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Football helmet fitment and its effect on helmet performance

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FOOTBALL HELMET FITMENT AND ITS EFFECTS ON HELMET PERFORMANCE

by

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THESIS

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Chapter 1 – Introduction

1.1 Problem Statement

Sports are a method of teaching, team building, attaining a level of health, and maintaining or striving towards excellence in physical fitness. Despite the popularity of sport, there is high potential to become injured in virtually any sporting event, whether the sport be contact or non-contact, amateur or professional, competitive or recreational. While there is potential in any sporting event to become injured, high speed contact sports, such as hockey and football, have the highest potential for injury (Hootman et al., 2007). Concussion injuries were found to have a high incidence rate in these sports.

The potential for head injury in football and hockey has been recognized for many years. Football helmets, which have been used since the early days of football, began as a soft leather helmet and transitioned to a hard plastic shell with energy-absorbing padding in the 1950's. Hockey helmets began to gain popularity in the 1970's. These early helmets were implemented to provide protection against serious/life-threatening skull fractures which resulted in focal brain injuries. The prevention of concussions was not the design intent of helmets. While concussions are known to be prevalent in contact sports today, neither the effectiveness of the helmet in preventing concussion nor the mechanism or threshold at which a concussion is sustained is entirely understood. On-field experiments focusing on head accelerations have been conducted to assess the severity of impacts to the head resulting in concussion (Pellman et al., 2003). The Head Impact Telemetry System (Crisco, 2002) has been developed with the intent to monitor the severity and location of impacts in practice and game situations. Laboratory experiments have been conducted to assess the effects of chin strap design in football helmets (Craig, 2007).

Despite the large efforts undergone to identify a threshold for concussion, helmet fitment and its effect on helmet performance has not previously been documented. With increasing awareness of the incidence and severity of concussion, a method of obtaining objective helmet fitment data must be designed, and data regarding helmet fitment on athletes must be obtained. An objective method of helmet fitment is necessary to control one of the major boundary conditions when the helmet is placed on an athlete’s head. A loosely fitting helmet would not be retained on the athlete’s head, while a tightly fitting helmet may be uncomfortable. Similarly, a non-uniform fitting helmet could introduce pressure “hot-spots” on the athlete’s head, resulting in less than optimal helmet performance in an impact. Ultimately, an optimized helmet fitment (tightness and evenness) could help manage the energy transfer to the athlete’s head and reduce the incidence of concussion.

1.2 Background

The Centers for Disease Control and Prevention (2003) estimates that there are greater than 300,000 sport-related concussions that occur in the United States on an annual basis. More recently, Langlois et al. (2006) indicated that concussion incidence in the United States alone is approximately 1.6 - 3.8 million annually. Guskiewicz et al. (2000) reported that nearly 5% of all high school and intercollegiate football players sustain a concussion in a single season and approximately 15% of those sustain a repeat concussion. Pellman et al. (2004) reported an average of 0.41 concussions per game occurred over a six year span (1996-2001) in the National Football League (NFL). Biasca et al. (2005) have summarized the prevalence of concussion in ice hockey. Their summary indicated that, in four of the major hockey leagues throughout the world, concussion injuries constitute approximately 2 - 20% of all ice hockey injuries sustained. A study by Hootman et al. (2007) of National Collegiate Athletic Association (NCAA) athletes from 1988 to 2004 indicated Men's (American) football and ice hockey have some of the highest incidences of concussion. The actual incidence of concussion could be much higher than what is reported in epidemiological studies. McCrea et al. (1997) reported that 53% of high school-aged football players were suspected of not reporting their injury. Due to the focus on concussion awareness in the past decade, the reporting frequency may be somewhat higher than reported by McCrea.

The long-term effects of concussion or repeated concussions are not completely understood. However, the above statistics clearly indicate that, despite the ongoing research efforts, concussion remains a serious issue which needs to continue to be addressed either by increased protection, increased awareness, and/or rule changes in contact sports to prevent or limit the amount of direct head contact.

Two critical challenges for biomechanical engineers to design helmets to reduce the incidence of concussion are that:

1. The mechanism of concussion is not clearly understood, and
2. There is no universally accepted threshold for concussion.

Until recently, it had been thought that concussion only occurred with loss of consciousness. It has been shown that loss of consciousness does not need to happen for a concussion to occur (Cantu, 1996; Lovell, 1999). This results in more emphasis being placed upon diagnosis by the medical staff. Various tools (such as Standardized Assessment of Concussion, SCAT/SCAT2 and Balance Error Scoring System) are available to aid medical staff in diagnosis. Despite the available tools, a good set of baseline tests on the athletes prior to the start of a season can be a critical component for medical staff in assessing and protecting the athletes. These baseline tests are time consuming, and they can yield unhelpful results if the athlete is not forthright during the baseline test (Eckner, 2011).

A novel approach to acquiring data from athletes participating in contact sports has been developed. The Head Impact Telemetry (HIT) System (Crisco, 2002), consists of six non-orthogonally placed accelerometers with the ability to record data and to document the severity, location, and frequency of head impacts in football. It has also been proposed as a diagnostic aid to help medical staff identify substantial impacts that were sustained by the athlete in real-time and remove the athlete from play for further diagnosis. Various different validation studies and error rates have been reported for the original HIT System (Crisco, 2004; Manoogian, 2006; Duma, 2005; Funk, 2007; Funk, 2011; Beckwith, 2011). With the exception of one validation study (Manoogian, 2006), the validation of the HIT System was conducted using a medium-sized helmet on the Hybrid III headform. Manoogian (2006) utilized a large-sized helmet and exposed the Hybrid III headform to impacts ranging from 5 g to 50 g. Validation of a newer version of the HIT System utilizing 12 accelerometers has been reported (Rowson, 2007). Validation of the HIT System was generally completed by equipping the Hybrid III headform with a 3-2-2-2 accelerometer array (Padgaonkar, 1977) and computing the relative error between the reported HIT System data and the Hybrid III headform reported response parameters. Typical headform response parameters include peak linear acceleration (PLA) and peak angular acceleration (PAA). The HIT System is currently widely used, and it is reported that there have been over 1.5 million head impacts recorded to date (Rowson, August 2011).

Proposed Injury Thresholds

In efforts to establish an injury threshold over the past 70 years, many research studies have been carried out on cadavers, primates and/or animal surrogates in an attempt to assess thresholds for concussion in man. These have primarily focused on the head response parameters of linear or angular acceleration due to their relative ease of measurement. Testing conducted on animals requires scaling to correlate probability of injury in the animal to the probability of injury in a human. Cadavers cannot be assessed for concussion symptoms for obvious reasons. Hardy (Hardy, 2001; Hardy, 2007) has conducted impact testing on cadavers to measure brain motions relative to the skull. In his testing, he utilized a biplanar high-speed x-ray system during the impact and monitored the motion of Neutral Density Targets (NDT's) that had been implanted into the brain. Hardy (Hardy, 2001) reported on impacting 3 cadaver heads with a total of 10 impacts in the frontal and occipital regions. Hardy (Hardy, 2007) reported on an additional 35 impact tests conducted on 8 cadaver heads. Some of the cadaver heads in these testing impacts were helmeted and some unhelmeted. Based upon his two series of tests, he reported that angular speed was the most "convenient" measure for comparison with brain displacement. In 2007, he reported peak coup pressure and pressure rate increased with increasing linear acceleration, and no pressure parameters varied with angular acceleration. However, both peak average maximum principal strain and maximum shear decrease with increasing linear acceleration. In the helmeted impacts, linear and angular acceleration were reduced. With a helmet on the cadaver head, angular speed or brain displacement was not reduced, and strain increased. A measurement or study regarding the effects of head size was not presented.

Contact sports such as football and/or ice hockey provide a promising source for research into the thresholds for concussion. These players are voluntarily participating in high energy impact events. Recent research was conducted by the National Football League (NFL) Subcommittee on concussions (Pellman et al., 2006b) in which various player-to-player and player-to-ground collisions were reconstructed using Hybrid III Anthropometric Test Devices (ATD). The Hybrid III head was reportedly fitted with a large-sized helmet (Pellman et al., 2006a; Newman, 2005) for the reconstruction. The worst-case error with this reconstruction-based method was reported to be up to 17% for peak linear acceleration and up to 25% for peak angular acceleration. These collisions were also simulated using the Wayne State University Head Injury Model (WSUHIM) (Zhang et al., 2004; Viano et al., 2005) to compute tissue level responses that correlated to brain injury. In this model, the skull was assumed to be rigid. It was reported (Viano et al., 2005) that the simulations indicate that concussion is related to brain deformations occurring after the initial impact and that strain and strain rate responses correlated with concussion injuries and symptoms. Strain and strain-rates were higher in these simulations for impacts to the frontal oblique impacts on the facemask and shell. The simulation results also indicated that shear stress in the upper brain stem was most sensitive to rotational acceleration. Furthermore, it has been shown that human tolerance to rotational acceleration alone is quite high (Pincemaille et al., 1989).

If linear and angular acceleration, or functions based upon these accelerations, are the correct response metrics for establishing a concussion threshold, it appears that some combinations of linear and angular acceleration are essential for brain injury to occur. Zhang (Zhang et al., 2004) and King (King et al., 2003) proposed potential injury thresholds based upon the NFL research to be a 50% probability of injury when linear accelerations were 82 g and 79 g and rotational accelerations were 5900 rad/sec^2 and 5757 rad/sec^2, respectively. This study may have been biased to the injurious level since it did not consider all non-injurious impacts; therefore, it may underpredict the threshold of human tolerance to concussion. Alternatively, the study was conducted on professional athletes who may have a higher threshold to injury than collegiate- or high school-aged athletes (Viano et al., 2005). The threshold utilizing this method and linear acceleration as the metric is similar to previously proposed Injury Assessment Reference Values (IARV's) for concussion (Ono et al., 1980; Lissner, 1960).

Guskiewicz (Guskiewicz et al., 2007) and Funk (Funk et al., 2007) have also reported acceleration response parameters in which human concussion occurred. The acceleration response parameters had been recorded by HIT System equipped helmets of Collegiate Football Players (NCAA). The accelerometer data were transmitted in real-time from the helmet-mounted accelerometers to a telemetry system stationed on the sidelines. Guskiewicz (Guskiewicz et al., 2007) reported concussions occurred to 13 players over a 3 year period at linear accelerations ranging from 60 g to 169 g and angular accelerations ranging from 163 rad/sec^2 to 15397 rad/sec^2. They do not comment on the number of non-injurious impacts; however, they indicate that less than 0.35% of all impacts which resulted in greater than 80 g linear accelerations resulted in concussion symptoms. Funk

(Funk et al., 2007) have proposed preliminary IARV's which result in a 10% probability of concussion as being a peak linear acceleration of 165 g and a peak angular acceleration of 9000 rad/sec^2. Funk indicates that angular acceleration values were calculated and they should be used with care. Funk (Funk et al., 2007) have also considered non-injurious impacts in their reporting. There were a total of 27,000 impacts in their study, four of these impacts resulted in concussion symptoms. This study suggests substantially higher IARV's than previous research. The helmet-mounted accelerometers may play some role in these higher values since they are fastened to the helmet and not to the athlete's head. Additionally, there is no discussion on how the study had measured and/or monitored the fit of helmets on the volunteers. More recently, Rowson (Rowson et al, 2011a) has analyzed greater than 300,000 impacts (286,636 using the HIT System and 14,341 using the Six Degree of Freedom [6DOF] measurement device): 57 concussive impacts were recorded using the original version of the HIT System (vs. 6DOF update), linear accelerations were recorded, and angular accelerations resulting in concussions were estimated.

Additionally, various other research studies have been reviewed which have reported peak linear and angular accelerations (Ewing et al., 1976; Ewing et al., 1975; Ewing et al. 1972; and Muzzy et al., 1976) during human volunteer tests. These volunteers were Navy personnel who were subjected to varying severities of frontal and lateral impacts. The volunteers in this study did not sustain head impacts, and no injuries were reported. Head accelerations of up to 40 g and approximately 2800 rad/s^2 were reported. Accelerations of typical daily activities have also been reported (Vijayakumar, 2006).

These acceleration levels were substantially lower, with linear head accelerations of up to 7 g and resultant angular accelerations of approximately 300 rad/s^2.

Pincemaille (Pincemaille et al., 1989) reported on head response parameters from amateur, volunteer boxers. There was no concussion in one subject who sustained an angular acceleration of 16,000 rad/s^2. In relation to football impacts, it has been demonstrated that Olympic caliber boxing punches tend to produce lower linear accelerations and higher rotational accelerations (Viano et al., 2005) which is likely due to the lower effective striking mass and smaller diameter of the boxing glove relative to the football helmet.

The above acceleration levels demonstrate the severity of impacts (particularly the football studies) which result in some probability of concussion. An analysis of the available head acceleration data is illustrated in **Figure 1.2.1**. This plot also illustrates various proposed injury thresholds based upon linear and angular acceleration values.

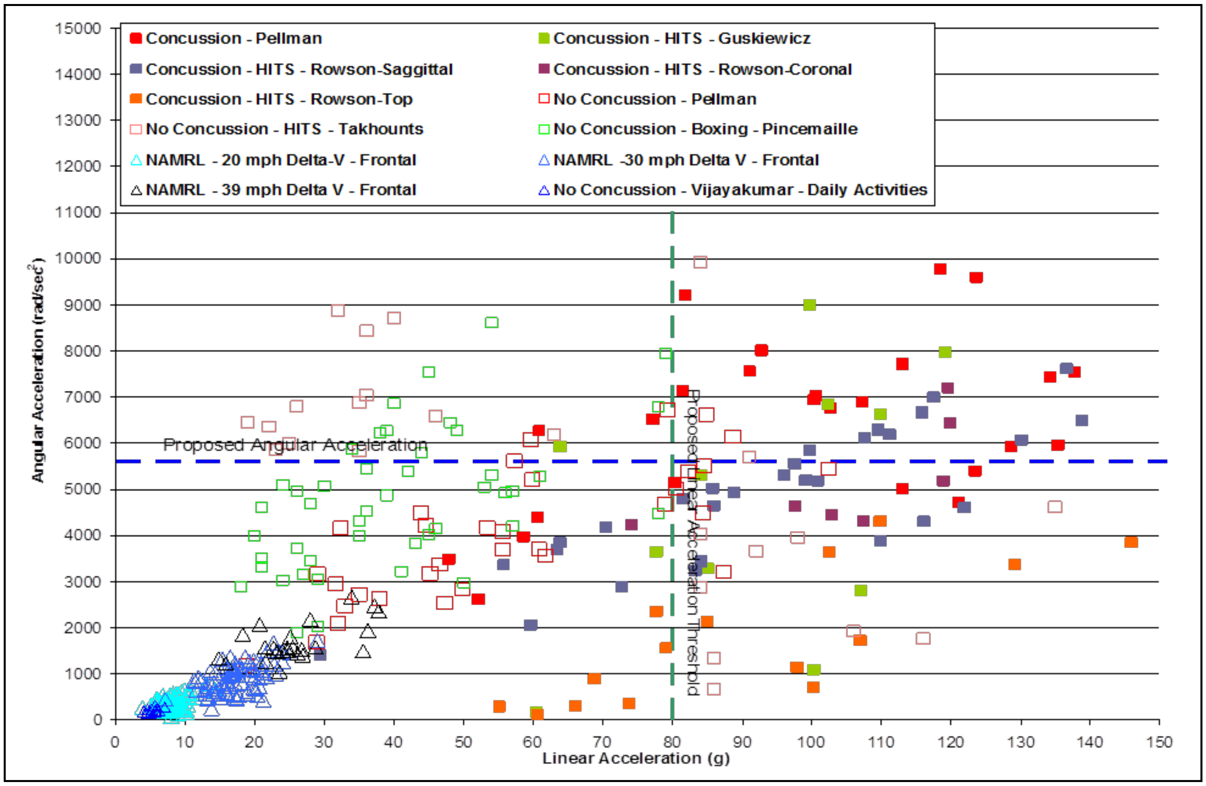


Figure 1.2.1 – Analysis of Human Volunteer Head Acceleration Data

Helmet Design

Helmets are commonly used in sporting activities to provide protection from injury. In football, hockey, and bicycle riding, helmets are generally used to provide protection to the head from impacting the ground/ice, the boards, or another player. In hockey, baseball, lacrosse, and cricket, they also must provide protection against ball and puck impacts.

Two of the primary design criteria for helmet protection (Newman, 1993) are to:

1. Cushion loading to the head, and
2. Spread the load over a larger area.

These design goals are similar to Eppinger's "*Maxims for Good Occupant Restraint Performance and Design*" (Eppinger, 1993), wherein he indicates it is desirable to:

1. Maximize the time over which the restraint forces are applied,
2. Apply as great a restraint force as soon as possible, and
3. Distribute forces over the greatest area.

The general intent is to distribute a focal load over a larger area. The primary design criteria are generally achieved by designing a helmet with a hard, rigid plastic shell adhered to an energy-absorbing material to dissipate the energy and spread the load over the player's head **(Figures 1.2.2a and b)**. Some newer helmets also have a comfort liner between the head and the energy-absorbing material to improve on helmet comfort and, possibly, fitment. Depending on the type of impact for which the helmet is designed, there may be substantial differences in the energy-absorbing material that is utilized. A bicycle helmet has a stiff and crushable energy-absorbing material which is designed to crush and absorb energy if the impact forces exceed its threshold. As a result, the bicycle helmet may have to be discarded after a substantial impact. Football, hockey, and baseball helmets are designed for repeated impacts, and the energy-absorbing material must maintain its properties over the expected life of the helmet.

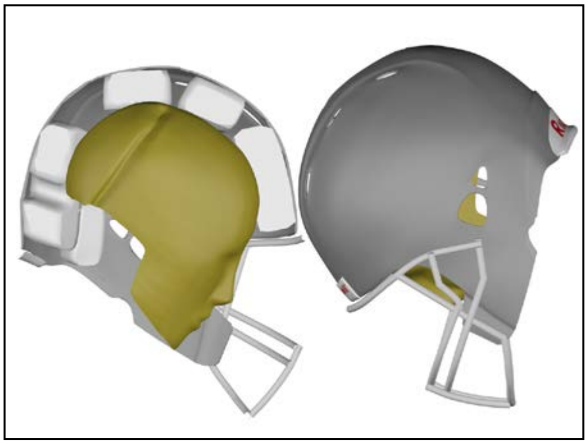


Figure 1.2.2a – Initial Contact

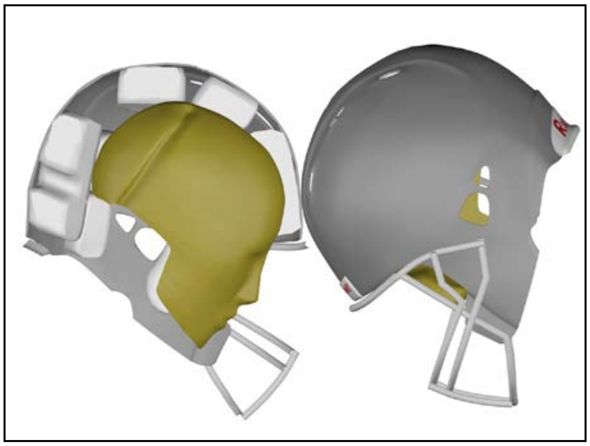


Figure 1.2.2b – Spreading of Impact Load

Based upon the above, a good-fitting helmet is critical to helmet performance and is also critical for the helmet to effectively spread the loading over the largest area. It is apparent from the helmet fitting instructions that the manufacturers recognize the importance of a properly fitting helmet. However, the helmet fitting guidelines are subjective, and there is currently no objective method of documenting helmet fitment. Additionally, current helmet testing standards record a response parameter from the headform (Gadd Severity Index - GSI) and a pass/fail criteria must be met (National Operating Committee on Standards for Athletic Equipment [NOCSAE]). These testing standards are not actually measuring the ability of the helmet to spread the load over a larger area.

With current advances in sensing and wireless technology, the HIT System uses the helmet to acquire acceleration data and compute potential injury predictors from impacts sustained during practice and game situations. This impact information has been utilized to propose concussion injury thresholds, identify areas and frequencies of impacts, and direct future helmet design (www.riddell.com, 2011). If a helmet is to be used as a device to measure head response parameters and to derive a concussion injury threshold, then the interaction between the head and the helmet (boundary conditions) must be identified, quantified, and understood. Only if these boundary conditions are well understood can a helmet's performance be designed to reduce response parameters in an impact event. When a helmet is placed onto an athlete's head in a non-impact condition, there are two major boundary conditions:

1. Retention (chin strap design and tightness), and
2. Helmet-Head Fitment.

The above two parameters likely have some inter-relationship. Previous research has been conducted to study chin strap design (Craig, 2007). This research indicated that jaw loading from the chin strap correlated with headform response parameters. It identified the need for further research to be conducted into the area of chin strap design.

Based upon a review of published research into the area of helmet design and protection, there is virtually no published research in the area of helmet fitment. Despite this, it is published in helmet fitting guides that a properly fitting helmet is of importance. As discussed, it is also recognized that one of the primary design parameters of the helmet is to spread the impacting load. The impact load will not be spread evenly if the helmet is not fitted evenly. There are various possibilities as to why research into fitment has not been extensively published in research. Two potential possibilities are:

1. The lack of an objective method to quantify or measure fitment.

2. Variability in human head size and shape, in conjunction with length of hair, creates many variables to control and analyze with precision.

Despite the above, various football (and hockey) helmets on the market today have air-filled bladders and/or other types of comfort-fit liners which assist in improving the comfort and, potentially, the fit of a helmet. The increase or decrease in helmet performance as it relates to fitment does not appear to be well understood. There are no objective methods available to measure and quantify scientifically the fitment of a helmet on an athlete's head and/or to quantify the ability of the helmet to spread an impact load.

The human head has various sizes and shapes. Therefore, to achieve a proper fit on each athlete, the helmet must be specifically fitted to that athlete. Sports helmets are designed so that one size of helmet (i.e., S, M, L, XL) is expected to accommodate a variety of head shapes for a given size. Since each athlete's head breadth, circumference, length, shape, and hair quantity can vary substantially, it is apparent that the contact pressure (tightness of fit) and pressure distribution (evenness of fit) between the helmet and the head can vary substantially within users of the same helmet size.

Research studies working toward the development of a concussion threshold commonly use the head of a 50th percentile Hybrid III anthropometric test dummy as a human surrogate. Measurements of the response parameters of the headform are then used to assess the protective capability of the helmet. The NFL Subcommittee research reportedly used a <u>large</u>-sized Riddell VSR4 helmet on the 50th percentile Hybrid III headform (Pellman et al., 2006a). The HIT System (Crisco, 2002) was developed as a method to acquire substantial amounts of data from football players participating in game and practice situations. However, a <u>medium</u>-sized helmet was fitted to the Hybrid III headform for much of the published validation of the HIT System (Beckwith et al., 2011; Rowson et al., 2011). To validate the HIT System, the headform data were compared to the HIT System data to validate results reported from helmet-mounted sensors versus reported headform accelerations. However, what is missing from these studies is the quantification of the helmet's fitment to the headform and how that fitment compares to that of athletes in the field. It is anticipated that fitment will affect the performance of the helmet and the ability of the HIT System to predict head response parameters accurately.

1.3 Specific Goals

The goals of this research project are to:

1. Develop an objective method of measuring helmet fit,
2. Document the fit of football helmets in a field study,
3. Assess the appropriate-sized helmet to be worn by the Hybrid III headform,
4. Assess the effects on helmet performance of varying tightness and evenness of fit, and
5. Assess the effects of helmet fitment on HIT System-reported impact response data versus Hybrid III headform-reported impact response data.

Chapter 2 – The FIT Cap - A Method of Objectively Measuring Helmet Fitment and Helmet Performance in an Impact Event

2.1 Introduction

Two of the primary design criteria for helmet protection (Newman, 1993) are to cushion loading to the head and to spread the load over a larger area. Based upon these criteria, a “properly fitting helmet” is essential to optimize helmet performance. The fitting of football helmets was discussed (Gieck et al., 1980), and it was indicated that the helmet should “fit snugly” and there should not be excessive movement of the helmet on the head. Gieck indicates that players should report an unsatisfactory fit to team staff.

Manufacturer helmet fitting instructions are available along with the purchase of a helmet. However, similar to the guidelines above, the helmet fitting guidelines are subjective, and there is no objective method of measuring helmet fitment. For example, football helmet fitting instructions for helmets with inflatable bladders have the following general fitting procedure: 1) Measure the player’s head circumference using a cloth tape measure, 2) Select the proper helmet size based upon the measured circumference, 3) Inflate the air bladder until the helmet fits snugly or properly, and 4) Check for proper fit by rotating the helmet on the wearer’s head; the helmet should not rotate on the wearer’s head (Adams USA, 2005; Riddell, 2010). The helmet should also sit approximately 1” above the eyebrows of the athlete.

These fitting methods are subjective for a variety of reasons. Since the helmet has an inflatable bladder, there is inherently a second person such as a trainer or equipment manager that must be involved in the fitting procedure. Each team would have different individuals fitting helmets to the players; therefore, there is a subjective criterion for "proper" or "snug" fit for each individual. Secondly, a tight fit does not ensure the helmet is fitting evenly or uniformly. The fit may fulfill the requirements of not rotating on the player's head but this does not assure that the fit is uniform. In these fitting instructions, there is no objective metric that is recorded or monitored to assure that the helmets are maintaining a "proper" fit. If the air volume changes in the inflatable bladders, the helmet fitment will also change.

Additionally, current helmet testing standards record a response parameter from the headform (Gadd Severity Index) and a pass/fail criteria must be met (www.nocsae.org). These testing standards are not measuring the ability of the helmet to spread the load over a larger area.

The purpose of this research was to develop an objective method of quantifying helmet fitment and to assess how helmets fit the athletes who wear them.

2.2 Materials

2.2.1 The Measurement System

There are various methods that could be undertaken to assess how football helmets typically fit. The approach taken for this research was to conduct a field study. To quantify helmet fit effectively, various athletes were measured while wearing the helmet that had been provided to them and reportedly fitted by team personnel per the manufacturer's fitment instructions. This "fitment" data could then be used to assess how helmets are typically worn in the field.

The purpose of this research was to obtain fitment data without significantly altering the existing fitment of the helmet. The chosen measuring technique would have to be a portable device that is not helmet dependent and would allow for efficient measurement and analysis of data in the field. The measurement technique must also be rigorous and responsive enough to withstand the contact forces associated with an impact testing environment. The metric chosen to assess the fitment of a helmet was the measurement of pressure (forces) at the helmet/head interface. Based on the available instrumentation and sensing technology, there are two general methods that were considered, these included; Pressure sensitive paper and Tactile force/pressure sensors.

Pressure sensitive paper is readily available and affordable; however, to analyze the data, specialized equipment is required and real-time analysis cannot be conducted in the field. The pressure sensitive paper would also require each helmet tested to be retrofitted with the paper. This is time consuming, causing this method of measurement to be impractical for the present study.

The pressure sensitive paper is available in a limited range of sensitivities. Subsequent to trial testing, it was felt that the sensitivities available were unsuitable for this testing.

An alternative to pressure sensitive paper is tactile force/pressure sensors. These sensors allow variable sensitivities, discrete measurement locations, and real-time analysis of the data. The advantages of using a tactile force/pressure measurement system include:

i) Customized real-time analysis of data,

ii) Efficient measurement and analysis, and

iii) The possibility of constructing a scalable system that could be used for static helmet fitment measurements as well as in a dynamic impact environment.

There are various types and models of tactile force/pressure measurement devices available. The measurement device chosen for this analysis was the *"Flexiforce™"* sensor (Tekscan, South Boston, MA). This sensor was the thinnest sensor available at the time of this research. The Flexiforce incorporates resistance-based technology. A voltage is applied to the sensor and, as a force is applied to the sensing area, the resistance of the sensing area is changed. The resistance is inversely proportional to the force applied. When a signal conditioning unit is assembled to the sensor, the output from the sensor is a voltage that changes linearly with force. The sensor chosen for this study had a sensing area with a 9.5 mm diameter. The sensitivity of the sensor and full scale output can be further scaled by hardware signal conditioning. To construct the signal conditioning hardware for the sensor, we fabricated a custom Printed Circuit Board (PCB). The PCB incorporated a toggle switch for each sensor which allowed the user to switch between a low level input and a high level input. This toggle switch was added to assure that the sensors being used were sensitive enough to measure extremely low level measurements that could be encountered during static fitment measurements versus higher level inputs during the impact testing of a helmeted headform.

The physical characteristics of the sensor were found to be optimal for this study; the sensor thickness was 0.208 mm, and it could be cut into varying lengths. The sensor sensitivity was adjustable, linearity was < +/- 5%, and temperature sensitivity was 0.36%/degree C. The sensors provided a high level voltage output that was linearly related to the force (or pressure) applied. The sensor also had a response time of < 5 µs which is suitable for impact testing.

The sensors were modified by adhering plastic shims to the sensing area of each individual sensor. This distributed the measurement over the entire sensing area, producing better linearity and reducing the risk of damaging the measuring area of the sensors. To construct these shims, we utilized plastic shim stock (thickness = 0.635 mm). The shims were created using a punch to a repeatable diameter of 9 mm. They were then adhered to one side of the sensor using a spray adhesive (3M Canada, London, Ontario, Canada). The side of the sensor with the small plastic shim adhered to it would be facing the volunteer's head. The plastic shim eliminated variability in measurements due to hair density and coarseness. It also created a measurement surface for the sensor that was consistent for all tests. This shim was of a small diameter to provide a discrete measurement location and minimize any uneven loading effects that curvature of the skull may cause.

A larger diameter (25 mm) shim (thickness = 0.3125 mm) was adhered to the opposite side of the sensing surface (facing the helmet). The larger diameter shim was used to improve the likelihood of the sensor coming in contact with one of the various pads within the helmet and to reduce the potential for damage to the sensors. The overall thickness of this sensor assembly was approximately 1.2 mm **(Figure 2.2.1)**.

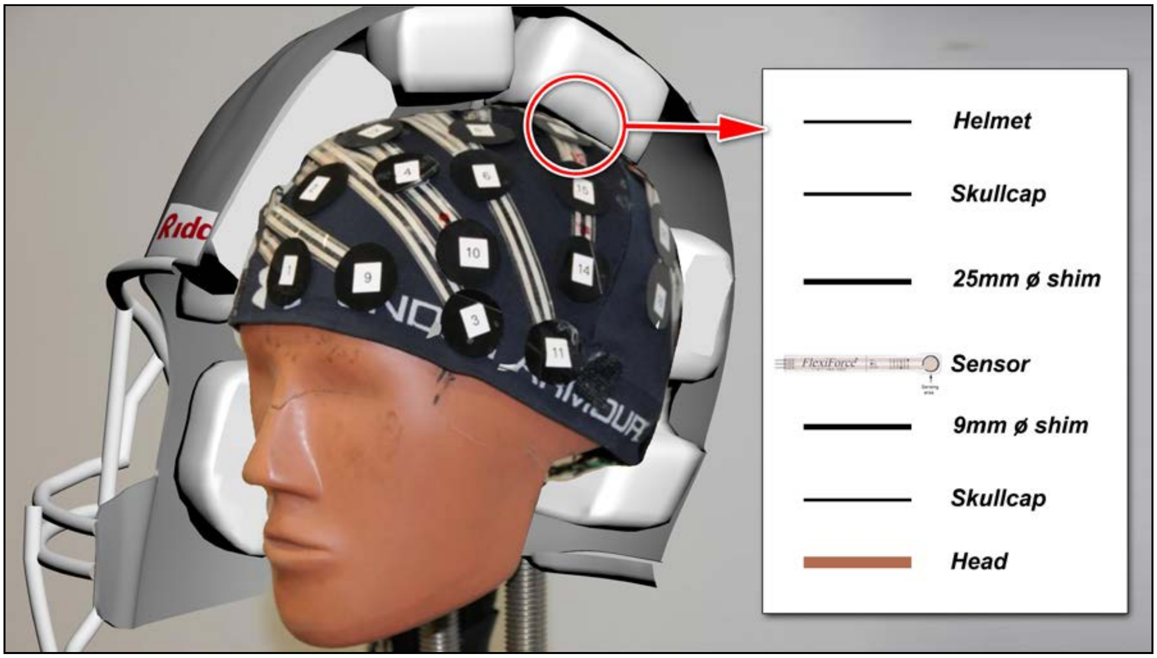


Figure 2.2.1 – Pressure Sensor Assembly

The sensor data were acquired using a 16-bit High Speed Measurement Computing Data Acquisition board (USB HS-1616) (Norton, MA). A computer program was written for acquiring sensor data during sensor calibration. The program acquired sensor data at a rate of 100 Hz for 10 seconds and computed the average reported voltage. To calibrate the sensors and convert voltage readings to Engineering Units (EU), we first connected them to their corresponding channel in the signal conditioning circuit as well as to the data acquisition board. These were labeled and remained dedicated to those channels for the duration of this research.

The calibration procedure consisted of incrementally loading the sensor with known masses. The calibration procedure was repeated three times for each sensor. The calibration weights were custom machined steel masses (of approximately 2.36 N [0.53 lb]), and were initially weighed using a laboratory scale accurate to within 0.1 g (0.001

N). Each sensor was calibrated in the range of 0 to 15 N. The sensing area was 71.26 mm^2 (based on a diameter of 9.5 mm). Therefore, the sensors had a pressure range of 0 to 210 kPa. This range was chosen based upon trial fitting of various helmets onto a volunteer. Linear curve fits were computed using Microsoft Excel, and the calibration for each sensor had good linearity (all $R^2 > .98$, Typically $R^2 > .99$). The calibration of the sensors was completed at a temperature of 22˚C (72˚F).

The manufacturer's specification for these sensors reported a linearity of 3%. To assess the linearity error of the sensors in this measurement environment, the data from the sensor calibrations were analyzed. This was done by comparing the 3 sensor calibration curves for each sensor. The study indicated the average linearity error for each of the individual sensors was less than +/- 2% (95% confidence). The maximum error for each sensor was less than 7% (95% confidence). The maximum linearity error always occurred at the extreme low-end of the calibration curve.

2.2.2 The FIT Cap

The sensors were incorporated into a *Skull Cap* (Under Armour, Baltimore, MD). The *Skull Cap* assembled to the measurement apparatus is referred to as the FIT Cap for this research. It was assumed that each volunteer's head would generate a symmetrical pressure distribution within the helmet; therefore, 24 sensors were assembled to, and covered half of, the *Skull Cap*. The nylon construction and portability of the *Skull Cap* allowed the FIT cap to be compliant to different volunteers' heads and also easily transferable from volunteer to volunteer. Since the FIT cap stretches differently when worn by various volunteers, maintaining constant sensor spacing was not possible. The sensor array was established using a Hybrid III headform with the sensors having a 50 mm centre-to-centre spacing. **Figure 2.2.2** illustrates the sensor array of the FIT cap. **Figure 2.2.3** illustrates a computer model of the sensor array on the Hybrid III headform and the projected sensing locations on a football helmet.

Figure 2.2.2 – FIT Cap

Figure 2.2.3 – FIT Cap Sensor Positions Projected onto Helmet

The design of the FIT measurement system allowed for a large amount of sensor data to be acquired (24 sensors). It was portable and transferrable from volunteer to volunteer for this study. A custom computer program was written to acquire the sensor data (Appendix A). The program was approximately one thousand lines of code and allowed for the input of various data elements, selection of sensitivity, zeroing of sensors, acquisition, and real-time review of sensor data as well as the saving of data. The program was written with a Graphical User Interface (GUI) so the data could be input and acquired easily while taking measurements in the field.

The FIT cap design and construction, coupled with the customized computer program, fulfilled the goal of this research project in developing an objective method of measuring force between the head and the helmet, and the FIT Cap provides a possible method of quantifying helmet fitment. The FIT cap is also capable of monitoring the helmet's ability to distribute the load during an impact event.

Since it was the intent for volunteers to wear the FIT cap, there was a potential for temperature to affect the readings because of the body temperature of the volunteers. The procedure (described in **Chapter 2.3.3**) would result in the FIT cap being worn by the volunteer for less than one minute; therefore, the temperature change of the sensor would likely be minimal. An uncertainty analysis was conducted to assess for potential temperature effects. The uncertainty analysis included the following assumptions:

- Linearity Error: 2% typical (7% maximum)
- Maximum temperature: 32 to 37˚C
- Temperature Sensitivity: 0.36%/˚C
- Calibration temperature: 22˚C

Based upon the maximum linearity error (7%) and the maximum temperature effects (ΔT_{MAX} = 15˚C), the maximum measurement uncertainty was calculated to be less than 9%. If the more typical linearity error was utilized for this calculation (2%) and field data regarding temperatures between padding and head is considered, the maximum temperature was likely less than 32˚C (Farquhar et al. 1998 – from Appendix D). Based upon a linearity error of 2% and a ΔT = 10˚C, the typical measurement uncertainty was calculated to be 4.1%. Due to the short amount of time that the FIT Cap would be on volunteer's heads, it is unlikely the sensor temperature would reach 37˚C. Therefore, it is very likely the uncertainty in the measurements was less than the maximum calculated of 9% and more likely in the range of 4%.

2.3 Methods – Field Study on Helmet Fitment

2.3.1 Volunteers

Various football teams belonging to the Essex Ravens Football Club (Ontario Varsity Football League [O.V.F.L.]) were asked to provide the volunteer data. The players on the football teams ranged from 14 to 20 years old and belonged to three separate teams (Junior, Junior Varsity, and Varsity). There were no identifiers recorded to provide any link between the volunteer and the data recorded. The measurements took place during spring training for the teams (April 27th, 28th, and 29th 2010). The players' helmets had each been fitted to the players by the Director of Football Operations and the Equipment Manager three weeks prior to the testing. This fitting procedure was reportedly completed by following the helmet fitting instructions provided by the helmet manufacturer.

Volunteer testing requires approval of the Wayne State University Human Investigation Committee (HIC). The necessary human investigation courses were completed and a research proposal was then submitted to the HIC. An expedited approval was granted (Appendix B).

The FIT cap (**Chapter 2.2.2**) was utilized to obtain measurement of the pressure between the volunteers' heads and the padding of the helmet. Data for the volunteer testing was acquired using the Measurement Computing (USB 1616-HS) Data Acquisition board. The data sampling rate used was 100 Hz, and sensor data was averaged over a 10 second period. The averaged measurements were reported as a pressure.

2.3.2 Helmet Fitment Metrics

The metric chosen for quantifying helmet fitment was pressure. There are no previously defined objective measures to quantify helmet fitment. Based upon the design objectives of a helmet, it is thought that there are two important parameters that should be maximized to result in a helmet fitting properly. It should:

1. Fit Evenly: This will optimize the helmet's ability to spread the load over the athlete's head.
2. Fit Tightly: This will assure that the helmet begins spreading the load immediately and also assist with helmet retention.

A third parameter that is of importance is the ability of the helmet to fit the athlete comfortably. An uncomfortably fitting helmet may erroneously cause the athlete to select a larger size. Based upon the above, it appears the optimal fitting helmet would be a perfectly evenly fitting helmet (i.e., uniform pressure on the athlete's head) that is fitted as tightly as possible while still remaining comfortable. Based upon the above, it was necessary to derive a measurement index to quantify helmet fit. As a result of the above design criteria, the Average Fit Index (AFI) was developed. The AFI was developed to quantify the helmet's ability to fit an athlete evenly and comfortably. There are three components which make up the AFI:

1. Compute the average pressure of all the sensor data of each volunteer, herein referred to as P_{AVG} [kPa],
2. Compute the standard deviation (SD) of the sensor readings, and

3. Compute the maximum sensor pressure for each volunteer, herein referred to as the P_{MAX} [kPa].

The average fit index (AFI) is defined as:

$$AFI = \frac{P_{AVG} \pm SD}{P_{MAX}} \ldots\ldots [unitless]$$

The above relationship is presented as a means of quantifying how evenly a helmet is fitting the volunteer. A perfectly evenly fitting helmet would have an AFI = 1 ± 0. This means that each sensor has the exact same reading. This relationship was developed with the P_{MAX} as the denominator. A more appropriate denominator can be the maximum “comfortable” pressure as reported by the volunteer athletes. If the maximum comfortable fitting helmet could be defined, then the AFI could reach values of greater than 1, indicating a helmet is fitting too tightly. However, there is currently no objective baseline data to establish at what tightness a helmet becomes “too tight”.

In addition to the above parameters (P_{AVG}, P_{MAX} and AFI), a pressure distribution mapping of the helmet pressure on the volunteer’s head was also completed for each volunteer.

2.3.3 Procedure

On the dates of the study, athletes were randomly approached and asked if they would participate. The information sheet was reviewed once again with the athlete. The athlete was then asked if there were any questions and if they would like to continue to participate in the study. If the athlete chose to continue, the procedure was:

1. Record the helmet make, model, size, player position, and head circumference (for some participants).
2. The FIT cap was then put on the athlete's head and aligned so the centre line of the FIT cap was approximately in line with the sagittal plane. The sides of the FIT cap were stretched downward to the ear, the rear of the FIT cap was stretched downward to just below the occipital condyle, and the front was pulled down to approximately 2.5 cm above eyebrow level.
3. The FIT cap sensors were zeroed.
4. The players were asked to a put on their helmets as they normally would in a game situation and to secure all chin straps as they normally would.
5. Immediately upon securing the chin straps, measurements were started. The measurements were taken over a 10 second interval at a sampling frequency of 100 Hz and an average value was computed.
6. A bar graph indicating the evenness and tightness of fit was observed immediately upon completion of the measurements. This allowed for real time visualization of the individual measurements.
7. The helmet and FIT cap were then removed and the athlete returned to the field to resume training.

2.4 Helmet Fitment Results – Volunteer Testing

A total of 75 football players were tested. After reviewing the data, 63 of the 75 participants were deemed to have usable measurements. A testing issue was encountered on day 1 of the testing where the batteries for the FIT cap unknowingly became discharged, resulting in "no data" for the last 12 volunteers on that day.

Each of the volunteers was wearing a Riddell football helmet. There were 50 Riddell Revolution, 8 Riddell Revolution Speed, and 5 Riddell VSR4.

Due to the time constraints during the volunteer testing, the head circumference measurement was omitted after the first day of the testing since it was delaying the throughput of volunteers. As a result, the first 20 volunteers' head circumferences were measured. Each of the 20 volunteers measured had the appropriate sized helmet for the measured head circumference per Riddell Helmet fitting instructions.

A large amount of measurement data was acquired (63 volunteers x 24 sensors = 1512 data points). The approximate sensor positions from the FIT cap are superimposed upon a model of the Hybrid III headform and illustrated in **(Figure 2.4.1)**. The individual sensor data for all participants is shown in **Figures 2.4.2a and b**.

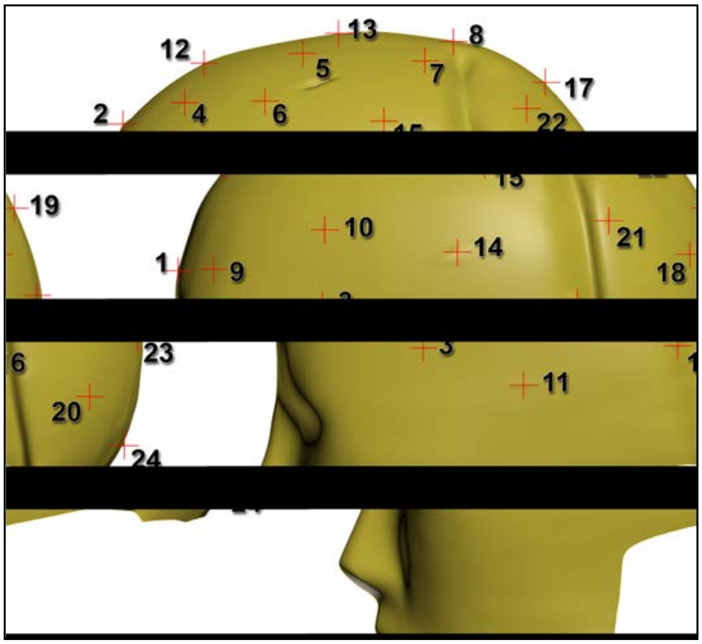


Figure 2.4.1 – Sensor Positions

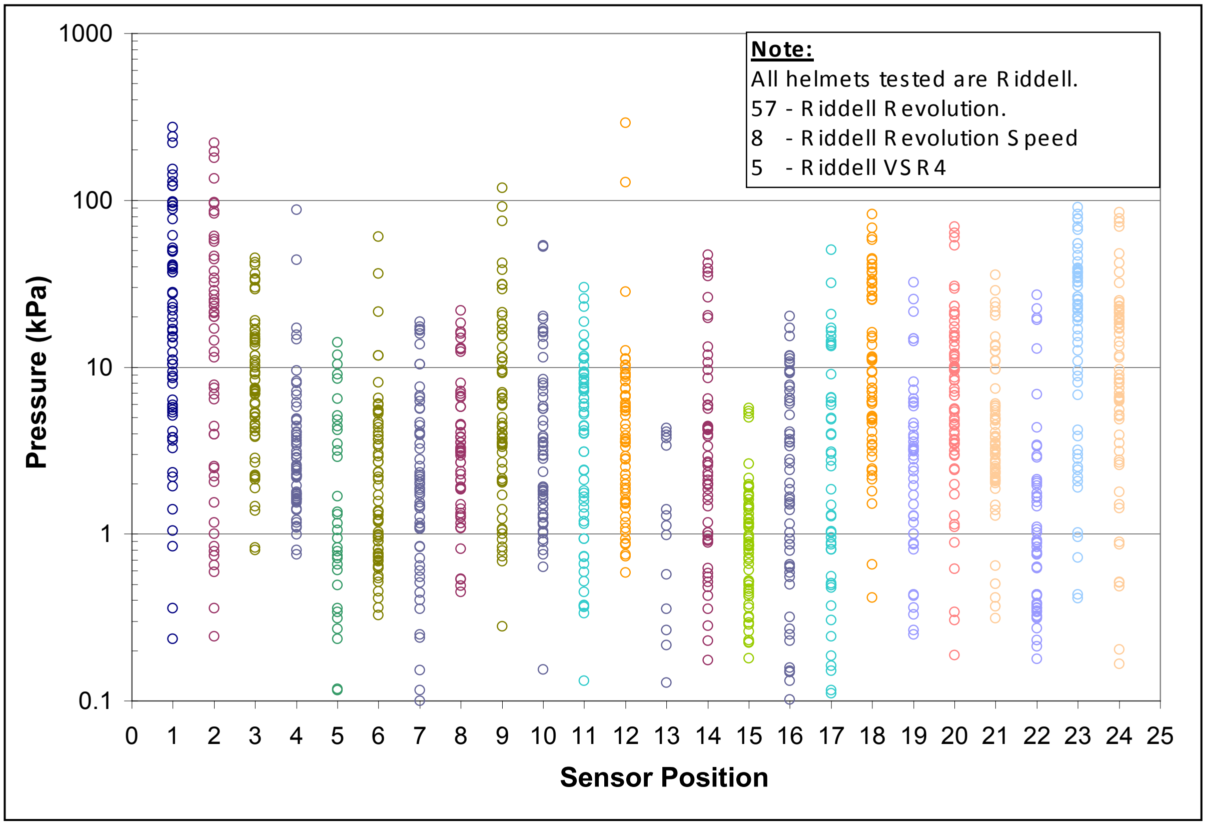


Figure 2.4.2a – Summary of Volunteer Data by Sensor Position

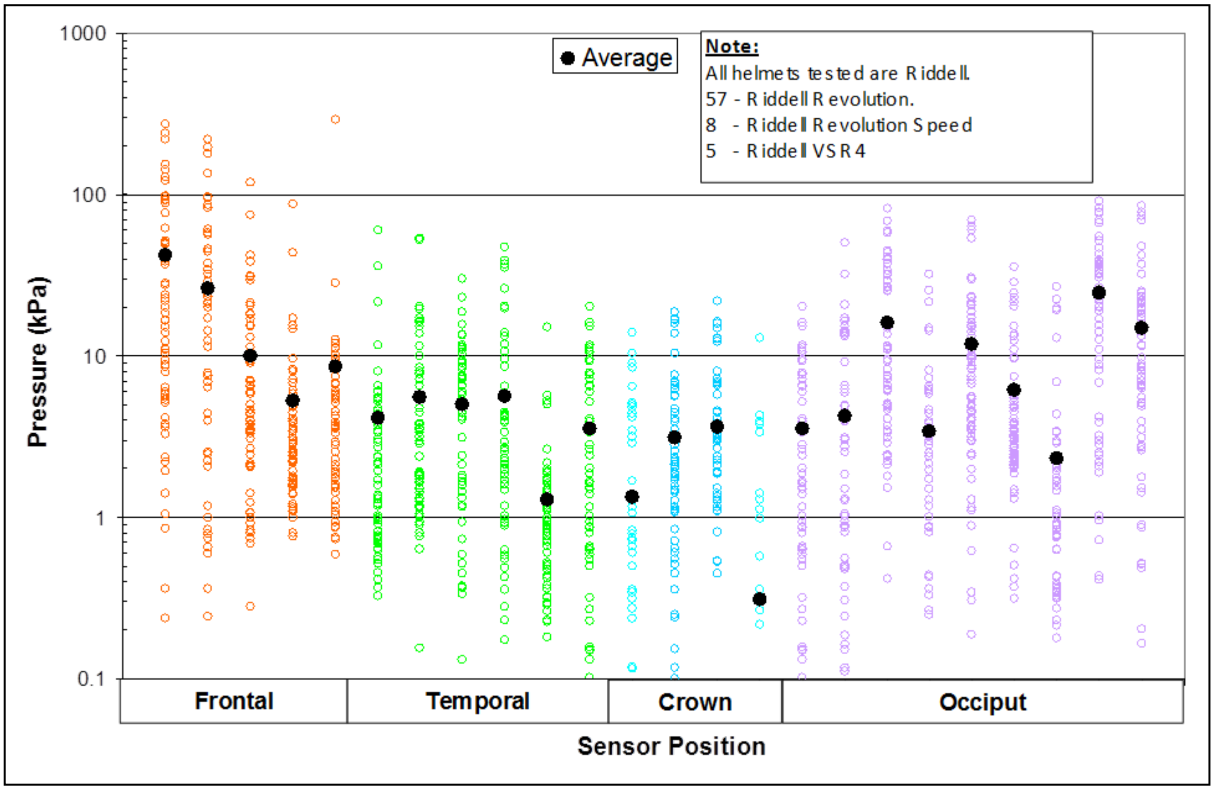


Figure 2.4.2b – Summary of Volunteer Sensor Data by Location

The FIT cap has 24 sensors on the left side of the cap. No pressure readings were taken on the right side of the head since it was assumed that the pressure distribution would be symmetrical. To visualize the pressure distribution on the headform, a linear interpolation between data points was applied. The 25th, 50th, 75th, and 95th percentile pressure maps of all the volunteer data are illustrated in **Figures 2.4.3 to 2.4.6.** Each illustrates a similar trend, showing higher pressure areas in the frontal and occipital regions. Appendix C includes a pressure map of the sensor data overlaid onto the computer model of the headform for each volunteer.

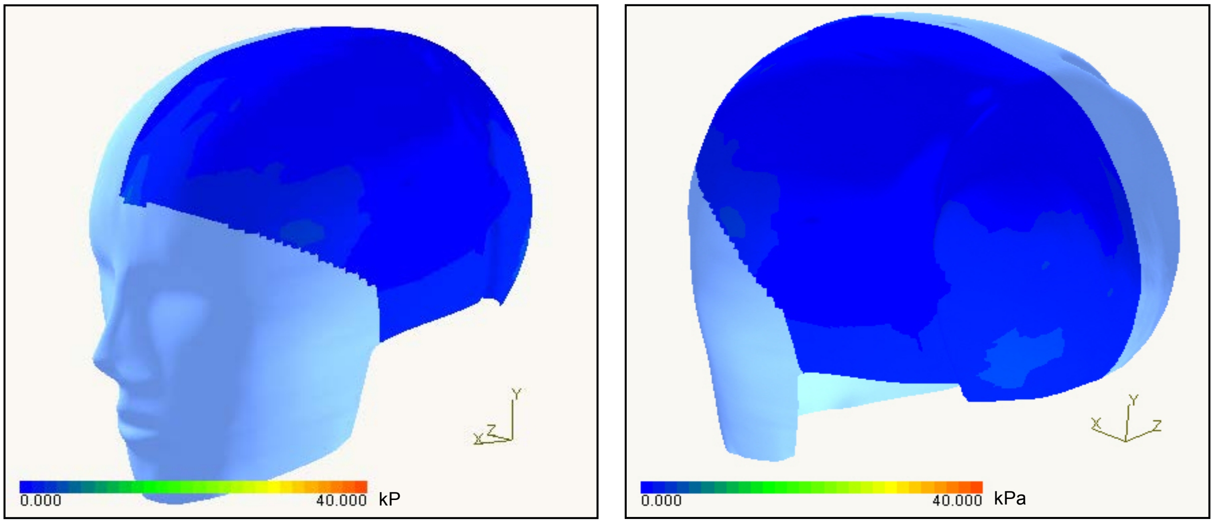


Figure 2.4.3 – 25th Percentile Volunteer Pressure Distribution

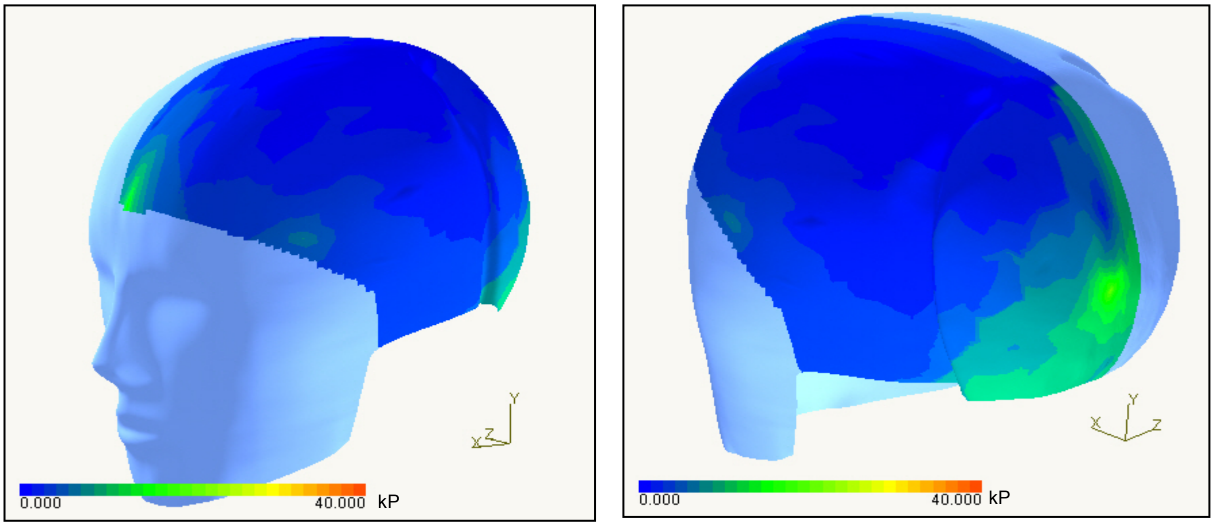


Figure 2.4.4 – 50th Percentile Volunteer Pressure Distribution

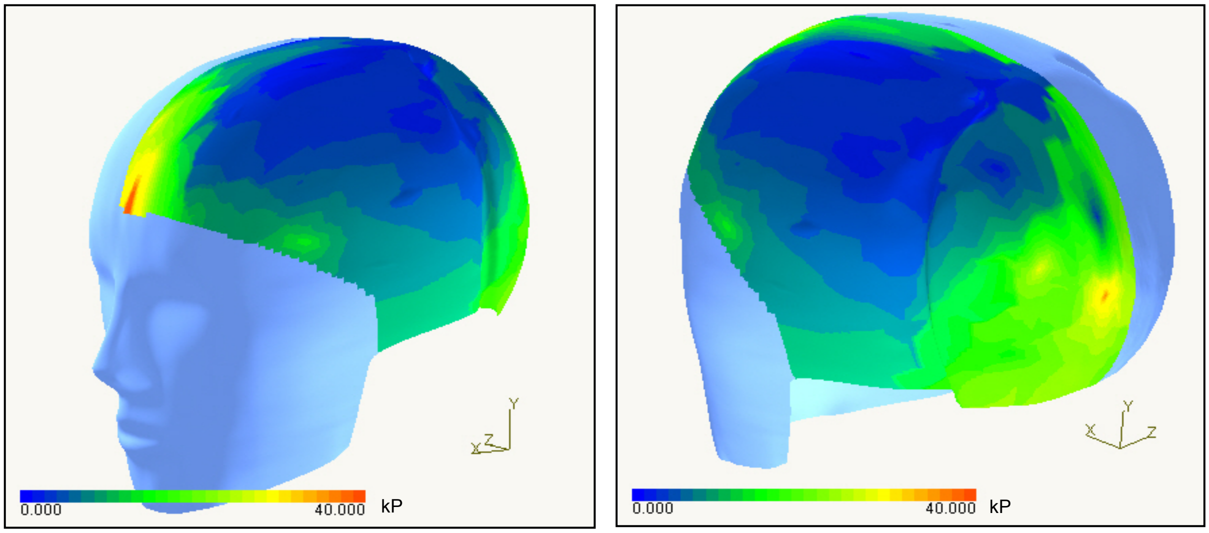


Figure 2.4.5 – 75th Percentile Volunteer Pressure Distribution

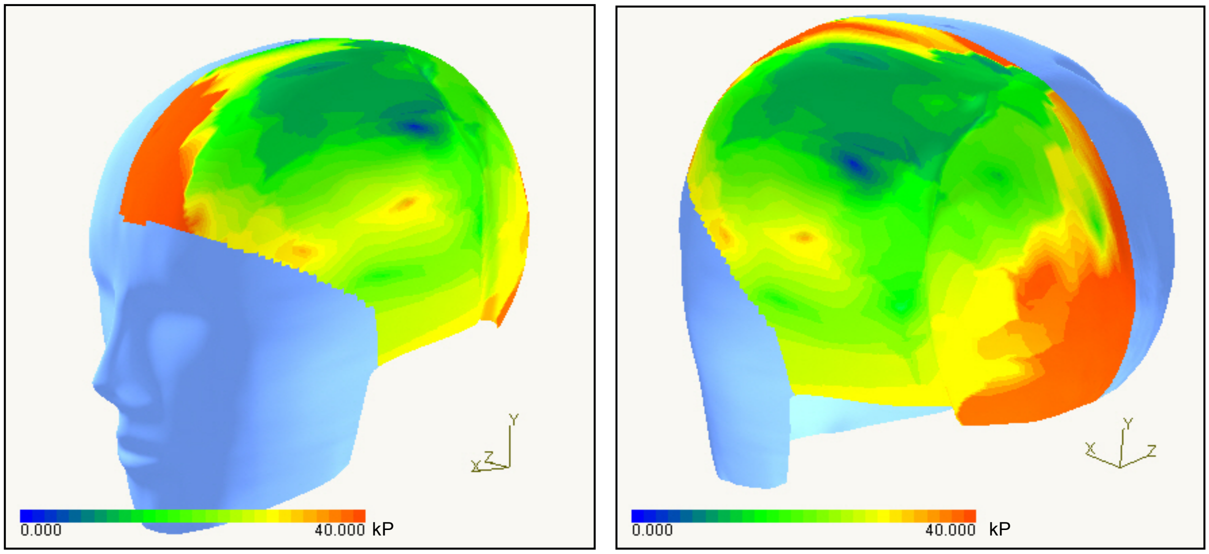


Figure 2.4.6 – 95th Percentile Volunteer Pressure Distribution

Volunteer P_{MAX}'s were also analyzed to assess the location of the maximum pressure on the volunteer. This is summarized in **Table 2.4.1.** Most volunteers' helmets had the P_{MAX} (i.e., tightest fit) in the frontal area (59%) followed by the occipital area (29%). This was in good agreement with the pressure mapping data as illustrated previously. Although not formally documented during the testing, the volunteers were asked for their general impression of fitment. It was noted that general comments regarding the fitment (tightness) of the helmet correlated with the pressure mappings. Also, if the P_{MAX} on the volunteer exceeded approximately 69 kPa (10 psi), the volunteers began to complain of an uncomfortably tight-fitting helmet.

