tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Linear Acceleration (g)	Standard Deviation (g)
Loose	Front	3.0	48	1
		4.6	82	2
		6.1	127	4
	Front Boss	3.0	42	2
		4.6	76	1
		6.1	122	1
	Rear	3.0	34	1
		4.6	63	0
		6.1	96	2
	Rear Boss	3.0	38	1
		4.6	73	2
		6.1	108	3
Tight	Front	3.0	54	2
		4.6	87	0
		6.1	126	3
	Front Boss	3.0	43	3
		4.6	80	4
		6.1	118	7
	Rear	3.0	35	1
		4.6	67	1
		6.1	100	1
	Rear Boss	3.0	41	1
		4.6	74	1
		6.1	110	2

Table 12: Average linear acceleration values for the Schutt Air XP Pro VTD in the air bladder tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Linear Acceleration (g)	Standard Deviation (g)
Loose	Front	3.0	41	0
		4.6	65	2
		6.1	79	2
	Front Boss	3.0	31	4
		4.6	57	3
		6.1	76	2
	Rear	3.0	36	0
		4.6	55	1
		6.1	80	3
	Rear Boss	3.0	29	0
		4.6	59	2
		6.1	140	14
Tight	Front	3.0	42	1
		4.6	70	3
		6.1	85	4
	Front Boss	3.0	31	6
		4.6	63	3
		6.1	75	1
	Rear	3.0	38	0
		4.6	62	4
		6.1	83	4
	Rear Boss	3.0	29	0
		4.6	64	7
		6.1	176	20

Table 13: Average angular acceleration values for the Riddell Speed in the air bladder tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Angular Acceleration (rad/s^2)	Standard Deviation (g)
Loose	Front	3.0	2162	64
		4.6	3072	65
		6.1	4063	89
	Front Boss	3.0	2755	70
		4.6	5533	74
		6.1	8027	278
	Rear	3.0	2208	112
		4.6	3331	150
		6.1	4936	9
	Rear Boss	3.0	2837	166
		4.6	3880	191
		6.1	6393	458
Tight	Front	3.0	1963	89
		4.6	3369	103
		6.1	4269	109
	Front Boss	3.0	3093	302
		4.6	5909	300
		6.1	8279	138
	Rear	3.0	2390	94
		4.6	3934	343
		6.1	5286	551
	Rear Boss	3.0	2549	58
		4.6	4412	213
		6.1	7124	96

Table 14: Average angular acceleration values for the Schutt Air XP Pro VTD in the air bladder tests.

Fit Condition	Location	Impact Velocity (m/s)	Average Peak Angular Acceleration (rad/s^2)	Standard Deviation (g)
Loose	Front	3.0	1755	94
		4.6	3257	291
		6.1	4250	151
	Front Boss	3.0	1964	324
		4.6	5004	76
		6.1	6661	127
	Rear	3.0	2176	129
		4.6	3966	123
		6.1	4621	144
	Rear Boss	3.0	2077	100
		4.6	3361	134
		6.1	8605	360
Tight	Front	3.0	1771	151
		4.6	3250	49
		6.1	4820	481
	Front Boss	3.0	1964	201
		4.6	5253	78
		6.1	6968	321
	Rear	3.0	2254	113
		4.6	4206	25
		6.1	4807	97
	Rear Boss	3.0	1900	29
		4.6	3477	205
		6.1	10902	999

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