Location of P_{MAX}	Number	Percentage
Frontal	37	59%
Occipital	18	29%
Temporal	5	8%
Crown	3	5%

Table 2.4.1 – Location of Maximum Pressure (P_{MAX})

The P_{AVG} was computed for each volunteer. There was a substantial range in the P_{AVG} for all volunteers (1.8 kPa to 26.8 kPa). Quartile P_{AVG} values were 4.98 kPa, 8.09 kPa, 10.40 kPa, and 22.18 kPa (99th percentile). **Figure 2.4.7** illustrates the P_{AVG} for each volunteer. The 25th, 50th, 75th, and 99th percentile P_{AVG}'s are also shown for reference.

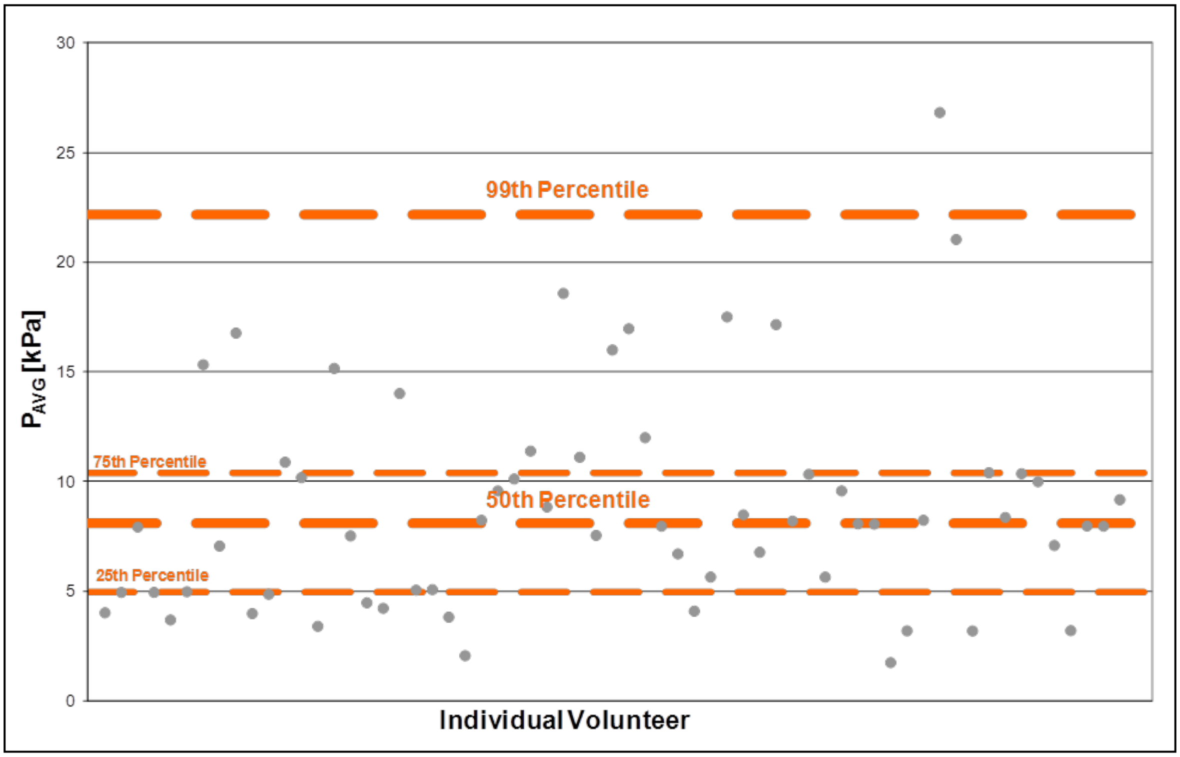


Figure 2.4.7 – Average Pressure (P_{AVG}) by Volunteer

The Average Fit Index (AFI) was computed for each volunteer using all sensors within the FIT cap. The average AFI for all volunteers was 0.15 (± 0.25). The range for AFI values was 0.07 (± 0.2) to 0.3 (± 0.33). The design intent of the FIT cap was such that it could be moved from volunteer to volunteer efficiently and allow the volunteers to use their own personal helmet. Due to the inherent variation in the specific location of the sensors (relative to the helmet padding and the athlete's head), this could have had an effect on the computed AFI. A more representative AFI may have been obtained if the sensors could have been attached to specific locations within the helmet. **Figure 2.4.8** illustrates the effects of this design and the potential for some of the sensors to have been located in gaps between padding areas. As a result, some sensors may not have been contacting an area of the padding while the fit measurements were being recorded.

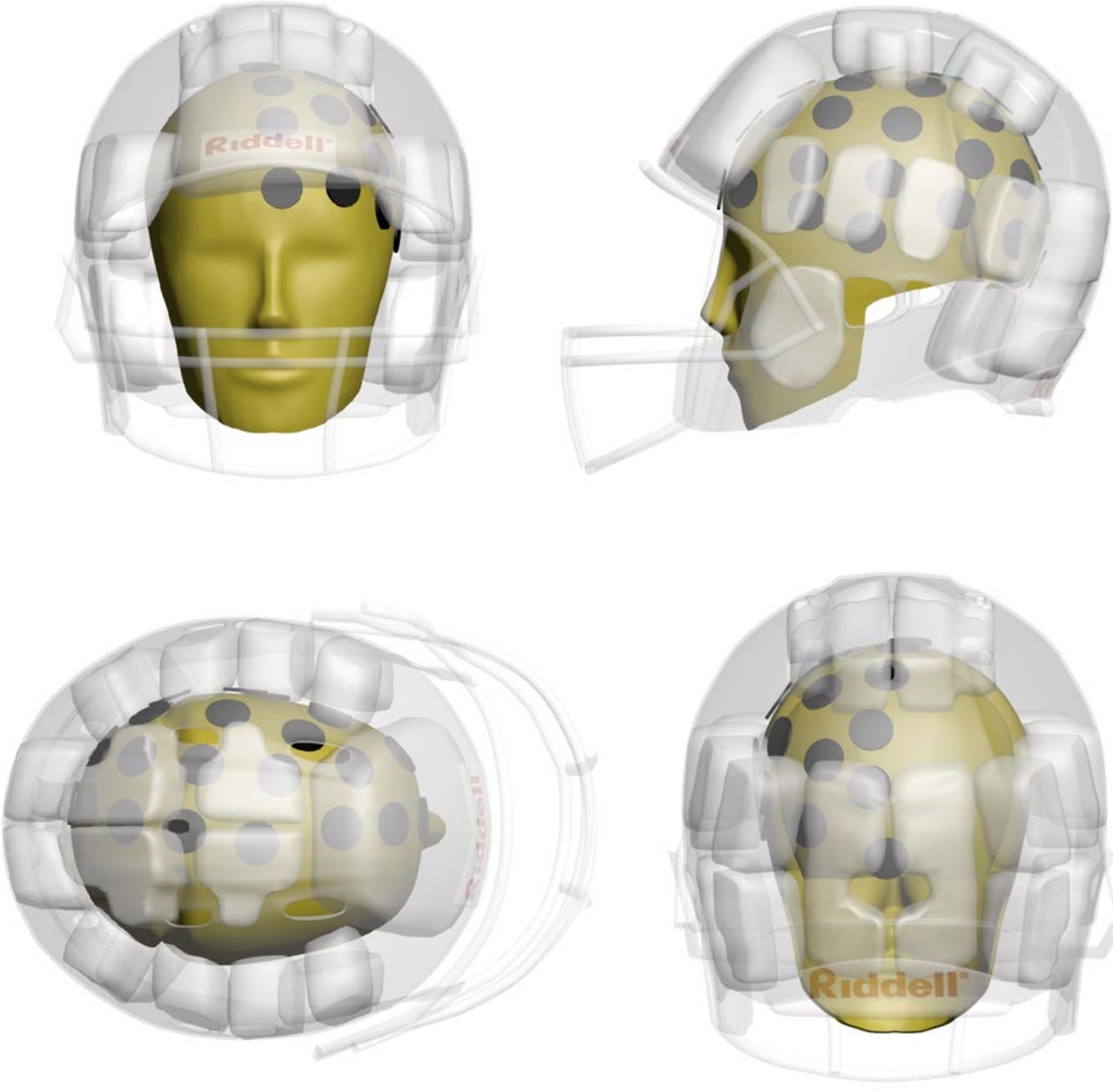


Figure 2.4.8 – Projected In-Helmet Sensor Positions

Given that the optimal AFI would be 1 ± 0, the computed AFI values indicate that the helmets worn by the volunteers in this set of field testing did not fit the volunteers evenly. This finding was confirmed by the pressure distribution plots. Since one of the primary design intents of the helmet is to spread the impact load, this data would suggest that an unevenly fitting helmet will cause the helmet's protective ability to be less than optimal.

2.5 Helmet Fitment Results – Hybrid III Headform

To determine the most appropriate helmet size to be used on the headform, two separate methods were utilized:

1. The Riddell Helmet Fitment Guide, and
2. Comparison of Helmet Fitment on Volunteers versus Helmet Fitment on the Hybrid III headform.

2.5.1 Helmet Size per Riddell Helmet Fitment Guide

The circumference of the Hybrid III headform is 57.2 cm (22.5") (Hubbard 1974). The circumference of a Hybrid III headform was measured physically by using a string and also from a laser scan and a generated computer model of the Hybrid III headform. The measurement obtained from these methods was 58 cm. The helmet fitment guide was consulted for the Riddell Revolution, Riddell Revolution Speed, and Riddell Revolution IQ helmets. Each of these fitment guides indicates a large-sized helmet is appropriate for head circumferences between 55.9 cm and 59.7 cm (22 to 23½").

2.5.2 Volunteer Helmet Fitment versus Hybrid III Helmet Fit

The second method for selecting the most representative size of helmet to be used on the Hybrid III headform was by utilizing a helmet size which achieves a representative P_{AVG}, P_{MAX}, and pressure distribution to the field test data obtained from the volunteer testing. The helmets selected for the analysis were a Riddell Revolution IQ HITS (size L) and a Riddell VSR4 (size M). The jaw pads in the large-sized helmet were inflated to assure contact occurred with the jaw area of the headform. The P_{AVG} and P_{MAX} results from these helmets fitted on the Hybrid III headform were compared to the volunteer fitment data.

Based upon the comparison of the Riddell Revolution IQ (size L) helmet to the volunteer data, the P_{AVG} from this helmet on the Hybrid III headform was representative of the 39th percentile volunteer P_{AVG}. The P_{MAX} was also compared, and it had maximum pressures (38 kPa) that were representative of the 35th percentile volunteer. A pressure map illustrating the Riddell Revolution IQ helmet (size L) on the Hybrid III headform versus the average and 50th percentile volunteer fit data is illustrated in **Figures 2.5.1 (a to c)**. The pressure mapping indicates there was a more even fit in the volunteers in the temporal area; however, the helmet fit more evenly on the headform in the parietal region.

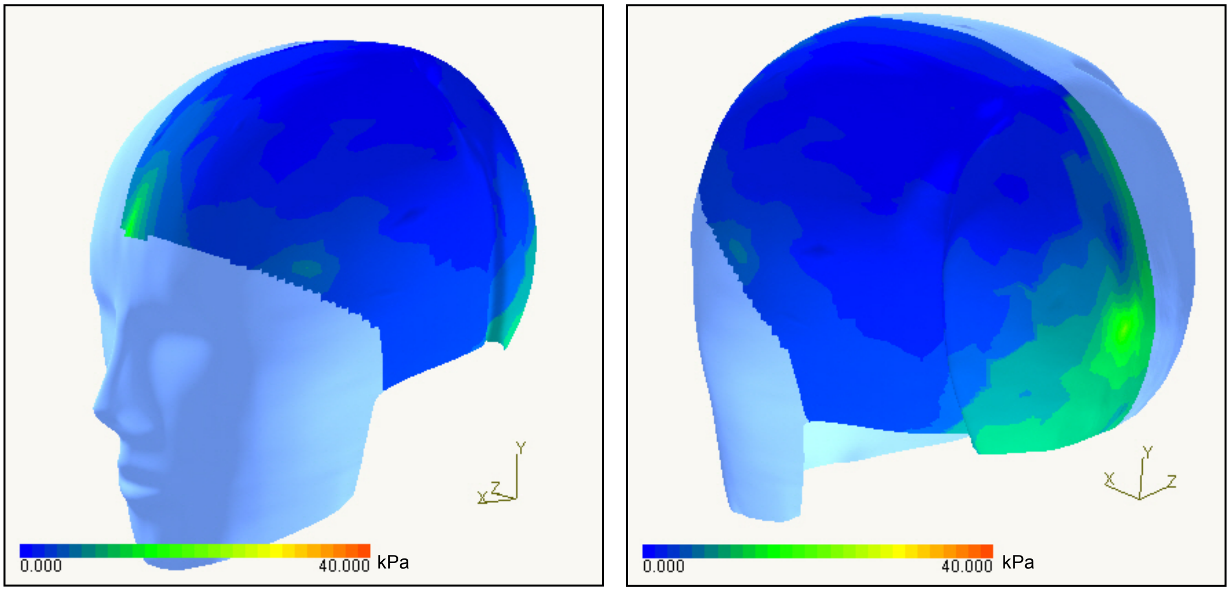


Figure 2.5.1a – 50th Percentile Volunteer

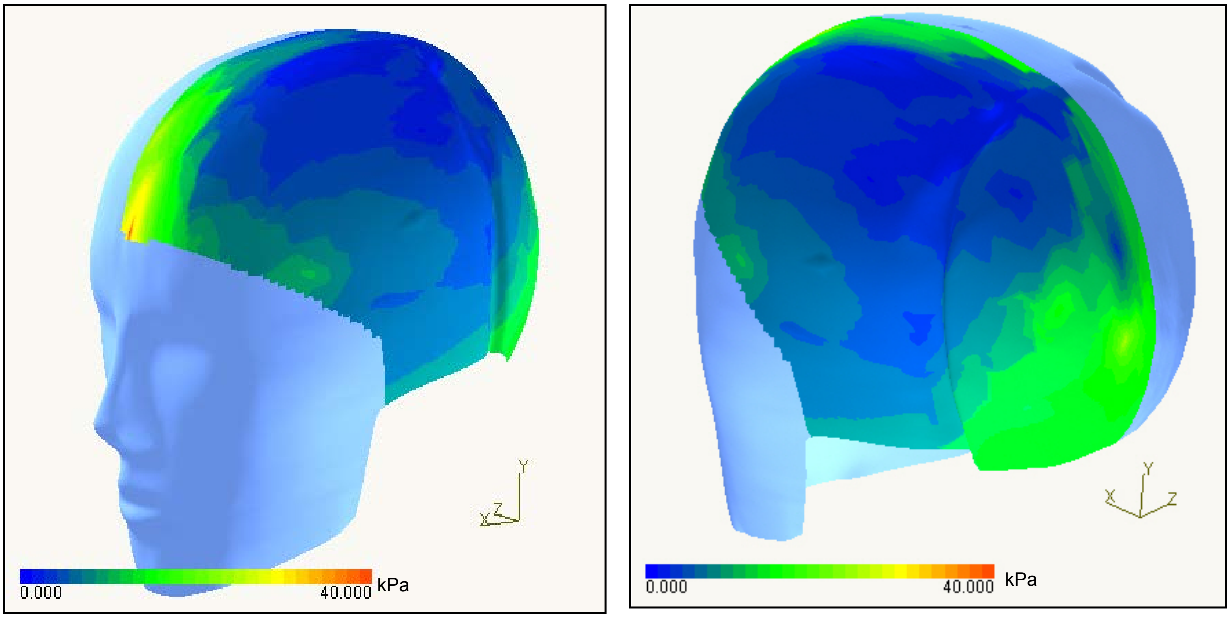


Figure 2.5.1b – Average Volunteer

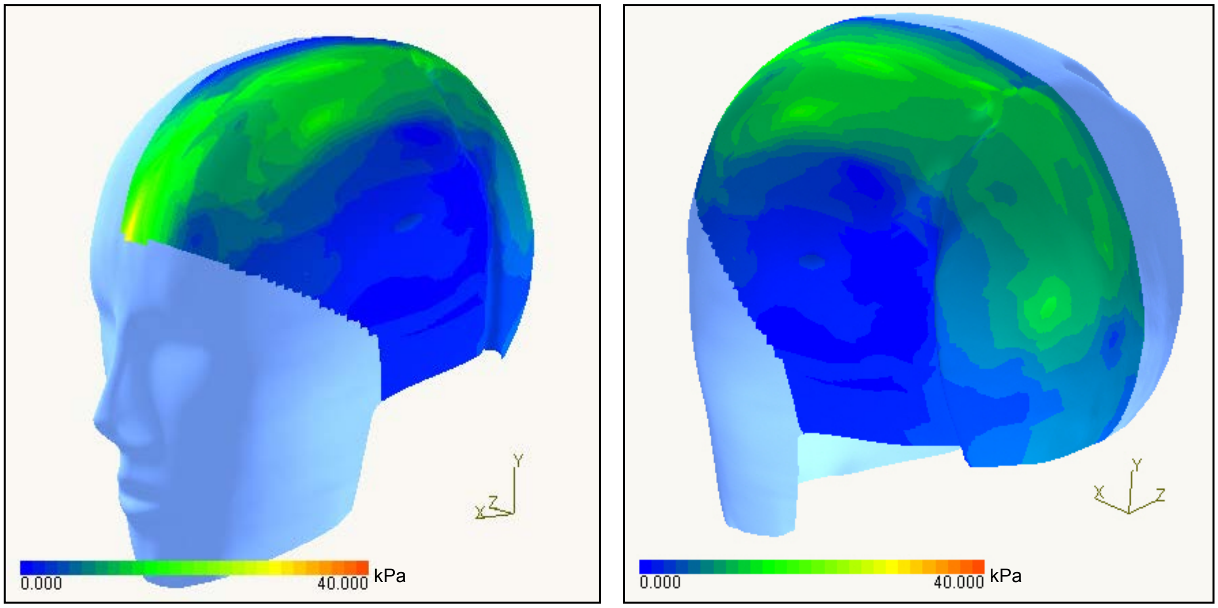


Figure 2.5.1c – Large-sized Helmet on Hybrid III Headform

The Riddell VSR4 (size M) helmet was representative of the 99th percentile P_{AVG} on the volunteers tested. It also had a P_{MAX} of 93 kPa that was representative of the 76th percentile volunteer P_{MAX}. Additionally, the P_{MAX} measured on the Hybrid III headform with the Riddell VSR4 helmet are above the approximate pressure threshold at which volunteers began to indicate their helmets were fitting uncomfortably tightly (approximately 69 kPa). The Riddell Revolution IQ (size L) helmet and the Riddell VSR4 (size M) helmet compared to the volunteer P_{AVG} data are illustrated in **Figure 2.5.2**.

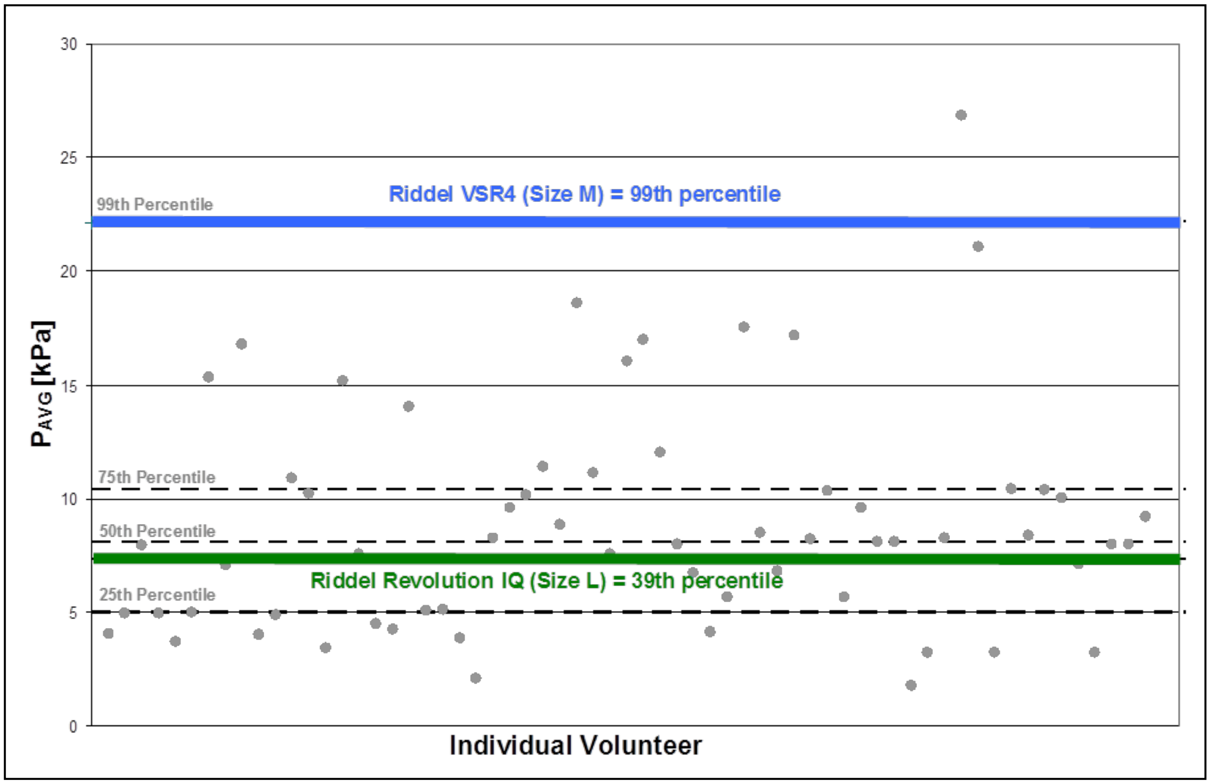


Figure 2.5.2 – Large- and Medium-sized Helmets on Hybrid III Headform versus Volunteer Data

Pressure mappings comparing the medium-sized helmet on the Hybrid III headform to the volunteer test data are illustrated in **Figures 2.5.3 (a to c)**. It is clear from these pressure mappings that the medium-sized helmet on the Hybrid III headform is representative of the 90th percentile volunteer pressure mapping. Therefore, a medium-sized helmet on the headform is not representative of how most volunteers wore their helmets, and its fit is also tighter than the level at which volunteers began to report that the helmet was uncomfortably tight.

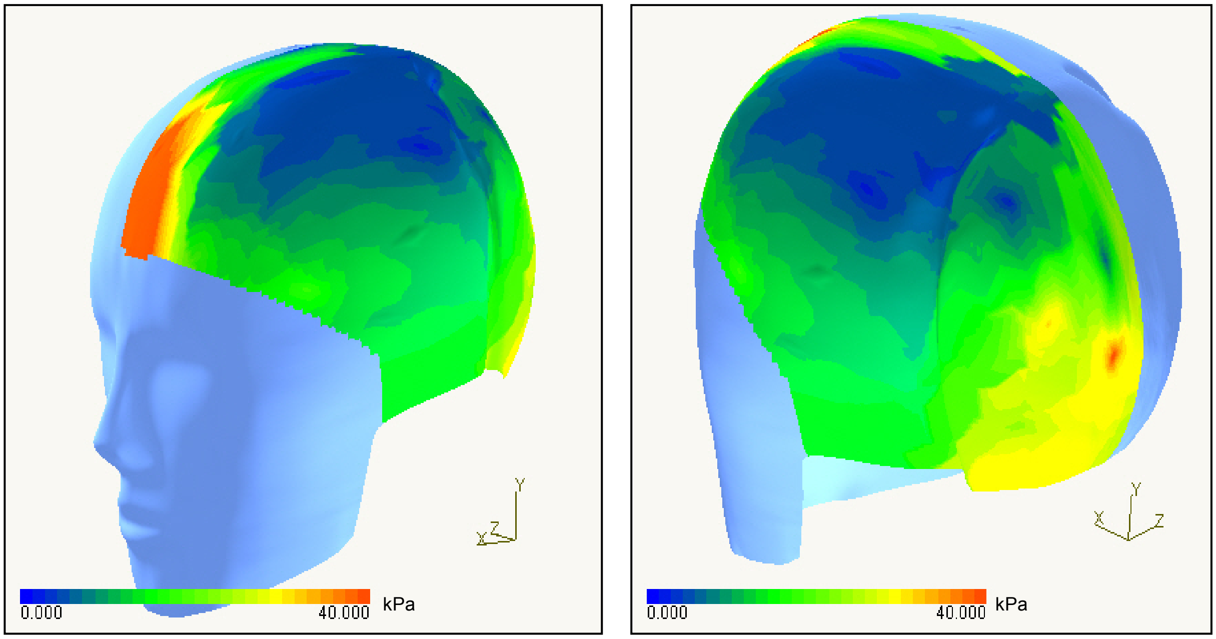


Figure 2.5.3a – 85th Percentile Volunteer

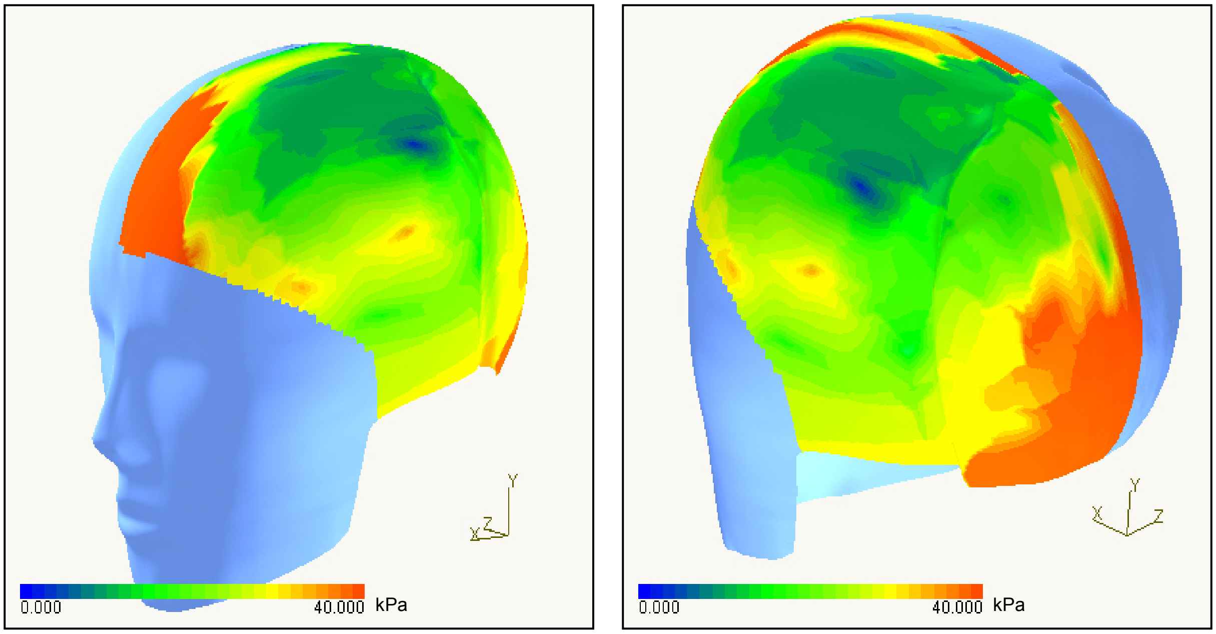


Figure 2.5.3b – 95th Percentile Volunteer

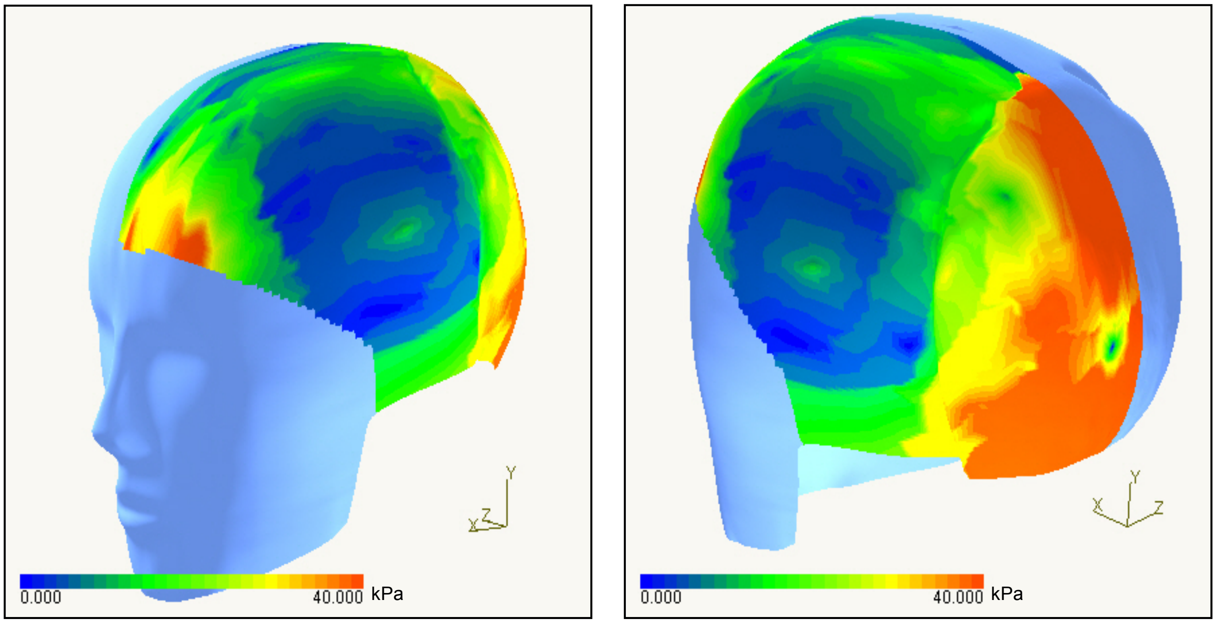


Figure 2.5.3c – Medium-sized Helmet on Hybrid III Headform

Based upon the P_{AVG}, P_{MAX} and the pressure mapping data, the appropriate size of helmet for the Hybrid III headform is a size large. The large-sized helmet produced a pressure distribution, P_{AVG}, and P_{MAX} that were more similar to the 50th percentile values of the volunteer data. The medium-sized helmet on the headform produced P_{AVG} values equal to the 99th percentile volunteer, P_{MAX}'s (93 kPa) representative of the 76th percentile volunteer, and the P_{MAX}'s were also greater than the threshold at which volunteers began to report an uncomfortably fitting helmet (69 kPa). The pressure mapped data for the medium-sized helmet on the headform is substantially tighter than the 50th percentile or average volunteer.

Therefore, the recommendation in the helmet fitment guide is that the large-sized helmet is appropriate for the headform circumference. The volunteer helmet fitment measurements also indicate the fitment of the large-sized helmet on the headform is representative of how these football helmets are comfortably fitting athletes in field.

2.6 Conclusions – Part I Helmet Fitment

In summary, the following conclusions appear to be warranted:

1. An objective method of measuring pressure between the helmet and the head was designed and constructed.
2. A metric (The Average Fit Index – AFI) was proposed to quantify how evenly a helmet is fitting an athlete's head. If sensors could be incorporated into a helmet, this metric would provide a more representative value of helmet fitment.
3. The pressure distribution, P_{AVG} and P_{MAX} between the head and the interior of the helmet, varied significantly within the athletes tested.
4. Volunteers generally reported an uncomfortable fitting helmet if a P_{MAX} exceeded 69 kPa (10 psi).
5. Most helmets (59%) were found to fit the volunteers tightest in the frontal area; the second most common area of tight fit was in the occipital area (29%).
6. A medium-sized helmet on the Hybrid III headform is not representative of how most volunteers wore their helmets, and its fit is above the pressure threshold at which the volunteers reported that the fitment was uncomfortable.
7. The recommendations in the helmet fitment guide, and also our helmet-to-head volunteer pressure measurements, indicate the appropriate Riddell Revolution IQ helmet size for the Hybrid III headform is a large.

Chapter 3 – The Effects of Helmet Fit on Head Impact Response and Recorded Helmet Accelerations by a Riddell Revolution IQ HITS Helmet

3.1 Introduction

Two of the primary design criteria for helmet protection (Newman, 1993) are to:

1. Cushion loading to the head, and
2. Spread the load over a larger area.

Based upon the above, a well-fitting helmet is essential to optimize helmet performance. In **Chapter 2**, an apparatus for the objective measurement of helmet fitment was described. The field testing data that were also presented indicated that helmet fit among athletes varied in tightness and evenness of fit. **Chapter 2** has also indicated that a large-sized helmet is more representative of the 50th percentile volunteer than the medium-sized helmet on the Hybrid III headform. The medium-sized helmet has a tighter P_{AVG} than the 85th percentile volunteer, and the P_{MAX} were greater than the threshold at which volunteers began to report an uncomfortable fit.

Despite the importance of an even- and tightly-fitting helmet, the effects of helmet fit on performance do not appear to have been extensively studied. Furthermore, previous research has been conducted with a large-sized (Pellman et al., 2003a; Pellman et al., 2003b; Pellman et al., 2006a) or a medium-sized helmet (Beckwith et al., 2011; Rowson et al., 2011) on the Hybrid III headform. **Chapter 2** has illustrated that a large-sized helmet is the appropriate helmet based upon the Riddell helmet's fitting instructions and by the field study results of how athletes comfortably wore football helmets. The goals of the research presented in this chapter are to, 1) Compare the effects on helmet performance in a loose-fitting condition (representative of the 50th percentile volunteer) versus a tighter-fitting condition and 2) Evaluate the effects of helmet fitment on the HIT System in terms of measurement errors in comparison with the Hybrid III headform reported response parameters.

3.2 Materials and Methods

3.2.1 Equipment

The impact testing conducted for this research was completed at the Wayne State University (WSU) Sports Biomechanics Laboratory. For impact testing, a Hybrid III 50th percentile male headform was mounted on the Hybrid III 50th percentile male neck. The helmeted headform was impacted using a pneumatic linear impactor (Biokinetics and Associates, Ltd., Ottawa, Ontario, Canada) **(Figure 3.2.1)**. The helmeted headform was mounted to a linear bearing table which allowed for translational movement of the assembly subsequent to the impact. The linear impactor design was previously described (Pellman et al., 2006a). Impacting the helmeted Hybrid III headform with the pneumatic linear impactor resulted in the response of the helmeted headform representing kinematic responses of the head when compared to the real-life game impacts. The National Operating Committee on Standards for Athletic Equipment (NOCSAE) is also in the process of adopting this testing procedure for its evaluation of football helmets (www.nocsae.org 2011).

Figure 3.2.1 – Biokinetics Linear Impactor

The helmet utilized for this testing was the Riddell Revolution IQ HITS helmet (size Large) (Riddell, Elyra, Ohio). The IQ HITS helmet was chosen for this study for a variety of reasons:

1. Riddell is the official helmet of the NFL and is largely used by collegiate and high school football athletes.
2. All helmets tested in the volunteer fitment study were Riddell **(Chapter 2)**.
3. The Revolution IQ helmet (size Large) fitted onto the Hybrid III headform is comparable to the 50th percentile 'average' pressure and maximum pressures recorded during volunteer testing of helmet fitment **(Chapter 2)** and is the size recommended by the Riddell helmet fitting guide based on the circumference of the headform.
4. The HIT System helmet is equipped with helmet-mounted accelerometers which are reported to have the capability of measuring various response parameters when worn by a player. At the onset of this research, it was

hypothesized that fitment (tightness and evenness) of the helmet on a headform (or a player) could affect the reported response parameters from the HIT System helmet.

3.2.2 Data Acquisition and Measurement

The headform was instrumented with 9 single axis accelerometers, oriented in the 3-2-2-2 array (Padgaonkar et al., 1975). This array permitted the measurement of head linear and angular acceleration and angular velocity. Impactor speed was measured at the impactor velocity trap. The Hybrid III upper neck load cell was utilized to measure neck forces and moments (Denton, Plymouth, MI., 6-axis load cell model 1716). The above data were acquired using the TDAS-Pro (Diversified Technical Systems [DTS Inc.]) data acquisition system at a rate of 10 kHz. These data were sent through an anti-aliasing filter prior to digitization and were subsequently filtered per SAE J-211 (SAE, 1995) using a CFC1000 filter. During the analysis of the data, it was noted that ringing occurred in some of the accelerometers. A band-pass filter (0.1 to 1000 Hz) was used to remove the ringing, and the data were re-checked to ensure that the ringing had been removed and that there was no phase shift.

The Hybrid III headform was equipped with the FIT Cap **(Chapter 2)**. The attachment and hardware signal conditioning for the FIT Cap are previously described. The sensors and channels to which each sensor was attached remained unchanged for this testing. Data from the FIT Cap were acquired using the USB 1616HS-4 (Measurement Computing Corporation., Norton, MA) data acquisition system at a rate of 1000 Hz.

A summary of the sensors and filtering is illustrated in **Table 3.2.1**.

Instrumentation	Description	Filter
Head Accelerations	Endevco 7264-2K	Band-pass [0.1-1000 Hz]
Upper Neck Moment (X,Y,Z)	Denton (Model 1716)	CFC1000
Upper Neck Force (X,Y,Z)	Denton (Model 1716)	CFC1000
Headform Surface Pressure	Tekscan (Model Flexiforce-A201)	-

Table 3.2.1 – Summary of Sensors and Filtering for Impact Testing

The Riddell Revolution IQ helmet was equipped with the HIT System equipped with the latest Mx Encoder with six single axis accelerometers. The trigger on the helmet was set to record for 40 ms (8 ms pre-impact, 32 ms post-impact) if the impact exceeded 10 g. The data from the HIT System were transferred wirelessly to a laptop computer, uploaded to, and processed by the Redzone software. All calculations were completed by the Redzone software.

3.2.3 Test Conditions and Impact Orientations

Pellman (Pellman et al., 2003b) have summarized common impact orientations resulting in concussion to players in the NFL. Craig (Craig, 2007) has also proposed that A’ and A” impact orientations to the facemask should also be studied since these impacts resulted in a large fraction of reported concussions and also resulted in chin strap loading. Some of these impact orientations have been considered for NOCSAE football helmet testing, and a new standard is currently in the proposed status (www.nocsae.org 2011). The NFL has also undertaken a helmet testing program (Helmet Concussion Assessment Program [HCAP]). A presentation summarizing the impact orientations to be considered in HCAP is in Appendix D. Some of the impact conditions illustrated in this presentation were used for this impact testing **(Figure 3.2.2)**. The impact conditions used were based upon the original research by the NFL Subcommittee (Pellman et al., 2003b).

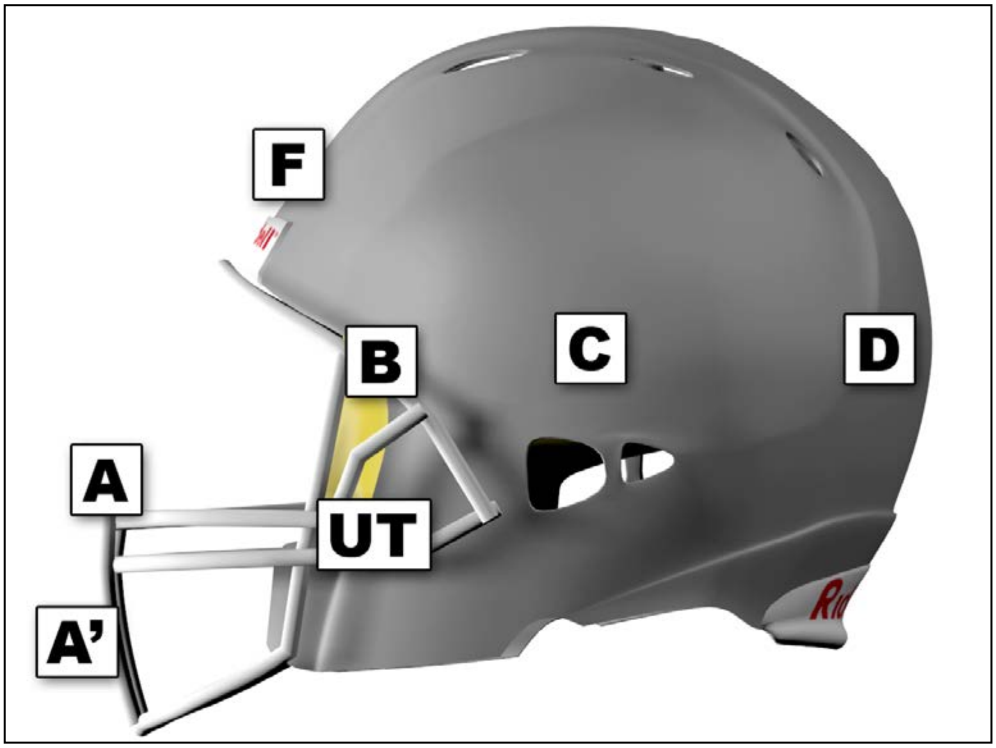


Figure 3.2.2 – Impact Conditions

Since the focus of this study was the effect of fitment on the performance of a football helmet on the headform, the impact orientations were chosen specifically to impact areas of differing tightnesses of fit. For this reason, conditions F, UT, C, and D were chosen. Conditions F and D impact the tightest (front) and second tightest (rear) locations on the headform while Condition C impacts the more loosely-fitting area on the headform. Condition UT is impacting the helmet in the jaw pad, an area to which the FIT cap does not extend. Each of these impact orientations resulted in a direct impact to the helmeted headform as opposed to a glancing blow. The facemask impacts A, A', A'' and B were omitted to avoid damage to the facemask and since they did not result in a direct impact to the shell of the helmet.

A summary of the Hybrid III neck orientations and the base table locations utilized for this research are summarized in **Table 3.2.2**, and the coordinate systems for the table setup are illustrated in **Figure 3.2.3**.

Impact Condition	Neck Orientation		Table Location		
	α	β	X	Y	Z
F	0 deg.	15 deg.	200 mm	283 mm	478 mm*
UT	-90 deg.	0 deg.	142 mm	283 mm	558 mm
C	-105 deg.	11 deg.	173 mm	283 mm	536 mm
D	-157 deg.	11 deg.	172 mm	283 mm	536 mm
*The table height was adjusted to prevent striking the facemask.					

Table 3.2.2 – Hybrid III Neck Orientation and Table Location for Linear Impactor Testing

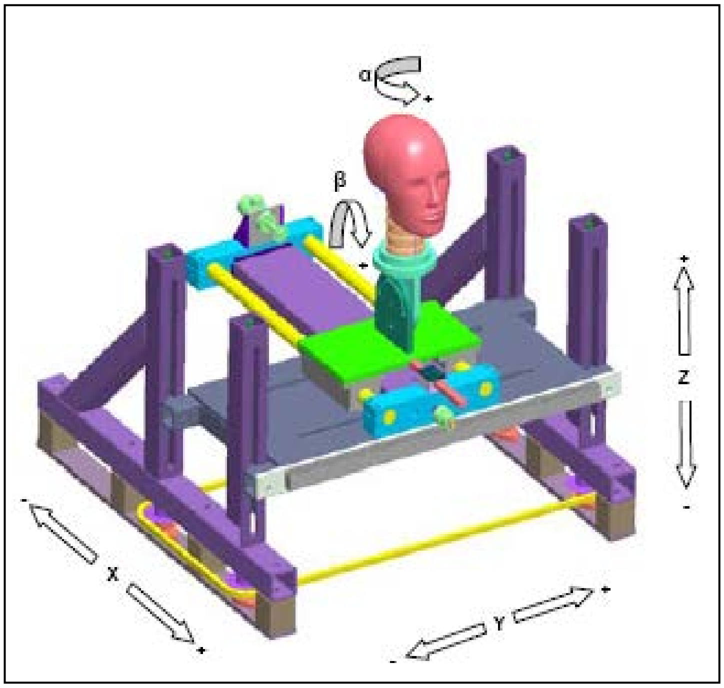


Figure 3.2.3 – Linear Impactor Table Co-ordinate System

Each of the impact conditions are further illustrated in **Figures 3.2.4 (a to d)**.

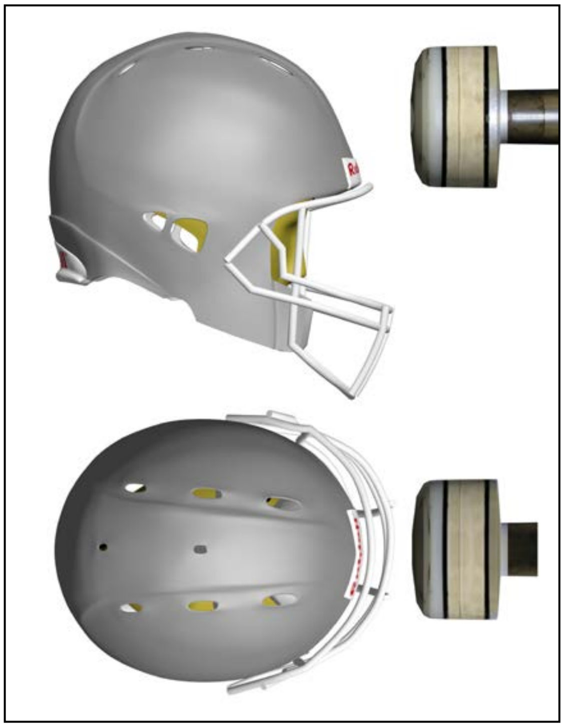


Figure 3.2.4a – Impact Condition F

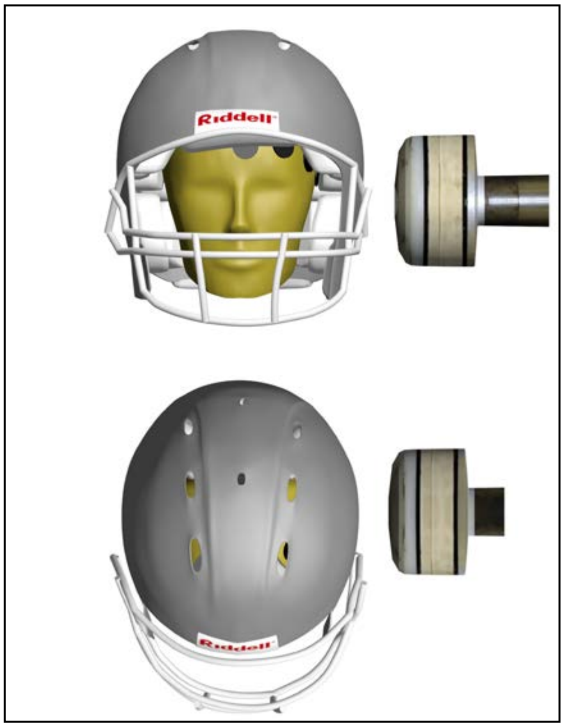


Figure 3.2.4b – Impact Condition UT

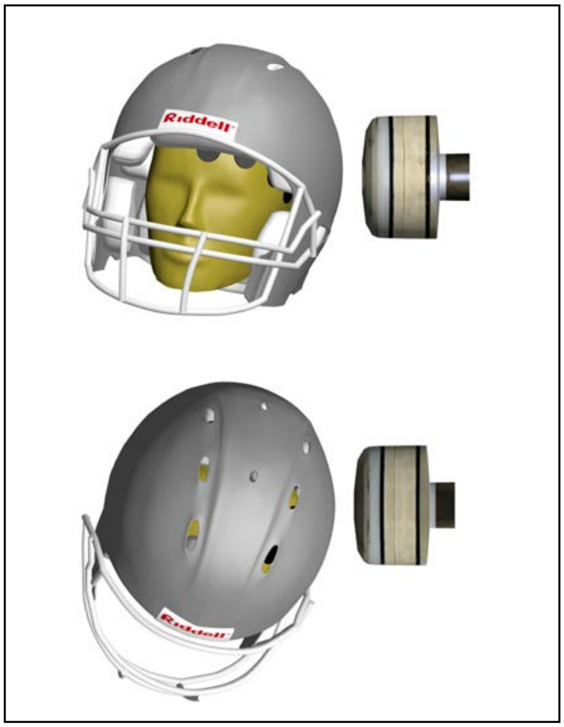


Figure 3.2.4c – Impact Condition C

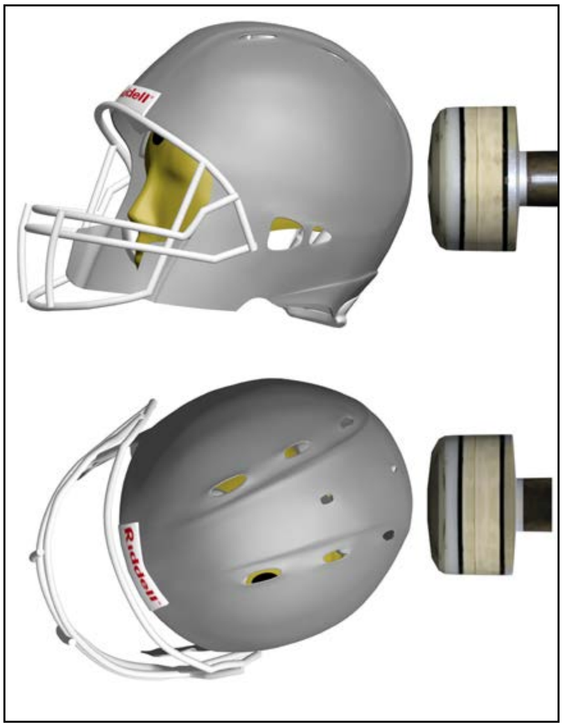


Figure 3.2.4d – Impact Condition D

Tightness of helmet fit was analyzed for this testing. Varying helmet fit was conducted by increasing the bladder pressure(s) in the helmet. The “loose”-fitting condition (air only in the jaw-pad bladders) was used as a baseline for the analysis. The jaw-pad bladders were inflated until they contacted the headform. The looser fit condition represented the 39th and 35th percentile P_{AVG} and P_{MAX} volunteer fitment data. The loose-fitting condition also correlated well with the overall pressure distribution between the helmet and the headform of the average volunteer **(Chapter 2)**. The tight-fitting condition was chosen to be greater than the 100th percentile volunteer fitment data. When the bladders for the helmet were inflated for the tight-fitting condition, it also resulted in a more uniform helmet fit on the headform. The bladder pressure in the tight-fitting condition could not be controlled well, and the goal was simply to create a fit condition that was much tighter than the “comfortable” volunteer fitment. This was done to provide as great a spread in helmet tightness as possible.

In total, four orientations were used (F, UT, C, and D). Loose- and tight-fitting conditions were considered, and each test was repeated a minimum of five times. There were 48 tests in total. The tests were conducted by targeting an impact speed of 9.3 m/s. This test speed was chosen because the NFL Subcommittee research (Pellman et al, 2003b) has described this as being the average impact velocity resulting in concussion (9.3 m/s ± 1.9 m/s). The number of tests and average impact velocity for each condition is illustrated in **Table 3.2.3**.

Impact Condition	Loose Condition		Tight Condition	
	N	Impact Speed (m/s)	N	Impact Speed (m/s)
F	6	9.428 (+/- 0.219)	5	9.377 (+/- 0.147)
UT	6	9.250 (+/- 0.168)	5	9.208 (+/- 0.173)
C	7	9.021 (+/- 0.246)	5	9.350 (+/- 0.019)
D	6	9.367 (+/- 0.076)	7	9.149 (+/- 0.228)

Table 3.2.3 – Summary of Linear Impactor Test Speeds by Impact Condition

3.2.4 Helmet Performance Metrics

To assess the effects of helmet fitment on headform response and also the effects of helmet fitment on reported response parameters from the HIT System, common injury measures were utilized. These are discussed below.

Peak Linear Acceleration Injury Measures

Linear acceleration injury measures related to head impacts have been widely studied. Studying head injury measures using linear accelerations are reported to be desirable due to the ease of measurement. Various head injury assessment reference values have been developed and have been associated with brain injury as well as skull fracture. The Wayne State Tolerance Curve (WSTC) (Lissner et al., 1960) and Japan Automotive Research Institute (JARI) Head Tolerance Curves (Ono et al., 1980) were developed in which linear acceleration was expressed as a function of impact duration.

Pellman (Pellman et al., 2003b), Zhang (Zhang et al., 2004), King (King et al., 2003), Funk (Funk et al., 2007), Funk (Funk et al., 2011), and Rowson (Rowson et al., 2011) have proposed concussion injury thresholds based upon helmeted football impacts.

Pellman and Funk have also proposed concussion risk functions to predict the probability of injury. The concussion injury thresholds proposed by Pellman, Zhang, and King are based upon reconstruction of injurious impacts in the NFL Studies; whereas, the thresholds proposed by Funk and Rowson are based upon HIT System data. A summary of the proposed criteria is illustrated in **Table 3.2.4.**

	Peak Acceleration (g)	**Probability of Concussion**
Pellman	81	50%
King	79	50%
Zhang	82	50%
Funk (2007)	165	10%
Funk (2011)	199	10%
Rowson (2011)	149	10%

Table 3.2.4 – Summary of Proposed Peak Linear Acceleration (PLA) Based Injury Criterion

<u>Head Injury Criterion (HIC)</u>

HIC is an injury criterion that is based upon linear acceleration and the Wayne State Tolerance Curve. It is traditionally used for the assessment of head protection in the automotive industry when an impact occurs with an interior vehicle component. It is utilized as a measure of head injury assessment in various Federal Motor Vehicle Safety Standards (FMVSS). When applying HIC in the automotive testing environment, it has been recommended that the duration over which HIC is calculated is less than 15 ms (HIC15) (Prasad et al., 1985). The majority of the data presented by Prasad have HIC duration < 10 ms. HIC15 will be considered here. The expression to calculate HIC15 is:

$$HIC_{15} = (t_2 - t_1)\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a_r(t)dt\right]^{2.5}$$

Gadd Severity Index (GSI)

GSI is a head injury criterion that it based upon linear acceleration and the Wayne State Tolerance Curve. It is traditionally used for the assessment of helmet performance in the NOCSAE standards and was originally proposed by Gadd (Gadd, 1966). The expression to calculate GSI is:

$$GSI = \int^{T} a(t)^{2.5}\,dt$$

Rotational Acceleration

Rotational acceleration was also considered as a helmet performance measure. It has been shown to be related to brain strain. Brain strain and strain rate have shown a strong correlation to concussion in the reconstruction of helmet impacts in the NFL studies (Viano et al, 2005a; Zhang et al., 2004). A summary of proposed angular acceleration-based criteria is illustrated in **Table 3.2.5**.

	Ang. Accel. (rad/s^2)	**Probability of Concussion**
Pellman	5490	50%
King	5757	50%
Zhang	5900	50%
Rowson	6383 (@28.3 rad/s)	50%
Funk	9000	10%

Table 3.2.5 – Summary of Proposed Peak Angular Acceleration (PAA)-Based Injury Criterion

Pressure Distribution on the Headform Surface

Newman (Newman, 1993) has identified that the primary design functions of a helmet are to cushion an impact to the head and to spread the load over a larger area. These design goals are consistent with Eppinger's (Eppinger, 1993) "*Maxims for Good Restraint Performance and Design,*" wherein he indicates it is desirable to distribute forces over the greatest area. Pressure is not a typical metric utilized for helmet performance measures; however, pressure or force is considered a headform "*input*" parameter rather than a "*response*" parameter of the headform (e.g., *acceleration-related parameters*). Based upon the above noted design goals of a helmet, it would appear that an appropriate metric to evaluate helmet performance is pressure distribution. Due to the implementation of the FIT Cap **(Chapter 2)** in this research, head surface pressure can be measured and evaluated as a performance metric.

3.2.5 Analysis of Data

An analysis of the headform accelerometer and FIT Cap data was conducted using the Diadem Software (Version 11.1, National Instruments, Austin, Texas). The headform accelerometer data and the upper neck load cell data were captured with the same data acquisition system and, therefore, synchronized. The FIT Cap data were acquired using separate data acquisition equipment, and the data were not synchronized with the acceleration data ; therefore, a direct temporal comparison of pressure and acceleration could not be made. The HIT System data were acquired through use of the Redzone Software (Simbex, Lebanon, NH). Time-history was not available, and only maximum values for the various injury criteria were reported.

Statistical analysis was conducted on the acquired data. Descriptive statistics (mean and standard deviation) were calculated using Microsoft Excel (Microsoft, Seattle, WA). Comparative plots were also computed, where applicable, to analyze the differences between the HIT System reported data versus the headform reported values. In this testing, the headform data were considered to be the 'gold standard'. The relative error plots were calculated based upon the equation:

$$\operatorname{Re} lativeError(RE) = \left[\frac{(HITS - H3)}{H3} \right] \times 100$$

In addition to the relative error calculation, the absolute error between the HIT System data and the headform data was also calculated. Absolute error is the absolute value of the relative error and was used to compare the tight-fitting versus loose-fitting conditions for each impact location.

$$AbsoluteError(AE) = \left| \frac{(HITS - H3)}{H3} \right| \times 100$$

A linear regression analysis was undertaken to assess whether there was a correlation that could be made between the paired samples (i.e., HITS data versus Headform data). A Pearson Correlation Coefficient, R, was utilized to assess the correlation between the samples, and the significance of the correlation was also assessed.

A multiple sample t-test approach was undertaken to analyze the paired samples (e.g., HITS data versus Headform data and Headform data tight-fit versus Headform data loose-fit). Two-tailed t-tests were used to assess whether there were significant differences between the paired samples. The t-statistic is a measure of the difference in means of two populations divided by the standard deviation of the mean. A 95%

confidence interval of the paired differences was used to assess significance. When one uses this approach, if the significance (sig.) is less than 0.05, there is a high probability of error in the HIT System.

3.3 Results

A total of 48 tests were performed using the linear impactor. Twenty-five of the tests were conducted under the loose-fitting condition and twenty three tests were conducted with the air bladders inflated to a tight (but "uncomfortable") and more uniform-fitting condition. When comparing the HIT System data versus the headform data, there were only 22 tests recorded using the HIT System in a looser-fitting condition and 19 tests recorded in the tighter-fitting condition. The HIT System filtered out various impacts due to its built-in filtering algorithms and, therefore, did not record these impacts. Four additional HIT System records were 'filtered' out of the HIT data set by the built-in algorithms but were recoverable through correspondence with Simbex. Therefore, from the original dataset, 11 of the 48 impacts (22.9%) were removed from the dataset by the HIT System algorithms.

The focus of the analysis of the results was a comparison between the loose- and tight-fitting conditions and their effect on helmet performance as well as reported parameters from the HIT System versus the accelerometer data from the headform.

3.3.1 Headform Response and Tightness of Helmet Fit

The bladders in the helmet were used to control the tightness of fit. **Table 3.3.1** summarizes the descriptive statistics and the results of a student *t*-test comparison of tightness of helmet fit versus headform response for all impact conditions. Tightness of helmet fit had an effect on helmet performance. The tight-fitting condition also resulted in a more uniform-fitting helmet. As the tightness of fit increased, the linear acceleration related performance parameters increased (i.e., HIC, GSI, and Peak Linear Acceleration), but when all impact conditions were averaged, the differences were not significant. Peak Angular Acceleration (PAA) was found to be significantly lower (t=3.226, p=0.003) in the tighter and more uniform-fitting condition.

Paired Samples Statistics					**Significance**		
	Mean	N	Std. Deviation	Std. Error Mean	Mean Difference	t	Sig. (2-tailed)
LooseHIC	215.2	25	27.2	5.4	-11.1	1.150	0.256
TightHIC	226.3	23	25.8	5.4			
LooseGSI	310.5	25	41.3	8.3	-19.6	1.748	0.088
TightGSI	330.0	23	26.5	5.5			
LoosePLA	70.4	25	6.1	1.2	-3.6	1.695	0.097
TightPLA	74.0	23	6.1	1.3			
LoosePAA	4407.5	25	396.7	79.3	477.4	3.226	0.003
TightPAA	3930.1	23	563.8	117.6			
LoosePAV	42.5	25	5.7	1.1	2.3	1.802	0.081
TightPAV	40.1	23	2.2	0.5			

Table 3.3.1 – Comparison of Loose-Fitting versus Tight-Fitting Helmet

The individual impact locations were also analyzed. As the tightness of fit increased, linear acceleration-related performance parameters (i.e., HIC, GSI, and Peak Linear Acceleration) increased for impact conditions C and F. In impact condition UT, there were no significant findings with regard to any of the response parameters; however, these parameters still showed an increase of the mean. In impact condition D, the performance parameters increased. The significance level (95% Confidence Interval [CI]) of the difference by impact location is summarized in **Table 3.3.2**. As tightness of fit increased, it had the opposite effect on angular acceleration. The tight- (and more uniform) fitting condition resulted in lower angular accelerations in impact conditions C, F, and UT. There were substantial differences in angular acceleration in impact condition F (32% reduction in angular acceleration).

Location	HIC15	GSI	PLA	PAA	Ang Vel
D	0.000	0.002	0.001	0.009	0.002
C	0.034	0.042	0.000	0.008	0.005
F	0.006	0.003	0.001	0.000	0.256
UT	0.405	0.435	0.394	0.301	0.070

Table 3.3.2 – Loose- versus Tight-Fitting Condition, Significance

Figures 3.3.1 to 3.3.5 illustrate the loose-fitting condition and the tight-fitting condition versus the selected performance metrics. Conditions which resulted in a statistically significant finding are shown with an asterisk (*). Average values are shown in these plots, and the error bars represent ±1 standard deviation.

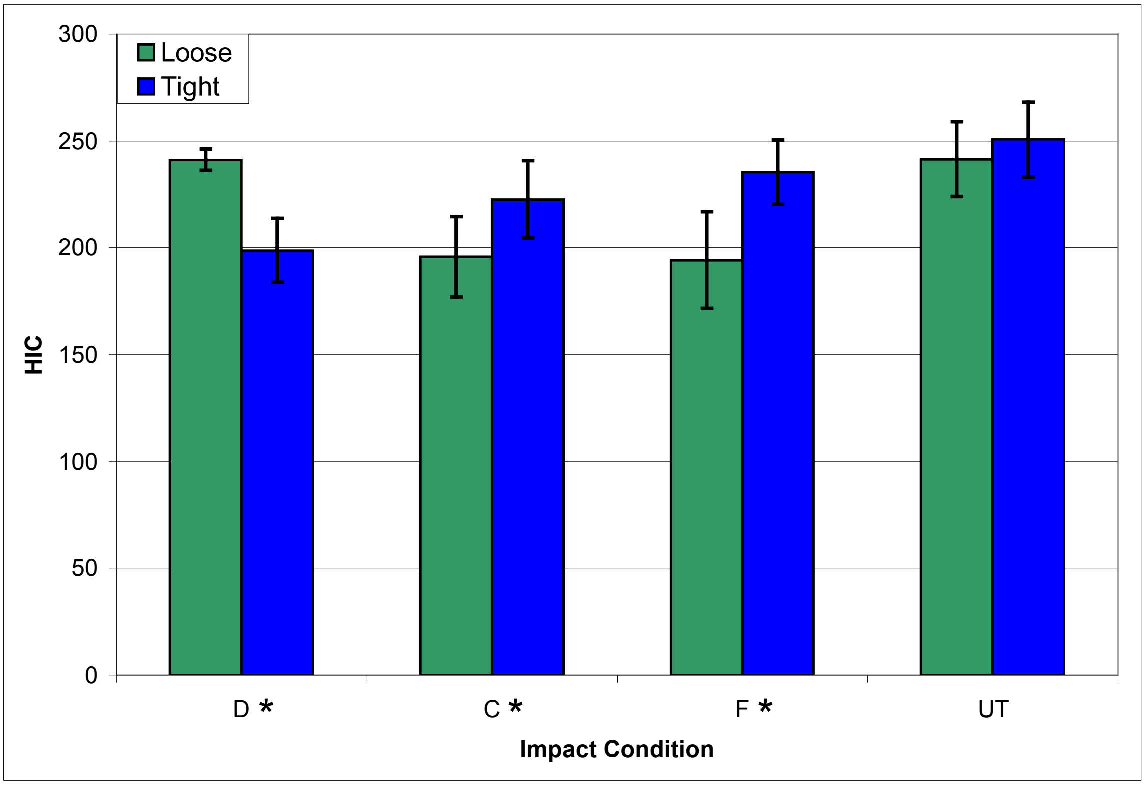


Figure 3.3.1 – HIC: Loose- versus Tight-Fitting Condition

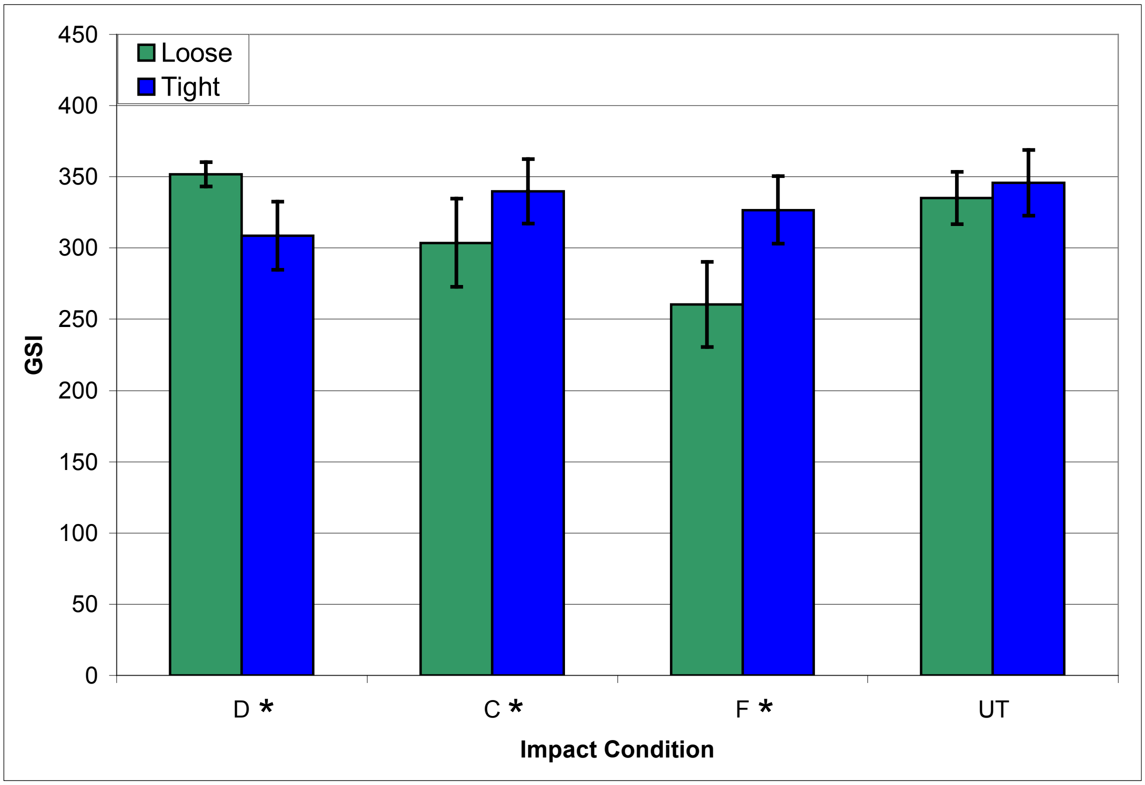


Figure 3.3.2 – GSI: Loose- versus Tight-Fitting Condition

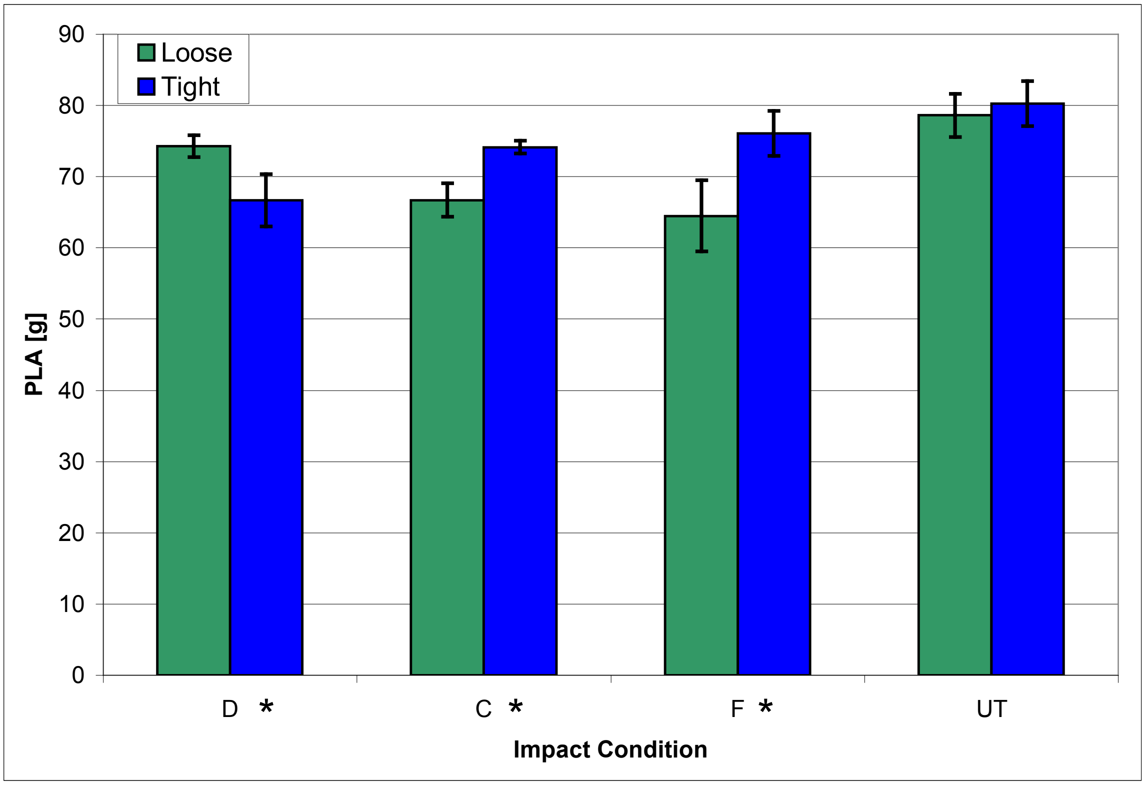


Figure 3.3.3 – PLA: Loose- versus Tight-Fitting Condition

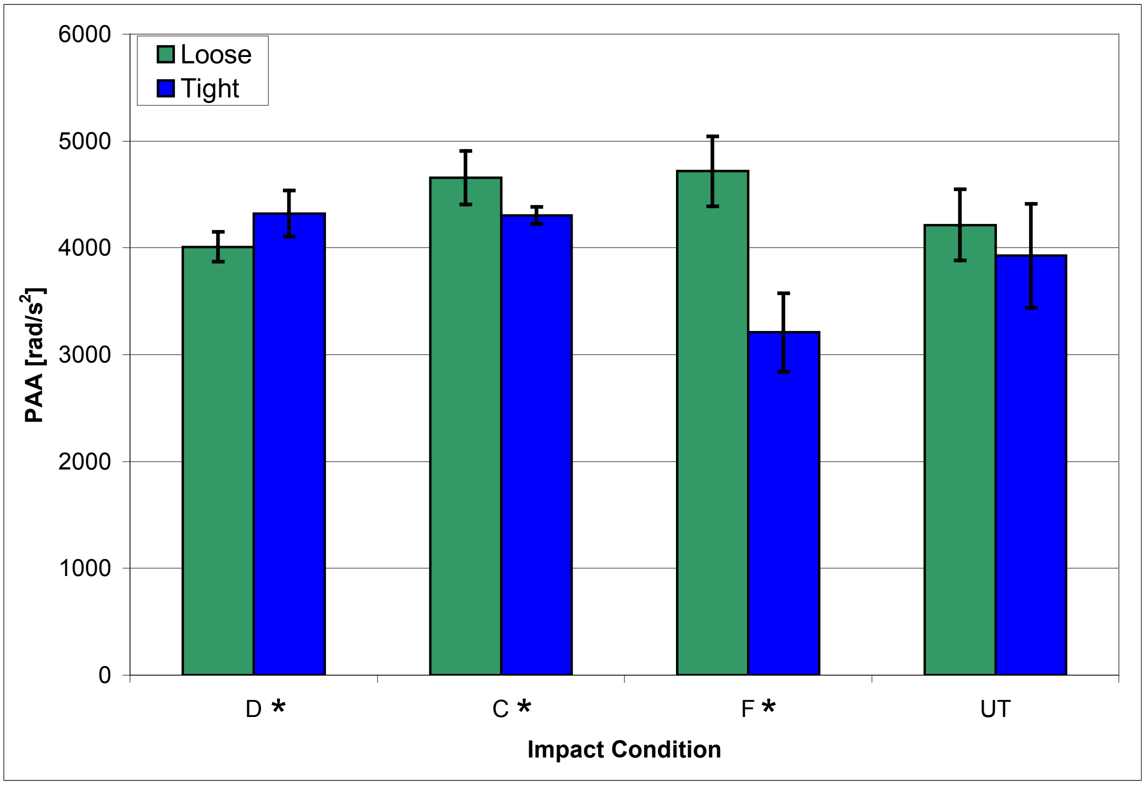


Figure 3.3.4 – PAA: Loose- versus Tight-Fitting Condition

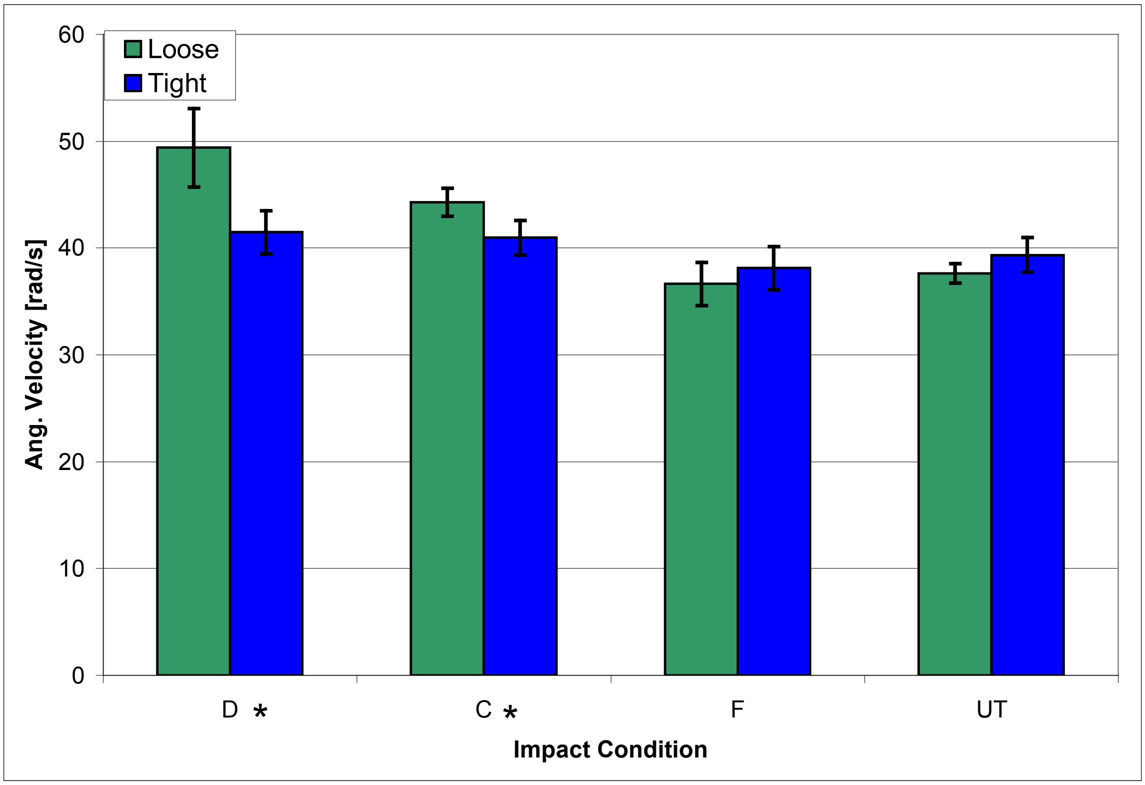


Figure 3.3.5 – Angular Velocity: Loose- versus Tight-Fitting Condition

Peak surface pressure data that occurred during the impact were also analyzed **(Figure 3.3.6)**, and there were significant differences in the test results in two of the four impact orientations (C, D). Peak pressure increased in each of these two conditions as tightness of fit increased.

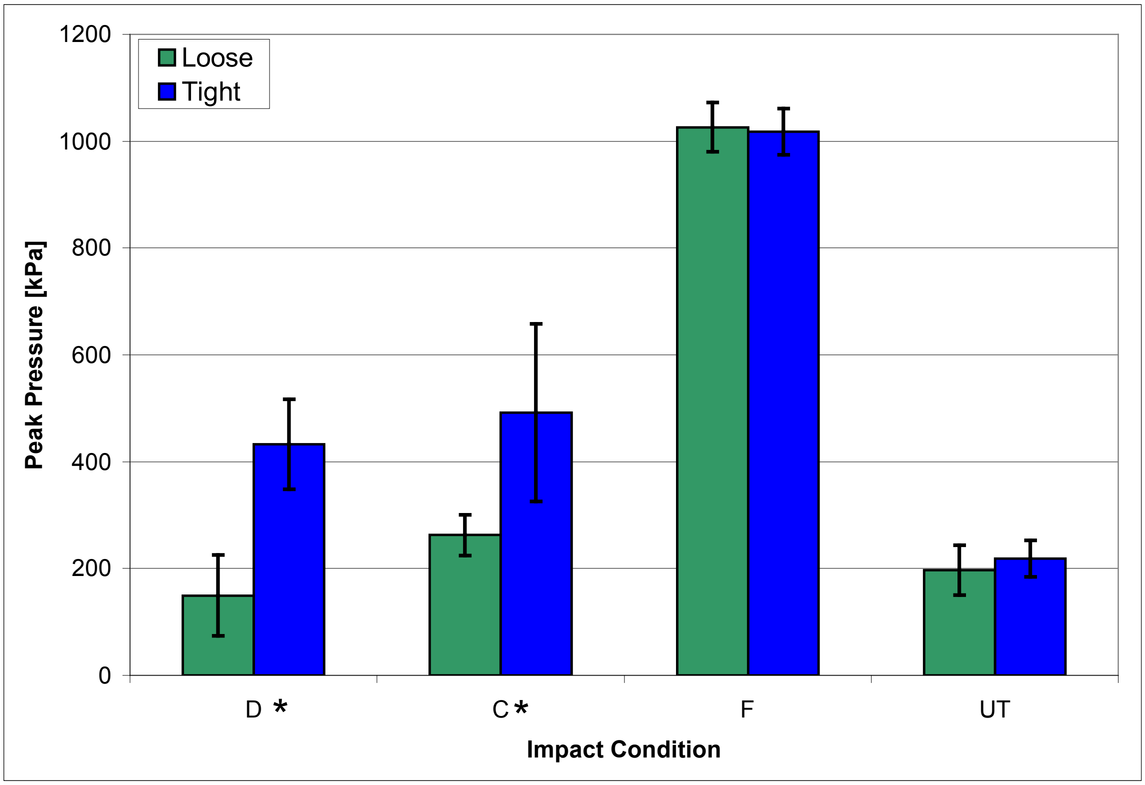


Figure 3.3.6 – Peak Surface Pressure: Loose- versus Tight-Fitting Condition

Peak pressure varied substantially depending on impact orientation regardless of the fit condition. In impact condition F, the peak pressure during the impact was substantially higher when compared to the other impact conditions. The fitment on the front of the headform also had higher surface pressures than the rest of the headform. The substantially higher surface pressures observed during the impact testing may have been the result of a combination of parameters. These are listed below:

- Stiffness of padding in the frontal area,

- A tighter fit in the frontal area, and/or
- Ineffective spread of the impact load on the headform.

Firstly, measuring the stiffness of the padding in various areas of the helmet was not a goal of this research and, therefore, was not investigated; however, manual compression of the padding indicated that the frontal padding appeared to be stiffer than the padding in other areas of the helmet.

Secondly, it was summarized previously **(Chapter 2)** that helmet fit in the frontal area of the headform was substantially tighter than all other areas of the headform. This finding was also consistent with the volunteer fitment testing. The tight-fitting condition also resulted in a more uniform-fitting condition.

To assess the ability of the helmet to spread the load over the frontal area of the headform, we compared a tight- and loose-fitting condition of the helmet in impact condition F **(Figures 3.3.7a and b)**. In the loose-fitting condition, the pressure is concentrated in the frontal area of the helmet and it is distributed primarily in the sagittal plane. The tighter and more evenly fitting condition distributed the impact over the entire anterior aspect of the headform.

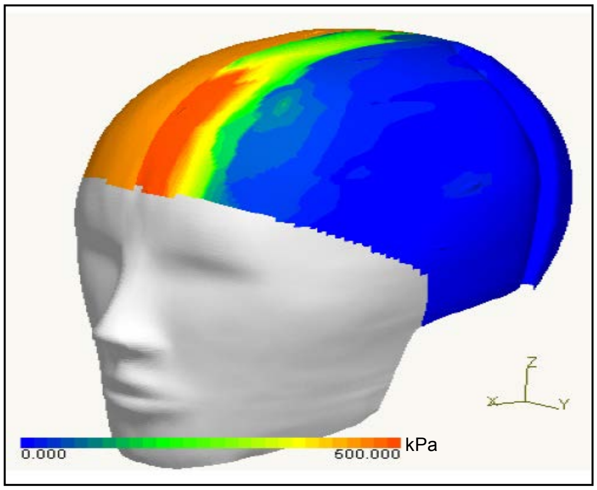


Figure 3.3.7a – Peak Pressure – Loose-Fitting Condition

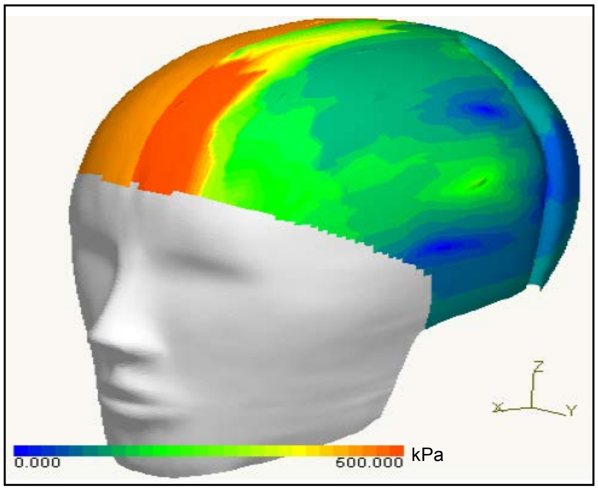


Figure 3.3.7b – Peak Pressure – Tight-(Uniform) Fitting Condition

The tighter (and uniform) fitting helmet resulted in a more even spread of the impact forces, and as a result, there was an increase in linear acceleration (18%). There was also a nominal increase in angular speed (1%), and a substantial decrease in angular acceleration (32%) for impact condition F. A representative impact event is illustrated in **Figure 3.3.8a**. This finding indicates that a more uniform-fitting helmet is more efficient at spreading the impact load over a larger area. The more evenly spread loading pattern results in the headform undergoing a more linear response to the impact and substantially reduces the angular acceleration component. The tighter and more uniform-fitting helmet also resulted in higher angular speeds; however, the rate at which the angular speed increased was more linear. This is also illustrated in the angular acceleration curve where, in the loose-fitting condition, there is a slow onset of the angular acceleration, followed by a steep increase. These differences also illustrate that a tighter and more uniform-fitting helmet applies protection to the head earlier during the impact event. Similar response characteristics were noted in impact conditions UT, C, and D **(Figures 3.3.8b to d)**. The response parameters in these impact conditions did not illustrate as substantial a decrease in angular acceleration response. This may be a result of the frontal area being the tightest fitting area on the headform.

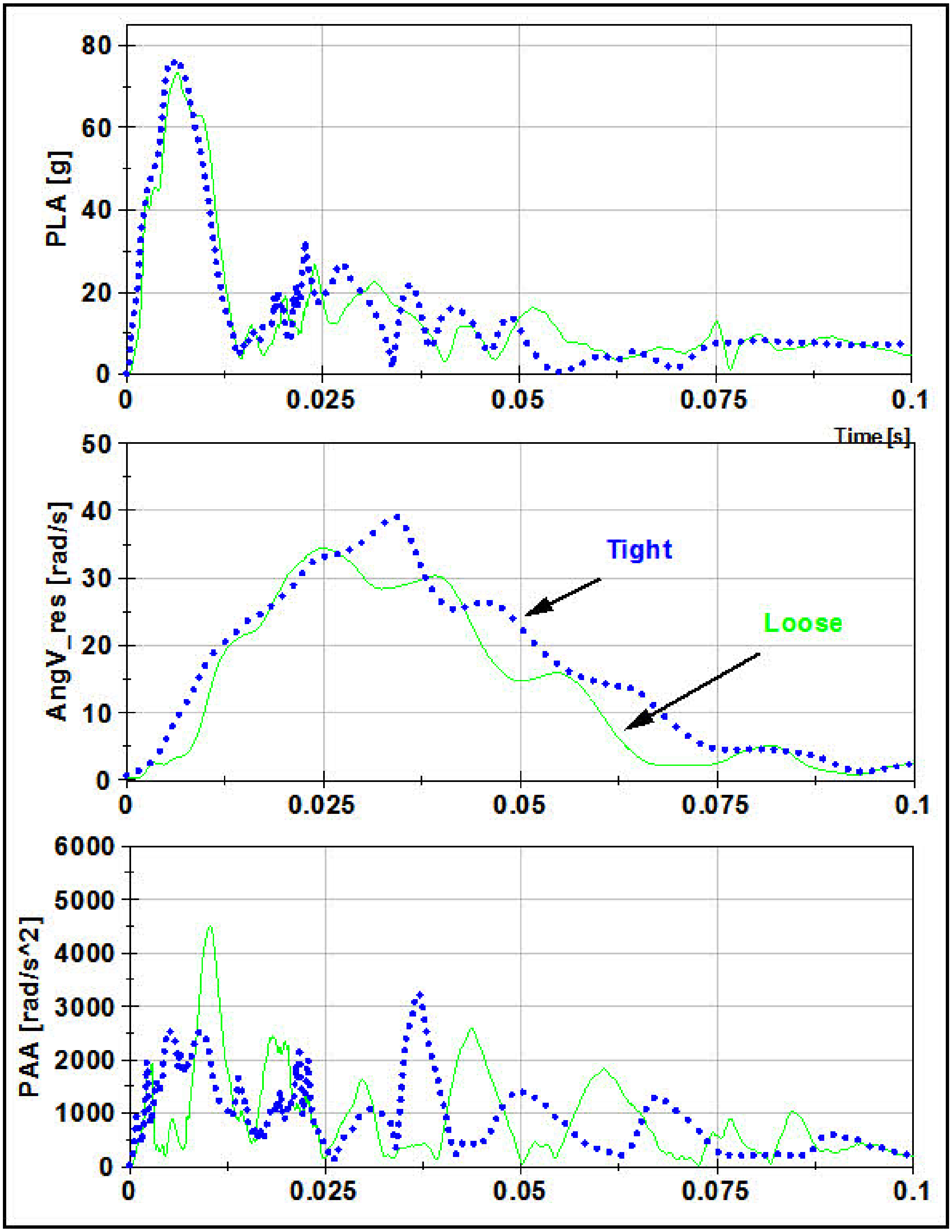


Figure 3.3.8a – Impact Condition F

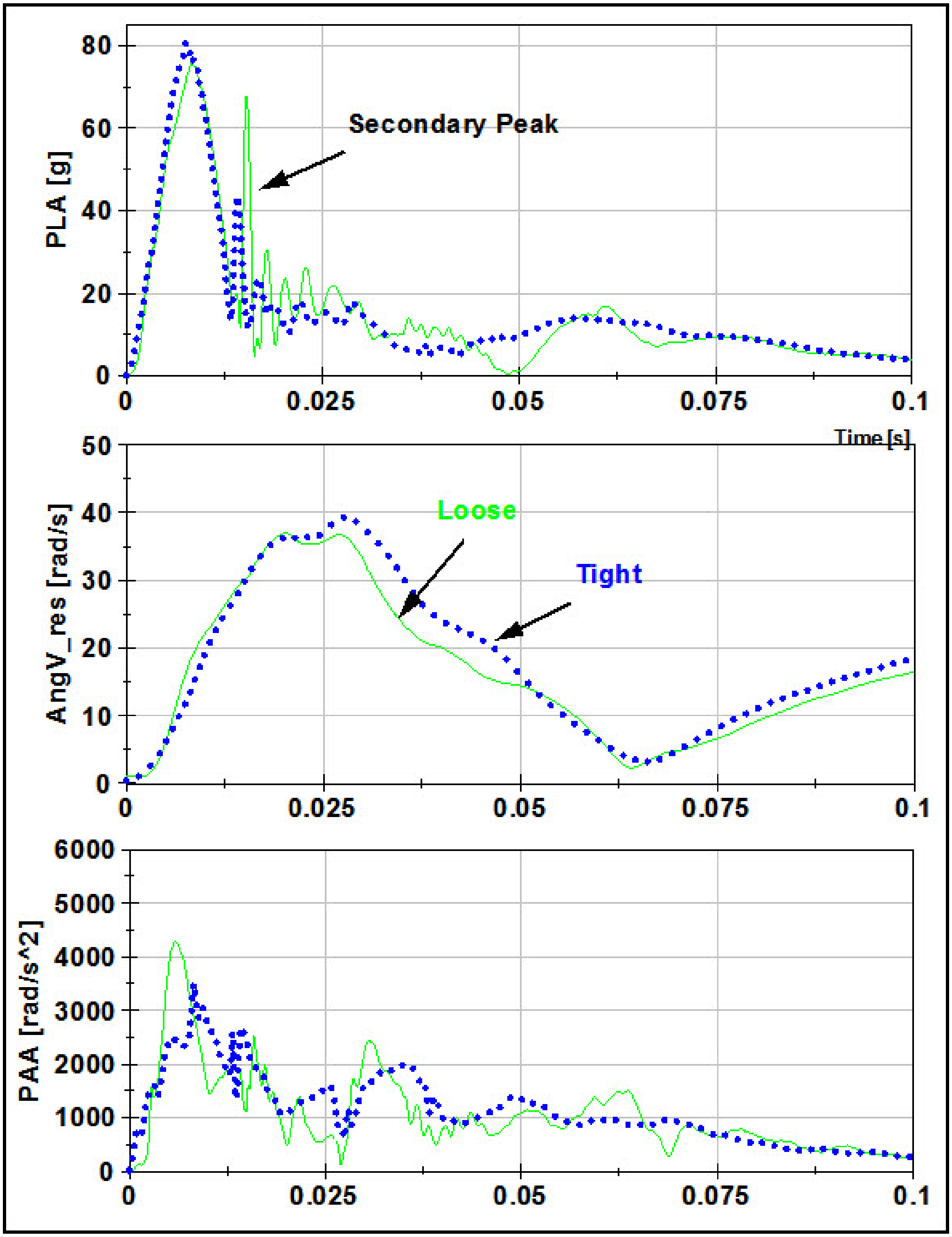


Figure 3.3.8b – Impact Condition UT

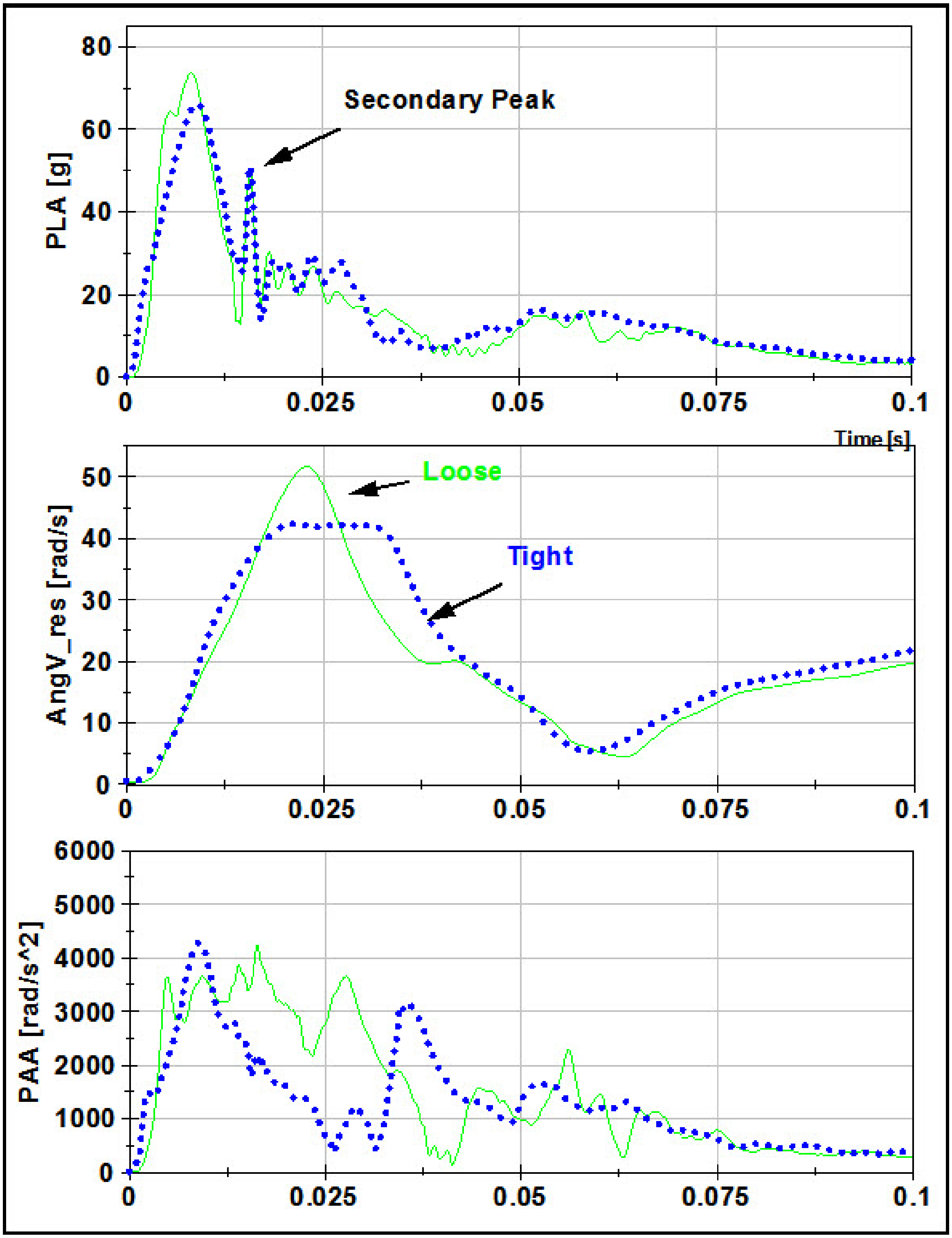


Figure 3.3.8c – Impact Condition C

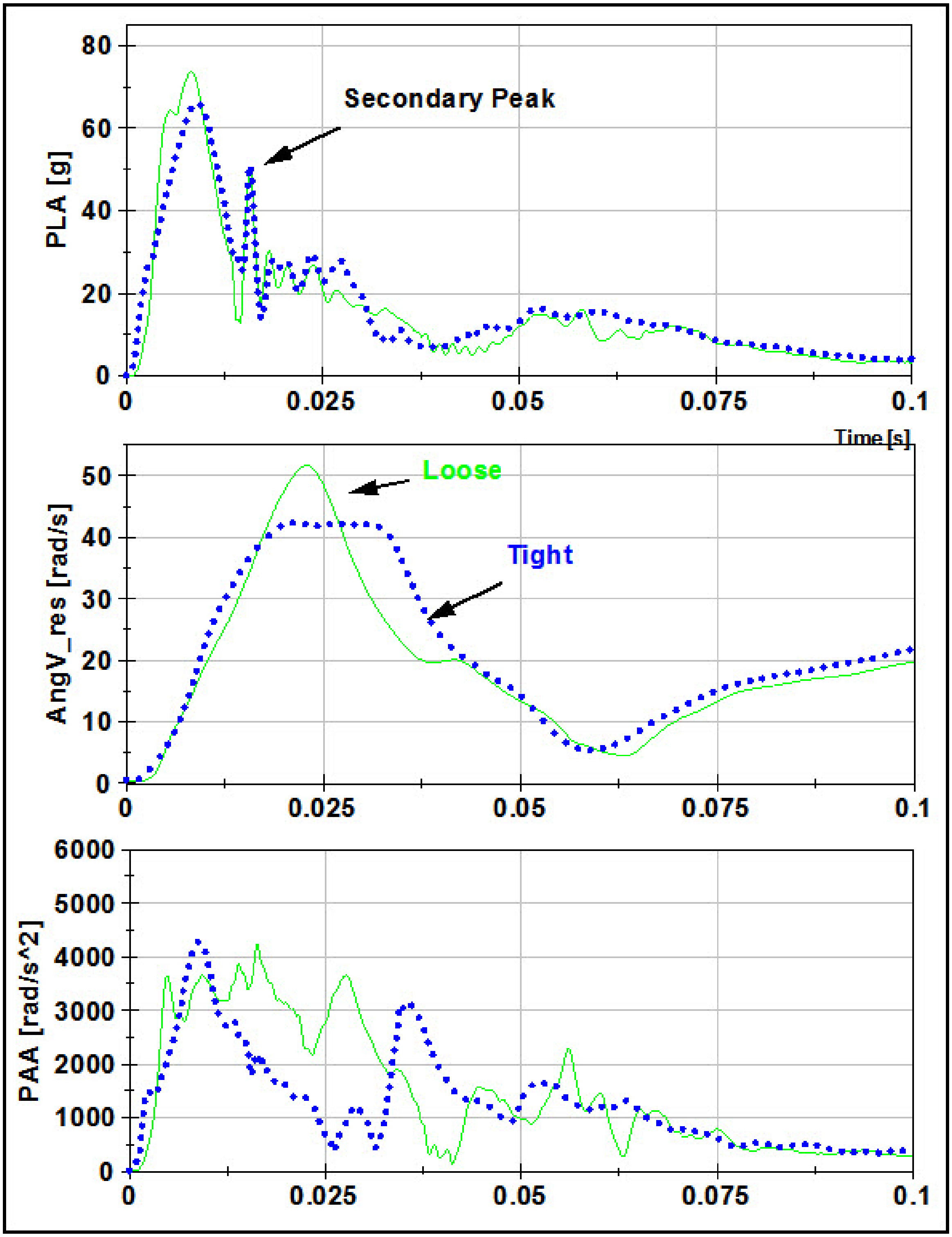


Figure 3.3.8d – Impact Condition D

In three of the four impact conditions above (C, D, and UT), there was a secondary peak in the linear acceleration data which occurred approximately 8 to 10 ms after the initial peak acceleration. This condition was present in all tests, loose and tight, for conditions C, D, and UT. Analysis of the data indicates the signals from accelerometers OZ, XZ, and YZ of the 3-2-2-2 array displayed this characteristic. The sensing axis from each of these accelerometers was the z-axis. In the accelerometer data, there was a relatively large peak in the negative (upward) z acceleration data at this time. The Fz peak tensile load in the upper neck load cell data also correlated with the timing of this peak upward acceleration **(Figure 3.3.9)**. Since each of these 3 accelerometers was mounted on a different mounting location, and the Fz peak load also correlated with this time, it does not appear that the secondary peak is an artifact of improper accelerometer mounting.

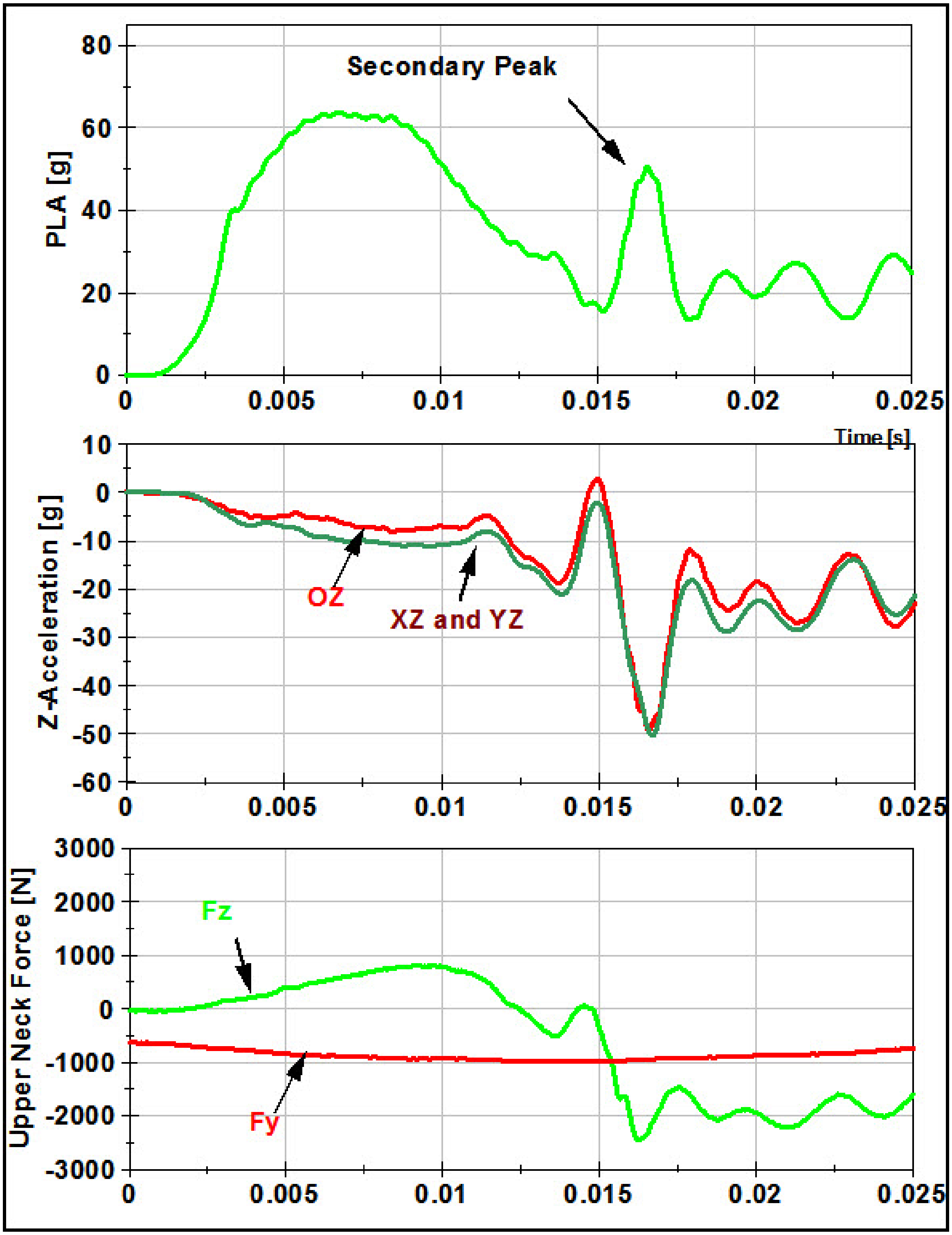


Figure 3.3.9 – Secondary Acceleration Peak

Craig (Craig, 2007) conducted an analysis of jaw loading due to chin strap interaction using a similar setup to this linear impactor testing. Generally, peak linear accelerations in the testing conducted by Craig occurred at approximately 5 – 10 ms after the initial impact, and the peak jaw loading occurred at approximately 15 to 20 ms after the initial impact. The three impact conditions conducted by Craig were all frontal impact conditions (A, A' and A") to the facemask area. Based upon the Craig data, it appears the secondary peak in the linear acceleration data is associated with chin strap loading through the jaw of the headform.

3.3.2 Head Response vs. Reported HITS Data

Peak response parameters only were recorded by the HIT System. Time history data were not available. A comparison of the data from the individual tests is illustrated in **Figures 3.3.10a to 3.3.10h**. These data illustrate that there are differences in the HITS-reported values for each of the headform related, performance characteristics: HIC, GSI, peak linear acceleration (PLA), and peak angular acceleration (PAA). For HIC and GSI, the values varied from being over-reported by 50% to being under-reported by 79%. Peak linear acceleration was generally within ±25% with the exception of impact condition D where errors reached 98% for the tight-fitting condition. Peak angular acceleration was substantially over-predicted by the HITS. Error in angular acceleration varied between -59% and approximately 203%. This is despite the fact that the HIT System only reports angular acceleration in two of the three axes.

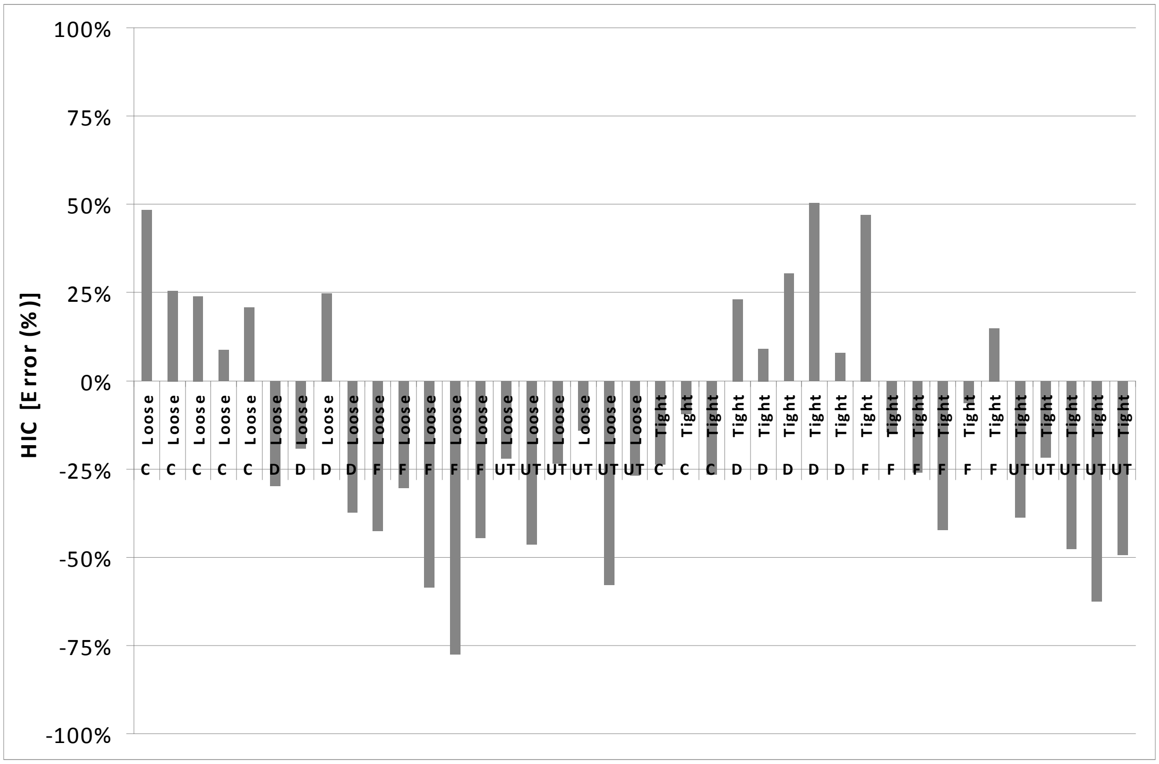


Figure 3.3.10a – HIC: Relative Error HITS vs Hybrid III

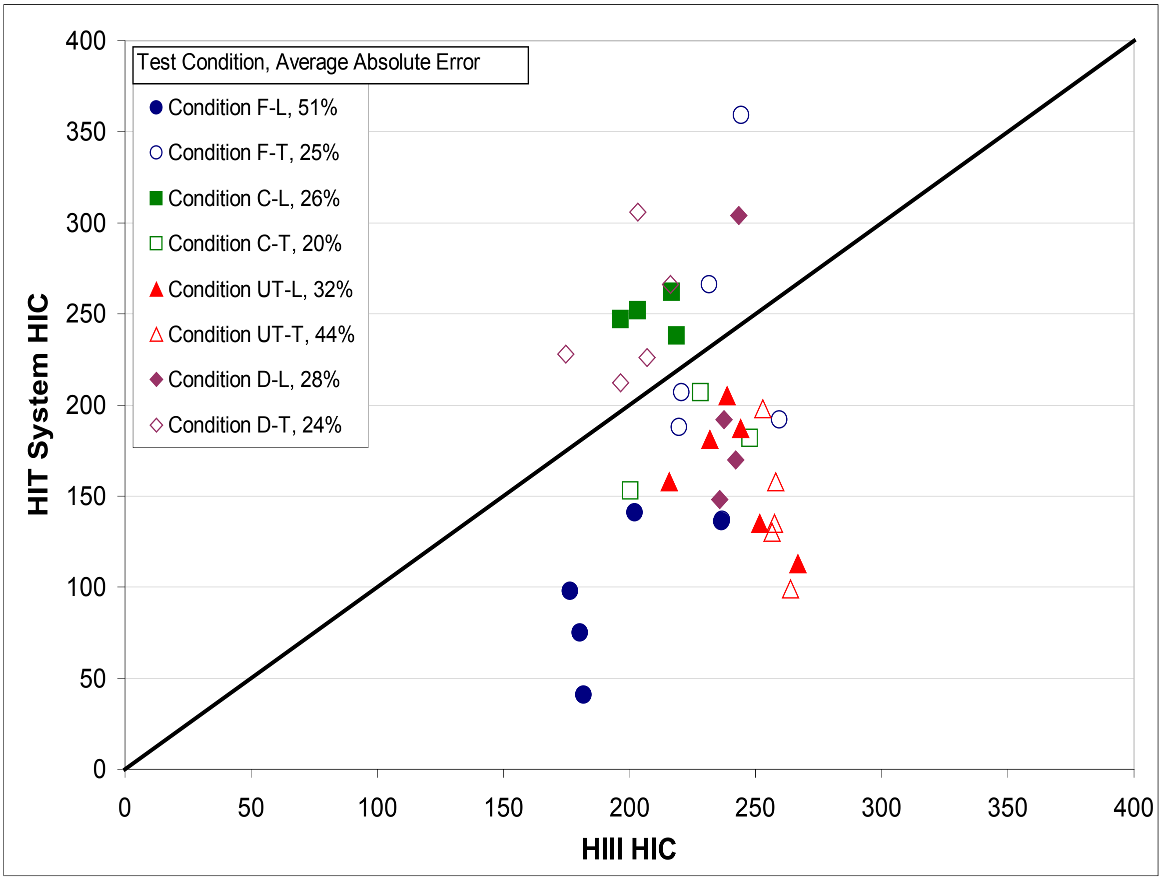


Figure 3.3.10b – HIC: HIT System vs. Hybrid III Data and Absolute Error

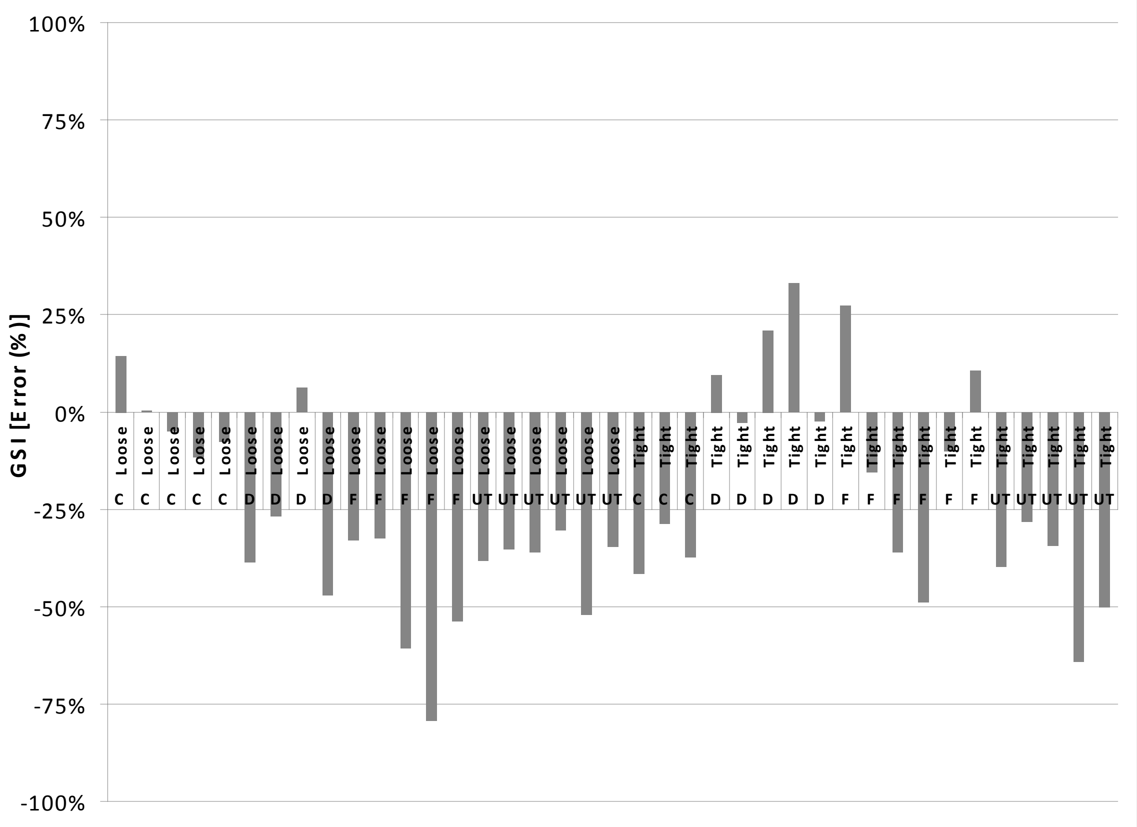


Figure 3.3.10c – GSI: Relative Error HITS vs Hybrid III

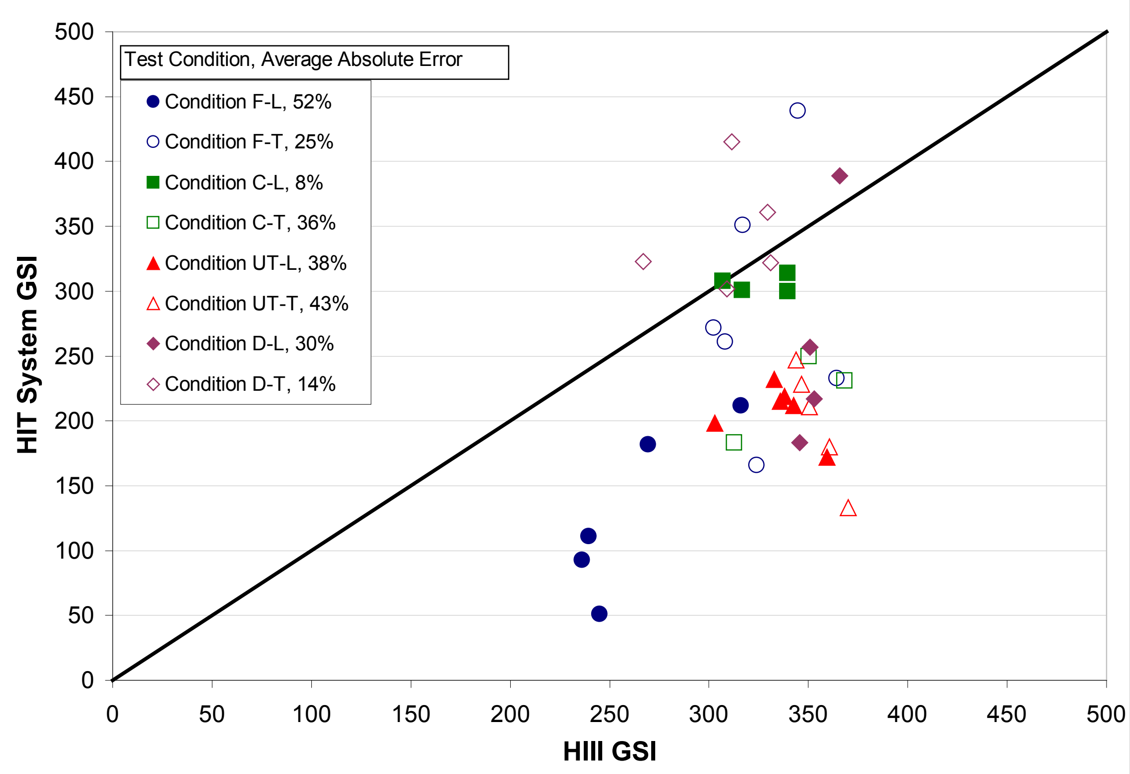


Figure 3.3.10d – GSI: HIT System vs. Hybrid III Data and Absolute Error

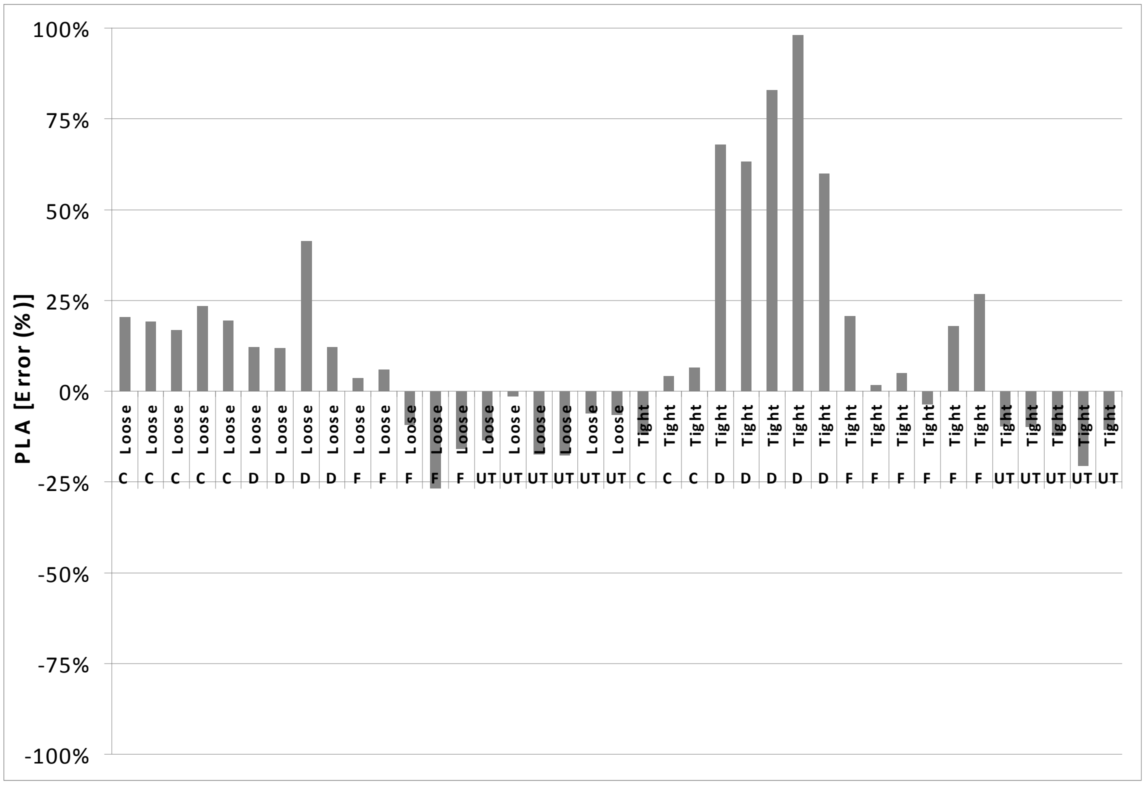


Figure 3.3.10e – PLA: Relative Error HITS vs Hybrid III

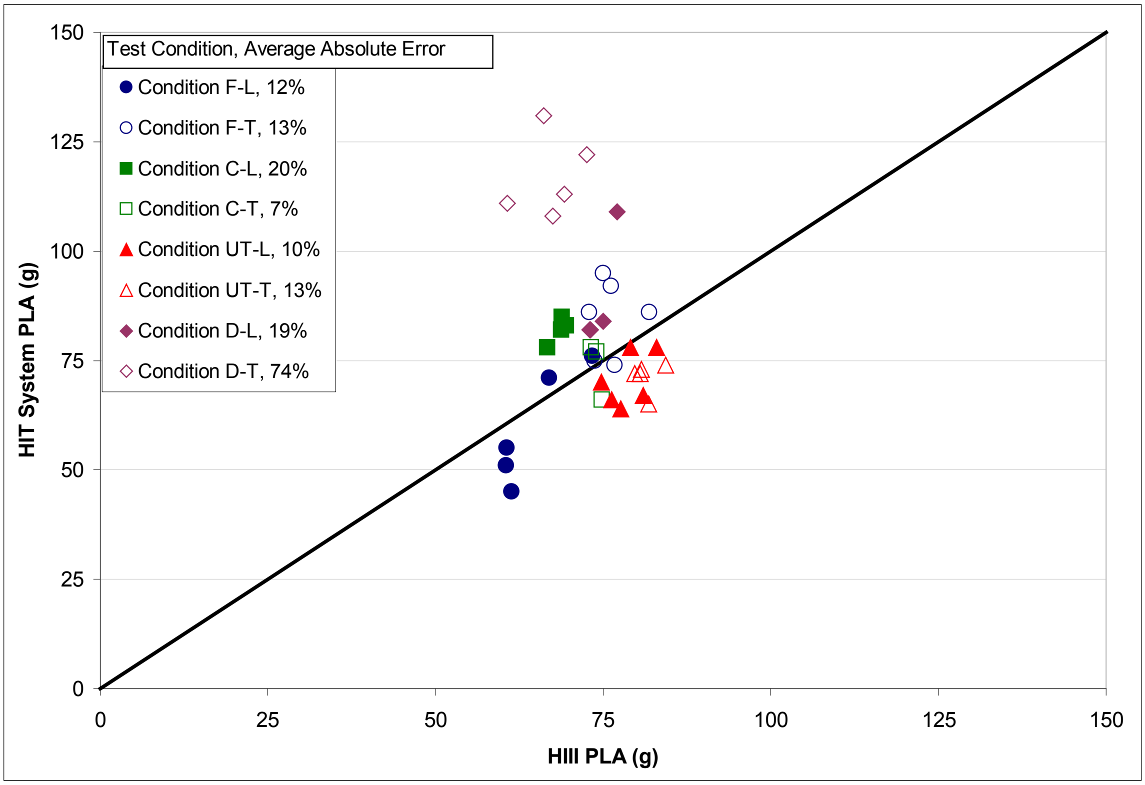


Figure 3.3.10f – PLA: HIT System vs. Hybrid III Data and Absolute Error

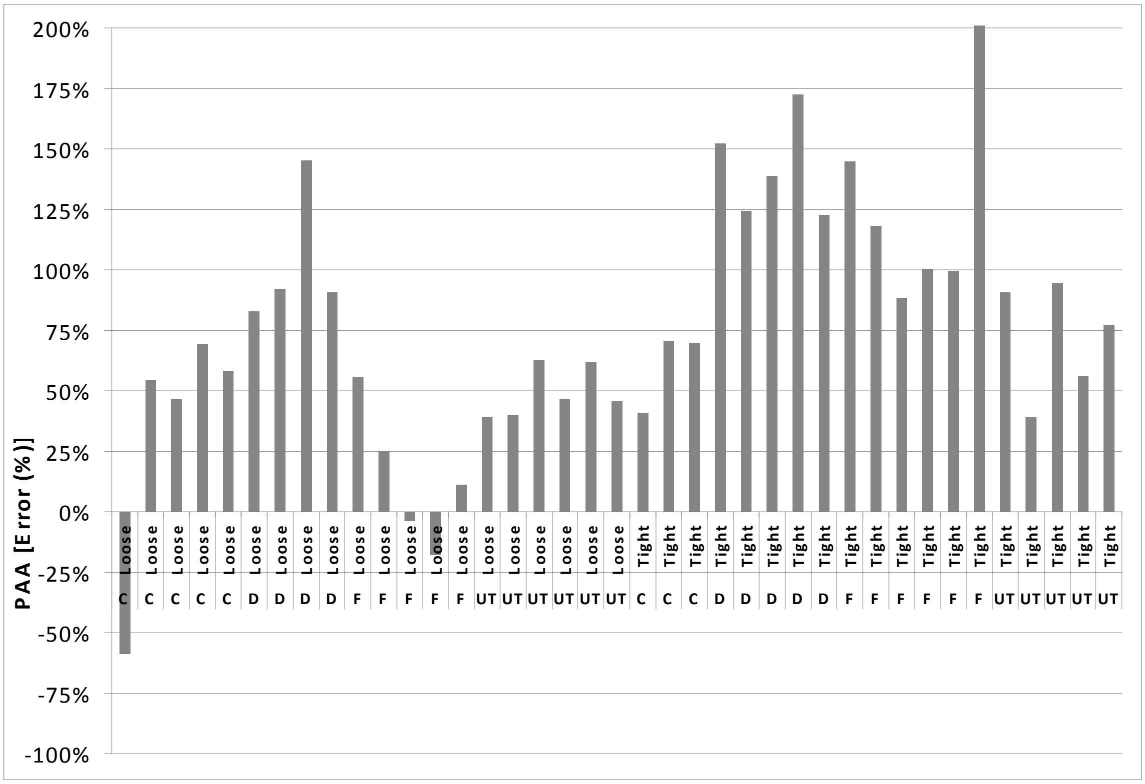


Figure 3.3.10g – PAA: Relative Error HITS vs Hybrid III

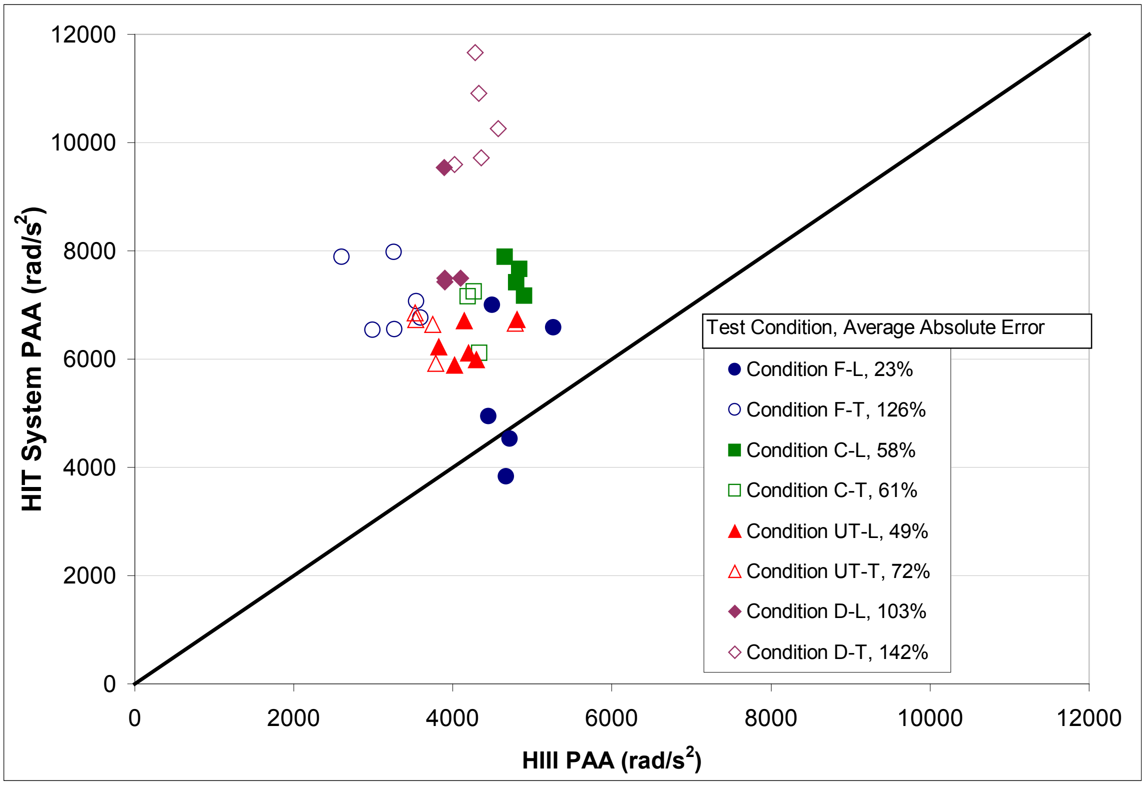


Figure 3.3.10h – PAA: HIT System vs. Hybrid III Data and Absolute Error

Table 3.3.3 summarizes the average absolute error for the loose- and tight-fitting conditions as well as the overall absolute error.

Condition	Fit	HIC	GSI	PLA	PAA
All	Loose	33%	32%	14%	55%
All	Tight	29%	28%	28%	106%
All	All	32%	30%	21%	80%

Table 3.3.3 – Summary of HIT System Absolute Error

Table 3.3.4 summarizes the headform response data versus HIT System response data as well as the paired samples correlation. The paired samples analysis was conducted by comparing the loose- and tight- fitting conditions. The data in this table are a combination of the tight- and loose-fitting conditions. There are apparent differences in the mean values of the response parameters reported by the HITS versus the headform data. The standard deviation of the HITS is substantially greater than the standard deviations reported by the headform (2.6 to 2.9 times greater). The paired samples correlation indicated there was not a strong correlation between any of the HITS and headform response parameters. GSI had a significant correlation; however, the correlation coefficient was low (r =0.386, sig = 0.012). A paired samples test was conducted on the combined HITS versus headform reported data. The HITS under-predicted HIC by a mean difference of 45.8 (t=-3.669, p = 0.001), under-predicted GSI by a mean difference of 88 (t=-6.278, p=0.000), and over-predicted peak angular acceleration by a mean difference of 2287 rad/s^2 (t=11.647, p=0.000). HITS peak linear acceleration was slightly greater with a mean difference of 7.9 g (t=2.595, p=0.013).

Paired Samples Statistics					Correlation	
	Mean	N	Std. Deviation	Std. Error Mean	Correlation	Sig.
HITSHIC	176.0	42	81.5	12.6	0.191	0.225
H3HIC	221.9	42	28.1	4.3		
HITSGSI	231.2	42	99.0	15.3	0.386	0.012
H3GSI	319.7	42	37.4	5.8		
HITSPLA	80.6	41	17.9	2.8	-0.055	0.734
H3PLA	72.7	41	6.6	1.0		
HITSPAA	7215.0	41	1561.1	243.8	-0.046	0.777
H3PAA	4151.2	41	565.2	88.3		

	Paired Differences					t	Df	Sig. (2-tailed)
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
HITSHIC - H3HIC	-45.8	80.9	12.5	-71.1	-20.6	-3.669	41	0.001
HITSGSI - H3GSI	-88.5	91.3	14.1	-117.0	-60.0	-6.278	41	0
HITSPLA - H3PLA	7.9	19.4	3.0	1.7	14.0	2.595	40	0.013
HITSPAA - H3PAA	3063.7	1684.4	263.1	2532.1	3595.4	11.647	40	0

Table 3.3.4 – Summary of HIT System versus Hybrid III Data (Combined Tight and Loose)

Tightness of helmet fit had an effect on the HITS reported parameters versus the headform response. In the loose-fitting condition, the HITS PLA was not statistically different from headform PLA (t=1.303, p=0.207); however, HIC, GSI, and PAA were **(Table 3.3.5)**.

Paired Samples Statistics					Correlation	
	Mean	N	Std. Deviation	Std. Error Mean	Correlation	Sig.
HITSHIC	154.1	23	88.7	18.5	0.394	0.063
H3HIC	215.0	23	28.6	6.0		
HITSGSI	200.1	23	101.6	21.2	0.626	0.001
H3GSI	309.3	23	41.9	8.7		
HITSPLA	74.3	22	13.4	2.9	0.424	0.049
H3PLA	70.9	22	6.7	1.4		
HITSPAA	6707.3	22	1216.9	259.4	-0.194	0.386
H3PAA	4420.1	22	400.2	85.3		

	Paired Differences					t	df	Sig. (2-tailed)
				95% Confidence Interval of the Difference				
	Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
HITSHIC - H3HIC	-60.8	81.8	17.1	-96.2	-25.5	-3.568	22	0.002
HITSGSI - H3GSI	-109.3	82.2	17.1	-144.8	-73.7	-6.377	22	0.000
HITSPLA - H3PLA	3.4	12.2	2.6	-2.0	8.8	1.303	21	0.207
HITSPAA - H3PAA	2287.2	1352.8	288.4	1687.4	2887.0	7.93	21	0.000

Table 3.3.5 – Summary of HIT System versus H3 Data (Loose Condition)

In the tight-fitting condition **(Table 3.3.6)**, PLA reported by HITS was higher than PLA reported by the headform (t=2.303, p=0.033). The tight-fitting condition also resulted in HITS data more closely representing the headform-reported HIC (t=-1.542, p=0.14), GSI (t=-2.828, p=0.011), and PLA; however, GSI and PLA were still significantly different. PAA remained significantly different for this condition. In addition to the improvements to the t-statistic, a tighter fitting helmet also resulted in HIT system PLA correlating with headform PLA (r=0.739, sig < 0.001). The standard deviations for HIC and GSI of the HIT system reduced in the tight-fitting condition (relative to looser-fitting condition); however, standard deviations of PLA and PAA increased.

Paired Samples Statistics					Correlation	
	Mean	N	Std. Deviation	Std. Error Mean	Correlation	Sig. (2-tailed)
HITSHIC	202.6	19	64.4	14.8	-0.392	0.097
H3HIC	230.3	19	25.8	5.9		
HITSGSI	268.8	19	83.4	19.1	-0.409	0.082
H3GSI	332.2	19	27.0	6.2		
HITSPLA	87.9	19	19.9	4.6	-0.739	0
H3PLA	74.8	19	6.0	1.4		
HITSPAA	7802.7	19	1734.5	397.9	0.381	0.108
H3PAA	3839.9	19	576.5	132.3		

	Paired Differences					t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
HITSHIC - H3HIC	-27.7	78.2	17.9	-65.4	10.0	-1.542	18	0.14
HITSGSI - H3GSI	-63.3	97.6	22.4	-110.4	-16.3	-2.828	18	0.011
HITSPLA - H3PLA	13.1	24.8	5.7	1.1	25.0	2.303	18	0.033
HITSPAA - H3PAA	3962.9	1606.0	368.4	3188.8	4736.9	10.756	18	0

Table 3.3.6 – Summary of HIT System versus Hybrid III Data (Tight Condition)

Chapter 4 – Discussion and Limitations

This research study provided an objective method of measuring pressure between the head and the helmet. An index was proposed to quantify how tightly and evenly a helmet fits a head. The research has also quantified how football helmets fit on volunteer players as well as on the Hybrid III headform. Finally, it has discussed the effects of helmet fitment on various Hybrid III headform response parameters and how helmet fitment affects the ability of the HIT system to predict headform responses accurately. Various statistically significant findings were noted.

4.1 A Method of Measuring Helmet Fit

A method of objectively measuring the pressure between the helmet padding and an athlete's head (or a headform) has been established. The FIT cap is a portable system which allowed for transferability from volunteer to volunteer. The design and construction of this FIT cap, as well as computer programming undertaken, allowed for a large number of volunteer data to be captured without significantly interrupting football teams' practice schedules. Up until now, helmet fitment has been reported as being "an important" aspect of helmet protection. However, there has been no objective method of measuring how evenly or how tightly a helmet fits. Published fitting guides appear to rely purely on a subjective method of helmet fitment. This research provides for a means to quantify helmet fit objectively and to monitor how tightly and evenly a helmet is fitting the athlete. The fitting method and apparatus that were developed are economical, and the potential for a commercial helmet fit system does exist. This system could aid helmet manufacturers in achieving a more uniform fit on the athletes who wear the helmets. This, in turn, would provide insight into this major boundary condition for helmet manufacturers and allow the manufacturers to focus on improving padding and/or other methods to increase helmet performance.

The major limitation regarding the current FIT system design is that it was designed to be a portable device for the purpose of collecting volunteer fitment data while the volunteers wore their own, previously-fitted helmets. As discussed, this led to the potential for sensors not to contact the interior padding of the helmet since many helmets have air gaps between the padding. Due to the small, lightweight, and low cost design of the system, it could be incorporated directly into a helmet design. If incorporated into a helmet, the system could also provide impact-related data which could be used as an input for finite element modeling of the brain.

4.2 Volunteer Helmet Fitment

The goals of the volunteer helmet fitment measurements were to:

1. Quantify the level of fitment (tightness and evenness) which existed for current football players who had reportedly been fitted according to the helmet manufacturer's recommended practice and
2. Assess the fitment of a helmet on the Hybrid III headform.

In total, 63 volunteers were tested, varying in ages from 14 to 20 years old. The results of this study indicate helmets fit volunteers in varying degrees of tightness and evenness. Most volunteers had the tightest-fitting area on the frontal portion of the head (59%). The second most common region with a tight-fitting section was in the occipital area (29%). Volunteers within this study reported an uncomfortable fit when the FIT cap pressure readings exceeded 69 kPa (10 psi). It was commonly observed in these volunteers that there were red markings or indentations on the volunteers' foreheads to complement their comments of tightness of fit. To date, this study appears to be the only volunteer-based study that has objectively measured helmet fitment and quantified it. This research of volunteer helmet fitment identifies that further improvements can be made in order to achieve a more optimally fitting helmet. A method and apparatus has been designed so that helmet manufacturers could incorporate it into their fitting instructions or helmet designs to provide an objective measure of helmet fitment.

Once the volunteer helmet fitment data had been collected, it was possible to assess which sized helmet on the Hybrid III headform is representative of how helmets are worn in a field environment. Two methods were undertaken: Method I was strictly as a basis for a comparison of the manufacturer's helmet sizing recommendations. This procedure compared the head circumference of the Hybrid III headform and selected the helmet size based upon that measurement. The head circumference of the Hybrid III headform is 57.2 cm. The helmet manufacturer's (Riddell) fitment guide indicates that a large-sized helmet is appropriate for head circumferences between 55.9 and 59.7 cm. Therefore, based upon this method, the large-sized Riddell helmet would be appropriate to be worn on the Hybrid III headform. The second method was utilized to assess an appropriate helmet size to be worn on the Hybrid III headform based upon a comparison to the volunteer fitment data. This method indicated the size large helmet was more representative of the volunteer data. The large-sized helmet represented approximately the 40th percentile P_{AVG} and approximately the 35th percentile P_{MAX} recorded on volunteer fitment data. The medium-sized Riddell helmet had a P_{MAX} representative of the 76th percentile volunteer fit and a P_{AVG} representative of the 99th percentile volunteer. Additionally, the P_{MAX} measured on the Hybrid III headform with the medium-sized

Riddell helmet were above the threshold at which volunteers indicated their helmets were fitting uncomfortably tightly (approximately 69 kPa).

Therefore, based upon the two methods outlined above, the large-sized Riddell helmet worn on the Hybrid III headform is more representative of how helmets are being worn in the field, and it is also representative of the helmet manufacturer's recommended helmet size.

There are some limitations with regards to the volunteer helmet fitment measurements. The testing was conducted on 63 volunteers belonging to one football club. Firstly, an increase in the number of volunteers is always advantageous. The present study is a landmark study regarding helmet fitment using an objective method and provides a building block for further research. Secondly, although the football club did consist of three separate teams, it would be recommended that a similar study be undertaken on additional football clubs and other contact sports clubs, such as hockey, to understand variability in helmet fitment fully. Thirdly, in the current study, all volunteers tested wore Riddell football helmets. Although Riddell is a very popular helmet in youth-aged football, as well as being the official helmet of the NFL, there are other helmet makes and models that exist. It could be very beneficial to conduct such a study on other football helmet makes and models. Finally, in this study, the ability to capture data quickly and reduce training downtime for the athletes was a primary concern. There are additional steps which could be undertaken to understand helmet fit better. These may include anthropometric measurements of the athlete's head, documentation of hair length, and formal documentation of the athlete's subjective description of fitment. The subjective measurement of fit could direct helmet manufacturers to develop a tightly fitting helmet that can still remain comfortable to the athletes. After fitment is controlled, helmet designs can be further optimized for omni-directional protection.

4.3 Helmet Fit Effects on Headform Response

Linear impactor testing was conducted with varying helmet tightnesses and also evenness of fit. There were two fitting protocols selected. These were the baseline (loose) condition which was representative of the 50th percentile volunteer fitment. The loose-fitting helmet also resulted in a non-uniform pressure distribution on the Hybrid III headform. This non-uniform distribution was also observed in the volunteer testing. The second fit condition was achieved by inflating all air bladders in the selected football helmet. The bladders were inflated until the pressure distribution on the Hybrid III headform exceeded the 100th percentile tightness of fit documented in the volunteer testing. This tighter-fitting condition also resulted in a more uniform pressure distribution on the headform; however, it greatly exceeded the pressure at which volunteers reported that their helmets became uncomfortable.

Linear impactor testing was conducted with the same padding in the loose- and tight-fitting conditions. At the onset of the testing, it was not anticipated there would be major differences in headform response parameters during the loose- and tight-fitting conditions. However, there were two major findings that were apparent in the tight- (and more uniform-fitting condition) versus the loose-fitting condition. 1) The tight- (and more uniform-) fitting condition resulted in a reduction in angular acceleration response of the headform. This appears to be the result of the helmet more evenly spreading the load during the impact and effectively changing the line of force and subsequent moment arm. 2) The tight- (and more uniform-) fitting condition resulted in a more linear onset of the linear and angular acceleration pulses as well as the angular velocity pulse. The padding was contacting the headform at the time the impact occurred. During the loose-fitting condition, there was a slower onset of the pulse followed by a more severe rise, similar to a parabolic onset.

This study regarding helmet fitment indicates that, contrary to previous reports, a helmet may have the ability to reduce the angular accelerations being undergone by the head. Regardless, helmet fitment plays a critical role in the helmet's ability to spread the load and reduce angular accelerations.

There are limitations regarding the aforementioned testing. Firstly, the pressure in the air bladders could not be controlled well using the method selected for inflating the bladders. To achieve a more repeatable tight-fitting condition, a digital pressure gauge could be utilized; however, the volume of air in the padding is small, and there may be error introduced simply to pressurize the gauge. Secondly, while inflating the air bladders does increase the tightness of fit, it may also affect the properties of the interior padding. An alternative method to adjust tightness of fit could be to "shim" the padding as opposed to inflating the padding. Thirdly, although the FIT cap was capable of measuring dynamic forces, the individual sensors were not calibrated in a dynamic environment. The dynamic impact pressures would still be valid as comparative values; however, the actual pressure may be a different value.

4.4 Helmet Fit Effects on HIT System vs Headform Response

The linear impactor testing conducted in this research compared HIT System data versus headform response. Tightness and evenness of helmet fit were varied. The linear impactor target test speed was 9.3 m/s, which is representative of the average concussive event reported in the NFL Subcommittee research. Forty-eight impact events were conducted, 25 of which were at the looser-fitting condition and 23 were at the tighter-fitting condition. The HIT System algorithms removed 11 impacts from the data set (22.9%) because the algorithms classified these as not being “real” impacts. A large-sized Riddell Revolution IQ HITS helmet was utilized for this research with the jaw pads inflated until they fit firmly against the face of the headform.

The only performance measure wherein a statistically significant correlation was found between the headform response parameters and the HIT System data was GSI. This may be related to the fact that only one impact speed was selected for this testing. However, the scatter and/or relative error of the HIT System versus headform-reported response parameters became quite apparent when a single target impact speed was utilized. The response parameters reported by the headform were statistically different from the HIT System data reported. The relative error between the HIT System and the headform-reported data for HIC ranged from -77% to +50%, the GSI relative error ranged from -79% to +33%, the PLA relative error ranged from -27% to +98%, and the PAA relative error ranged from -59% to +203%. The average relative error for PLA was 12% ±29% (±1 standard deviation), and the relative error for PAA was 76% ±52%. The impact testing was conducted in a laboratory environment.

The Hybrid III headform was not fitted with a compliant scalp or hair, and it was not perspiring at the time of the impacts. Additionally, the four impact conditions considered in this linear impactor testing were relatively direct impacts to the shell of the helmet on the Hybrid III headform. In reality, the football impacts could result in varying degrees of glancing blows and impacts to the facemask. It is unknown how these glancing blows may affect the ability of the HIT System to predict headform accelerations. However, Beckwith (2011) conducted linear impactor testing and has reported that impacts to the facemask area resulted in the HIT System reporting acceleration values that were 2 to 5 times higher than the headform acceleration.

The relative error reported in this study represents a ±1 standard deviation window. One of the major advantages of the HIT System is its ability to capture an extremely large amount of volunteer data. Rowson (Rowson, 2011a) reports there have been over 1.5 million head impacts recorded to date. If 1.5 million impacts have been recorded, the cited error rate at ±1 standard deviation would indicate that approximately 2/3 (1 million) of the total reported values would lie within the error range; alternatively, 1/3 (0.5 million) would have an error greater than described. For this vast amount of data, it may be appropriate to consider an error of 2 or 3 standard deviations. If a team physician were to rely upon the HIT System data for a method of alerting to a potentially concussive impact, this level of error may be insufficient. For example, if an athlete actually received a 70 g impact to the head, the above relative error numbers would indicate that the HIT System would report this impact as 78 g ± 22 g (2/3 of the time). The other 1/3 of the time, this impact could be reported as being greater than 100 g or less than 56 g. The reported number may influence the team physician's decision whether to allow the player to remain on the field or to remove the player for further evaluation.

The relative error of the HIT System has been reported in various other publications . A summary of the reported relative errors for the HIT System versus headform accelerations, as well as the relative error computed in this study, are illustrated in **Table 4.4.1**.

				Average Relative Error			
Author	**Year**	**Helmet Size**	**Impact Speed**	**PLA**	**PAA**	**HIC**	**GSI**
Duma[2]	2005	-	-	±4%	±4%	±4%	-
Funk[2,3]	2007, 2011	-	-	8±11%	-	23%±28%	-
Beckwith[4]	2011	M	4.4,7.4,9.3,11.2 m/s	0.90%	6.10%	6.10%	5.20%
Beckwith[4,8]	2011	M	4.4,7.4,9.3,11.2 m/s	6±16%	2±32%		
Rowson[5,6]	2011	M[7]	3,5,6,7,8,9 m/s	1±18%	3±24%	-	-
Jadischke	**2011**	**L**	**9.3 m/s**	**12%±29%**	**76%±52%**	**-14%±33%**	**-24%±27%**

[1] The error cited in this study represents the Average Error ± 1 std deviation.

[2] There is no detailed validation of the HIT System presented in this study.

[3] The error is reported as an Average Error ± coefficient of variation. [$COV=\sigma/\mu$]

[4] Two impact conditions were omitted from the error calculations (A' and A").

[5] New 6DOF version of HIT System using 12 accelerometers.

[6] Impact energies reported instead of impact speeds. Speeds calculated assuming $m=15$ kg and $KE=1/2mv^2$.

[7] Helmet bladder was inflated "per manufacturer's specifications".

[8] Errors presented here are based upon an analysis of linear and rotational acceleration data

Table 4.4.1 – Summary of Calculated Relative Error Data for HIT System

The relative errors reported in this research are somewhat higher than previously reported. One contributing factor to the larger error reported in this research versus previously published research is the usage of a large-sized helmet versus a medium-sized helmet in previous linear impactor testing. However, it has been established, based upon headform size and volunteer fitment measurements, that the large-sized helmet on the Hybrid III headform provided a more representative helmet fitment of the volunteers tested **(Chapter 2)**. Despite the reported relative error data in **Table 4.4.1**, the more interesting parameter to study may be the absolute error. **Figures 3.3.10a to h** illustrate the scatter in the reported HIT system data with one impact speed. The average absolute error ranged from 21% for the PLA condition to as high as 80% for the PAA. Closer inspection of the PAA plots indicates that PAA was typically over-reported by the HIT System. This is contrary to what was expected since the HIT System only estimates the PAA about two-axes of rotation (x and y axis). The large absolute error number and tendency of the HIT system to over report PAA indicates there is rotational movement of the helmet occurring relative to the headform.

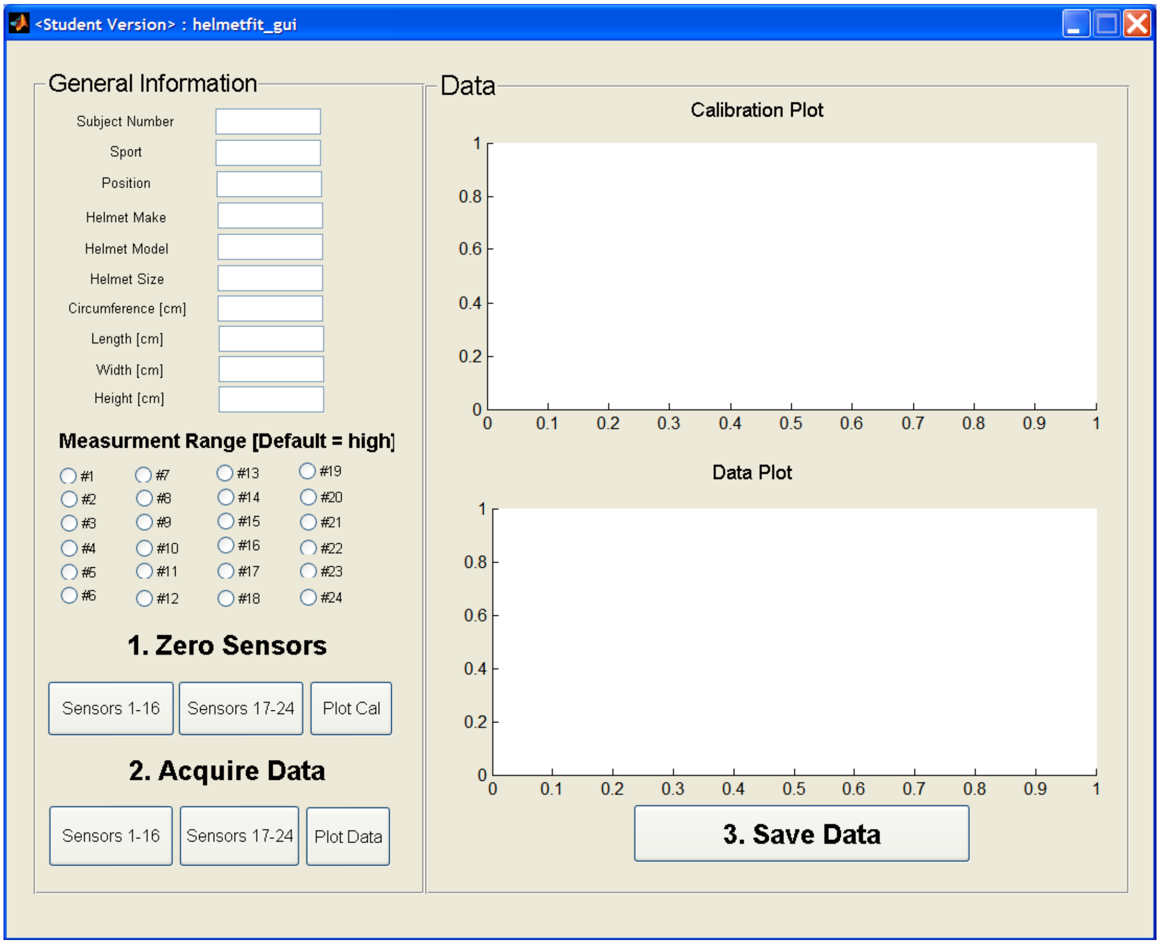
The HIT System has made vast advances in the ability to collect data regarding the number, and potentially the location, of impacts that a player sustains in practice and game situations. The ability of the HIT System to quantify the severity of the impact sustained could also be a promising "warning" system to classify the level of severity of impact (i.e., mild, moderate, or severe) and could aid in alerting medical staff of an impact that could require further investigation. However, the current system does have its limitations.

Firstly, this study was conducted with the commercially available HIT System. During the linear impactor testing, 48 tests were conducted and 11 tests (22.9%) were removed by the HIT System classifying them as not "real" impacts. If the HIT System were to be used as a "warning" device for level of severity, this testing suggests that the filtering algorithms may be too aggressive.

Secondly, the published validation testing conducted prior to this study appears to have been primarily conducted with a medium-sized helmet on the Hybrid III headform. The circumference of the headform, manufacturer's helmet fitting instructions, and field evaluations of helmets fitting onto various athletes each indicate that a large-sized helmet would be the more appropriate helmet for the Hybrid III headform. This study has provided a step to understanding better the effects that helmet fitment may have on the HIT System data.

Thirdly, the validation testing regarding acceleration-based response parameters has been conducted in a laboratory setting. Although, the laboratory setting with a headform may provide a repeatable environment for validation testing, it may not be representative of other factors that occur in game and practice situations. These factors may include, but are not limited to, variations in evenness and tightness of helmet fit and variations in chin strap tightness. In addition to the variations in how players wear the helmets, the laboratory testing conducted with the Hybrid III headform is also different from the human head. The surface of the Hybrid III headform is not representative of the human scalp/hair surface and also does not perspire as an athlete does in a practice or game situation. The differences in the Hybrid III headform to the human head would tend to prevent the movement of the helmet relative to the headform. In addition, the Hybrid III headform does not have ears. Based upon the above there are some notable anthropometric differences between the Hybrid III headform and the human head. The accuracy of the HIT System to predict impact location with a large-sized helmet on the Hybrid III headform was not evaluated in the present study.

APPENDIX A: COMPUTER PROGRAMMING



```
function varargout = helmetfit_gui(varargin)
% HELMETFIT_GUI M-file for helmetfit_gui.fig
%      HELMETFIT_GUI, by itself, creates a new HELMETFIT_GUI or raises the
existing
%      singleton*.
%
%      H = HELMETFIT_GUI returns the handle to a new HELMETFIT_GUI or the
handle to
%      the existing singleton*.
%
%      HELMETFIT_GUI('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in HELMETFIT_GUI.M with the given input
arguments.
%
%      HELMETFIT_GUI('Property','Value',...) creates a new HELMETFIT_GUI or raises
the
```

```
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before helmetfit_gui_OpeningFunction gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to helmetfit_gui_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help helmetfit_gui

% Last Modified by GUIDE v2.5 22-Feb-2010 21:32:57

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @helmetfit_gui_OpeningFcn, ...
                   'gui_OutputFcn',  @helmetfit_gui_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before helmetfit_gui is made visible.
function helmetfit_gui_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to helmetfit_gui (see VARARGIN)

% Choose default command line output for helmetfit_gui
handles.output = hObject;
handles.axes1plot=0;
handles.axes2plot=0;
```

```
handles.avg=10;
handles.stddev=0;
handles.min=0;
handles.max=0;
handles.sub=0;
handles.data_cal=0;
handles.data_cal2=0;
handles.data_acq=0;
handles.data_acq2=0;

handles.cal_1=0;
handles.cal_2=0;
handles.dat_1=0;
handles.dat_2=0;

handles.cal1=0;
handles.cal2=0;
handles.cal3=0;
handles.cal4=0;
handles.cal5=0;
handles.cal6=0;
handles.cal7=0;
handles.cal8=0;
handles.cal9=0;
handles.cal10=0;
handles.cal11=0;
handles.cal12=0;
handles.cal13=0;
handles.cal14=0;
handles.cal15=0;
handles.cal16=0;
handles.cal17=0;
handles.cal18=0;
handles.cal19=0;
handles.cal20=0;
handles.cal21=0;
handles.cal22=0;
handles.cal23=0;
handles.cal24=0;


handles.d1=0;
handles.d2=0;
handles.d3=0;
handles.d4=0;
handles.d5=0;
```

```
handles.d6=0;
handles.d7=0;
handles.d8=0;
handles.d9=0;
handles.d10=0;
handles.d11=0;
handles.d12=0;
handles.d13=0;
handles.d14=0;
handles.d15=0;
handles.d16=0;
handles.d17=0;
handles.d18=0;
handles.d19=0;
handles.d20=0;
handles.d21=0;
handles.d22=0;
handles.d23=0;
handles.d24=0;


% Update handles structure
guidata(hObject, handles);

% UIWAIT makes helmetfit_gui wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = helmetfit_gui_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;


%%-Returns subject number as handles.subject
function subject_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.subject = get(hObject,'String');
guidata(hObject, handles);
```

```
% --- Executes during object creation, after setting all properties.
function subject_CreateFcn(hObject, eventdata, handles)
% hObject    handle to sub_number (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function sport_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.sport = get(hObject,'String');
guidata(hObject, handles);


% --- Executes during object creation, after setting all properties.
function sport_CreateFcn(hObject, eventdata, handles)
% hObject    handle to sport (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function Position_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.Position = get(hObject,'String');
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function Position_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Position (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
```

```
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function make_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.make = get(hObject,'String');
guidata(hObject, handles);


% --- Executes during object creation, after setting all properties.
function make_CreateFcn(hObject, eventdata, handles)
% hObject    handle to make (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function model_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.model = get(hObject,'String');
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function model_CreateFcn(hObject, eventdata, handles)
% hObject    handle to model (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
```

```
   set(hObject,'BackgroundColor','white');
end



function size_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.size = get(hObject,'String');
guidata(hObject, handles);


% --- Executes during object creation, after setting all properties.
function size_CreateFcn(hObject, eventdata, handles)
% hObject    handle to size (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
end



function circum_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.circum = str2double(get(hObject,'String'));
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function circum_CreateFcn(hObject, eventdata, handles)
% hObject    handle to circum (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
end
```

```
function length_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.length = str2double(get(hObject,'String'));
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function length_CreateFcn(hObject, eventdata, handles)
% hObject    handle to length (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function width_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.width = str2double(get(hObject,'String'));
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function width_CreateFcn(hObject, eventdata, handles)
% hObject    handle to width (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function height_Callback(hObject, eventdata, handles)
get(hObject,'String');
handles.height = str2double(get(hObject,'String'));
guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
```

```
function height_CreateFcn(hObject, eventdata, handles)
% hObject    handle to height (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



% --- Executes on button press in calibrate.
function calibrate_Callback(hObject, eventdata, handles)
% hObject    handle to calibrate (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

AI_cal = analoginput('mcc',1);
AI_cal.InputType = 'SingleEnded';
numch = addchannel(AI_cal,0:15);
set(AI_cal,'SampleRate',100)
set(AI_cal,'SamplesPerTrigger',100)
Start(AI_cal)
wait(AI_cal,10);
handles.data_cal = getdata(AI_cal);
data_cal=handles.data_cal;

cal1_v=mean(data_cal(:,1));
handles.cal1=cal1_v;
guidata(hObject, handles);

cal2_v=mean(data_cal(:,2));
handles.cal2=cal2_v;
guidata(hObject, handles);

cal3_v=mean(data_cal(:,3));
handles.cal3=cal3_v;
guidata(hObject, handles);

cal4_v=mean(data_cal(:,4));
handles.cal4=cal4_v;
guidata(hObject, handles);
```

```
cal5_v=mean(data_cal(:,5));
handles.cal5=cal5_v;
guidata(hObject, handles);

cal6_v=mean(data_cal(:,6));
handles.cal6=cal6_v;
guidata(hObject, handles);

cal7_v=mean(data_cal(:,7));
handles.cal7=cal7_v;
guidata(hObject, handles);

cal8_v=mean(data_cal(:,8));
handles.cal8=cal8_v;
guidata(hObject, handles);

cal9_v=mean(data_cal(:,9));
handles.cal9=cal9_v;
guidata(hObject, handles);

cal10_v=mean(data_cal(:,10));
handles.cal10=cal10_v;
guidata(hObject, handles);

cal11_v=mean(data_cal(:,11));
handles.cal11=cal11_v;
guidata(hObject, handles);

cal12_v=mean(data_cal(:,12));
handles.cal12=cal12_v;
guidata(hObject, handles);

cal13_v=mean(data_cal(:,13));
handles.cal13=cal13_v;
guidata(hObject, handles);

cal14_v=mean(data_cal(:,14));
handles.cal14=cal14_v;
guidata(hObject, handles);

cal15_v=mean(data_cal(:,15));
handles.cal15=cal15_v;
guidata(hObject, handles);

cal16_v=mean(data_cal(:,16));
handles.cal16=cal16_v;
```

```
guidata(hObject, handles);

cal_1=[handles.cal1 handles.cal2 handles.cal3 handles.cal4 handles.cal5 handles.cal6
handles.cal7 handles.cal8 handles.cal9 handles.cal10 handles.cal11 handles.cal12
handles.cal13 handles.cal14 handles.cal15 handles.cal16];

handles.cal_1=cal_1;

guidata(hObject, handles);

delete(AI_cal)
clear AI_cal

% --- Executes on button press in calibrate2.
function calibrate2_Callback(hObject, eventdata, handles)
% hObject    handle to calibrate2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

AI_cal2 = analoginput('mcc',1);
AI_cal2.InputType = 'SingleEnded';
numch = addchannel(AI_cal2,0:15);
set(AI_cal2,'SampleRate',100)
set(AI_cal2,'SamplesPerTrigger',100)
Start(AI_cal2)
wait(AI_cal2,10);
handles.data_cal2 = getdata(AI_cal2);
data_cal2=handles.data_cal2;

cal17_v=mean(data_cal2(:,5));
handles.cal17=cal17_v;
guidata(hObject, handles);

cal18_v=mean(data_cal2(:,6));
handles.cal18=cal18_v;
guidata(hObject, handles);

cal19_v=mean(data_cal2(:,7));
handles.cal19=cal19_v;
guidata(hObject, handles);

cal20_v=mean(data_cal2(:,8));
handles.cal20=cal20_v;
guidata(hObject, handles);

cal21_v=mean(data_cal2(:,13));
```

```
handles.cal21=cal21_v;
guidata(hObject, handles);

cal22_v=mean(data_cal2(:,14));
handles.cal22=cal22_v;
guidata(hObject, handles);

cal23_v=mean(data_cal2(:,15));
handles.cal23=cal23_v;
guidata(hObject, handles);

cal24_v=mean(data_cal2(:,16));
handles.cal24=cal24_v;
guidata(hObject, handles);

cal_2=[handles.cal17 handles.cal18 handles.cal19 handles.cal20 handles.cal21
handles.cal22 handles.cal23 handles.cal24];
handles.cal_2=cal_2;

guidata(hObject, handles);

delete(AI_cal2)
clear AI_cal2

% --- Executes on button press in plot_cal.
function plot_cal_Callback(hObject, eventdata, handles)
% hObject    handle to plot_cal (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)



cal=[handles.cal_1 handles.cal_2];

bar(handles.cal_plot, cal);
xlabel(handles.cal_plot,'Location')
ylabel(handles.cal_plot,'Voltage [V]')
set(gca,'xlim',[1 24])
title(['Subject_' num2str(handles.subject)])

%%%==================================================================
=========%%%
%%%ENTER SENSOR CALIBRATION DATA INTO THIS
SECTION%%%%%%%%

% --- Executes on button press in radiobutton1.
```

```
function radiobutton1_Callback(hObject, eventdata, handles)

get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch1_conv = 0;
else
        handles.ch1_conv = 43.5;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton2.
function radiobutton2_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch2_conv = 0;
else
        handles.ch2_conv = 43.5;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton3.
function radiobutton3_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch3_conv = 0;
else
        handles.ch3_conv = 33.1;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton4.
function radiobutton4_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch4_conv = 0;
else
        handles.ch4_conv = 34.8;
end
```

```
guidata(hObject, handles);

% --- Executes on button press in radiobutton5.
function radiobutton5_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch5_conv = 1.10;
else
        handles.ch5_conv = 33.9;
end

guidata(hObject, handles);
% --- Executes on button press in radiobutton6.
function radiobutton6_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch6_conv = 1.59;
else
        handles.ch6_conv = 41.7;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton7.
function radiobutton7_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch7_conv = 1.0;
else
        handles.ch7_conv = 37.4;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton8.
function radiobutton8_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch8_conv = 0;
else
        handles.ch8_conv = 36.4;
end
```

```
guidata(hObject, handles);

% --- Executes on button press in radiobutton9.
function radiobutton9_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch9_conv = 1.91;
else
        handles.ch9_conv = 75.9;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton10.
function radiobutton10_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch10_conv = 0;
else
        handles.ch10_conv = 40.3;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton11.
function radiobutton11_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch11_conv = 0;
else
        handles.ch11_conv = 32.6;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton12.
function radiobutton12_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch12_conv = 0;
else
```

```
        handles.ch12_conv = 34.5;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton13.
function radiobutton13_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch13_conv = 1.08;
else
        handles.ch13_conv = 32.5;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton14.
function radiobutton14_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch14_conv = 1.27;
else
        handles.ch14_conv = 50.1;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton15.
function radiobutton15_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch15_conv = 1.25;
else
        handles.ch15_conv = 37.4;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton16.
function radiobutton16_Callback(hObject, eventdata, handles)

get(hObject,'Value')
```

```
if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch16_conv = 1.15;
else
        handles.ch16_conv = 37.5;
end

guidata(hObject, handles);


% --- Executes on button press in radiobutton17.
function radiobutton17_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch17_conv = 0;
else
        handles.ch17_conv = 37.8;
end

guidata(hObject, handles);


% --- Executes on button press in radiobutton18.
function radiobutton18_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch18_conv = 0;
else
        handles.ch18_conv = 38.2;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton19.
function radiobutton19_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch19_conv = 0;
else
        handles.ch19_conv = 32.6;
end

guidata(hObject, handles);
```

```
% --- Executes on button press in radiobutton20.
function radiobutton20_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch20_conv = 0;
else
        handles.ch20_conv = 40.3;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton21.
function radiobutton21_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch21_conv = 0;
else
        handles.ch21_conv = 27.2;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton22.
function radiobutton22_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch22_conv = 0;
else
        handles.ch22_conv = 39.9;
end

guidata(hObject, handles);

% --- Executes on button press in radiobutton23.
function radiobutton23_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch23_conv = 0;
else
        handles.ch23_conv = 39.1;
end
```

```
guidata(hObject, handles);

% --- Executes on button press in radiobutton24.
function radiobutton24_Callback(hObject, eventdata, handles)
get(hObject,'Value')

if (get(hObject,'Value') == get(hObject,'Max'))
        handles.ch24_conv = 0;
else
        handles.ch24_conv = 38.8;
end

guidata(hObject, handles);
%%%%=========================================================
=========%%%
%%%%THIS SECTION IS FOR THE DATA ACQUISITION%%%%%%%%%

% --- Executes on button press in acquire.
function acquire_Callback(hObject, eventdata, handles)
% hObject    handle to acquire (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

AI_acq = analoginput('mcc',1);
numch = addchannel(AI_acq,0:15);
set(AI_acq,'SampleRate',100)
set(AI_acq,'SamplesPerTrigger',500)
Start(AI_acq)
wait(AI_acq,15);
handles.data_acq = getdata(AI_acq);
data_acq=handles.data_acq;

data1_v=mean(data_acq(:,1));
handles.d1=43.5*(data1_v-handles.cal1);
guidata(hObject, handles);

data2_v=mean(data_acq(:,2));
handles.d2=43.5*(data2_v-handles.cal2);
guidata(hObject, handles);

data3_v=mean(data_acq(:,3));
handles.d3=33.1*(data3_v-handles.cal3);
guidata(hObject, handles);

data4_v=mean(data_acq(:,4));
handles.d4=34.8*(data4_v-handles.cal4);
```

```
guidata(hObject, handles);

data5_v=mean(data_acq(:,5));
handles.d5=33.9*(data5_v-handles.cal5);
guidata(hObject, handles);

data6_v=mean(data_acq(:,6));
handles.d6=41.7*(data6_v-handles.cal6);
guidata(hObject, handles);

data7_v=mean(data_acq(:,7));
handles.d7=37.4*(data7_v-handles.cal7);
guidata(hObject, handles);

data8_v=mean(data_acq(:,8));
handles.d8=36.4*(data8_v-handles.cal8);
guidata(hObject, handles);

data9_v=mean(data_acq(:,9));
handles.d9=75.9*(data9_v-handles.cal9);
guidata(hObject, handles);

data10_v=mean(data_acq(:,10));
handles.d10=40.3*(data10_v-handles.cal10);
guidata(hObject, handles);

data11_v=mean(data_acq(:,11));
handles.d11=32.6*(data11_v-handles.cal11);
guidata(hObject, handles);

data12_v=mean(data_acq(:,12));
handles.d12=34.5*(data12_v-handles.cal12);
guidata(hObject, handles);

data13_v=mean(data_acq(:,13));
handles.d13=32.5*(data13_v-handles.cal13);
guidata(hObject, handles);

data14_v=mean(data_acq(:,14));
handles.d14=50.1*(data14_v-handles.cal14);
guidata(hObject, handles);

data15_v=mean(data_acq(:,15));
handles.d15=37.4*(data15_v-handles.cal15);
guidata(hObject, handles);
```

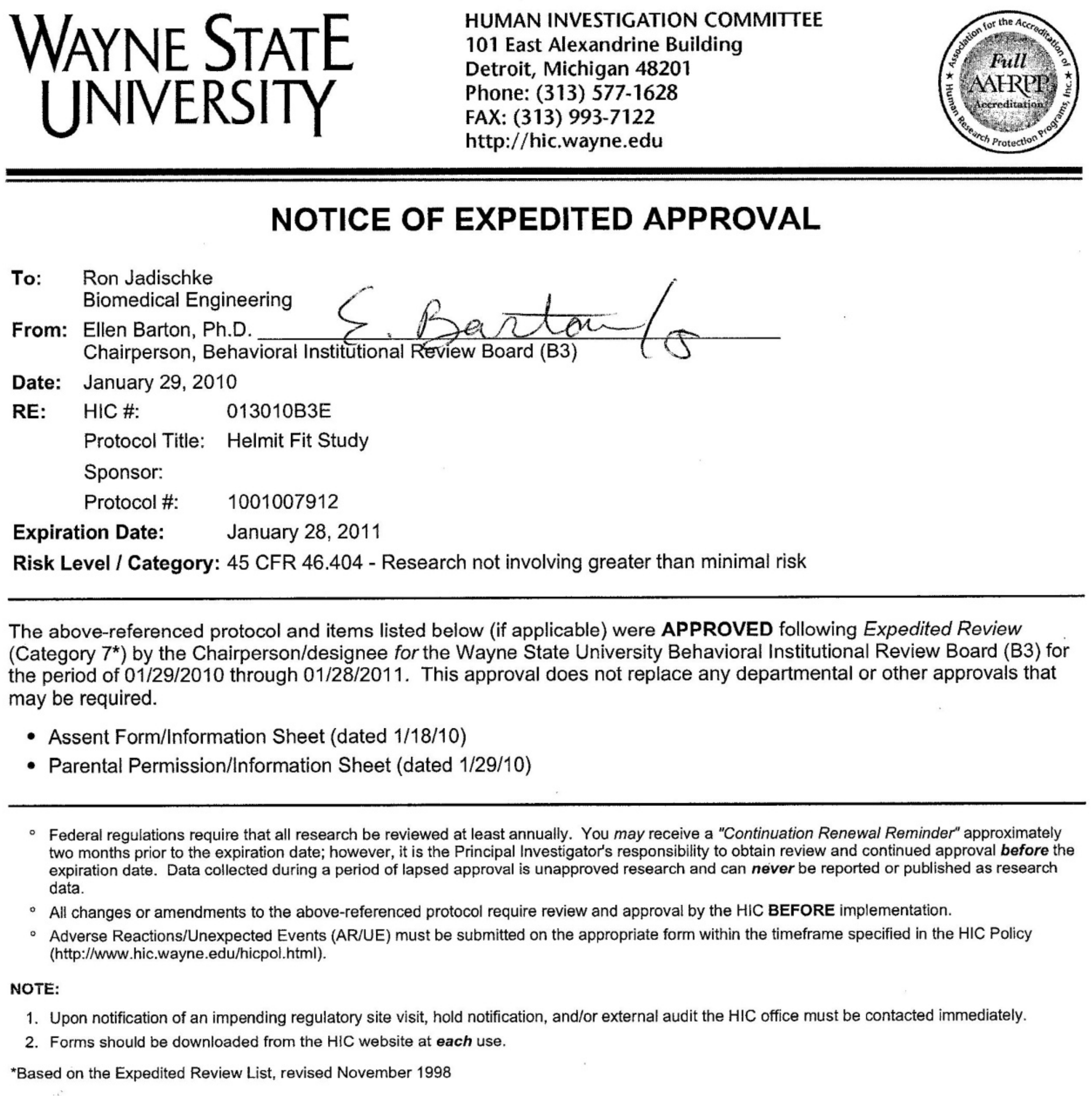
```
data16_v=mean(data_acq(:,16));
handles.d16=37.5*(data16_v-handles.cal16);
guidata(hObject, handles);

dat_1=[handles.d1 handles.d2 handles.d3 handles.d4 handles.d5 handles.d6 handles.d7
handles.d8 handles.d9 handles.d10 handles.d11 handles.d12 handles.d13 handles.d14
handles.d15 handles.d16];

handles.dat_1=dat_1;

guidata(hObject, handles);

delete(AI_acq)
clear AI_acq

% --- Executes on button press in acquire2.
function acquire2_Callback(hObject, eventdata, handles)
% hObject    handle to acquire2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

AI_acq2 = analoginput('mcc',1);
numch = addchannel(AI_acq2,0:15);
set(AI_acq2,'SampleRate',100)
set(AI_acq2,'SamplesPerTrigger',500)
Start(AI_acq2)
wait(AI_acq2,15);
handles.data_acq2 = getdata(AI_acq2);
data_acq2=handles.data_acq2;

data17_v=mean(data_acq2(:,5));
handles.d17=37.8*(data17_v-handles.cal17);
guidata(hObject, handles);

data18_v=mean(data_acq2(:,6));
handles.d18=38.2*(data18_v-handles.cal18);
guidata(hObject, handles);

data19_v=mean(data_acq2(:,7));
handles.d19=32.6*(data19_v-handles.cal19);
guidata(hObject, handles);

data20_v=mean(data_acq2(:,8));
handles.d20=40.3*(data20_v-handles.cal20);
guidata(hObject, handles);
```

```
data21_v=mean(data_acq2(:,13));
handles.d21=27.2*(data21_v-handles.cal21);
guidata(hObject, handles);

data22_v=mean(data_acq2(:,14));
handles.d22=39.9*(data22_v-handles.cal22);
guidata(hObject, handles);

data23_v=mean(data_acq2(:,15));
handles.d23=39.1*(data23_v-handles.cal23);
guidata(hObject, handles);

data24_v=mean(data_acq2(:,16));
handles.d24=38.8*(data24_v-handles.cal24);
guidata(hObject, handles);

dat_2=[handles.d17 handles.d18 handles.d19 handles.d20 handles.d21 handles.d22
handles.d23 handles.d24];

handles.dat_2=dat_2;
guidata(hObject, handles);
delete(AI_acq2)
clear AI_acq2

% --- Executes on button press in plot_data.
function plot_data_Callback(hObject, eventdata, handles)
% hObject    handle to plot_data (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

dat=[handles.dat_1 handles.dat_2];

bar(handles.data,dat);
xlabel(handles.data,'Location')
ylabel(handles.data,'Force [psi]')
title(['Subject-' num2str(handles.subject)])
set(gca,'xlim',[1 24])



figure
bar(dat);
xlabel('Location')
ylabel('Pressure [psi]')
title(['Subject-' num2str(handles.subject)])
set(gca,'xlim',[1 24])
```

```
saveas(gcf,['Subject_' num2str(handles.subject)],'jpg');

handles.avg=mean(dat);
guidata(hObject, handles);

handles.std=std(dat);
guidata(hObject, handles);

handles.min=min(dat);
guidata(hObject, handles);

handles.max=max(dat);
guidata(hObject, handles);


% --- Executes on button press in save.
function save_Callback(hObject, eventdata, handles)
% hObject    handle to save (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

sub = cellstr(handles.subject);
sport = cellstr(handles.sport);
position = cellstr(handles.Position);
make = cellstr(handles.make);
model = cellstr(handles.model);
size = cellstr(handles.size);
circum = handles.circum;
length = handles.length;
width = handles.width;
height = handles.height;

y = [sub, sport, position, make, model, size, circum, length, width, height, handles.d1,
handles.d2, handles.d3, handles.d4, handles.d5, handles.d6, handles.d7, handles.d8,
handles.d9, handles.d10, handles.d11, handles.d12, handles.d13, handles.d14,
handles.d15, handles.d16, handles.d17, handles.d18, handles.d19, handles.d20,
handles.d21, handles.d22, handles.d23, handles.d24, handles.avg, handles.stddev,
handles.min, handles.max];


%%Save the calibration data as an excel file [in volts]
%column={'Sensor 1 [v]','Sensor 2 [v]', 'Sensor 3 [v]', 'Sensor 4 [v]', 'Sensor 5 [v]',
'Sensor 6 [v]', 'Sensor 7 [v]', 'Sensor 8 [v]', 'Sensor 9 [v]', 'Sensor 10 [v]', 'Sensor 11
[v]','Sensor 12 [v]','Sensor 13 [v]','Sensor 14 [v]','Sensor 15 [v]','Sensor 16 [v]'};
%xlswrite(['Subject_' num2str(handles.subject)],column,'calibration','A1');
%xlswrite(['Subject_' num2str(handles.subject)],handles.data_cal,'calibration','A2');
```

```
%%Save the raw acquired data in an excel fil [in volts]
%xlswrite(['Subject_' num2str(handles.subject)],column,'data','A1');
%xlswrite(['Subject_' num2str(handles.subject)],handles.data_acq,'data','A2');

%%%Writing the summary excel file.
header={'Subject','Sport','Position','Helmet Make','Helmet Model','Helmet
Size','Circumference','Length','Width','Height','Position 1','Position 2','Position 3','Position
4','Position 5','Position 6','Position 7','Position 8','Position 9','Position 10','Position
11','Position 12','Position 13','Position 14','Position 15','Position 16', 'Position 17',
'Position 18', 'Position 19', 'Position 20', 'Position 21', 'Position 22', 'Position 23', 'Position
24', 'Average','Standard Dev','Minimum','Maximum'};
xlswrite('MediumVSR4Helmet.xls',header,'summary','A1');
xlswrite('MediumVSR4Helmet.xls',y,'summary','A6');
```

APPENDIX B:
HUMAN INVESTIGATION COMMITTEE APPROVAL



WAYNE STATE UNIVERSITY

HUMAN INVESTIGATION COMMITTEE
101 East Alexandrine Building
Detroit, Michigan 48201
Phone: (313) 577-1628
FAX: (313) 993-7122
http://hic.wayne.edu

Full AAHRPP Accreditation

NOTICE OF EXPEDITED APPROVAL

To: Ron Jadischke
Biomedical Engineering
From: Ellen Barton, Ph.D. E. Barton
Chairperson, Behavioral Institutional Review Board (B3)
Date: January 29, 2010
RE: HIC #: 013010B3E
Protocol Title: Helmit Fit Study
Sponsor:
Protocol #: 1001007912
Expiration Date: January 28, 2011
Risk Level / Category: 45 CFR 46.404 - Research not involving greater than minimal risk

The above-referenced protocol and items listed below (if applicable) were **APPROVED** following *Expedited Review* (Category 7*) by the Chairperson/designee *for* the Wayne State University Behavioral Institutional Review Board (B3) for the period of 01/29/2010 through 01/28/2011. This approval does not replace any departmental or other approvals that may be required.

- Assent Form/Information Sheet (dated 1/18/10)
- Parental Permission/Information Sheet (dated 1/29/10)

- Federal regulations require that all research be reviewed at least annually. You *may* receive a *"Continuation Renewal Reminder"* approximately two months prior to the expiration date; however, it is the Principal Investigator's responsibility to obtain review and continued approval ***before*** the expiration date. Data collected during a period of lapsed approval is unapproved research and can ***never*** be reported or published as research data.
- All changes or amendments to the above-referenced protocol require review and approval by the HIC **BEFORE** implementation.
- Adverse Reactions/Unexpected Events (AR/UE) must be submitted on the appropriate form within the timeframe specified in the HIC Policy (http://www.hic.wayne.edu/hicpol.html).

NOTE:

1. Upon notification of an impending regulatory site visit, hold notification, and/or external audit the HIC office must be contacted immediately.
2. Forms should be downloaded from the HIC website at ***each*** use.

*Based on the Expedited Review List, revised November 1998

Sports Helmet Fit Study

Research Information Sheet
Title of Study: **Sports Helmet Fit Study**

Principal Investigator (PI):	Ron Jadischke, BA Sc., P. Eng. Department of Biomedical Engineering, Wayne State University, and McCarthy Engineering Inc., Windsor, Ontario 519-966-3149

Purpose:
You are being asked to participate in a research study to determine how tightly and evenly helmets fit athletes in contact sports because you participate in contact sports. This study is being conducted at the Essex Ravens Football Clubhouse and the Kingsville Arena.

Study Procedures:
If you take part in the study, you will be asked to put your helmet on your head as you typically would when preparing for a practice or game. A tightly fitting skull cap which is equipped with various sensors will be worn under your helmet to measure how your helmet fits. Various additional measurements of your head, including length, width, height, and circumference, will also be taken. We will also record data regarding your position as well as the size, make, and model of your helmet. The entire length of your involvement in the study should take no more than 10 minutes.

Benefits
As a participant in this research study, there will be no direct benefit for you; however, information from this study may benefit other people now or in the future.

Risks
There are no known risks to participate in this study.

Costs
There will be no costs to you for participation in this research study.

Compensation
You will not be paid for taking part in this study.

Confidentiality:
All information collected about you during the course of this study will be kept without any personal identifiers. You will be identified in the research records by a code name or number. There will be no list that links your identity with this code.

Voluntary Participation /Withdrawal:
Taking part in this study is voluntary. You are free to participate or withdraw at any time. Your decision will not change any present or future relationships with Wayne State University or its affiliates. If you are under 18 years old, your parents have been asked if you can participate.

Sports Helmet Fit Study

[School] Parental Permission/Research Informed Consent/Information Sheet
Title of Study: **Sports Helmet Fit Study**

Purpose:
You are being asked to allow your child to participate in a research study at their school that is being conducted by Ron Jadischke from Wayne State University (Detroit, MI) and McCarthy Engineering Inc. (Windsor, ON), to determine how tightly and evenly helmets fit athletes in contact sports. Your child has been selected because he participates in contact sports which require a helmet.

Study Procedures:
If you decide to allow your child to take part in the study, your child will be asked to put his helmet on his head as he typically would when preparing for a practice or game. A tightly fitting skull cap which is equipped with various sensors will be worn under the helmet to measure how the helmet fits. Various additional measurements of his head, including length, width, height, and circumference will also be taken. We will also record data regarding his playing position as well as the size, make and model of his helmet. The entire length of his involvement in the study should take no more than 10 minutes.

Benefits:
There may be no direct benefits for your child; however, information from this study may benefit other people now or in the future.

Risks:
There are no known risks to your child for participation in this study.

Costs
There are no costs to you or your child to participate in this study.

Compensation:
You or your child will not be paid for taking part in this study.

Confidentiality:
All information collected about your child during the course of this study will be kept confidential to the extent permitted by law. All information collected about your child during the course of this study will be kept without any identifiers. Your child will be identified in the research records by a code name or number.

Voluntary Participation /Withdrawal:
Your child's participation in this study is voluntary. Your decision about enrolling your child in the study will not change any present or future relationships with Wayne State University or its affiliates, your child's school, your child's teacher, your child's team, your child's coach, your child's grades or other services you or your child are entitled to receive.

Questions:
If you have any questions about this study now or in the future, you may contact Ron Jadischke at the following phone number: 519-966-3149. If you have questions or concerns about your rights as a research

Questions:
If you have any questions about this study now or in the future, you may contact Ron Jadischke at the following phone number: 519-966-3149. If you have questions or concerns about your rights as a research participant, the Chair of the Human Investigation Committee can be contacted at (313) 577-1628. If you are unable to contact the research staff, or if you want to talk to someone other than the research staff, you may also call (313) 577-1628 to ask questions or voice concerns or complaints.

Participation:
By completing the interview you are agreeing to participate in this study.

APPROVAL PERIOD
JAN 29 '10 JAN 28 '11
HUMAN INVESTIGATION COMMITTEE

Sports Helmet Fit Study

[School] Parental Permission/Research Informed Consent/Information Sheet
Title of Study: **Sports Helmet Fit Study**

Purpose:
You are being asked to allow your child to participate in a research study at their school that is being conducted by Ron Jadischke from Wayne State University (Detroit, MI) and McCarthy Engineering Inc. (Windsor, ON), to determine how tightly and evenly helmets fit athletes in contact sports. Your child has been selected because he participates in contact sports which require a helmet.

Study Procedures:
If you decide to allow your child to take part in the study, your child will be asked to put his helmet on his head as he typically would when preparing for a practice or game. A tightly fitting skull cap which is equipped with various sensors will be worn under the helmet to measure how the helmet fits. Various additional measurements of his head, including length, width, height, and circumference will also be taken. We will also record data regarding his playing position as well as the size, make and model of his helmet. The entire length of his involvement in the study should take no more than 10 minutes.

Benefits:
There may be no direct benefits for your child; however, information from this study may benefit other people now or in the future.

Risks:
There are no known risks to your child for participation in this study.

Costs
There are no costs to you or your child to participate in this study.

Compensation:
You or your child will not be paid for taking part in this study.

Confidentiality:
All information collected about your child during the course of this study will be kept confidential to the extent permitted by law. All information collected about your child during the course of this study will be kept without any identifiers. Your child will be identified in the research records by a code name or number.

Voluntary Participation /Withdrawal:
Your child's participation in this study is voluntary. Your decision about enrolling your child in the study will not change any present or future relationships with Wayne State University or its affiliates, your child's school, your child's teacher, your child's team, your child's coach, your child's grades or other services you or your child are entitled to receive.

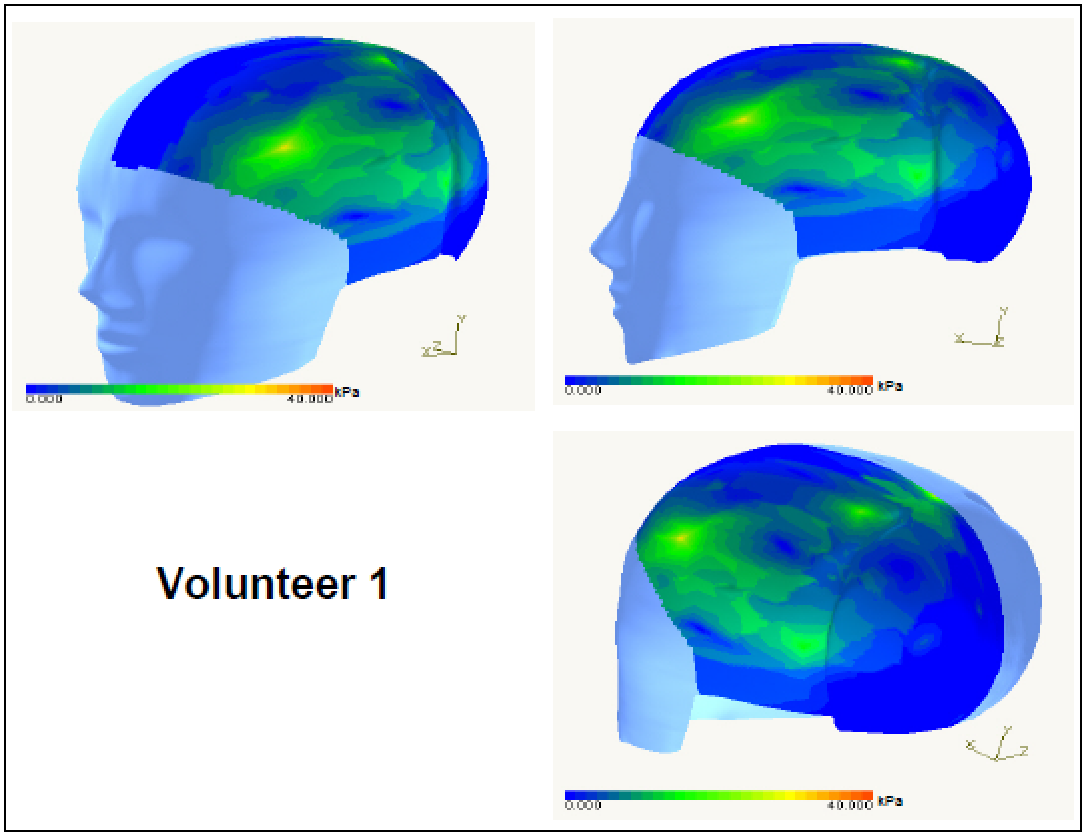
Questions:
If you have any questions about this study now or in the future, you may contact Ron Jadischke at the following phone number: 519-966-3149. If you have questions or concerns about your rights as a research

participant, the Chair of the Human Investigation Committee can be contacted at (313) 577-1628. If you are unable to contact the research staff, or if you want to talk to someone other than the research staff, you may also call (313) 577-1628 to ask questions or voice concerns or complaints.

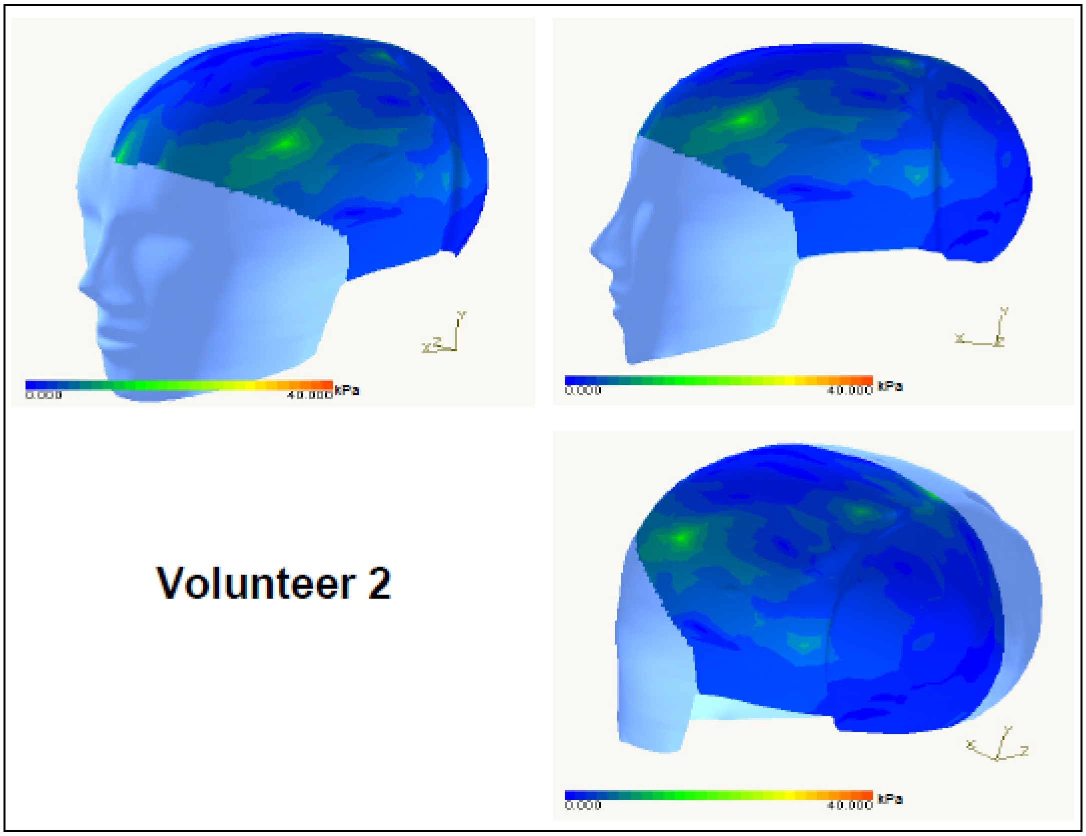
Participation:
If you do not contact the Principal Investigator (PI) within a 2-week period to state that you do not give permission for your child to be enrolled in the research trial, your child will be enrolled in the research. You may contact the PI at rjadischke@mccarthyengineering.ca, by phone at 519-965-9146, or by fax at 519-966-3418.

APPROVAL PERIOD
JAN 29 '10 JAN 28 '11
HUMAN INVESTIGATION COMMITTEE

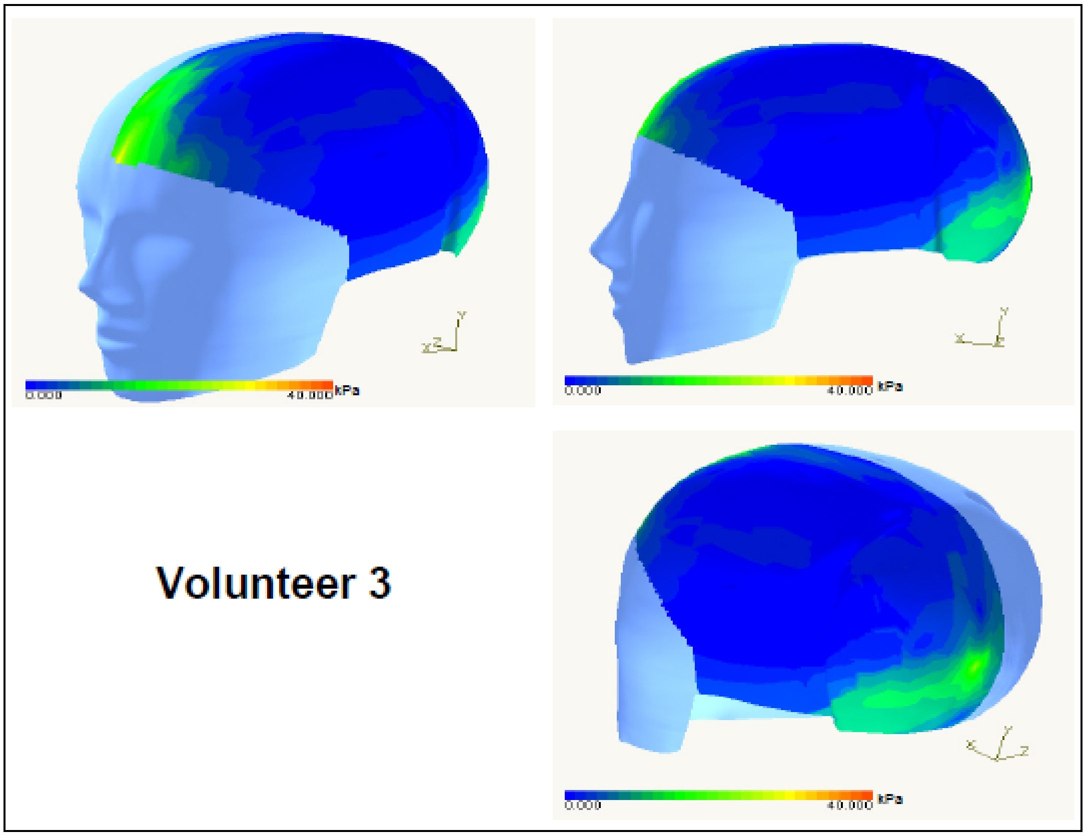
APPENDIX C: VOLUNTEER FITMENT DATA



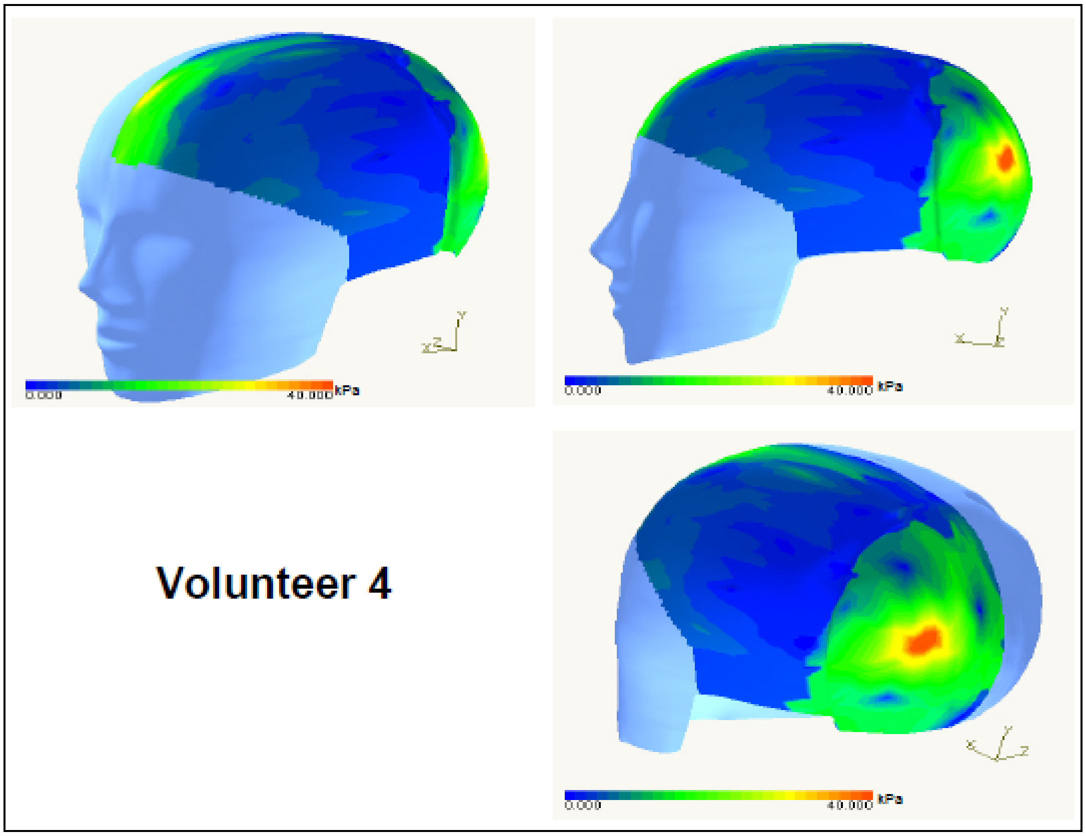
Volunteer 1



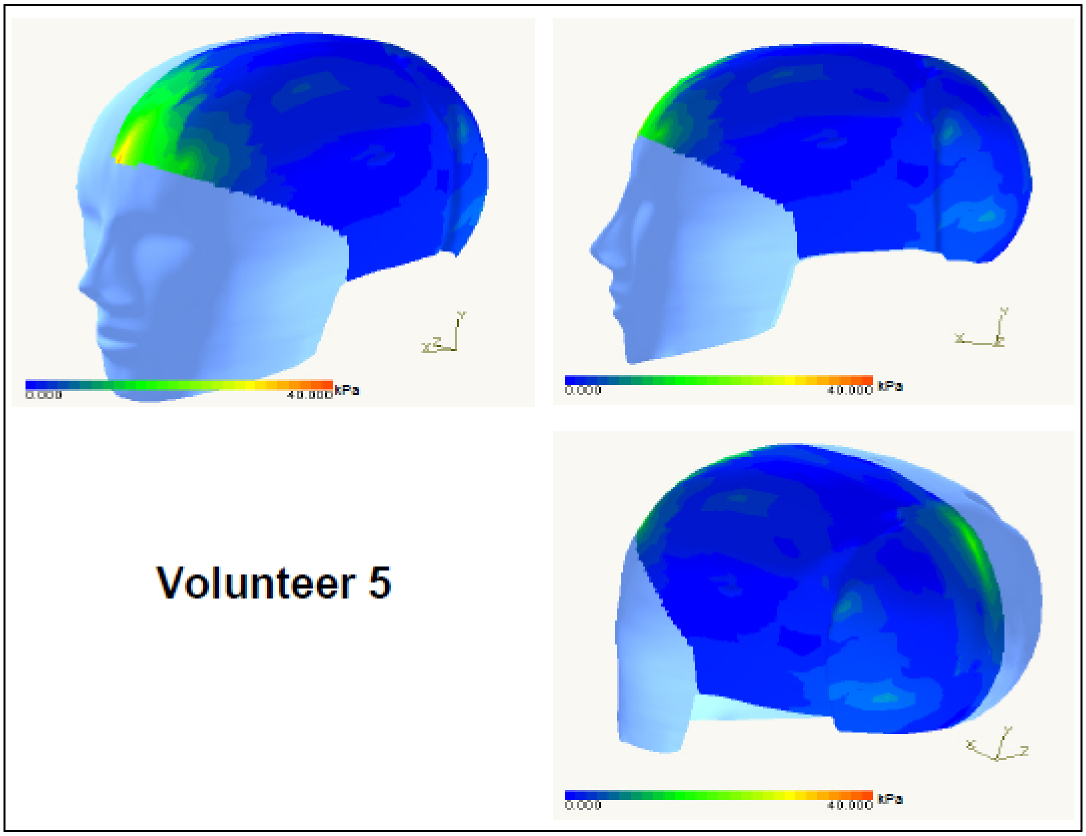
Volunteer 2



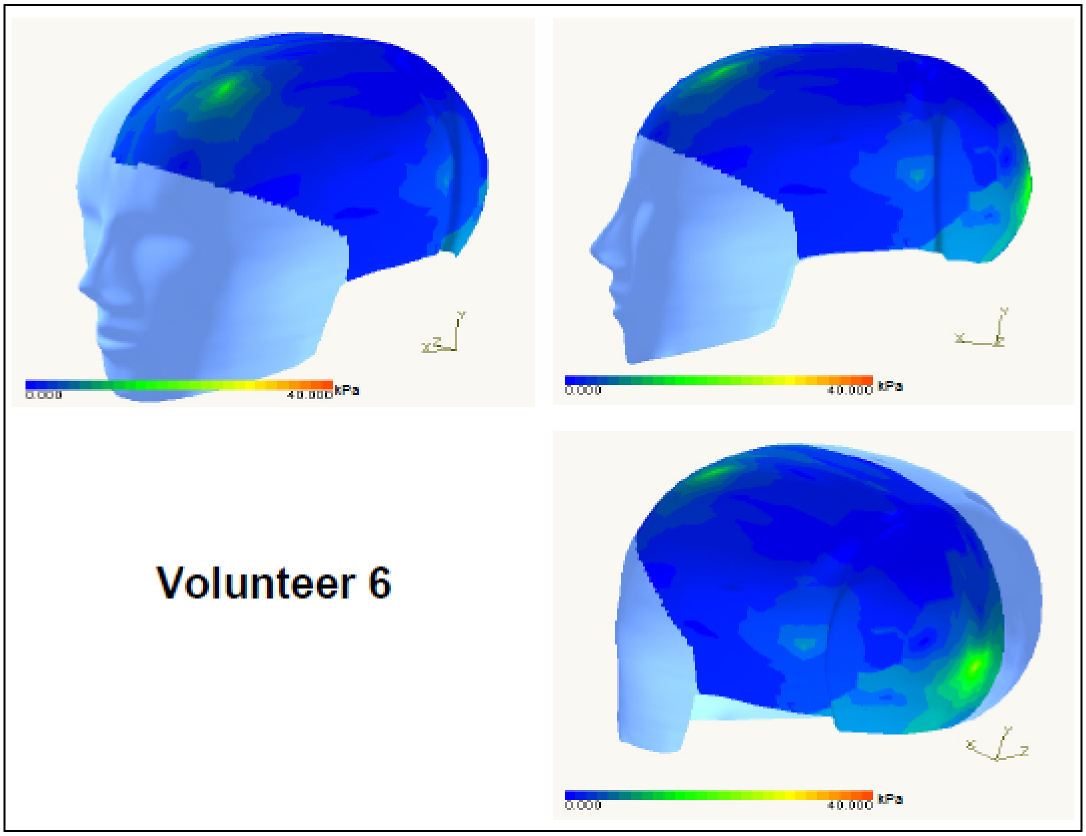
Volunteer 3



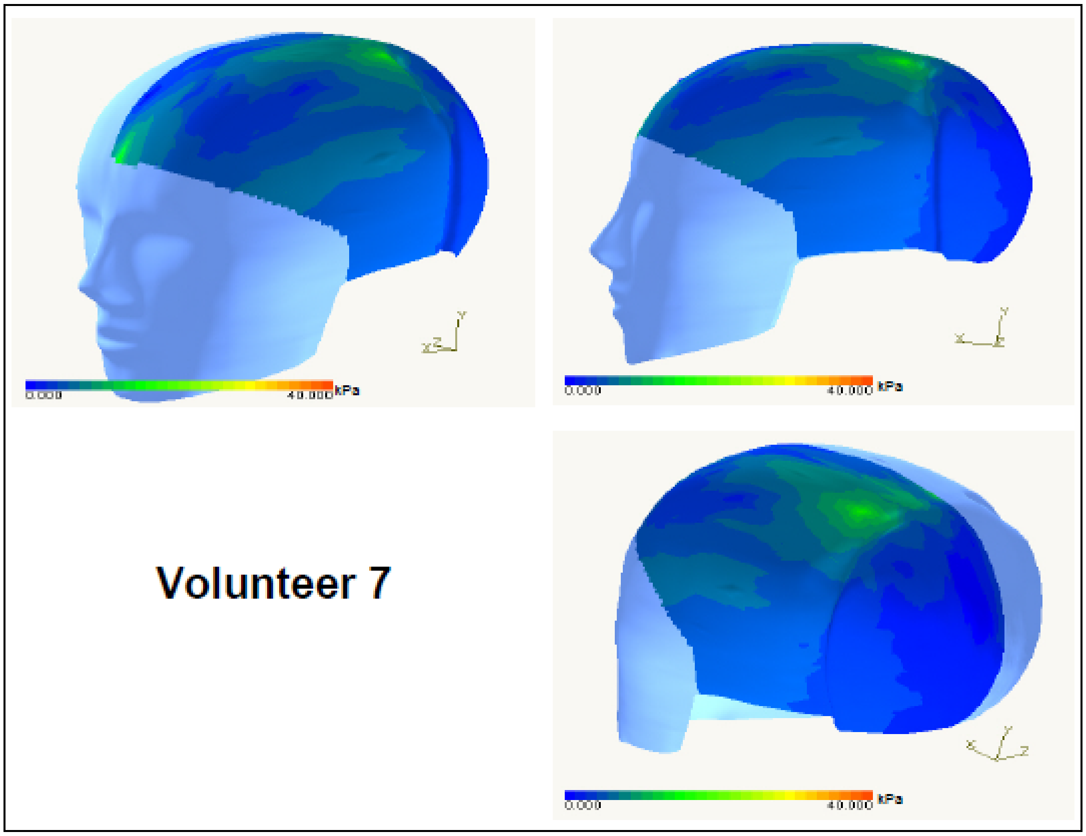
Volunteer 4



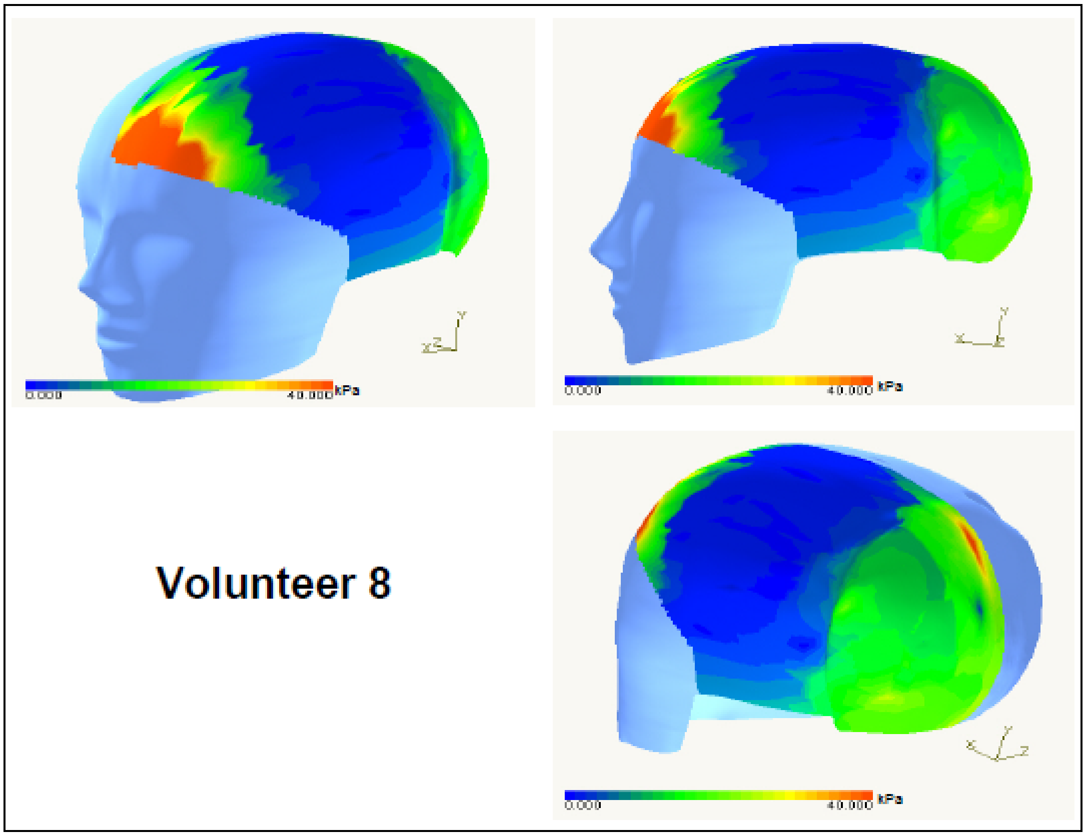
Volunteer 5



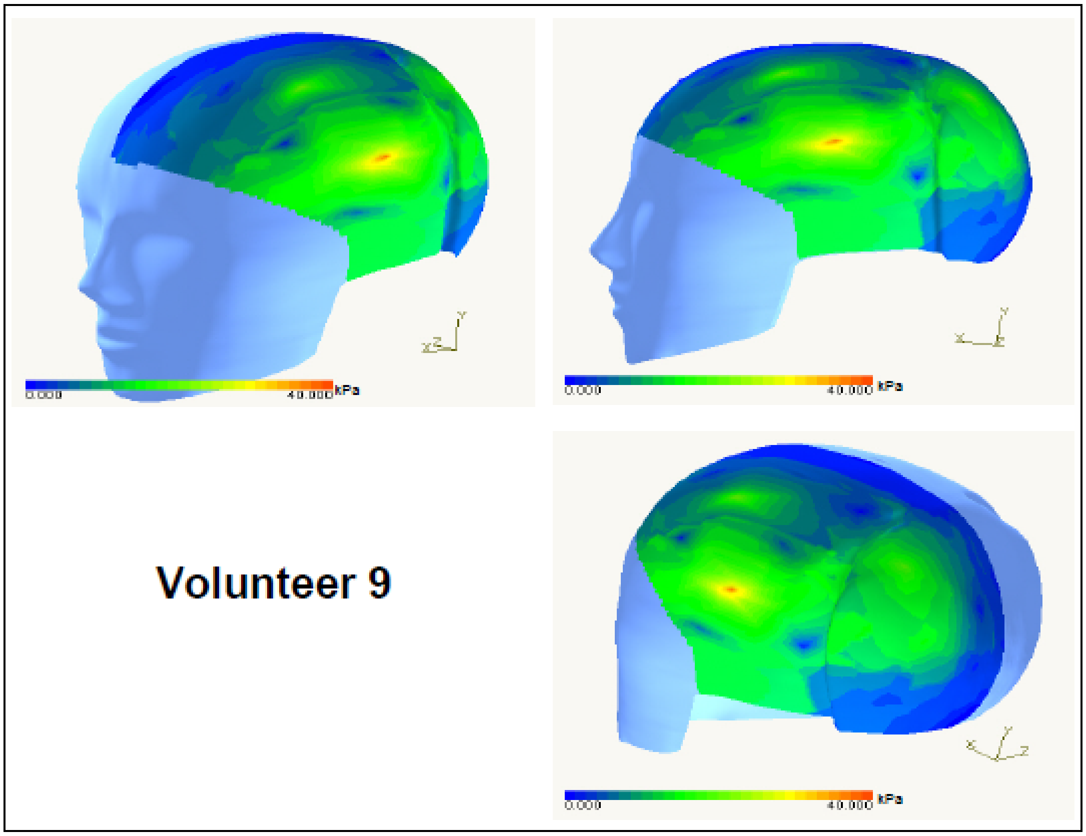
Volunteer 6



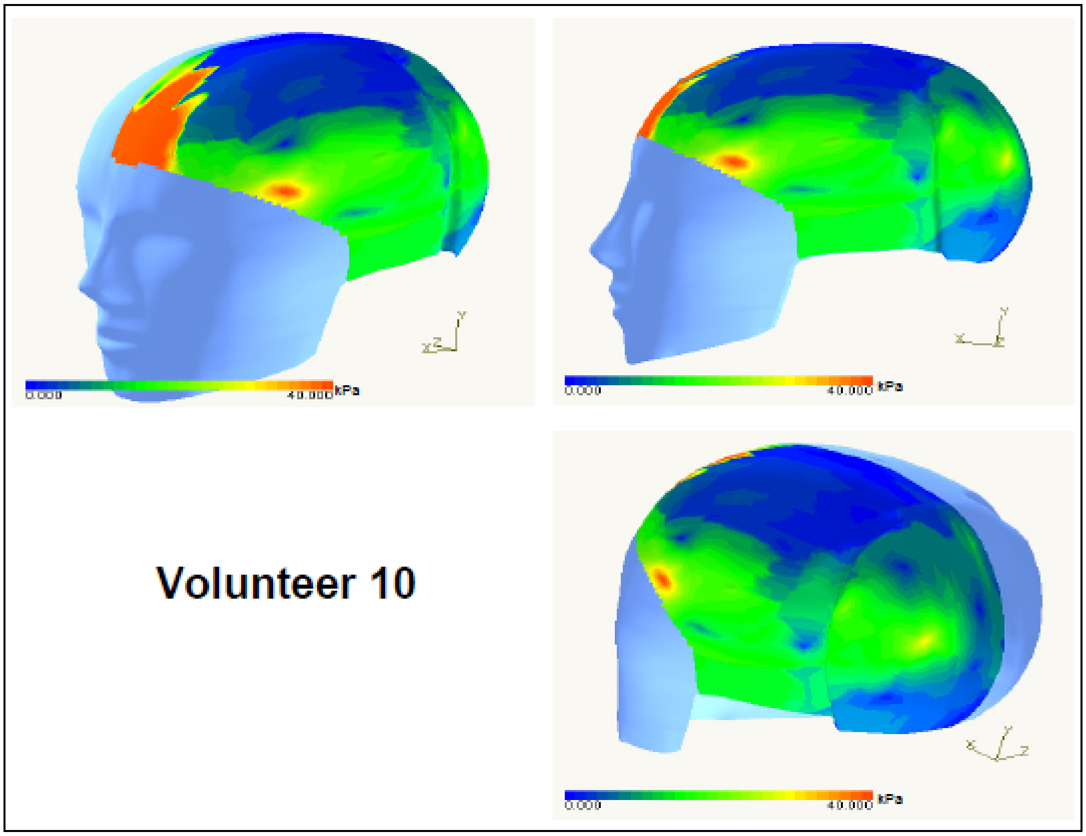
Volunteer 7



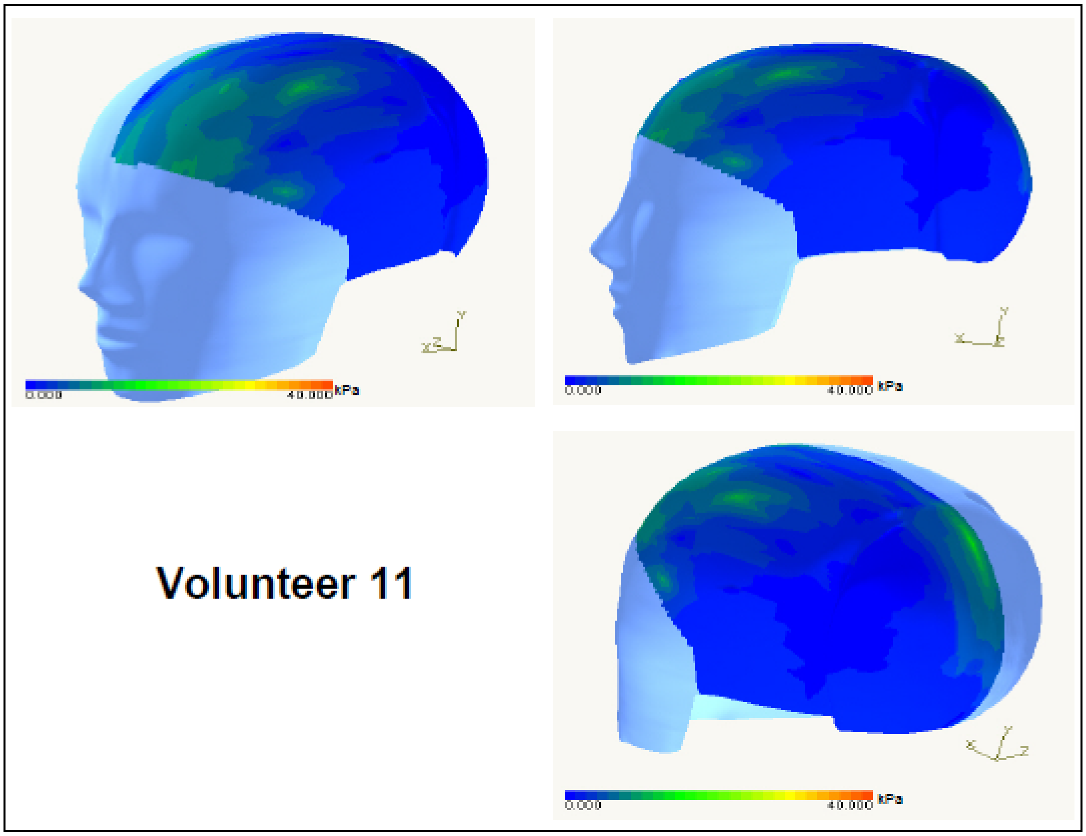
Volunteer 8



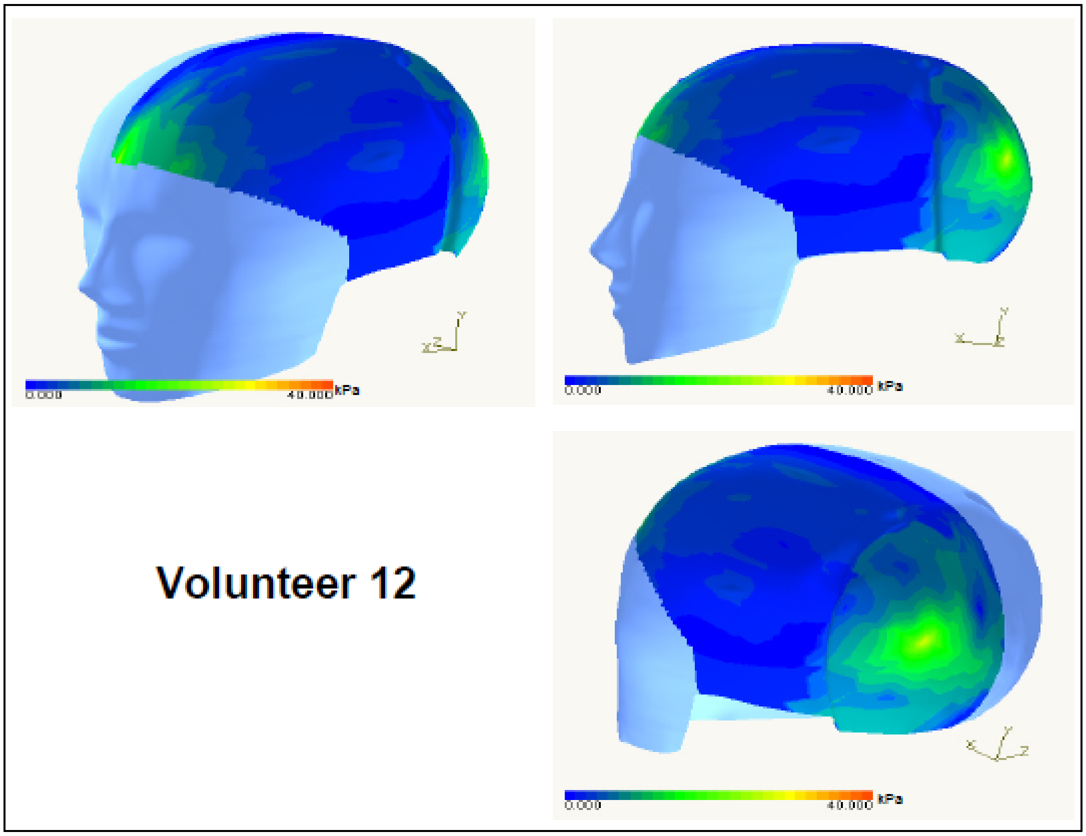
Volunteer 9



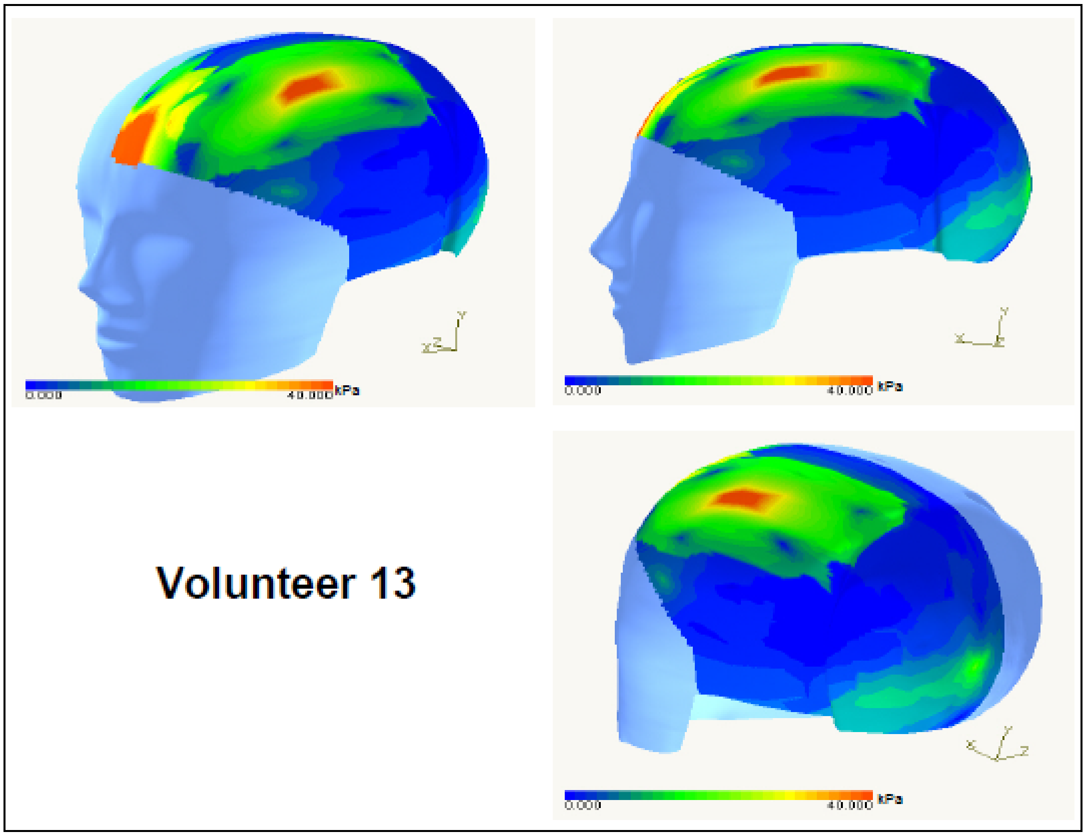
Volunteer 10



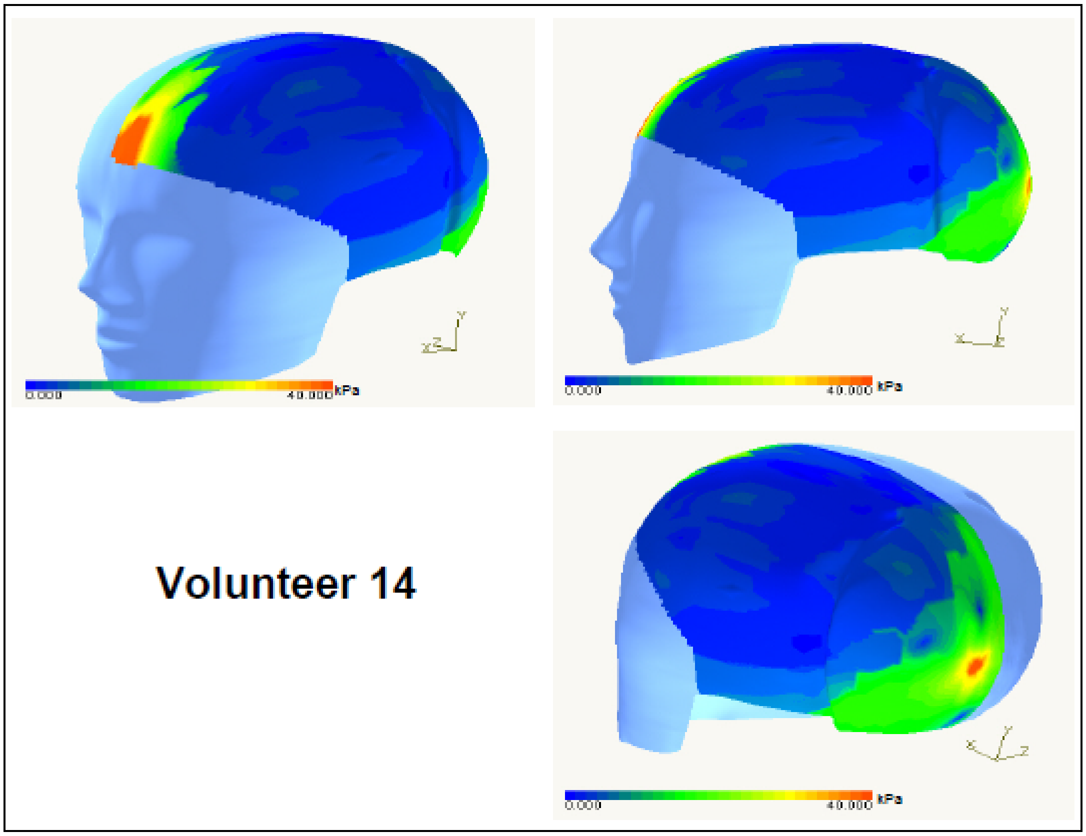
Volunteer 11



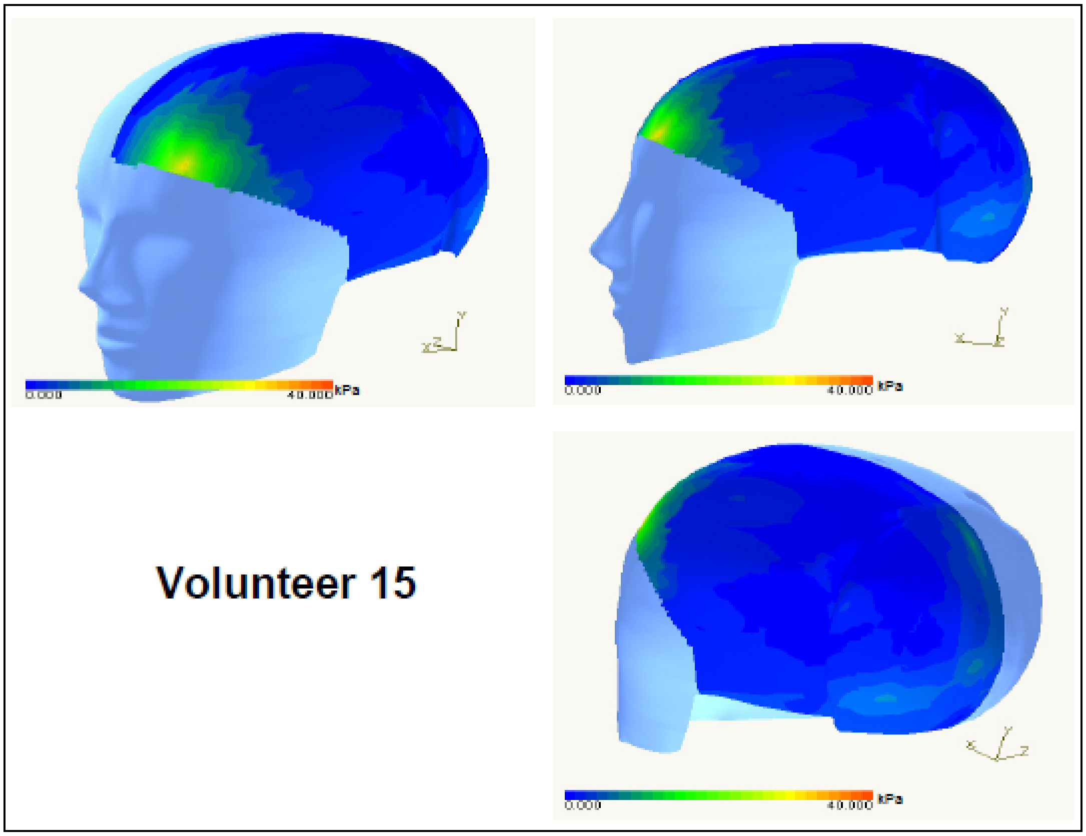
Volunteer 12



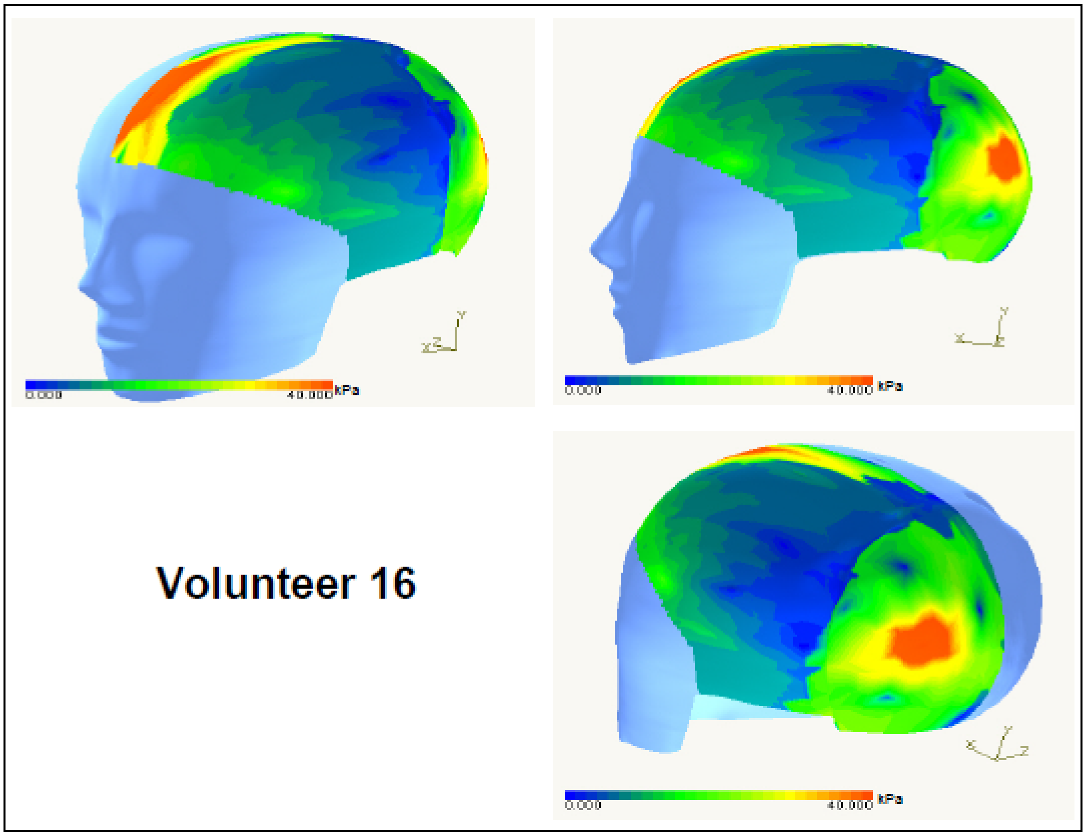
Volunteer 13



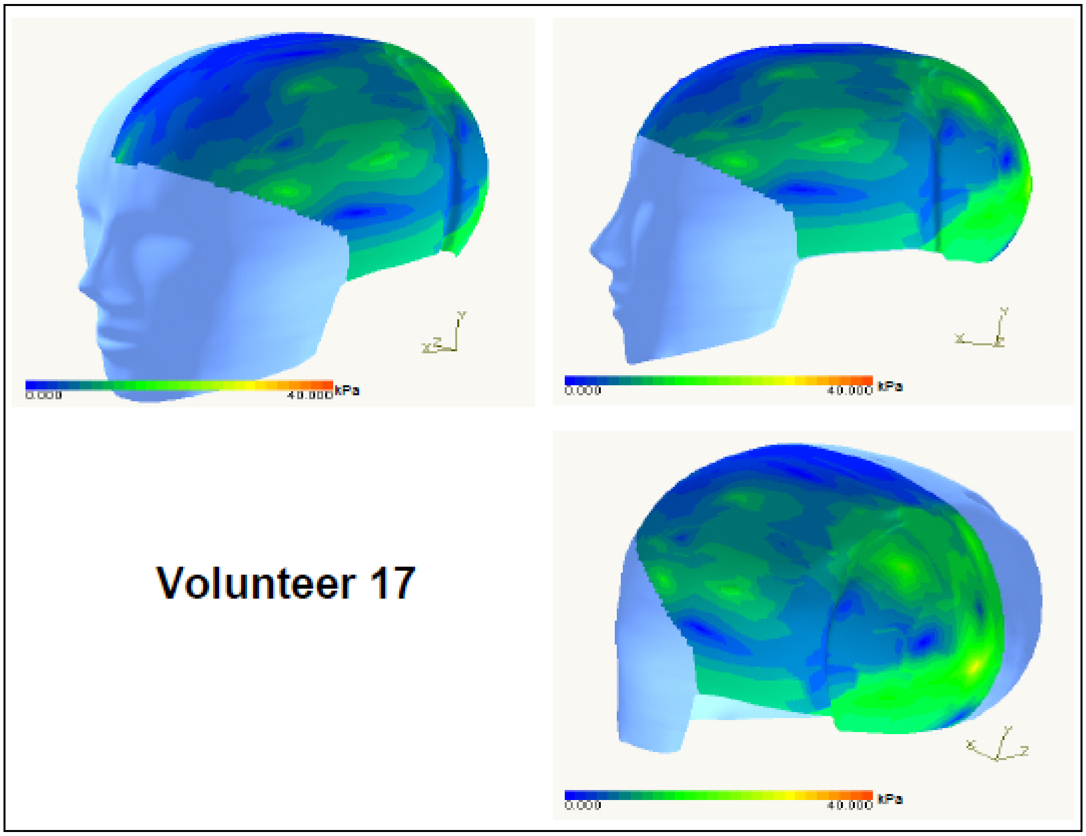
Volunteer 14



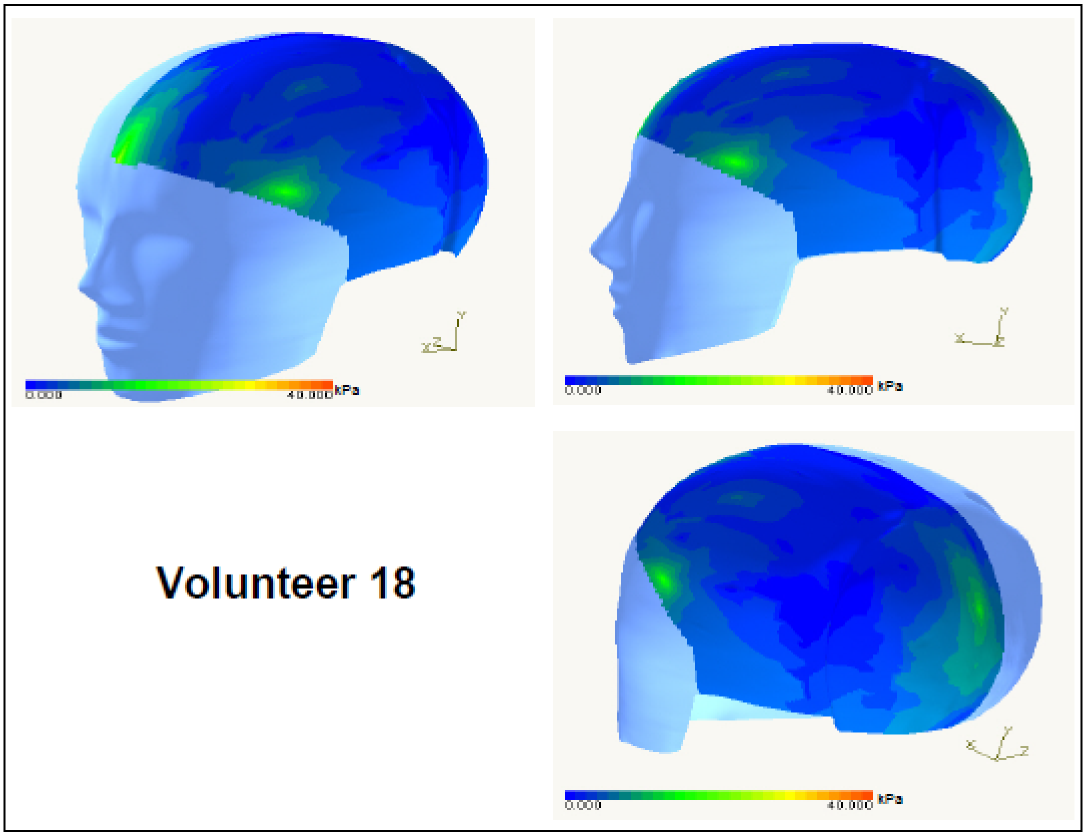
Volunteer 15



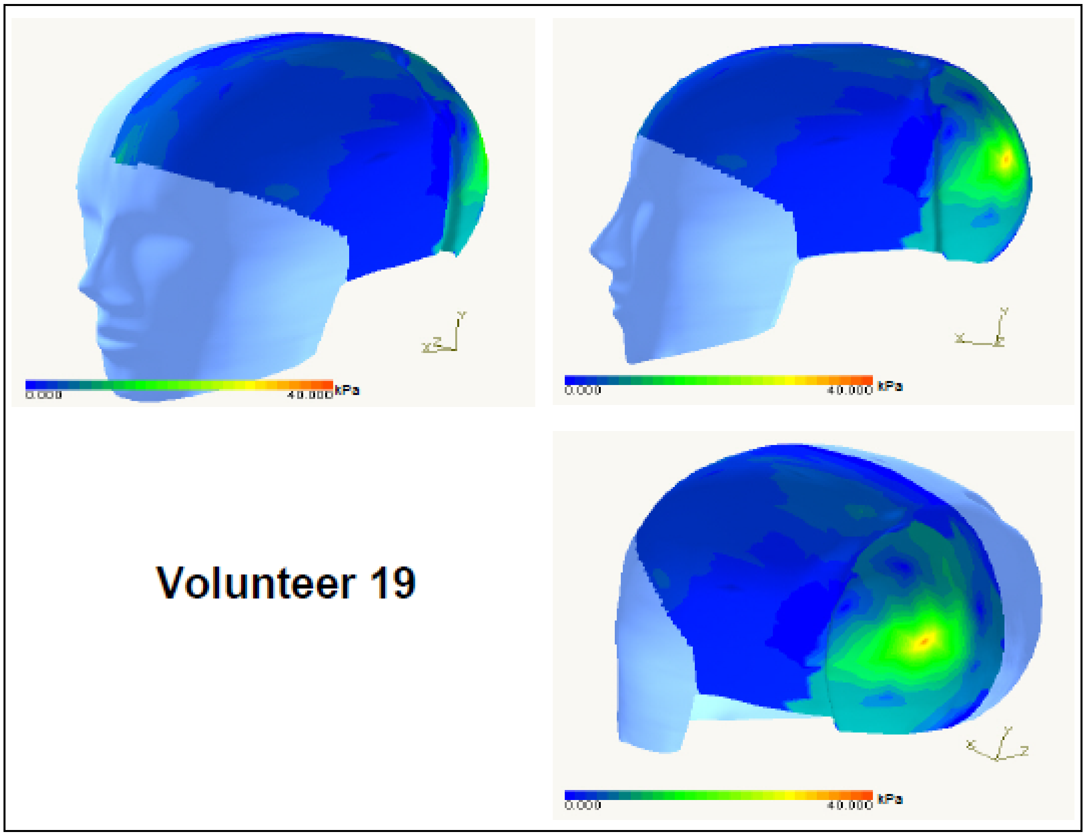
Volunteer 16



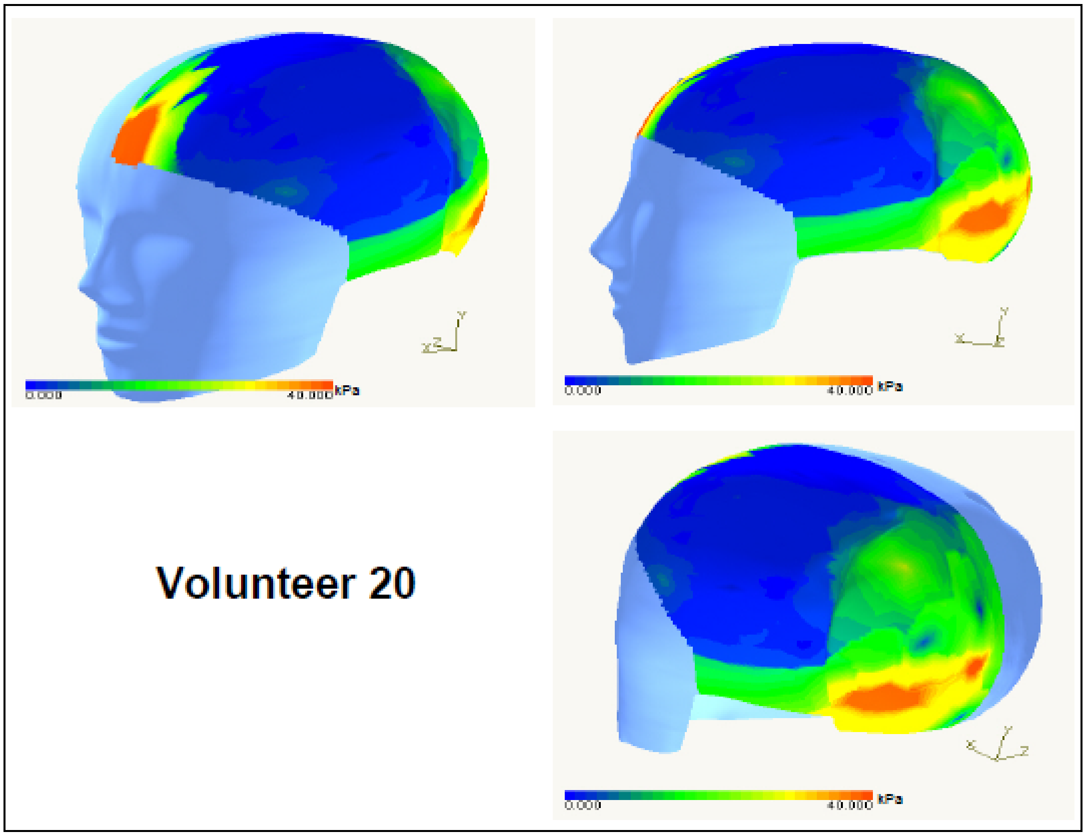
Volunteer 17



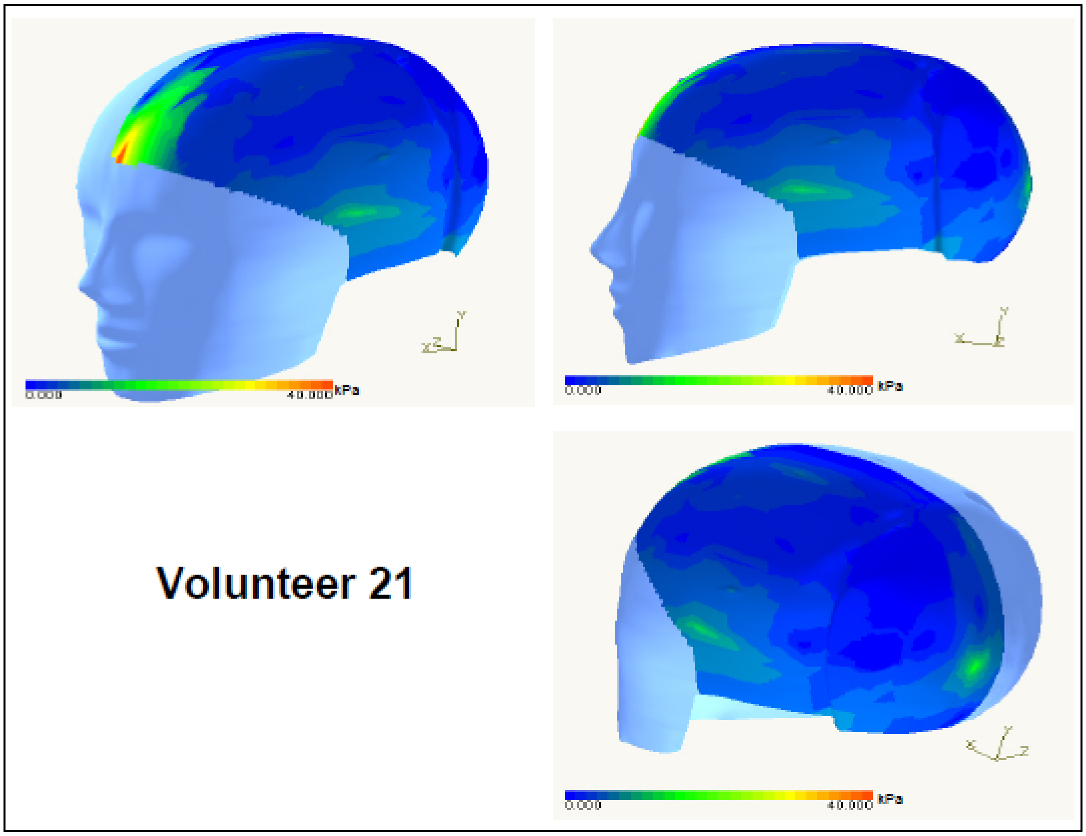
Volunteer 18



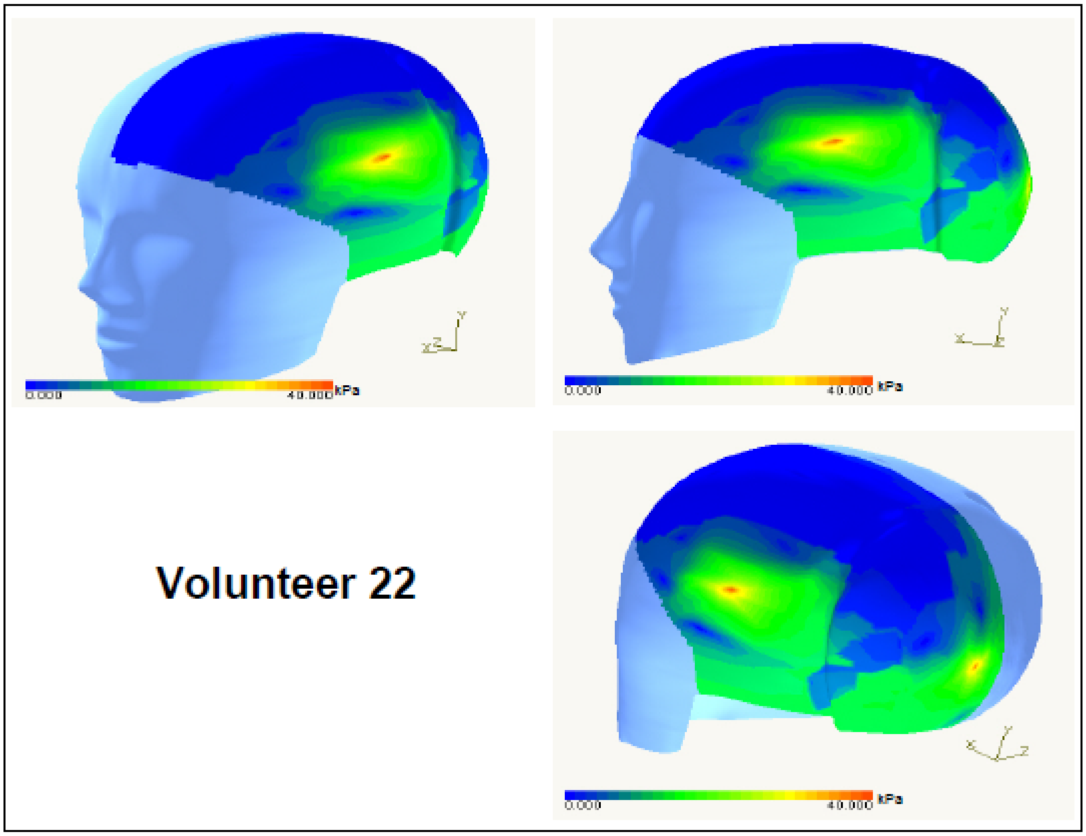
Volunteer 19



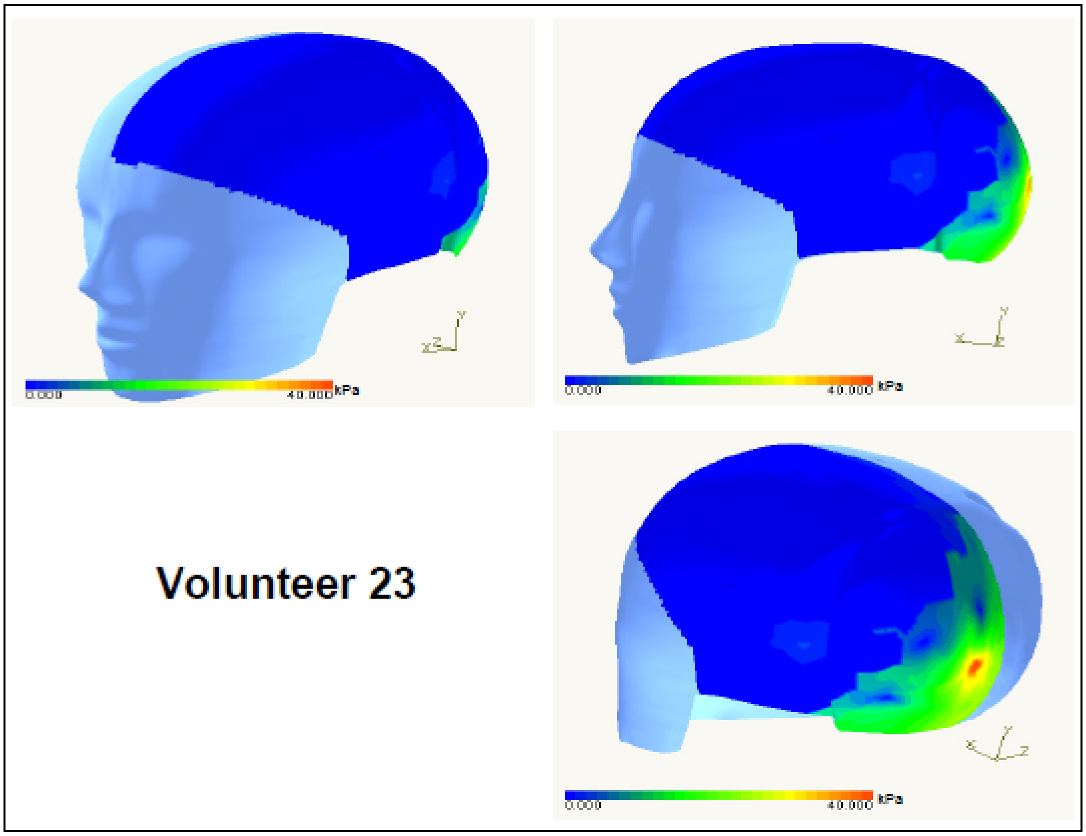
Volunteer 20

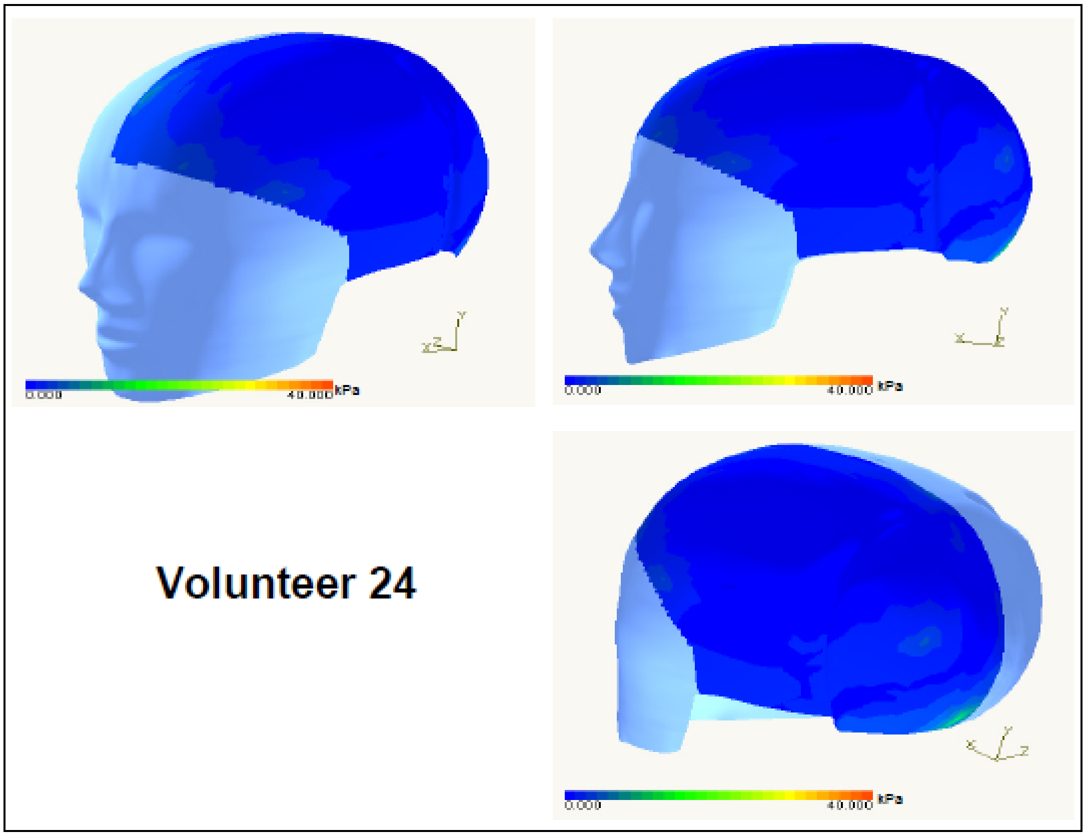


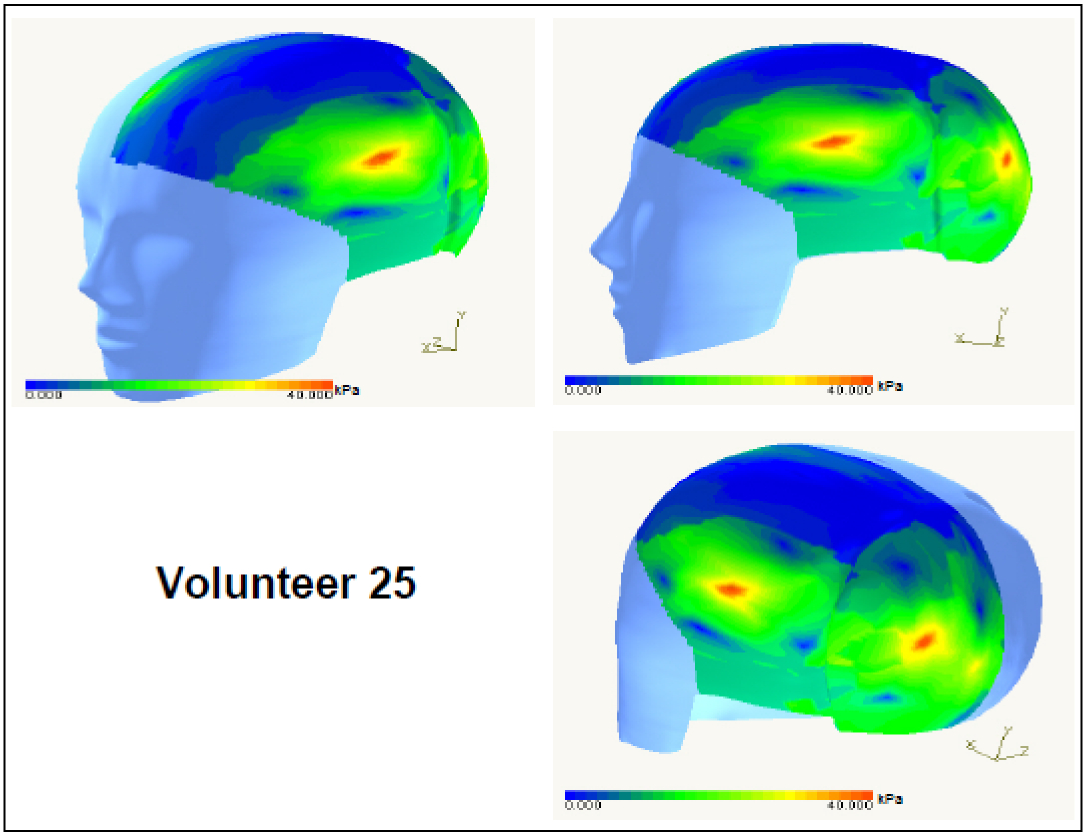
Volunteer 21



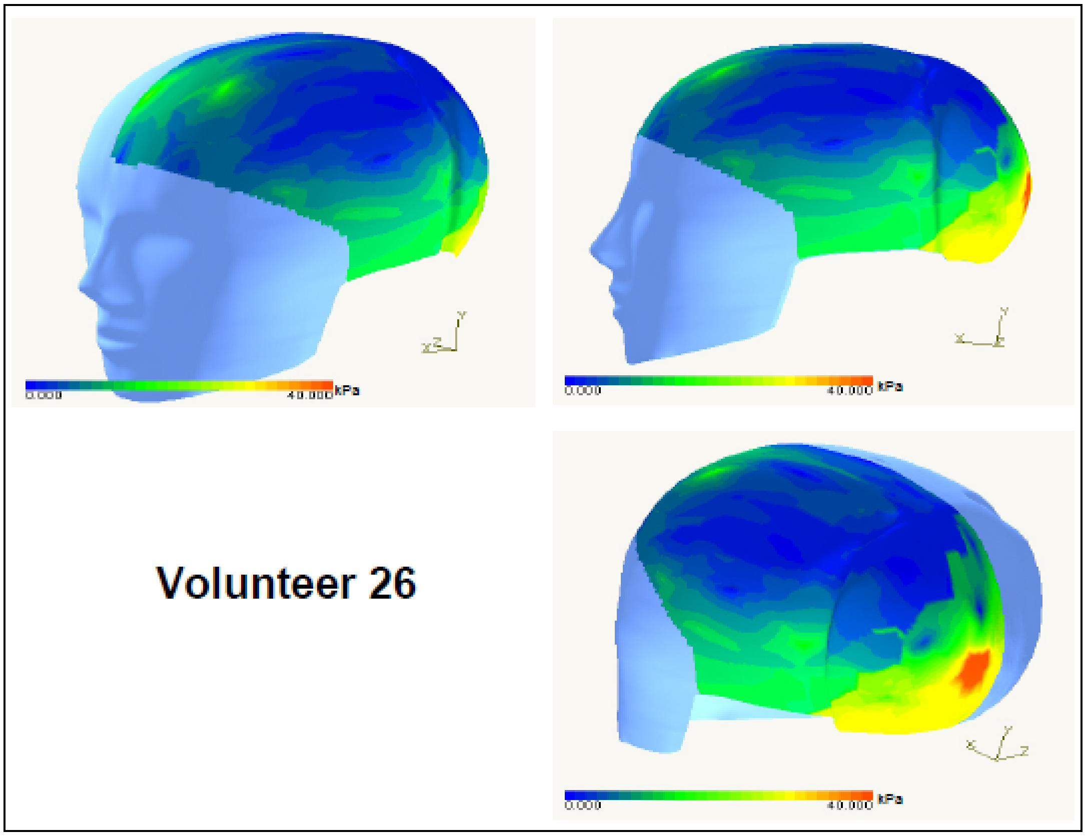
Volunteer 22


0.000
40.000 kPa
Volunteer 23
0.000
40.000 kPa
0.000
40.000 kPa

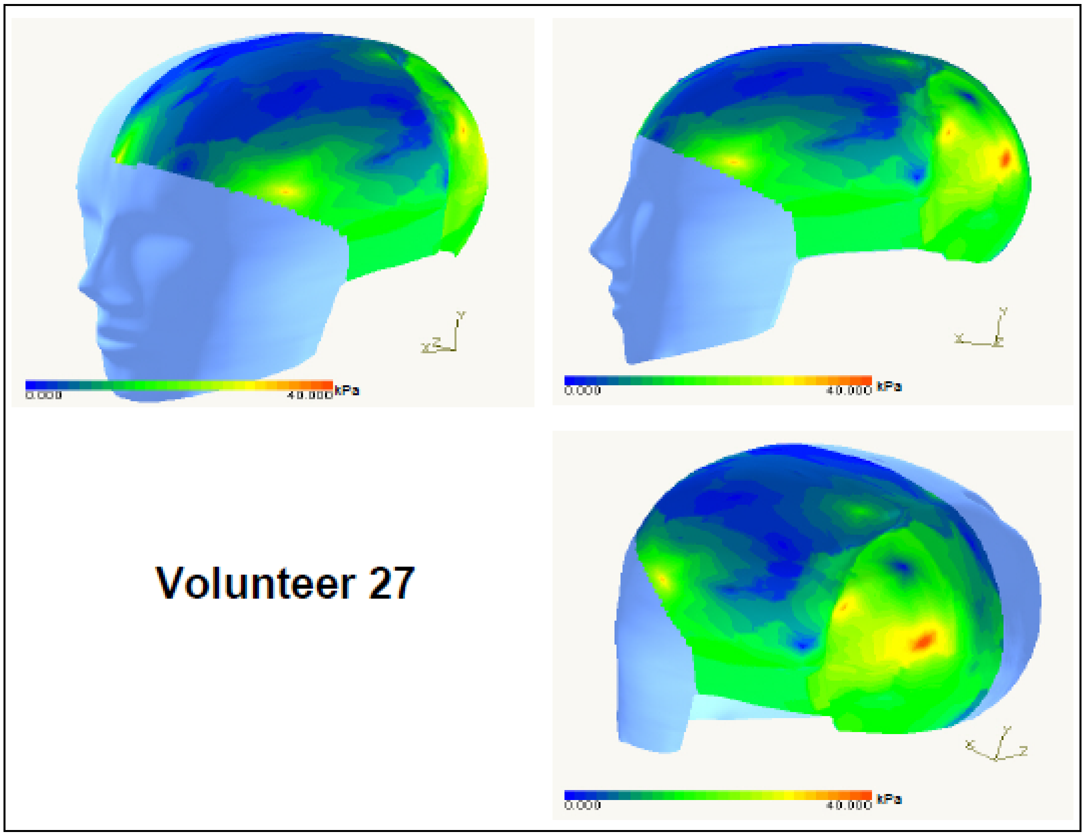

0.000
40.000 kPa
Volunteer 24
0.000
40.000 kPa
0.000
40.000 kPa



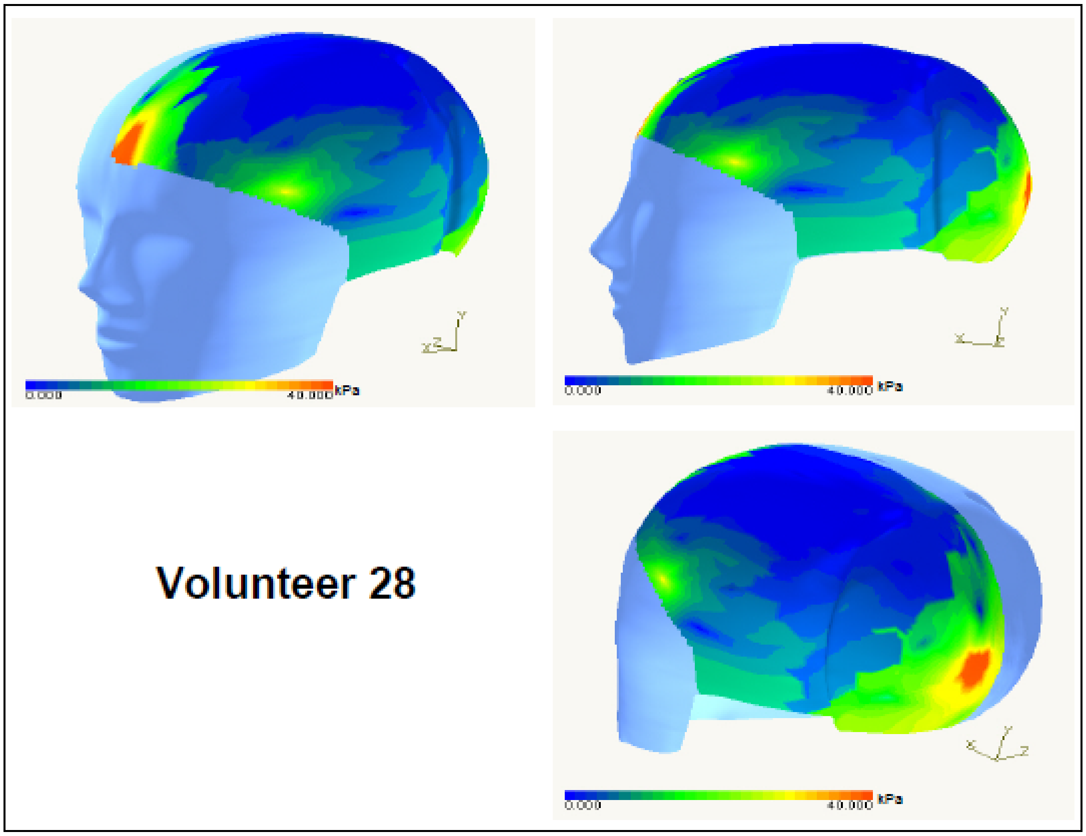
Volunteer 25



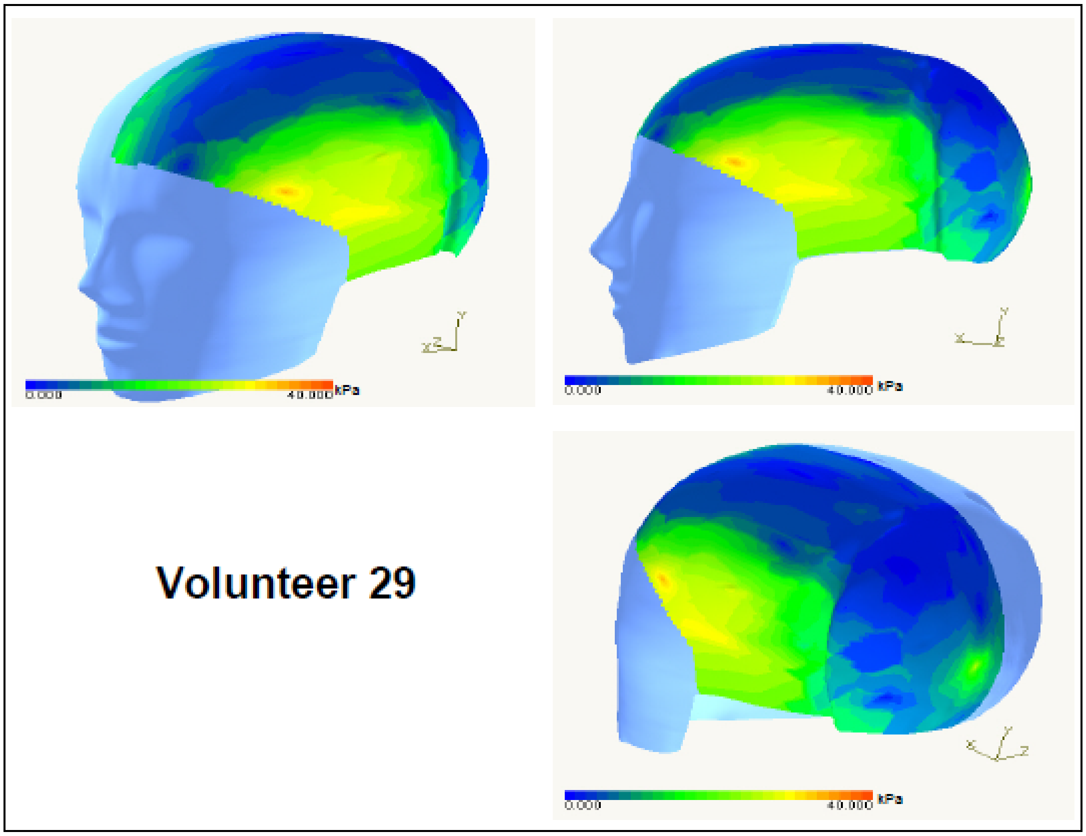
Volunteer 26

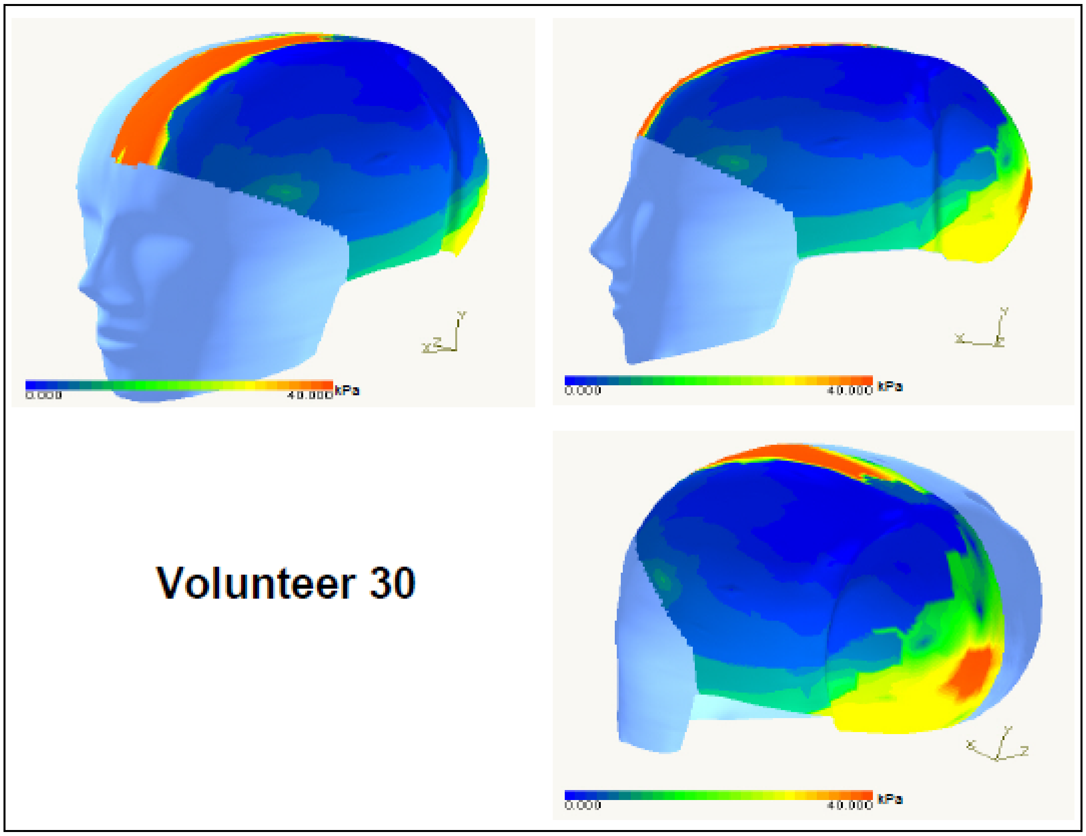


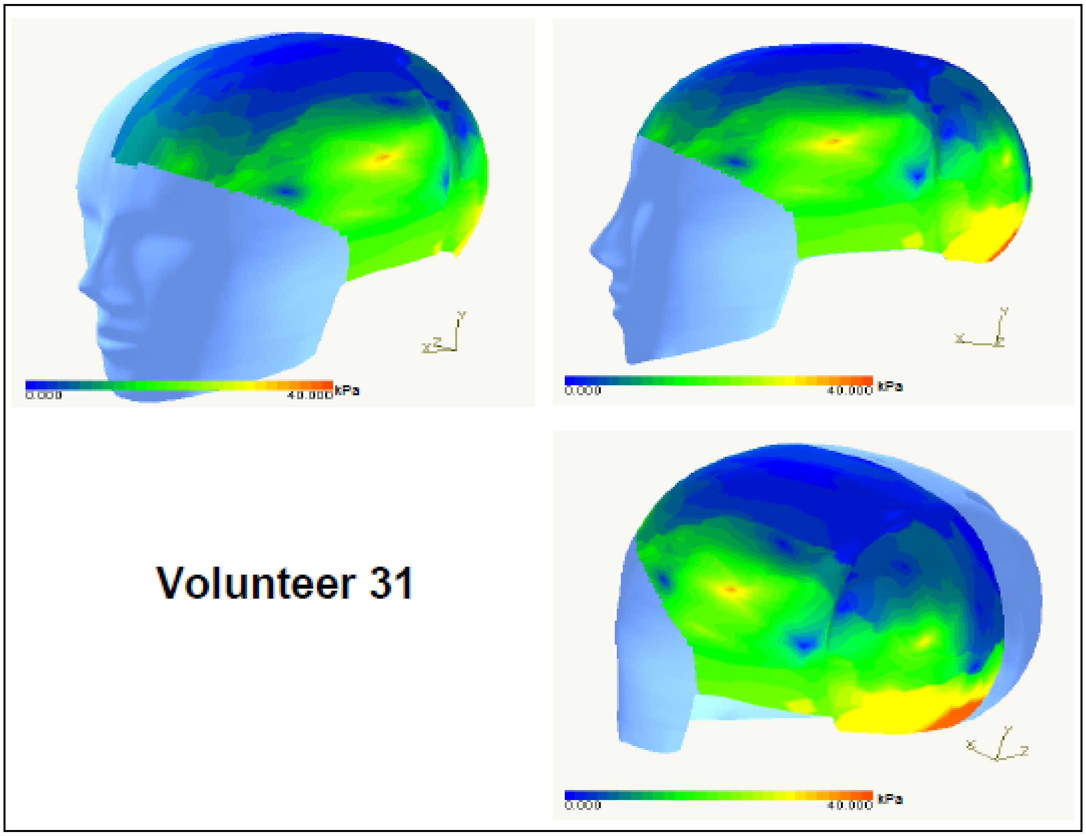
Volunteer 27



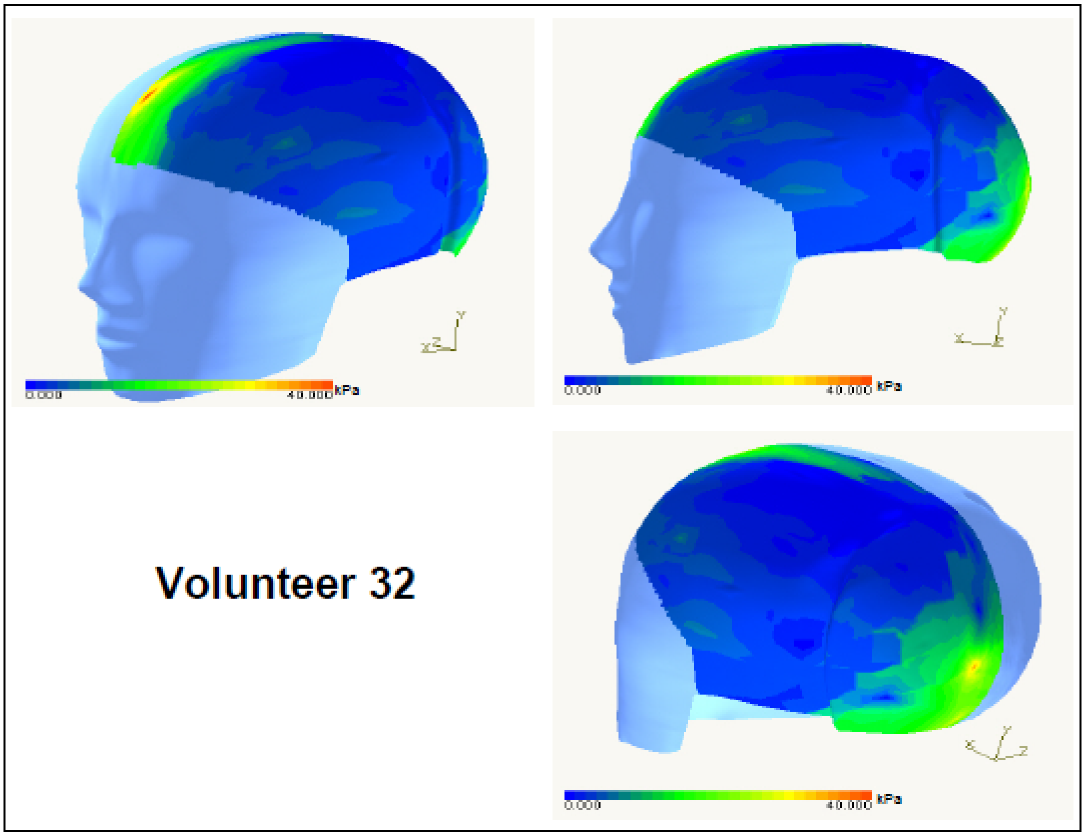
Volunteer 28


Volunteer 29
0.000
40.000 kPa
X
Y
Z


Volunteer 30
0.000
40.000 kPa
X
Y
Z



Volunteer 31



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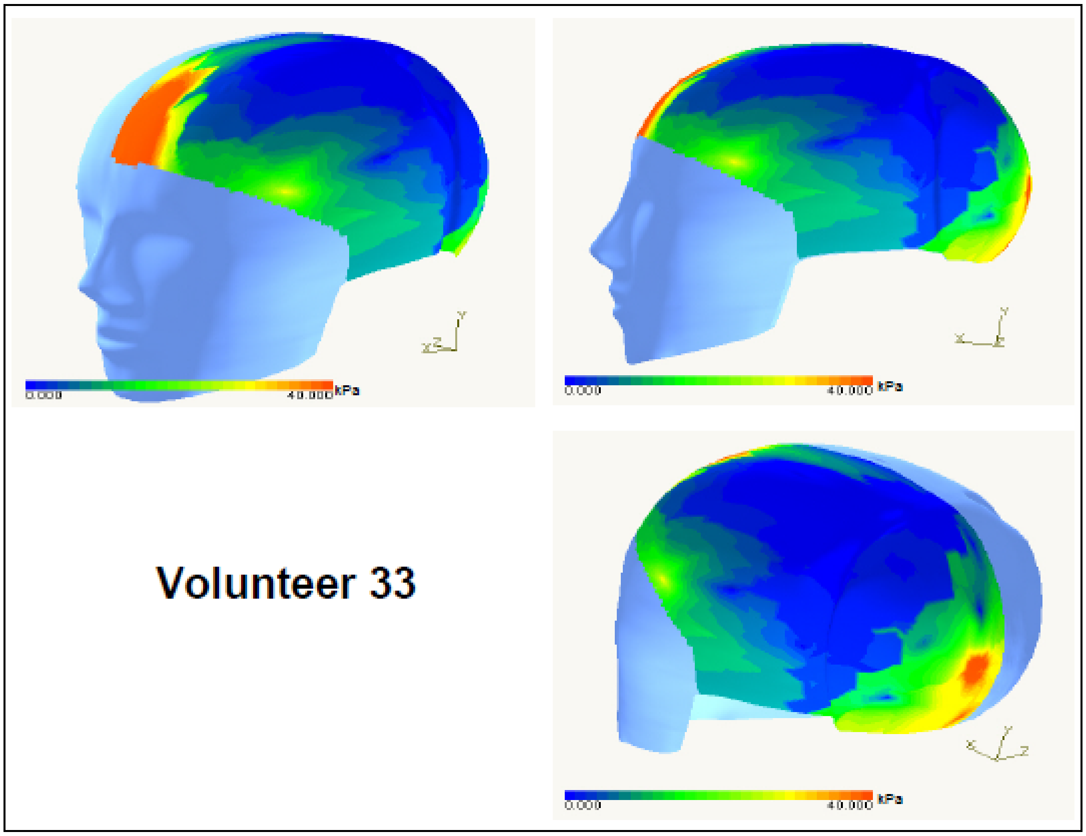

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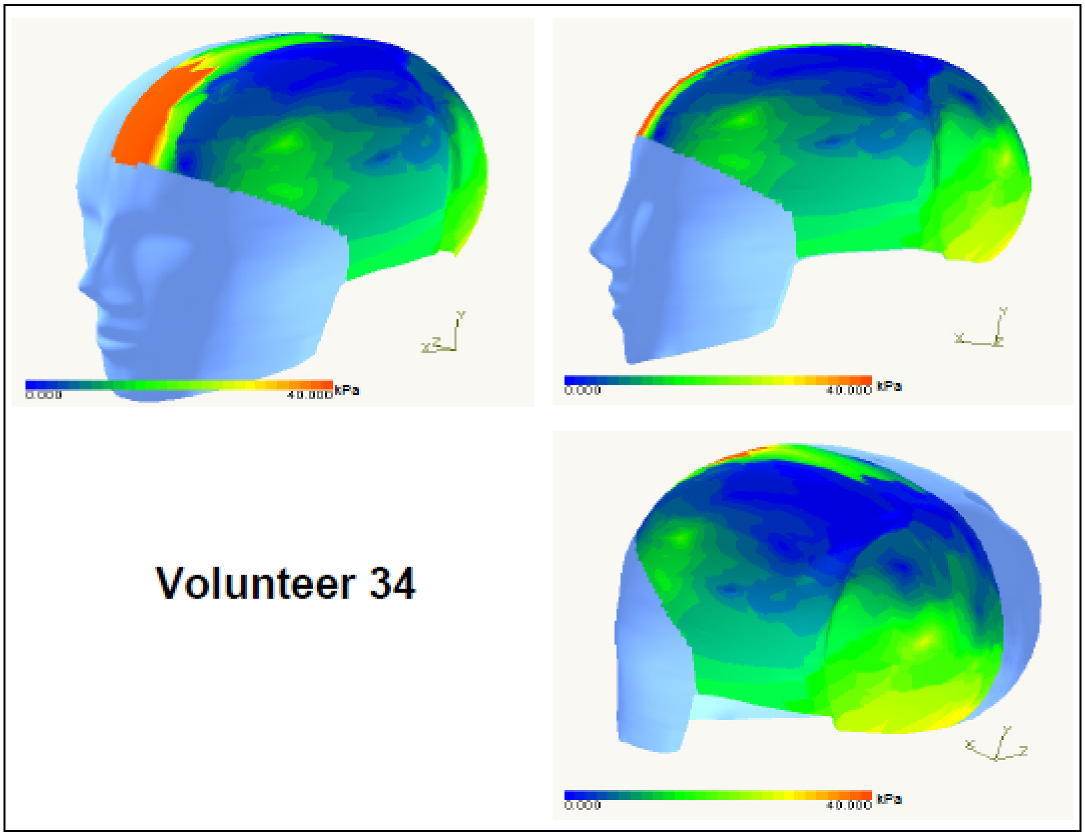

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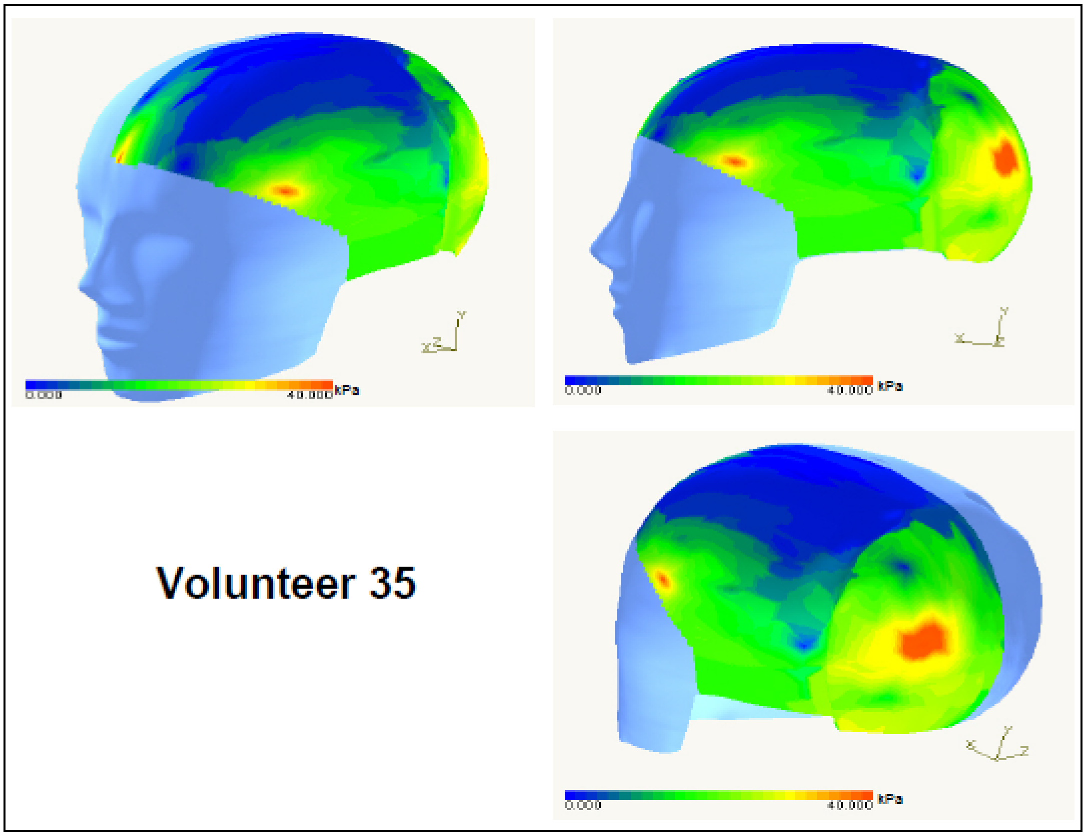

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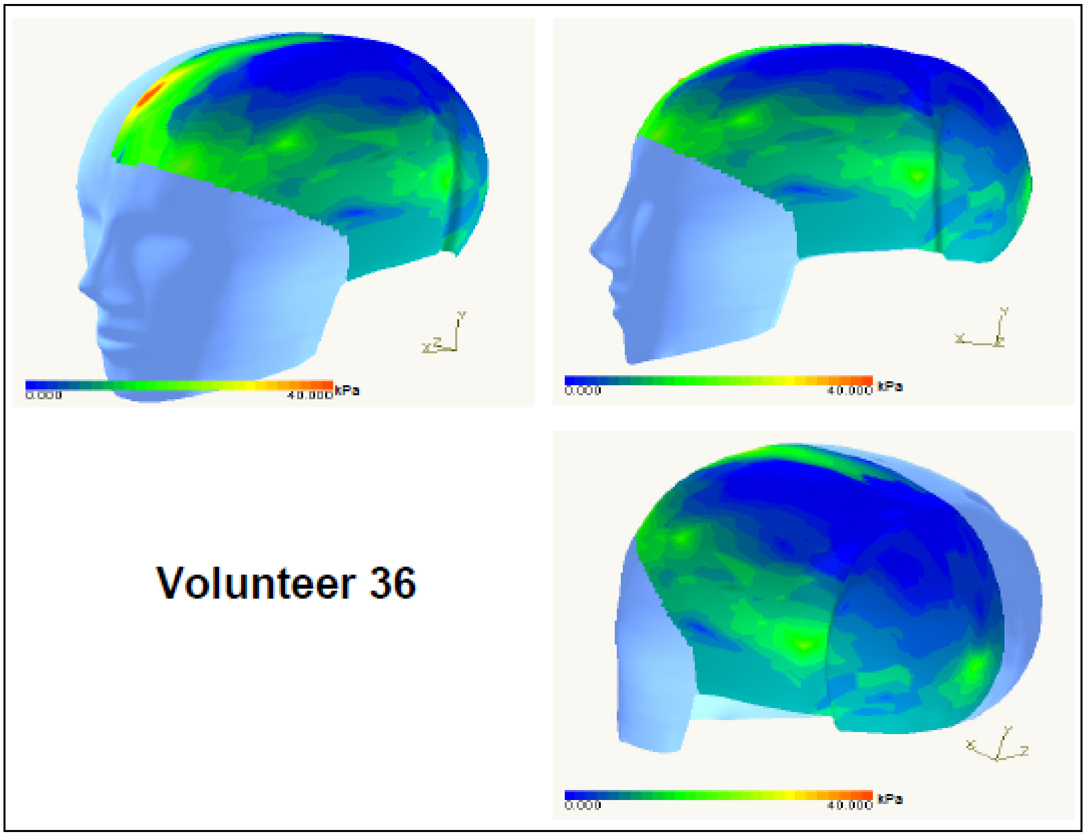

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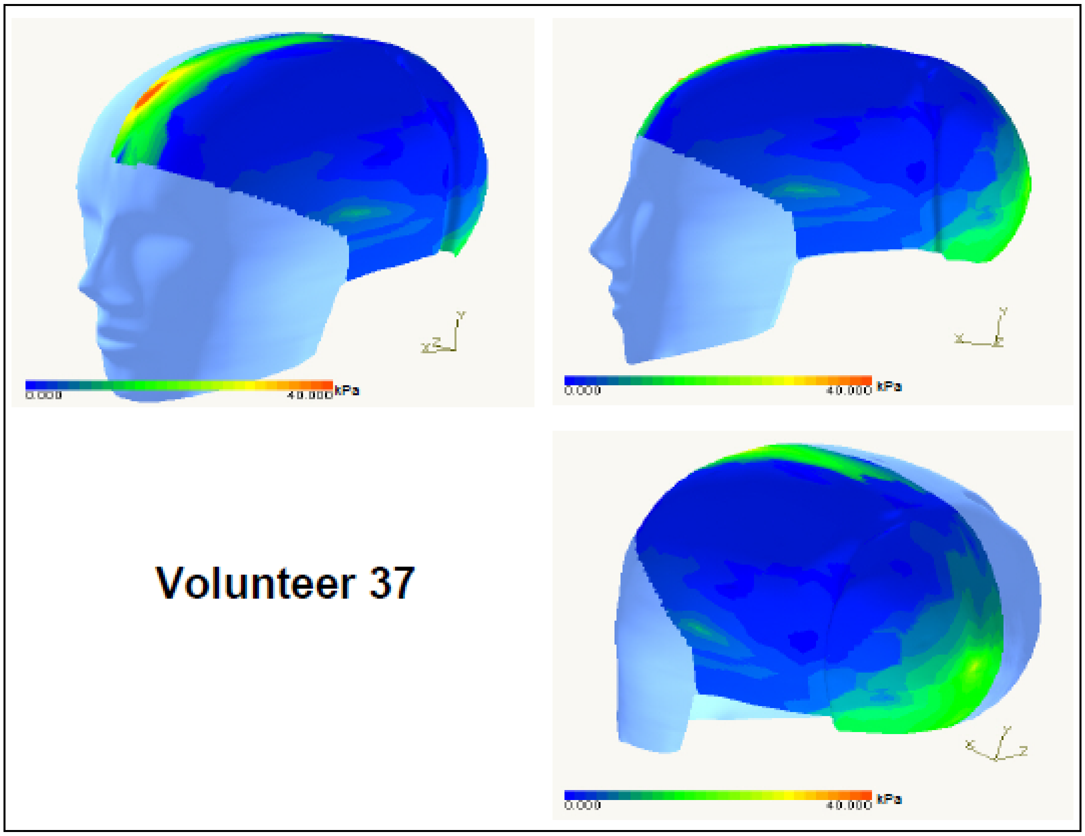

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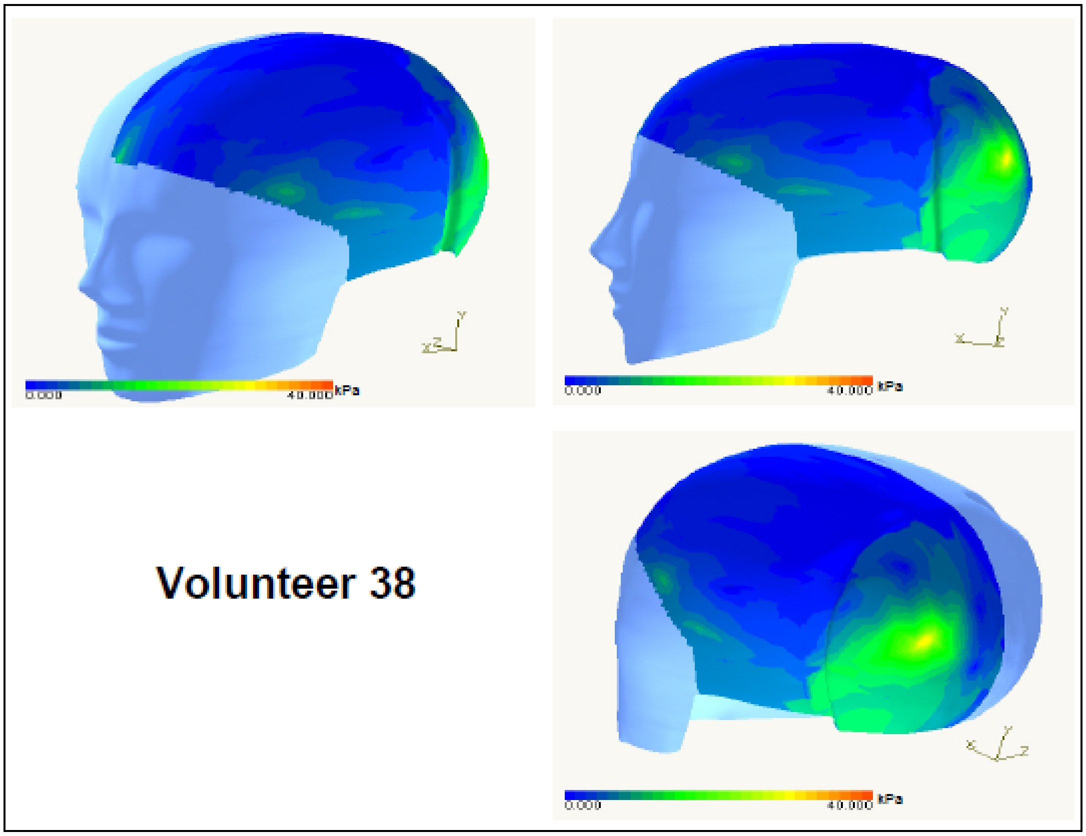

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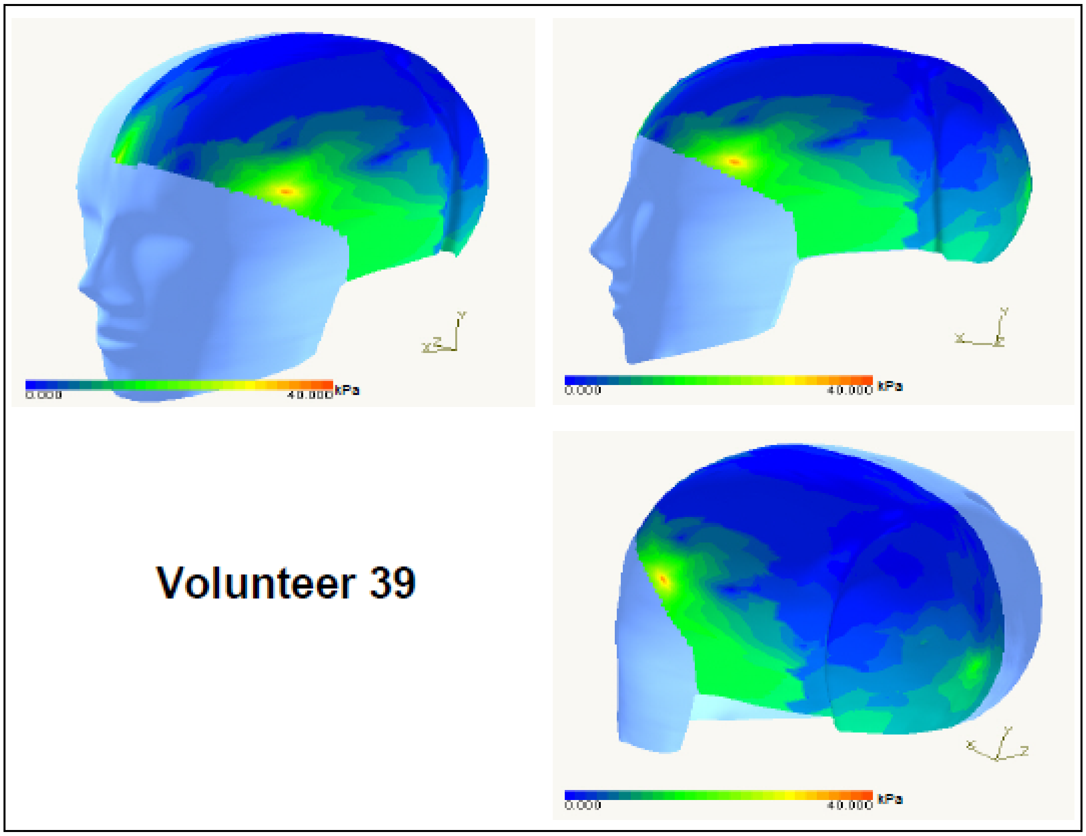

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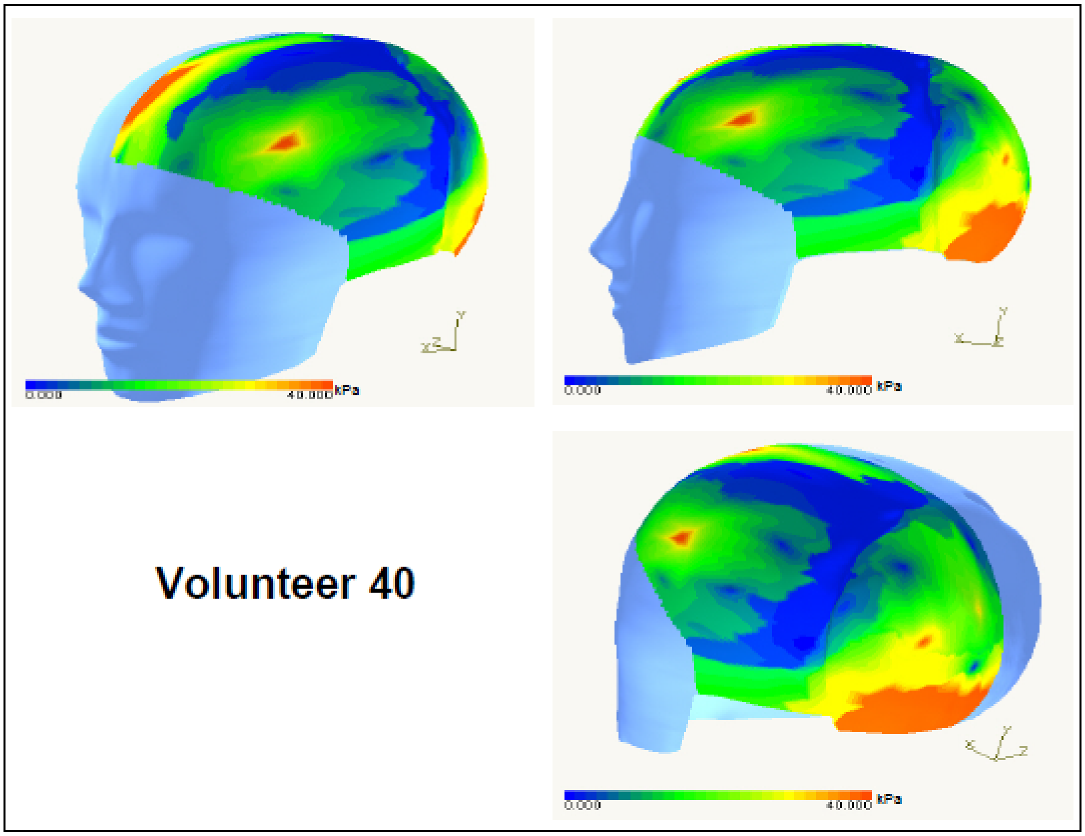

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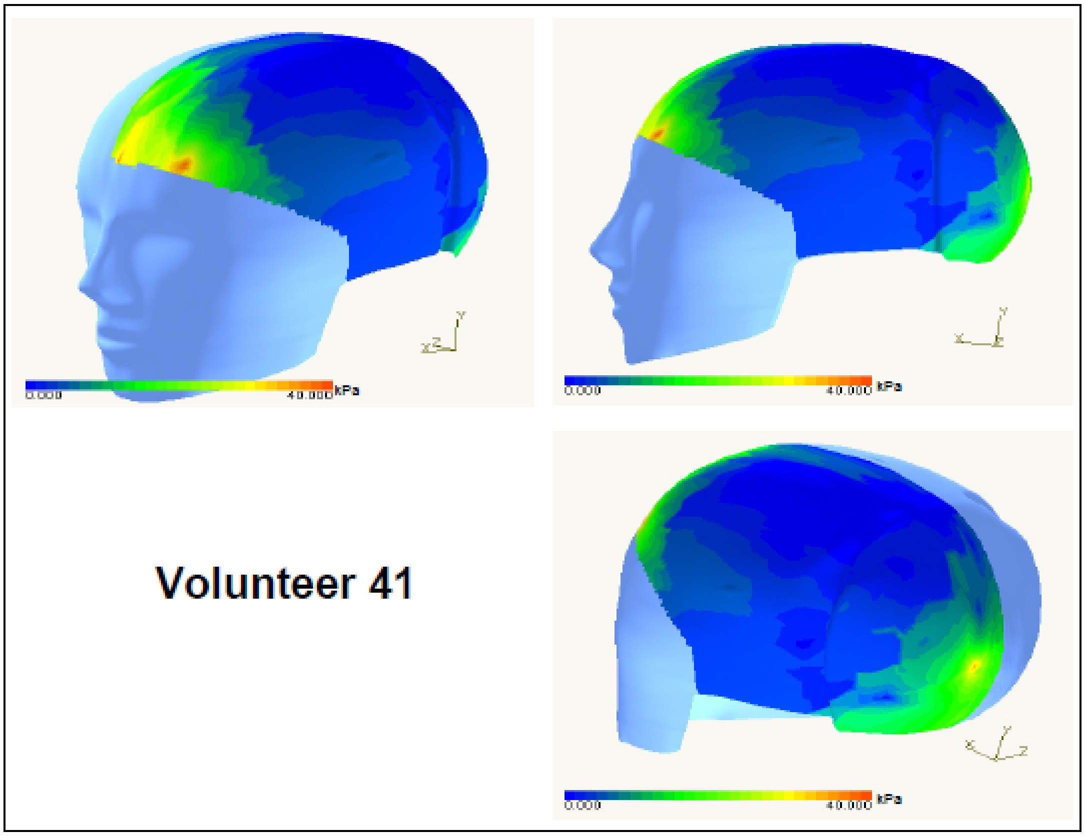

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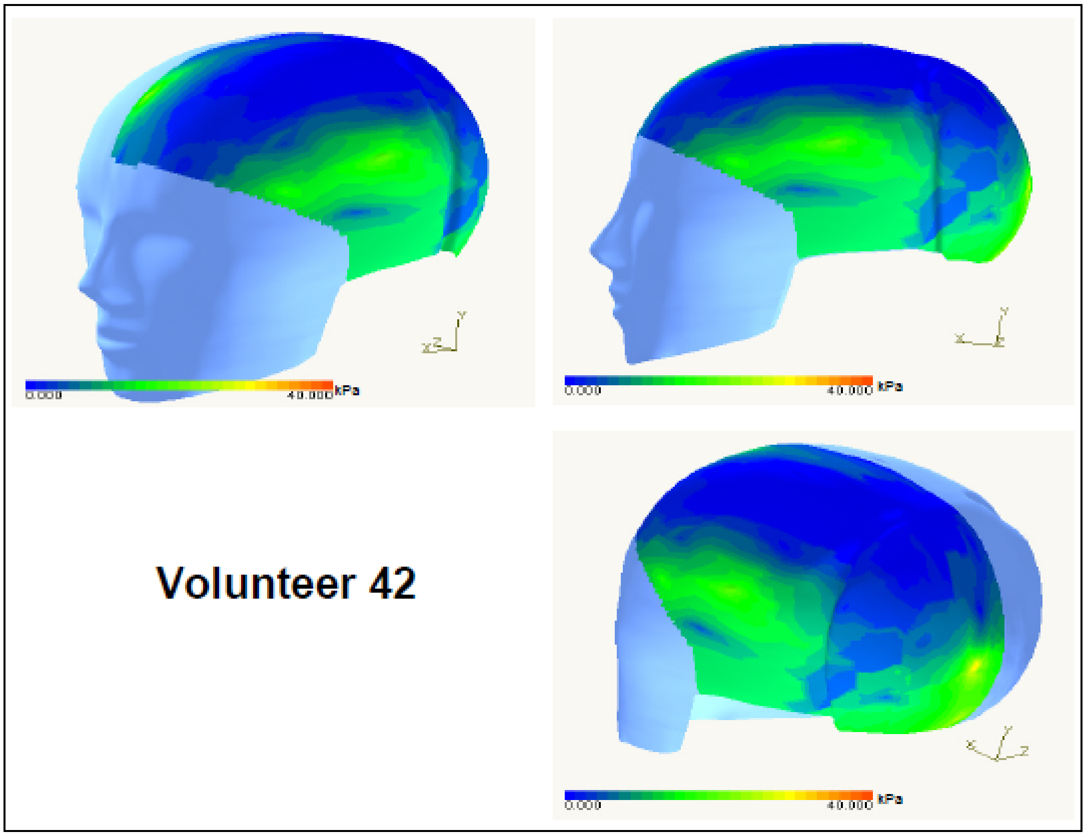

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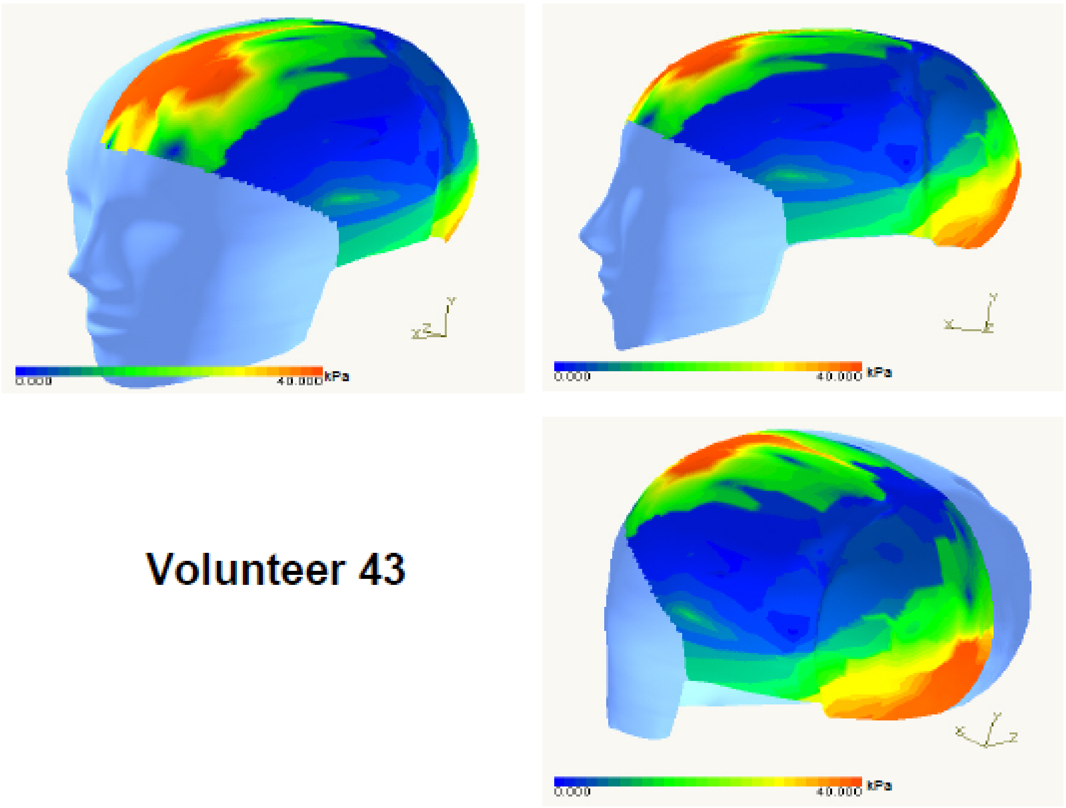

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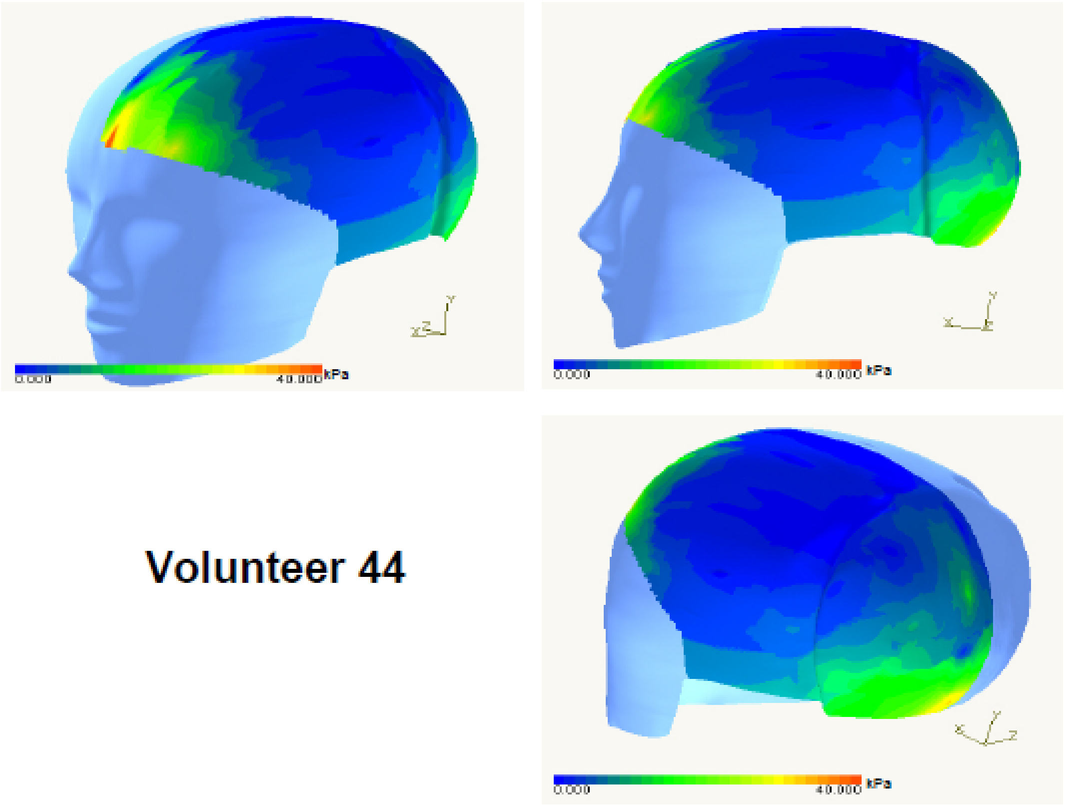

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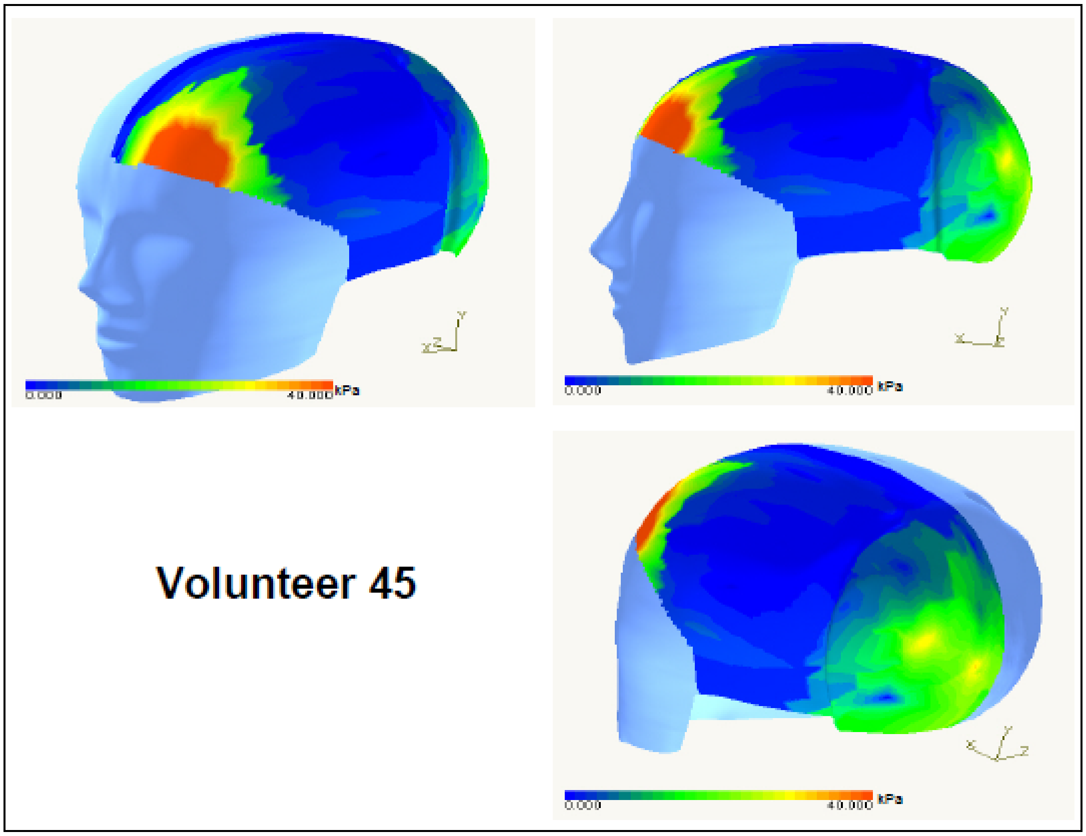

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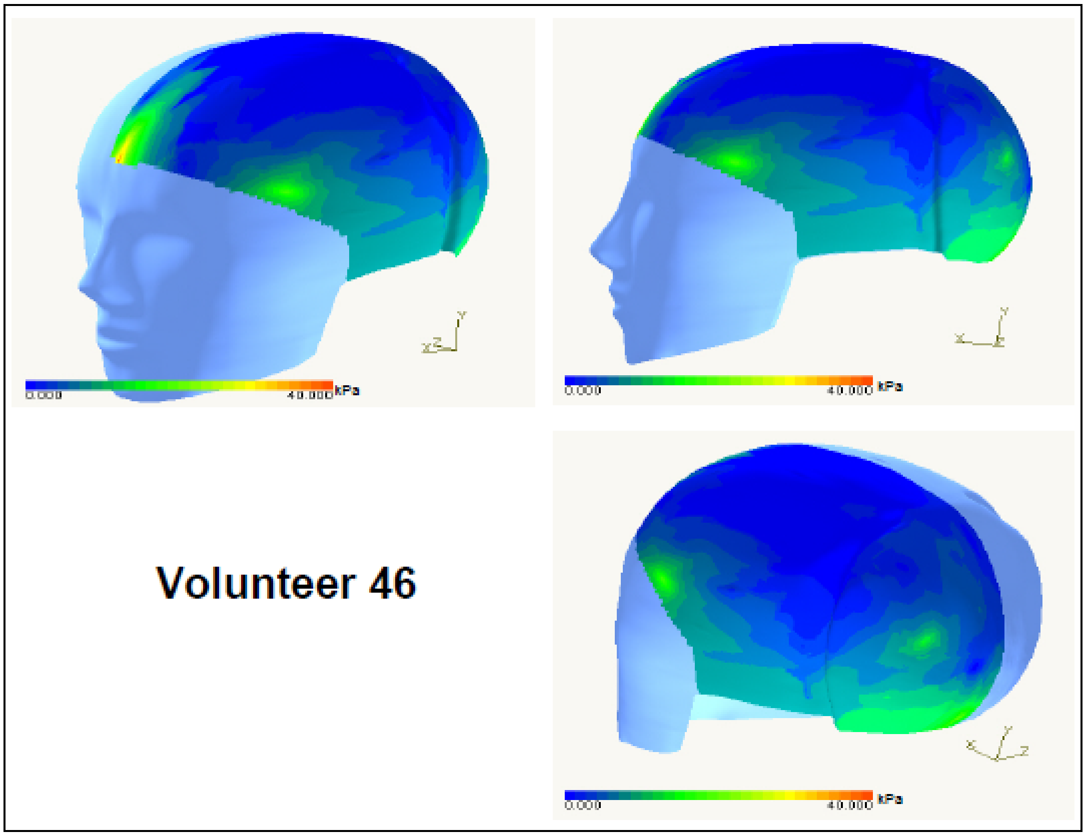

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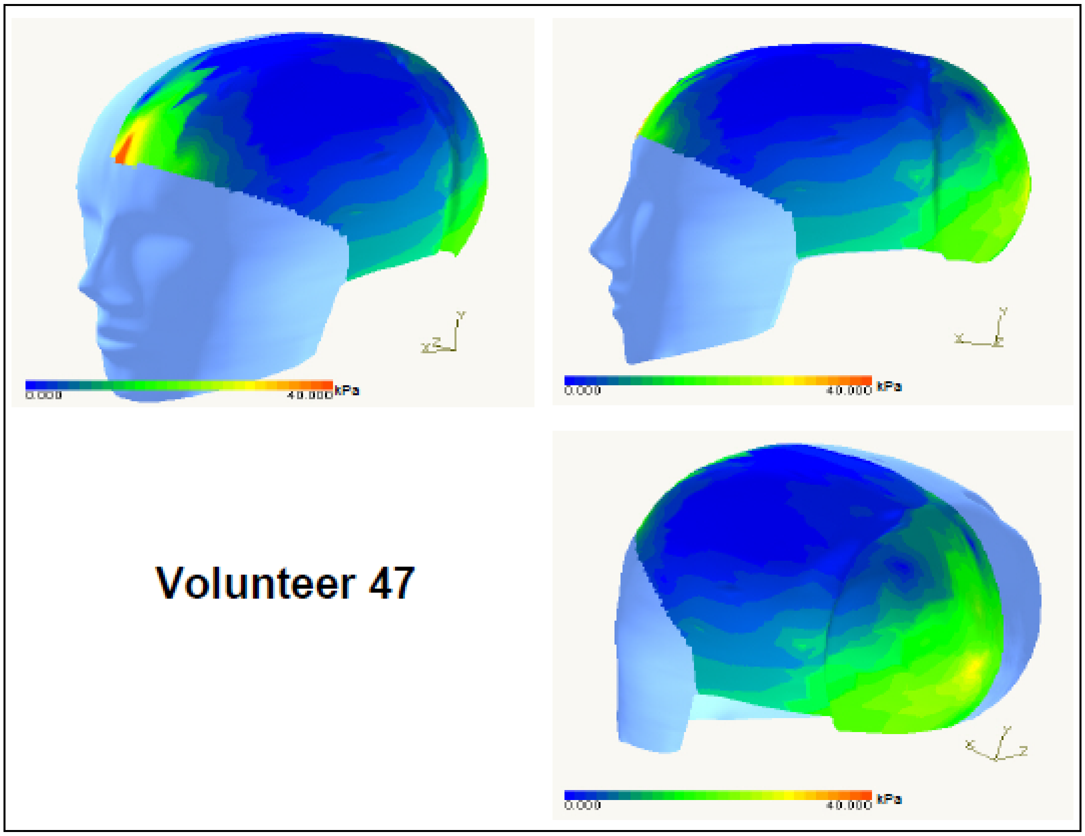

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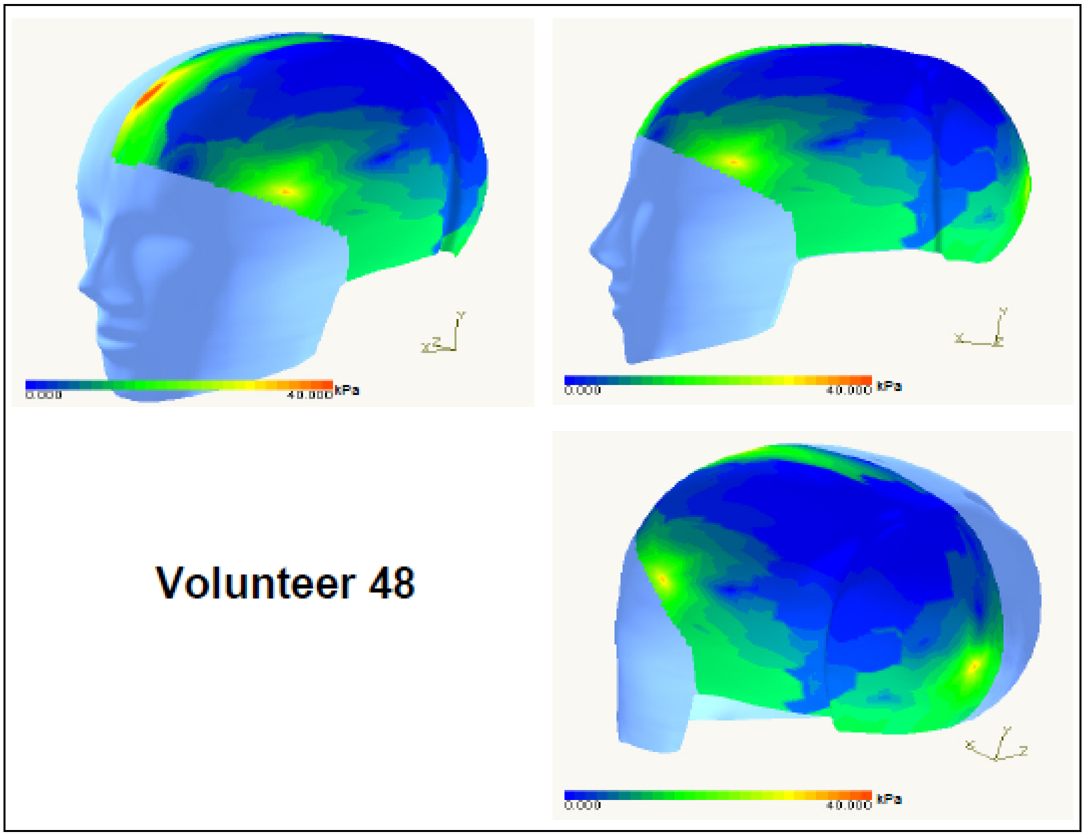

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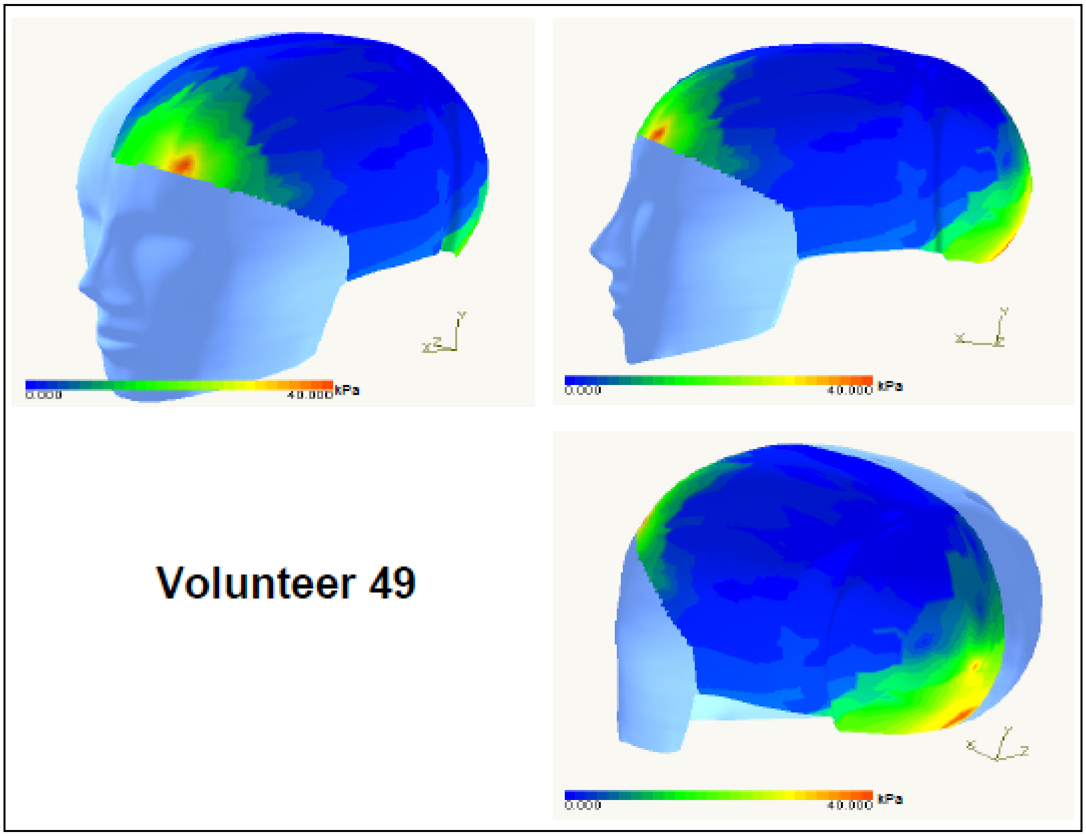

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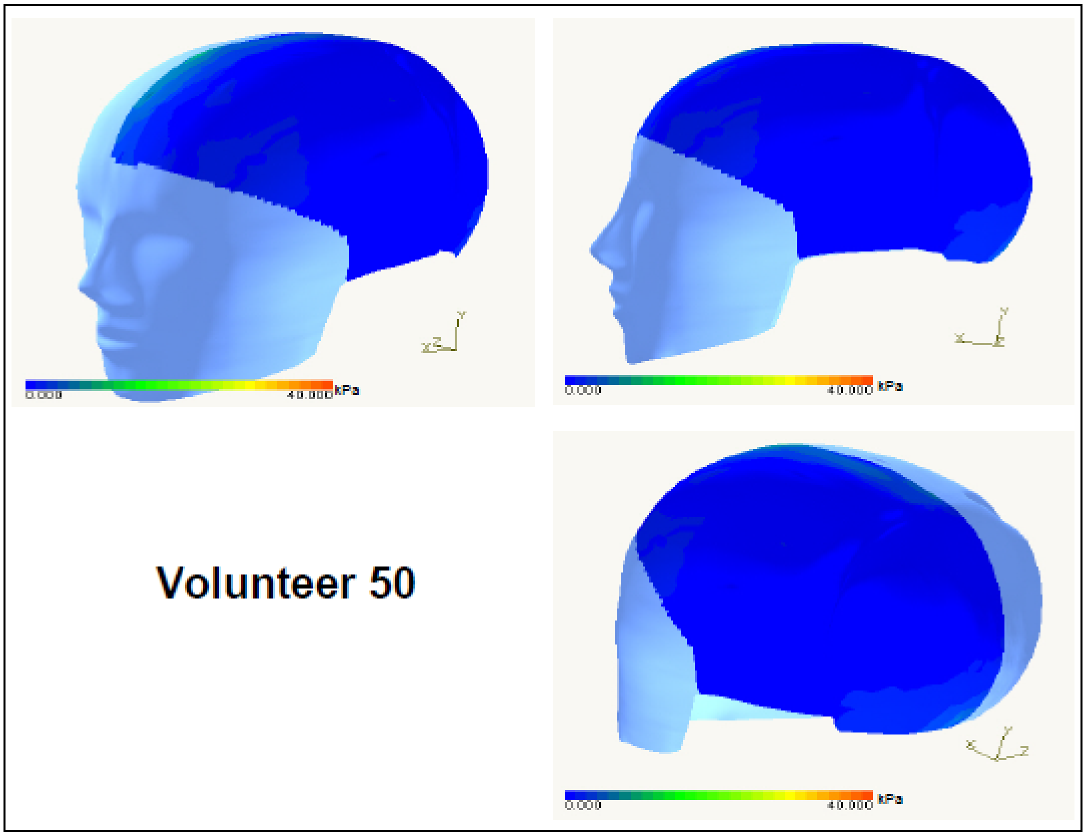

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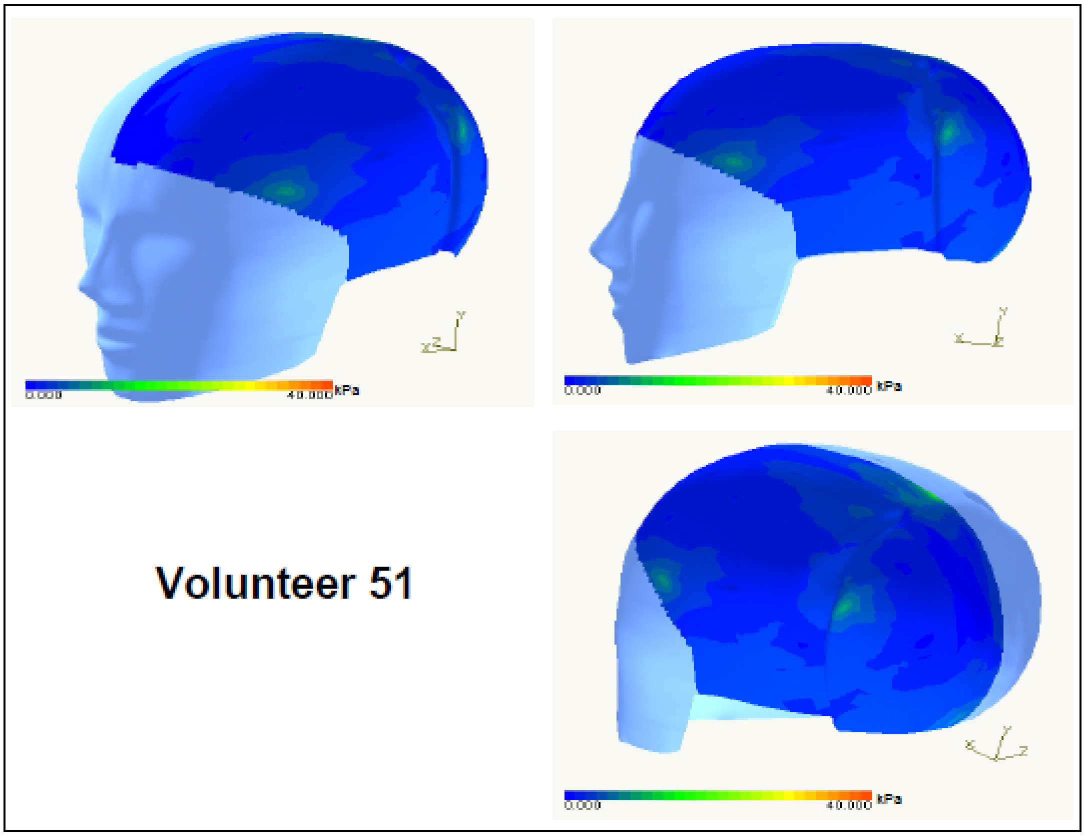

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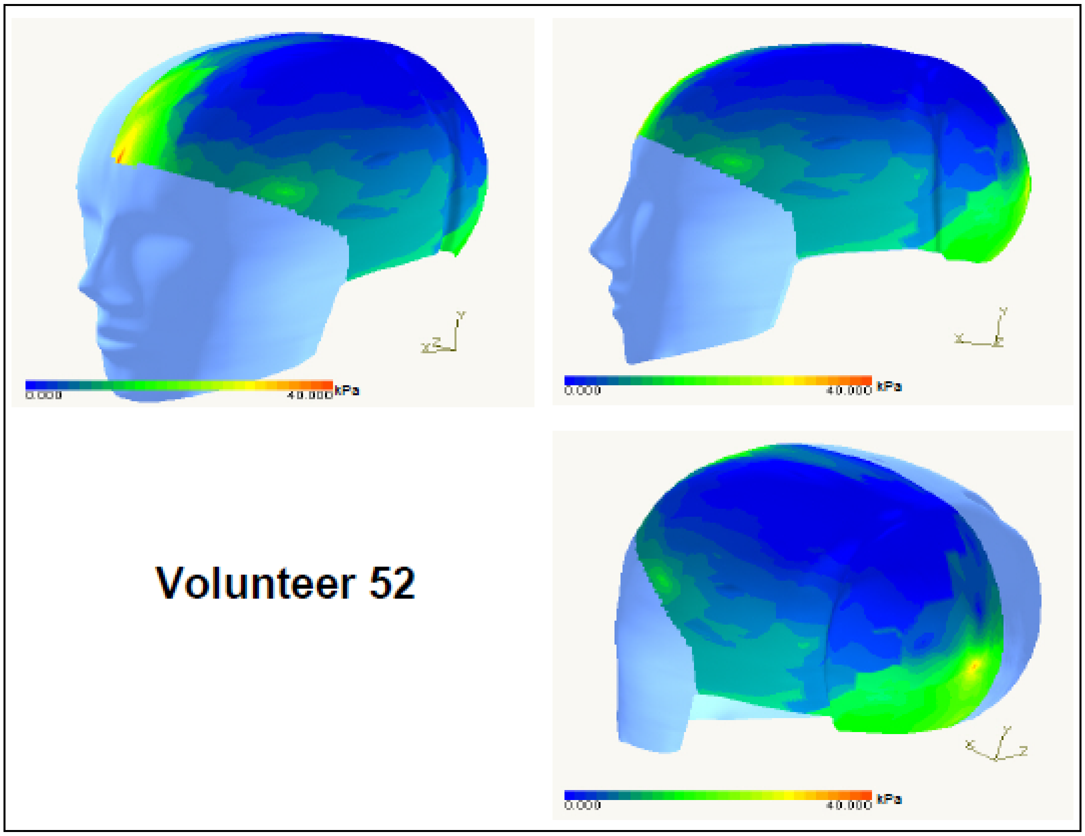

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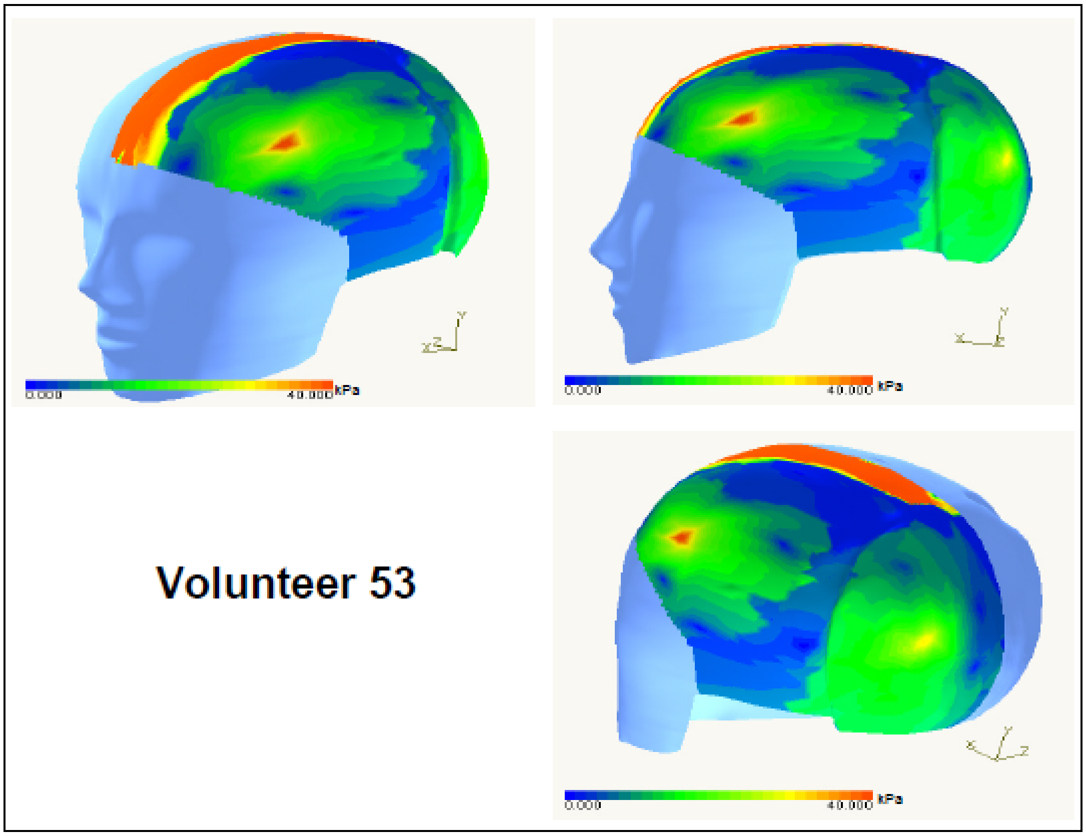

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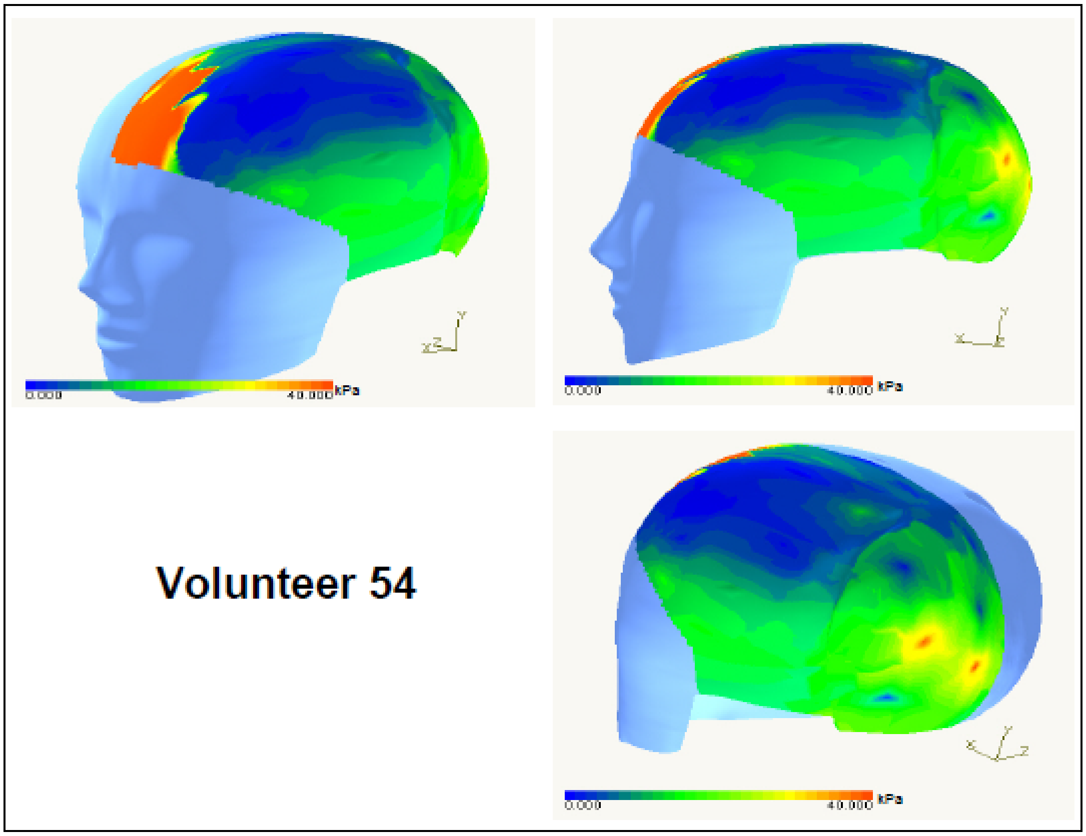

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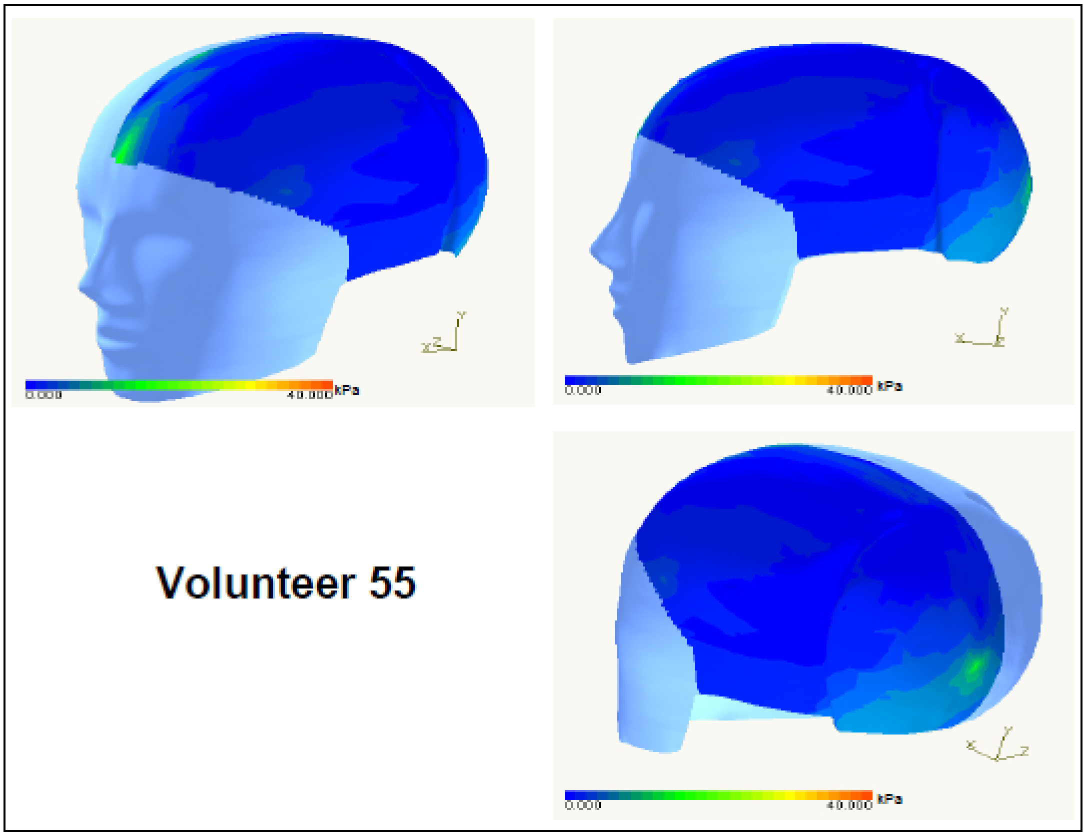
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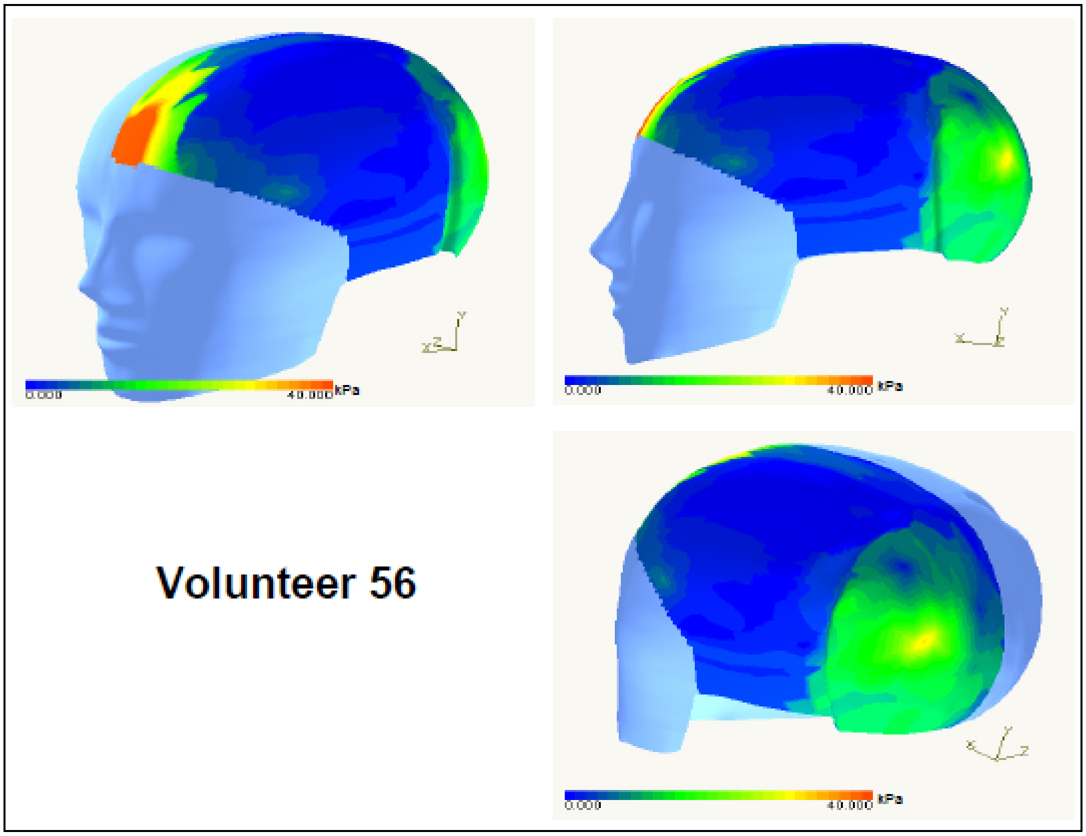
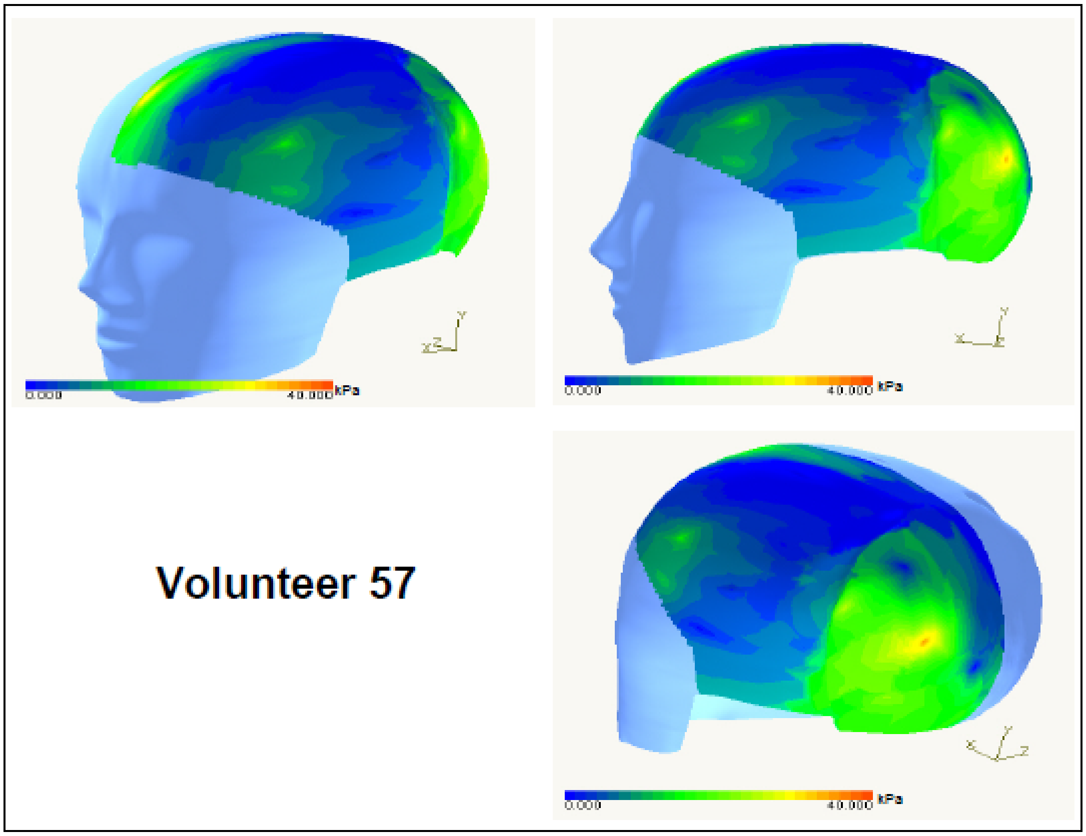
40.000 kPa
Volunteer 55
x
y
z


0.000
40.000 kPa
Volunteer 56
x
y
z



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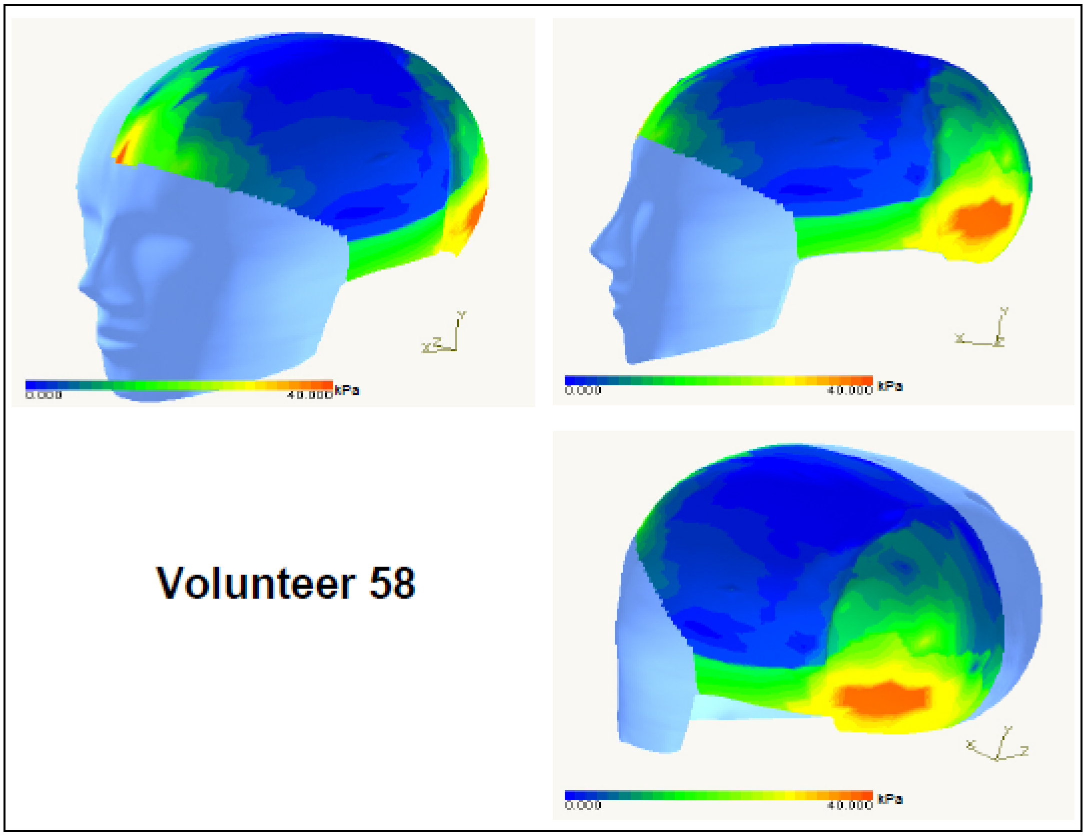

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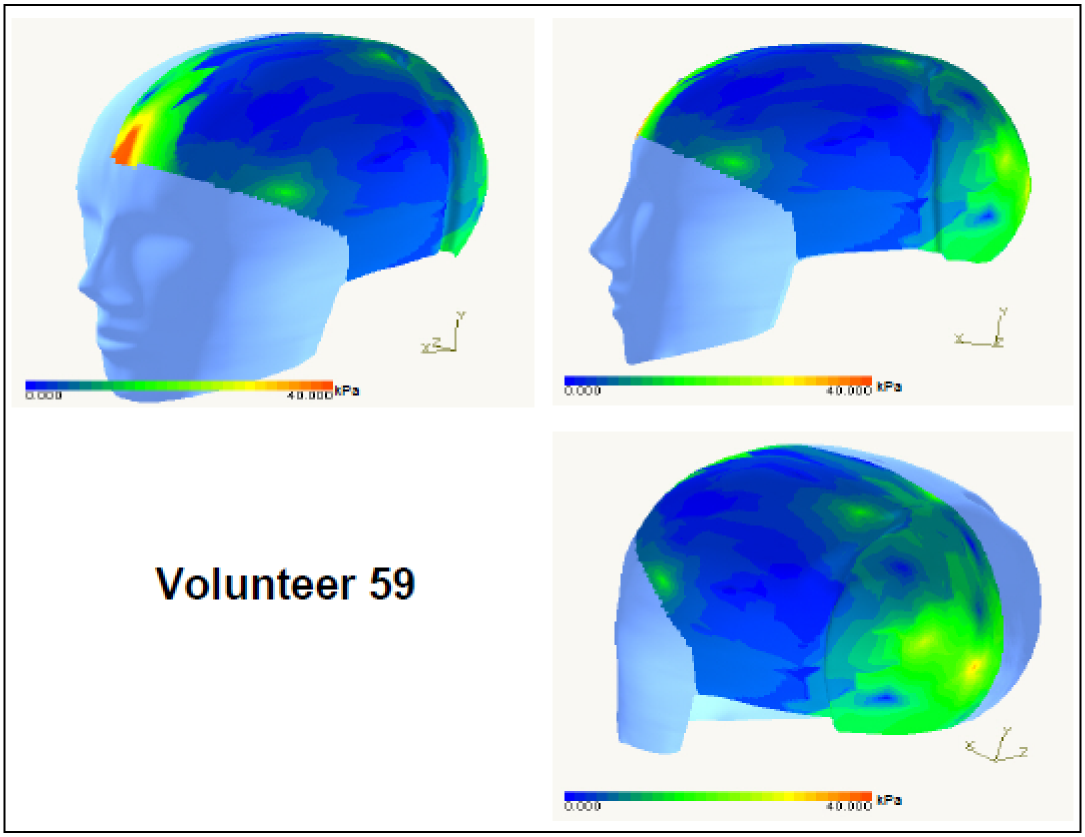

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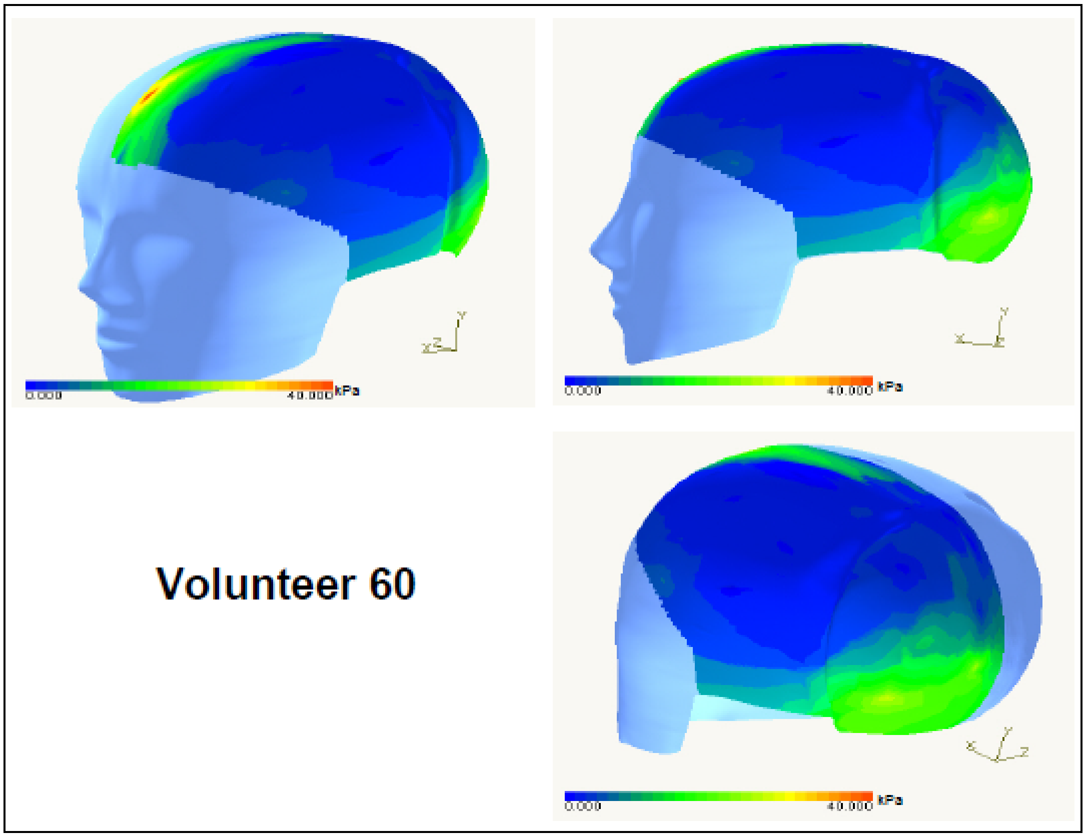

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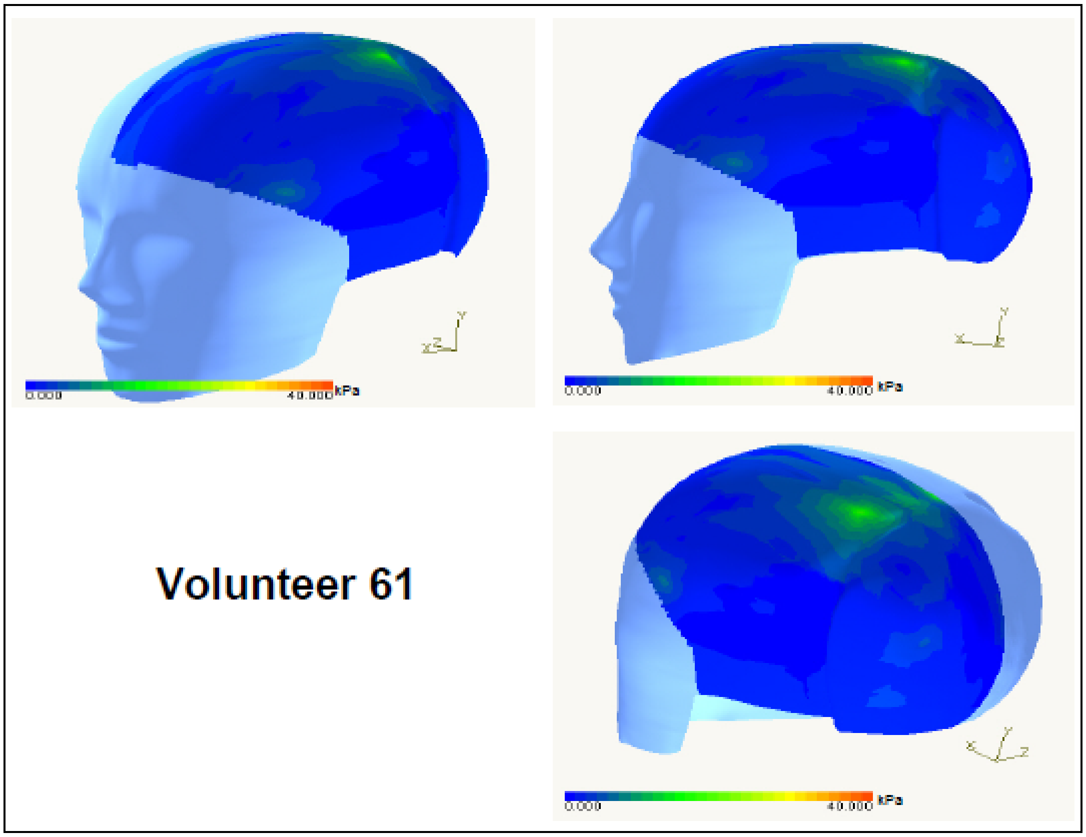

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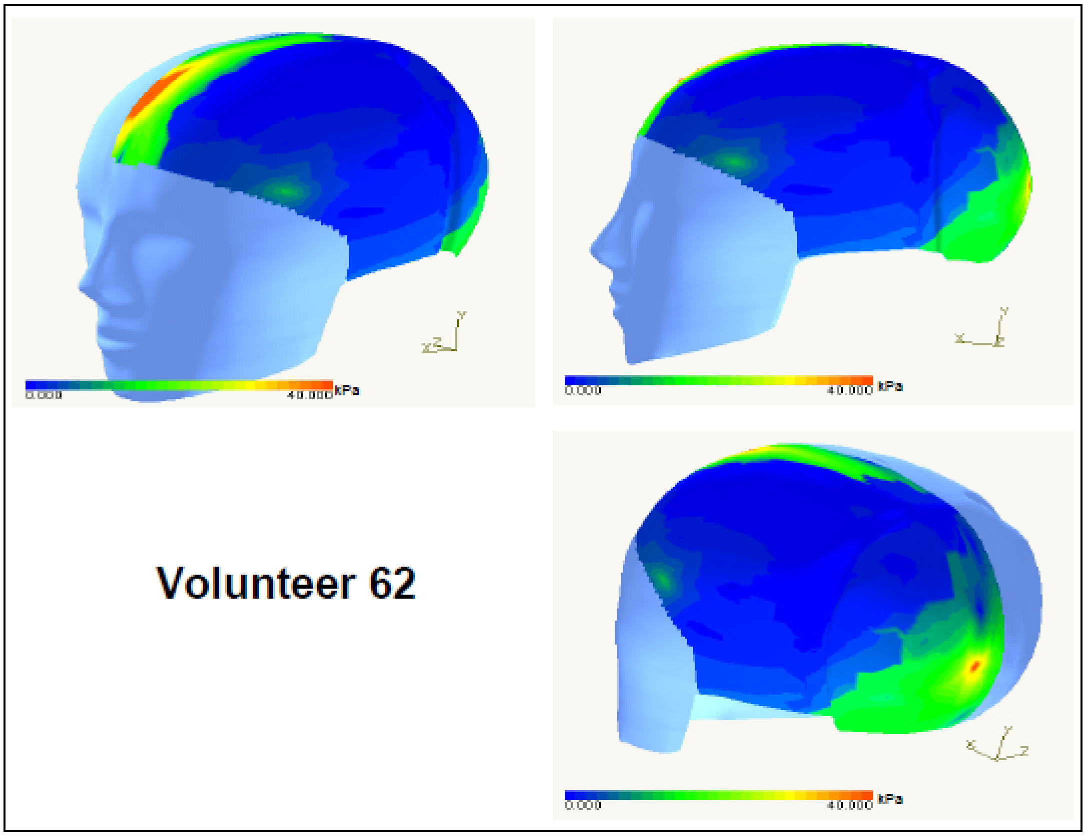

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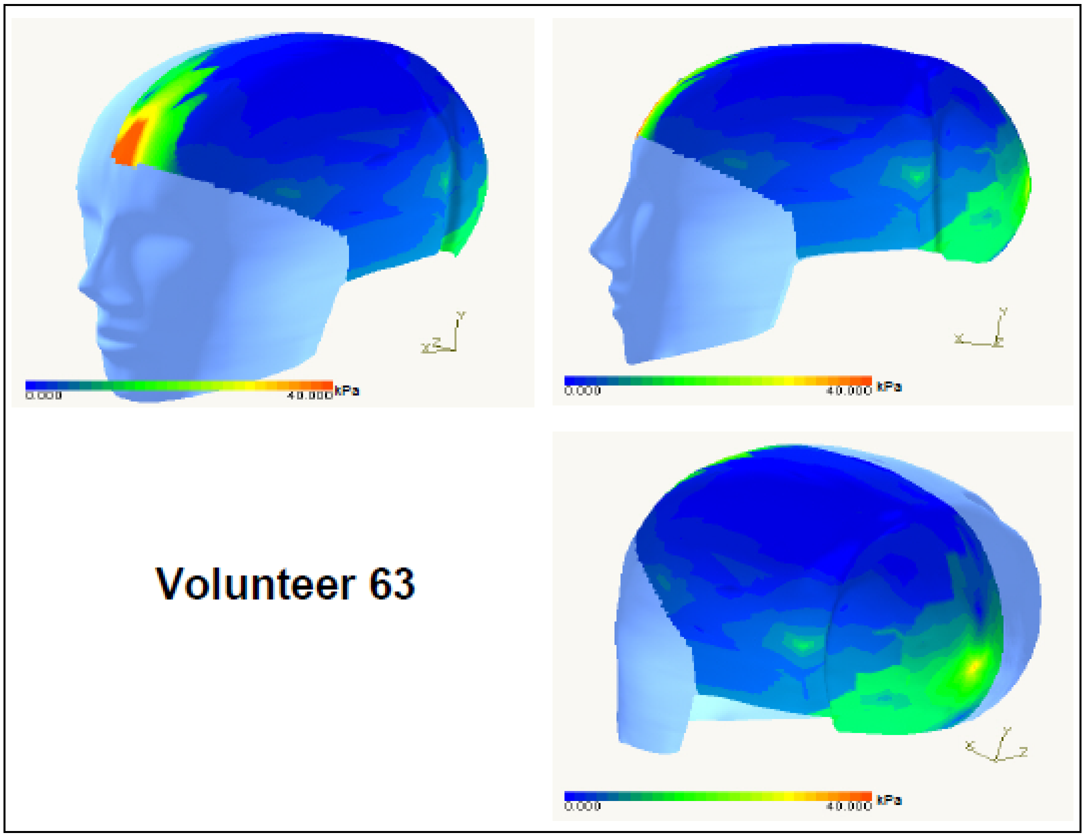

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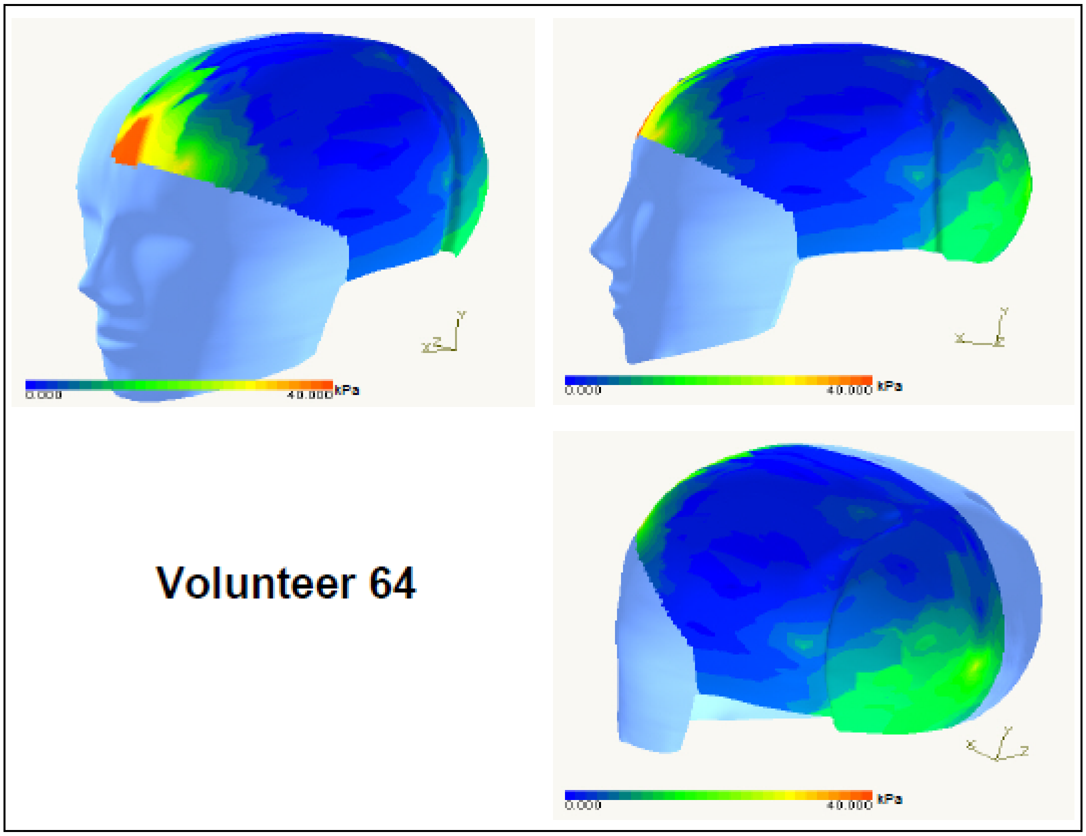
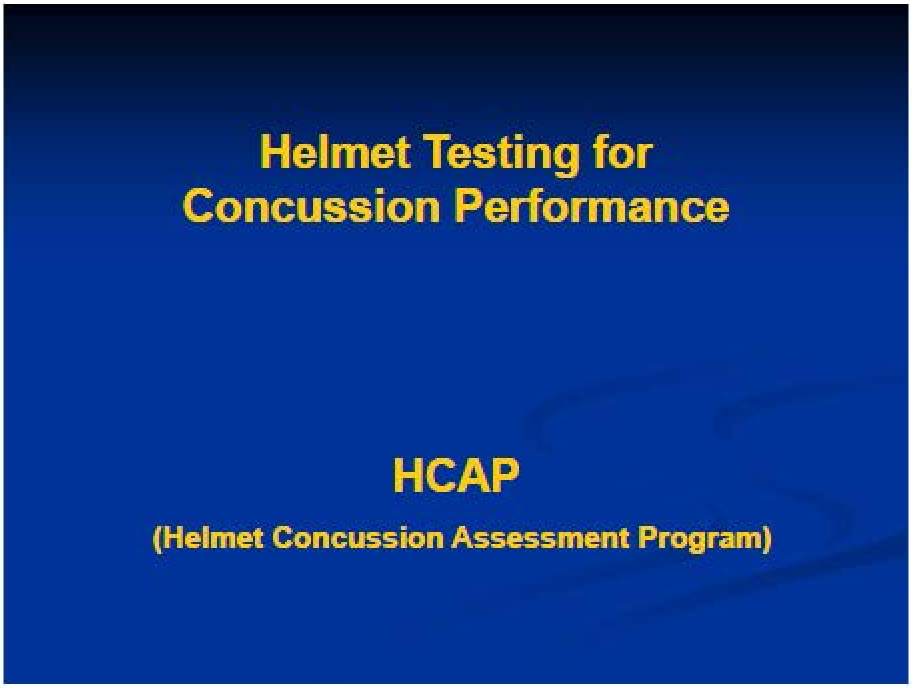


Volunteer 64

APPENDIX D – HELMET CONCUSSION ASSESSMENT PROGRAM



Helmet Testing for Concussion Performance

HCAP

(Helmet Concussion Assessment Program)

"Modern" Helmets

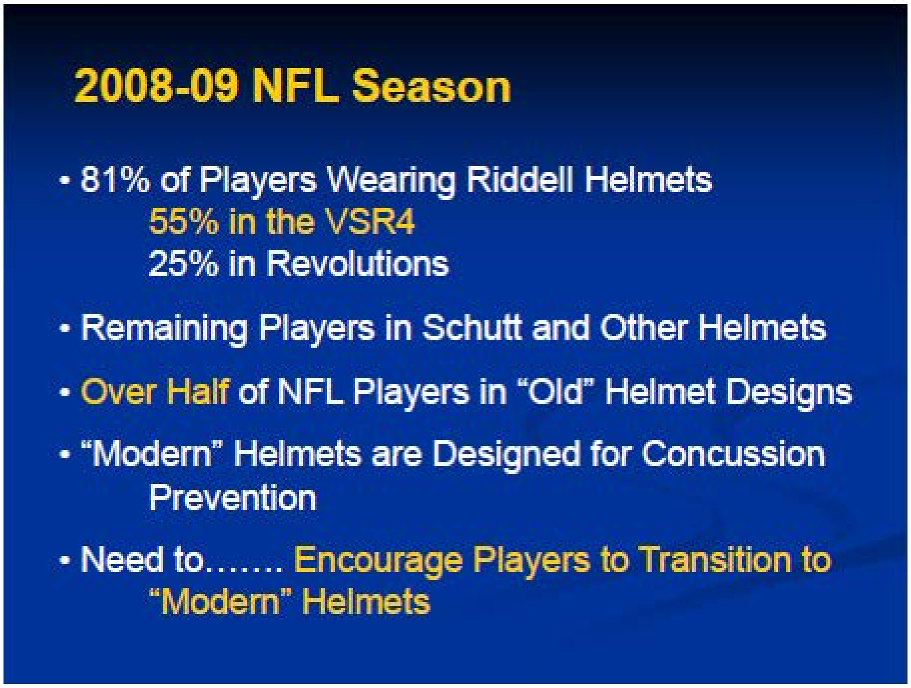
Purpose

1) Inform NFL players and equipment managers.

2) Demonstrate improvements with "modern" helmets over older models for concussion risk.

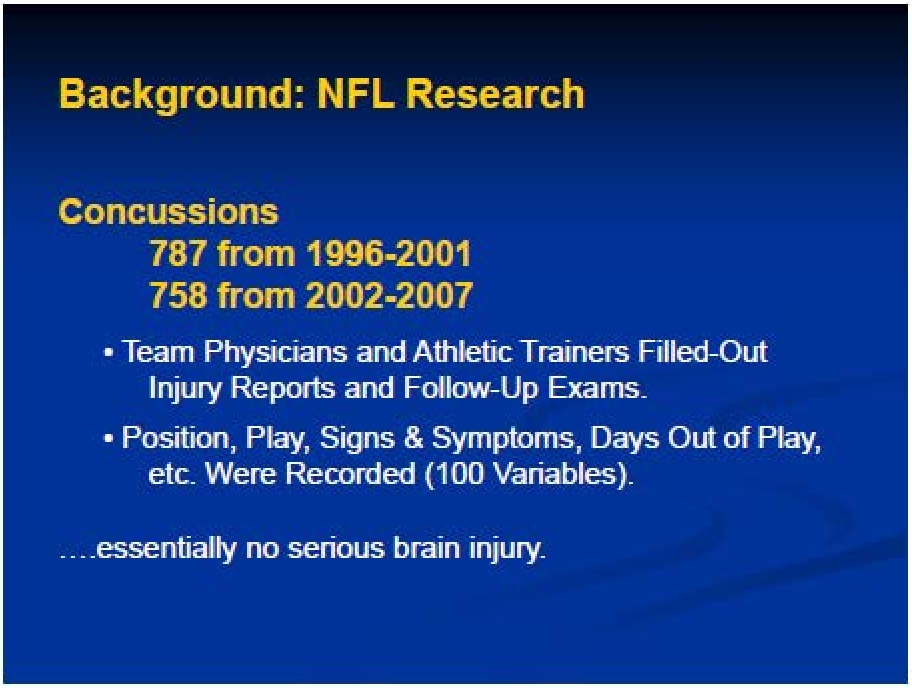
3) Provide independent, comparable data on helmets planned for sale to the NFL in 2010 by testing in conditions causing concussion.

4) Establish current helmet performance to compare future designs that may further reduce concussion risks.



2008-09 NFL Season

- 81% of Players Wearing Riddell Helmets
  55% in the VSR4
  25% in Revolutions
- Remaining Players in Schutt and Other Helmets
- Over Half of NFL Players in "Old" Helmet Designs
- "Modern" Helmets are Designed for Concussion Prevention
- Need to……. Encourage Players to Transition to "Modern" Helmets



Background: NFL Research

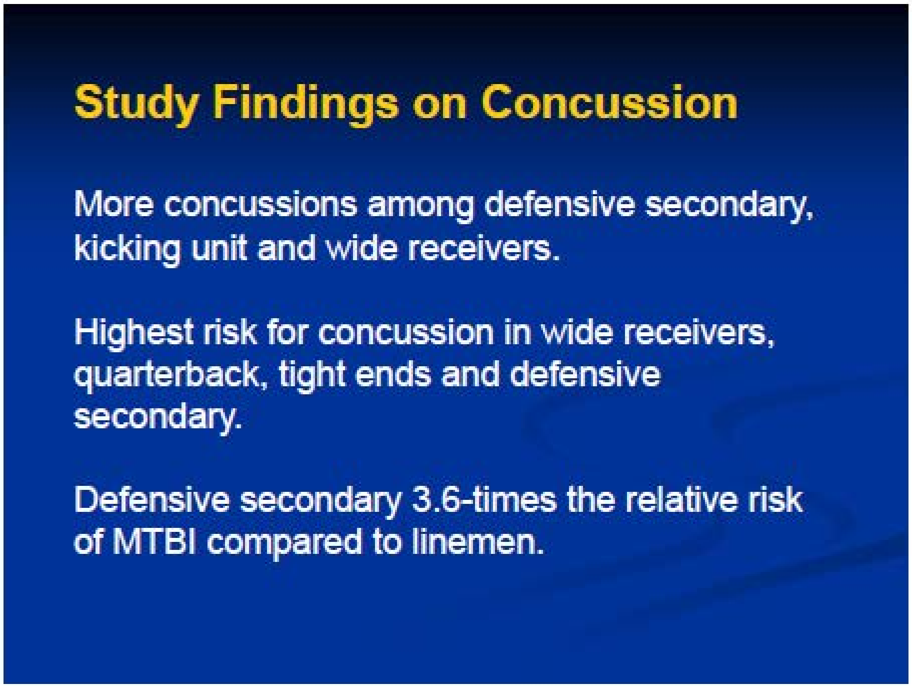
Concussions

787 from 1996-2001

758 from 2002-2007

- Team Physicians and Athletic Trainers Filled-Out Injury Reports and Follow-Up Exams.
- Position, Play, Signs & Symptoms, Days Out of Play, etc. Were Recorded (100 Variables).

….essentially no serious brain injury.

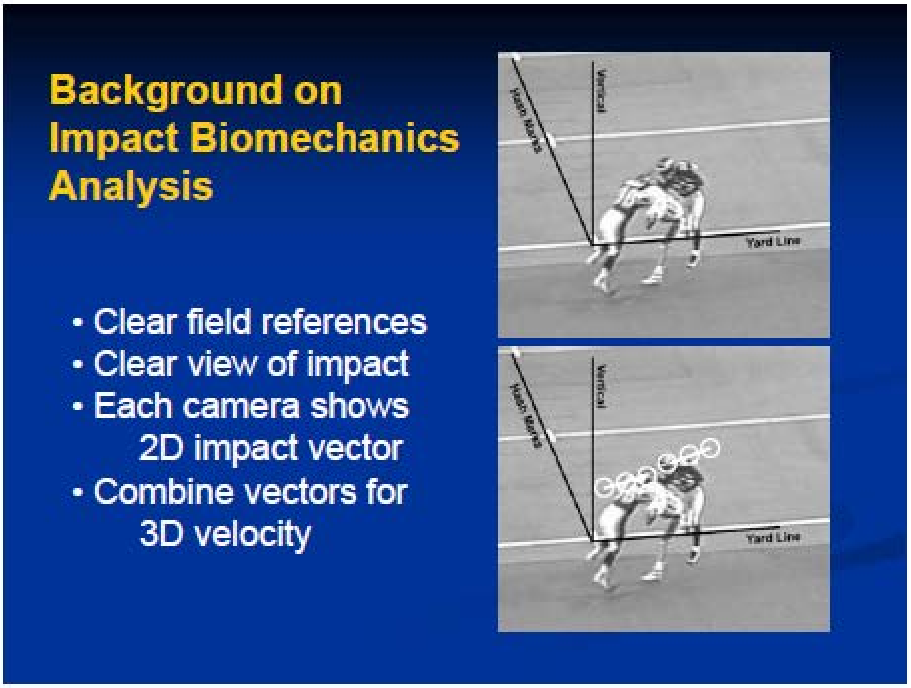


Study Findings on Concussion

More concussions among defensive secondary, kicking unit and wide receivers.

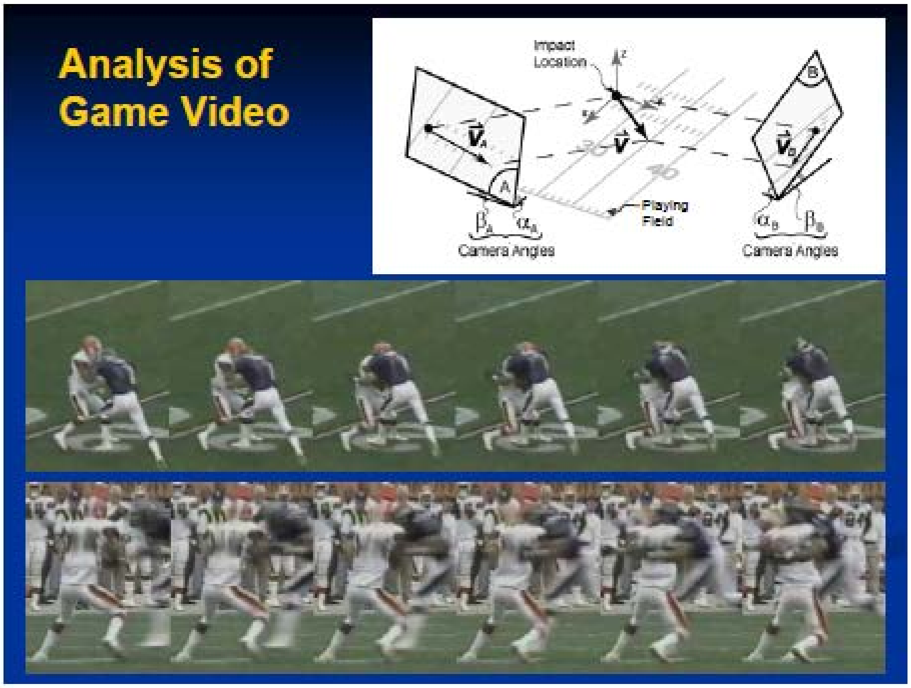
Highest risk for concussion in wide receivers, quarterback, tight ends and defensive secondary.

Defensive secondary 3.6-times the relative risk of MTBI compared to linemen.

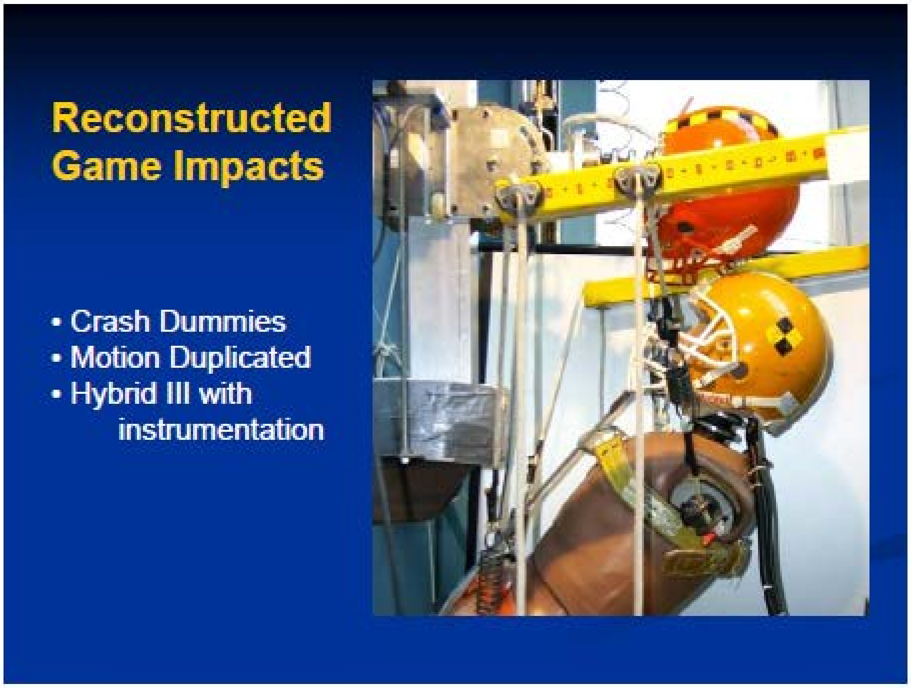


Background on Impact Biomechanics Analysis

- Clear field references
- Clear view of impact
- Each camera shows 2D impact vector
- Combine vectors for 3D velocity

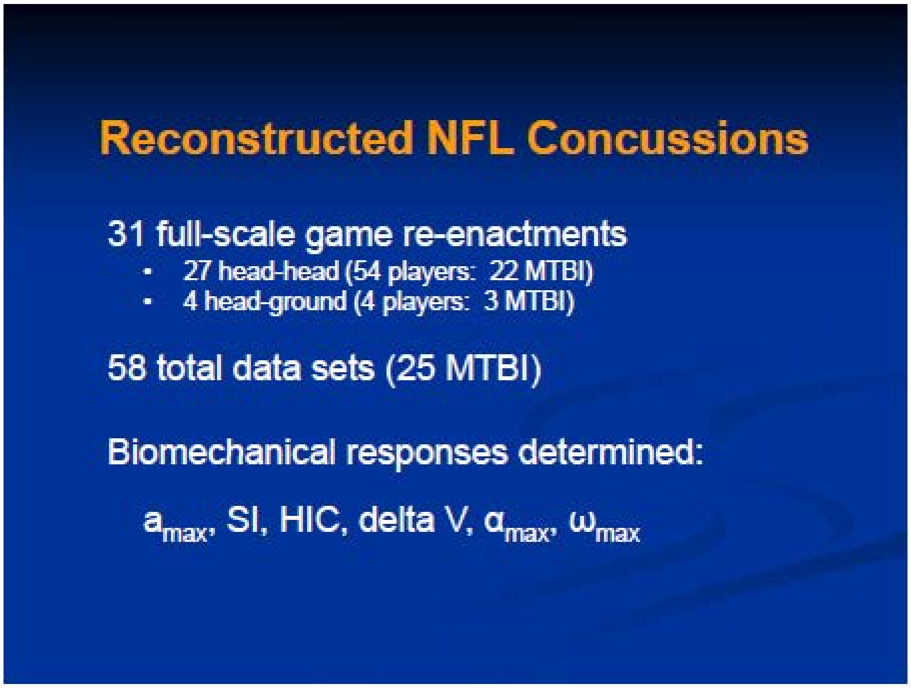


Analysis of Game Video



Reconstructed Game Impacts

- Crash Dummies
- Motion Duplicated
- Hybrid III with instrumentation



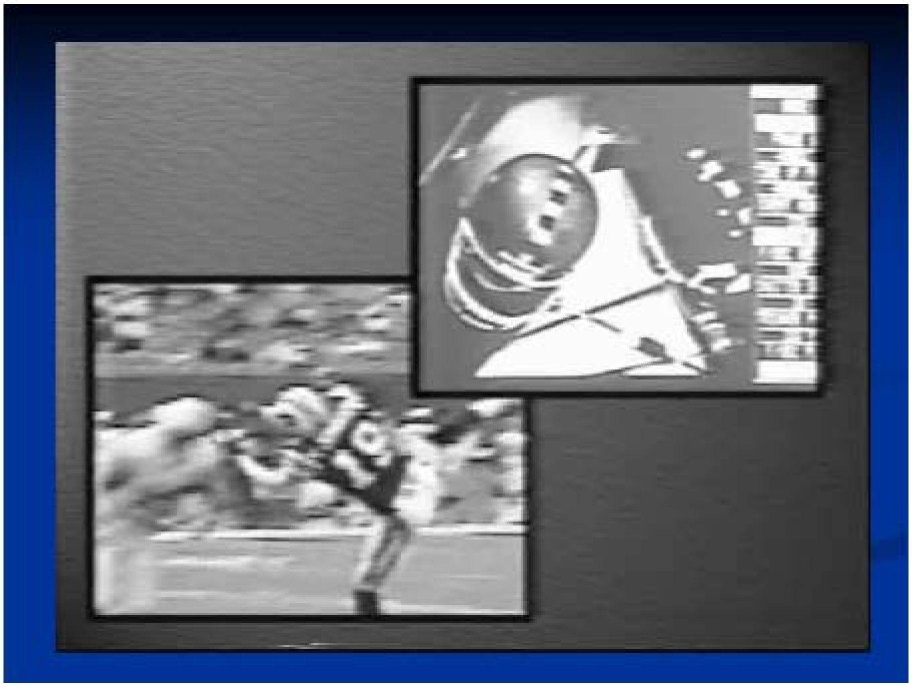
Reconstructed NFL Concussions

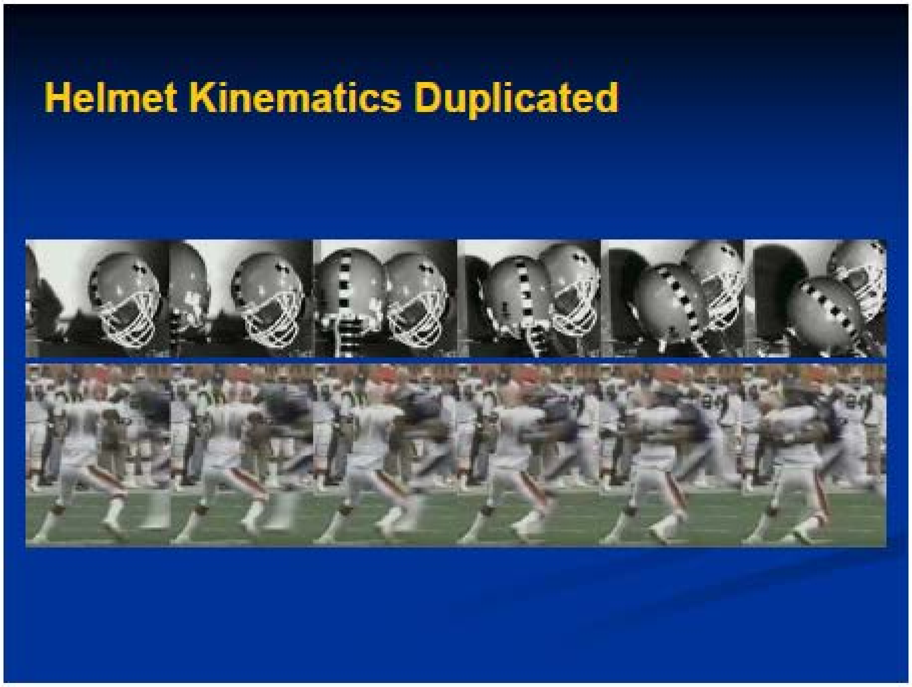
31 full-scale game re-enactments
  - 27 head-head (54 players: 22 MTBI)
  - 4 head-ground (4 players: 3 MTBI)

58 total data sets (25 MTBI)

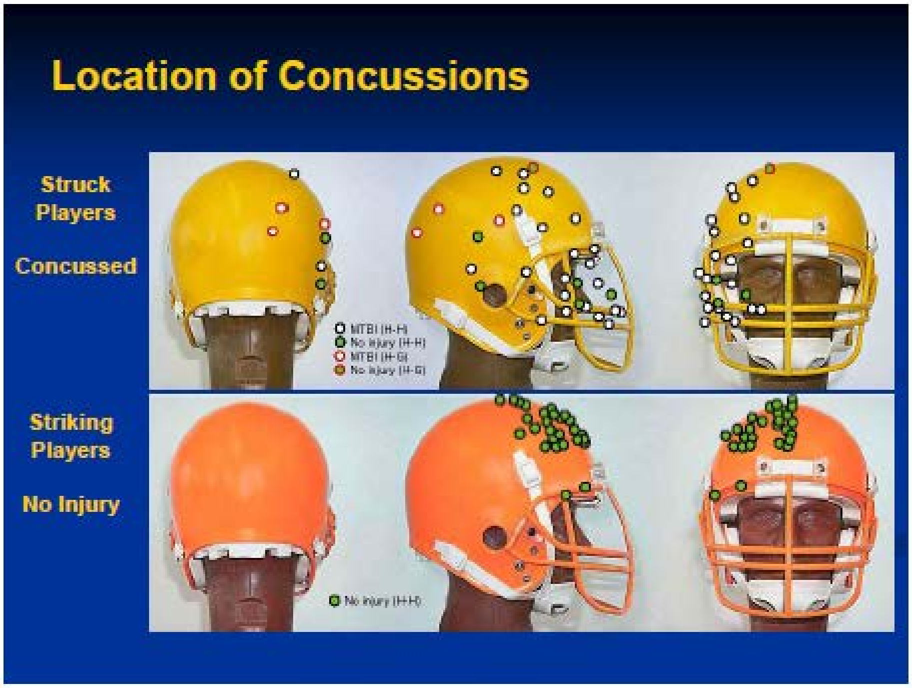
Biomechanical responses determined:

a_{max}, SI, HIC, delta V, α_{max}, ω_{max}





Helmet Kinematics Duplicated



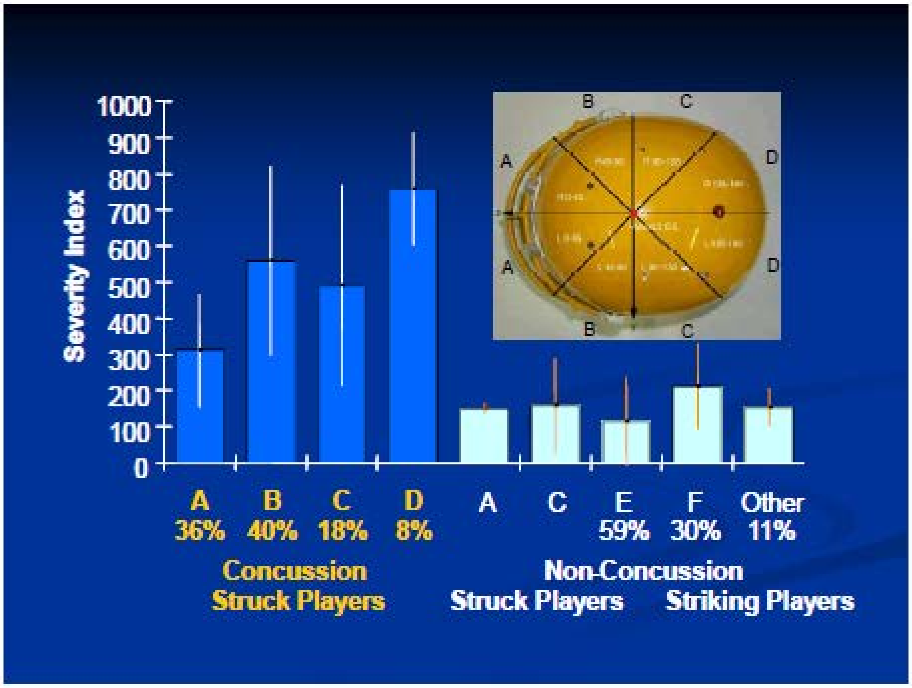
Location of Concussions

Struck Players

Concussed

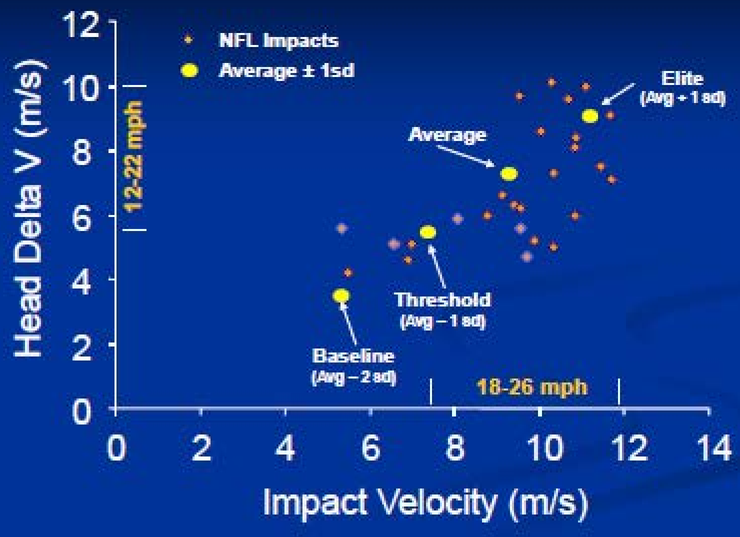
Striking Players

No Injury



Results of Biomechanics Study

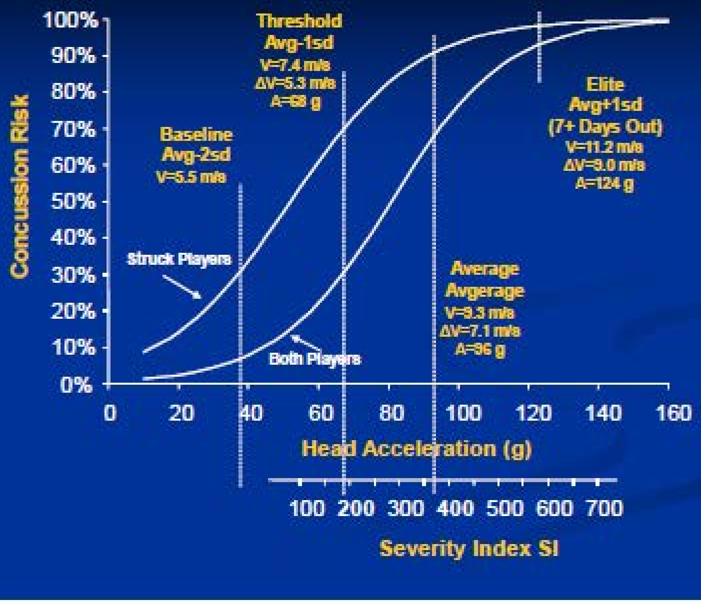
- Speed of concussion impact = 9.3 ± 1.9 m/s **(20.7 ± 4.2 mph)** to the side of the facemask and helmet.
- Head delta V = 7.2 ± 1.8 m/s **(16.4 ± 4.0 mph)**, or 77% of impact.
- Acceleration = 98 ± 28 g with 15 ms duration, Force = 4,300 ± 1,200 N **(970 ± 280 lbs)**.



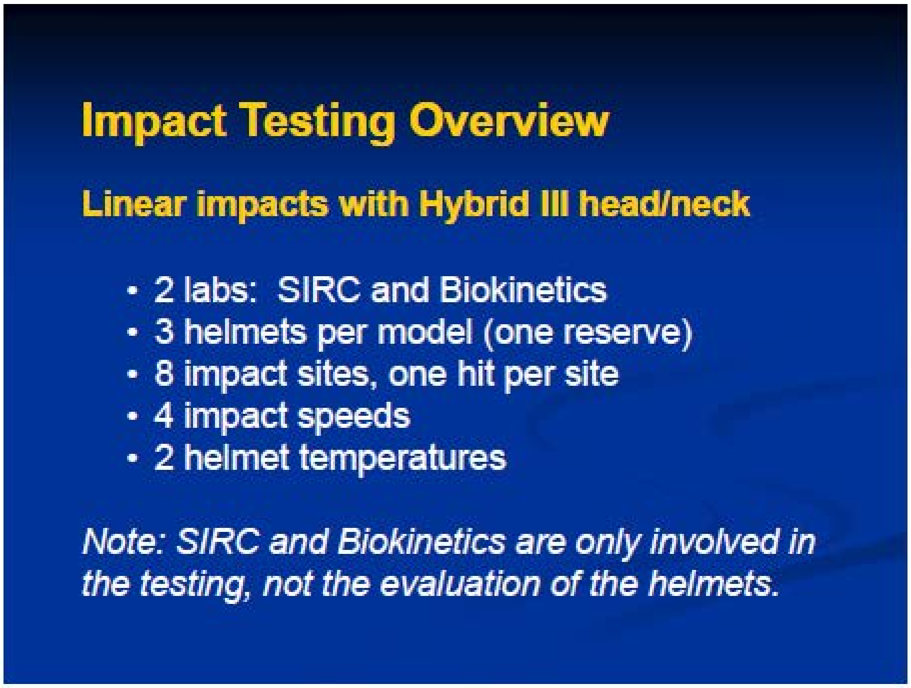
Correlation with Concussion

	Velocity (m/s)	SI	HIC	Peak Linear Accel (g)	Peak Delta V (m/s)	Peak Rotation Accel (r/s^2)	Peak Rotation Velocity (r/s)
Concussed							
Average	9.3	474	381	98	7.2	6432	34.8
sd	1.9	252	197	28	1.8	1813	15.2
No injury							
Average	7.0	154	121	60	5.0	4235	26.3
sd	2.6	82	64	24	1.1	1716	13.1
t statistic	2.45	3.04	3.16	3.10	2.91	2.69	1.26
p value	0.010	0.002	0.002	0.002	0.003	0.006	0.109

Translational Acceleration Correlated with Concussion



Linear Impactor

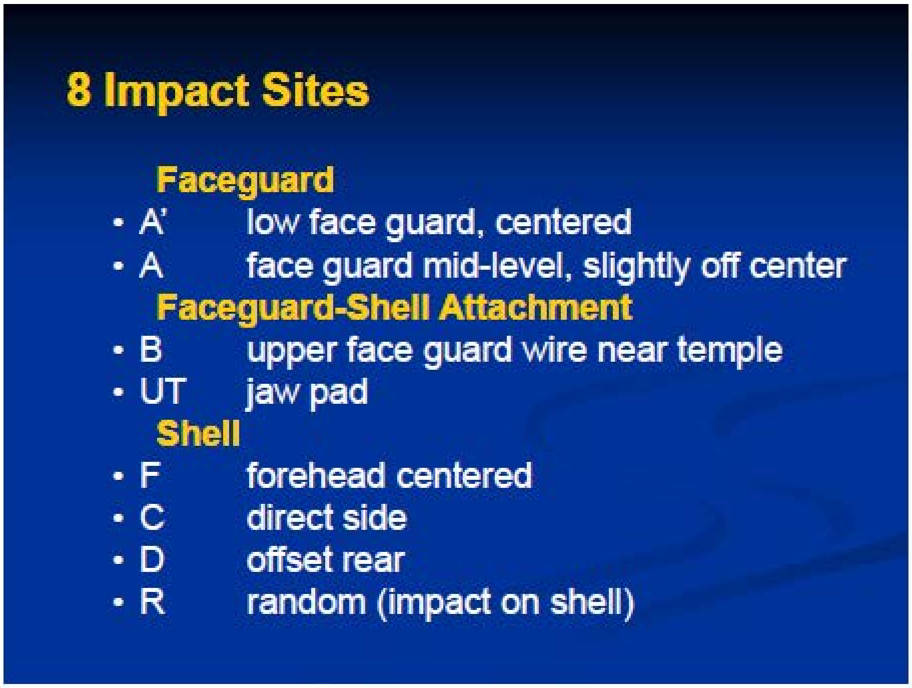


Impact Testing Overview

Linear impacts with Hybrid III head/neck

- 2 labs: SIRC and Biokinetics
- 3 helmets per model (one reserve)
- 8 impact sites, one hit per site
- 4 impact speeds
- 2 helmet temperatures

Note: SIRC and Biokinetics are only involved in the testing, not the evaluation of the helmets.



8 Impact Sites

Faceguard

- A' low face guard, centered
- A face guard mid-level, slightly off center

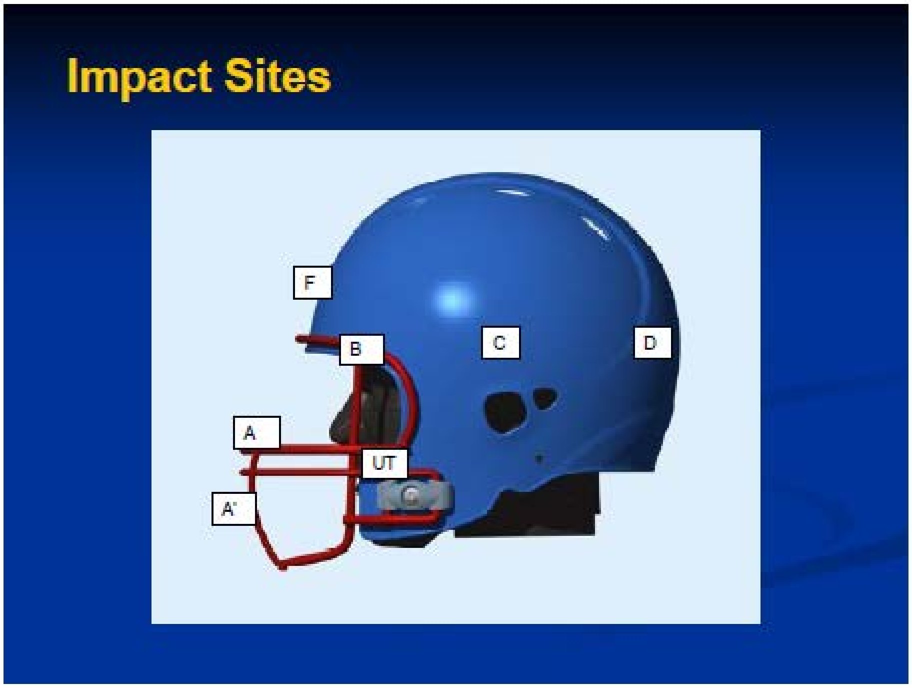
Faceguard-Shell Attachment

- B upper face guard wire near temple
- UT jaw pad

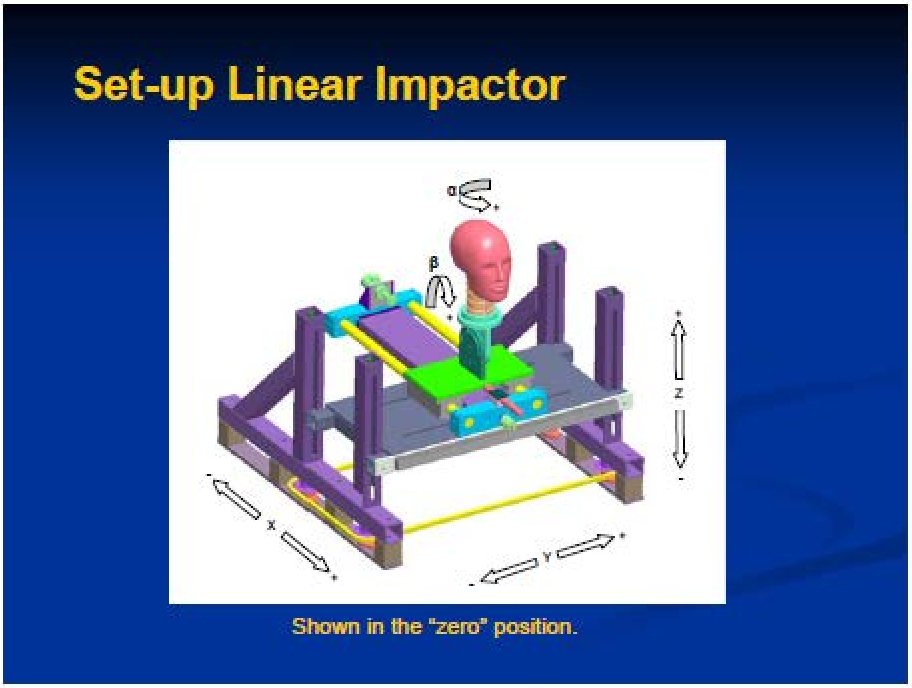
Shell

- F forehead centered
- C direct side
- D offset rear
- R random (impact on shell)

Impact Sites

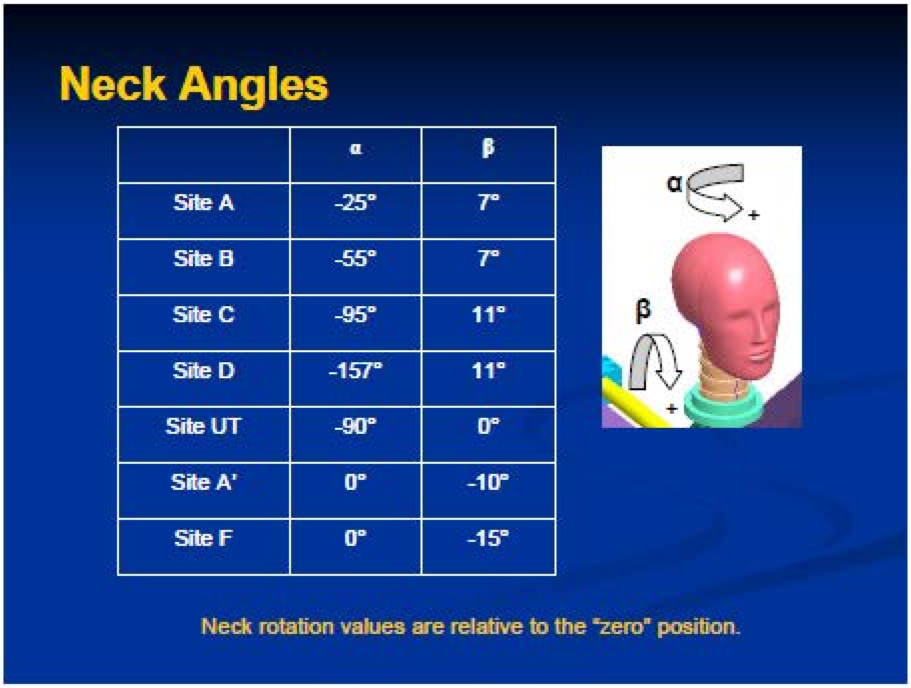


Impact Sites



Set-up Linear Impactor

Shown in the "zero" position.



Neck Angles

	α	β
Site A	-25°	7°
Site B	-55°	7°
Site C	-95°	11°
Site D	-157°	11°
Site UT	-90°	0°
Site A'	0°	-10°
Site F	0°	-15°

Neck rotation values are relative to the "zero" position.

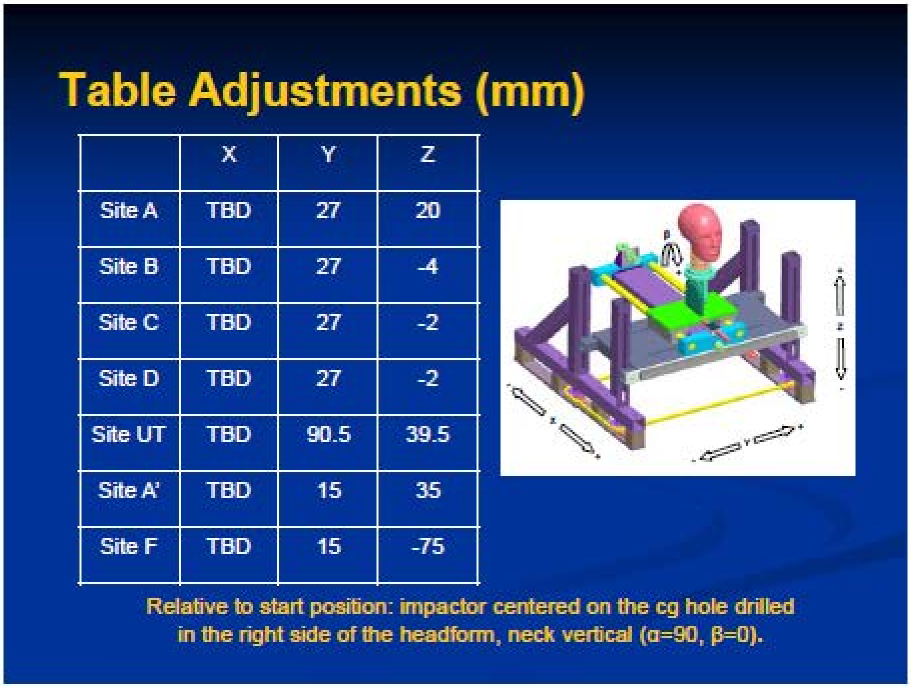
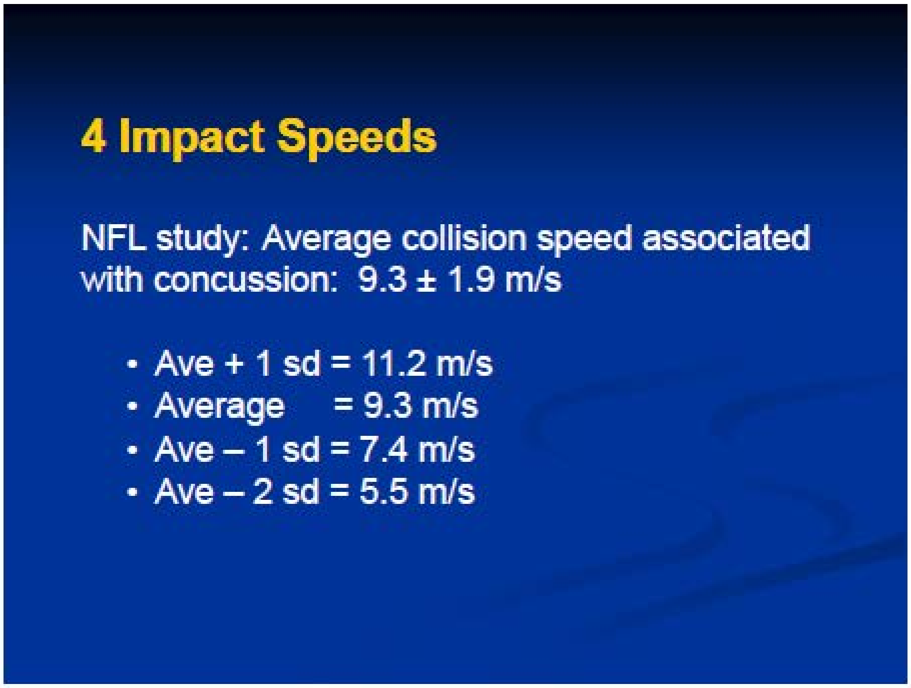


Table Adjustments (mm)

	X	Y	Z
Site A	TBD	27	20
Site B	TBD	27	-4
Site C	TBD	27	-2
Site D	TBD	27	-2
Site UT	TBD	90.5	39.5
Site A'	TBD	15	35
Site F	TBD	15	-75

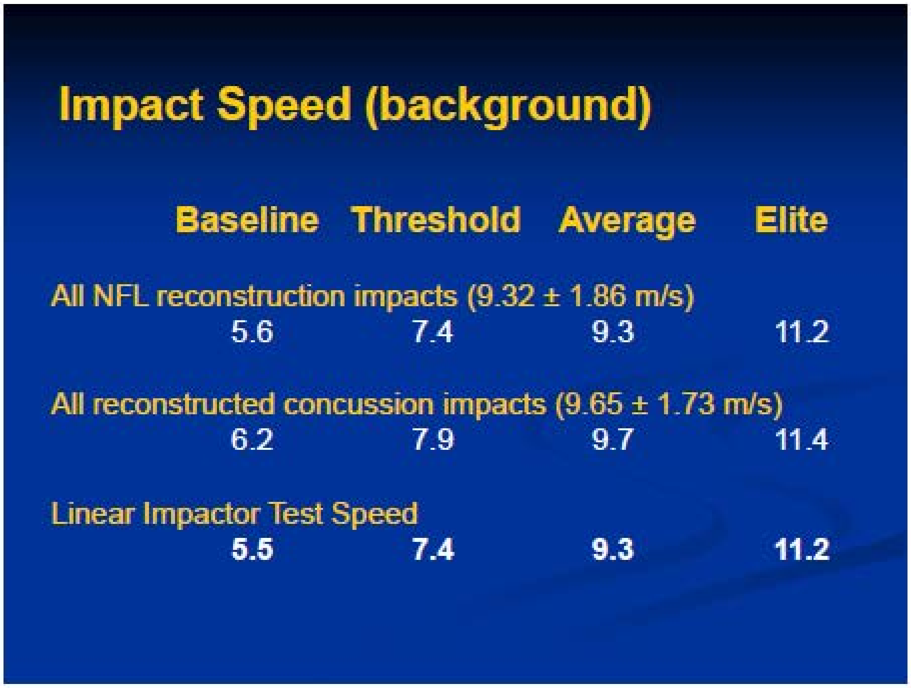
Relative to start position: impactor centered on the cg hole drilled in the right side of the headform, neck vertical (α=90, β=0).



4 Impact Speeds

NFL study: Average collision speed associated with concussion: 9.3 ± 1.9 m/s

- Ave + 1 sd = 11.2 m/s
- Average = 9.3 m/s
- Ave – 1 sd = 7.4 m/s
- Ave – 2 sd = 5.5 m/s

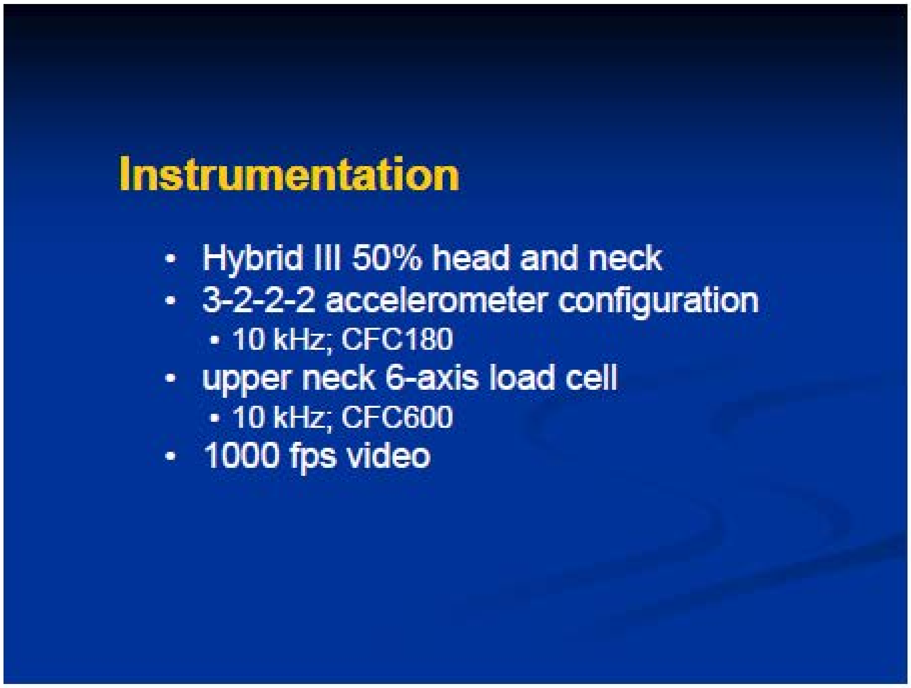


Impact Speed (background)

	Baseline	**Threshold**	**Average**	**Elite**
All NFL reconstruction impacts (9.32 ± 1.86 m/s)	5.6	7.4	9.3	11.2
All reconstructed concussion impacts (9.65 ± 1.73 m/s)	6.2	7.9	9.7	11.4
Linear Impactor Test Speed	**5.5**	**7.4**	**9.3**	**11.2**

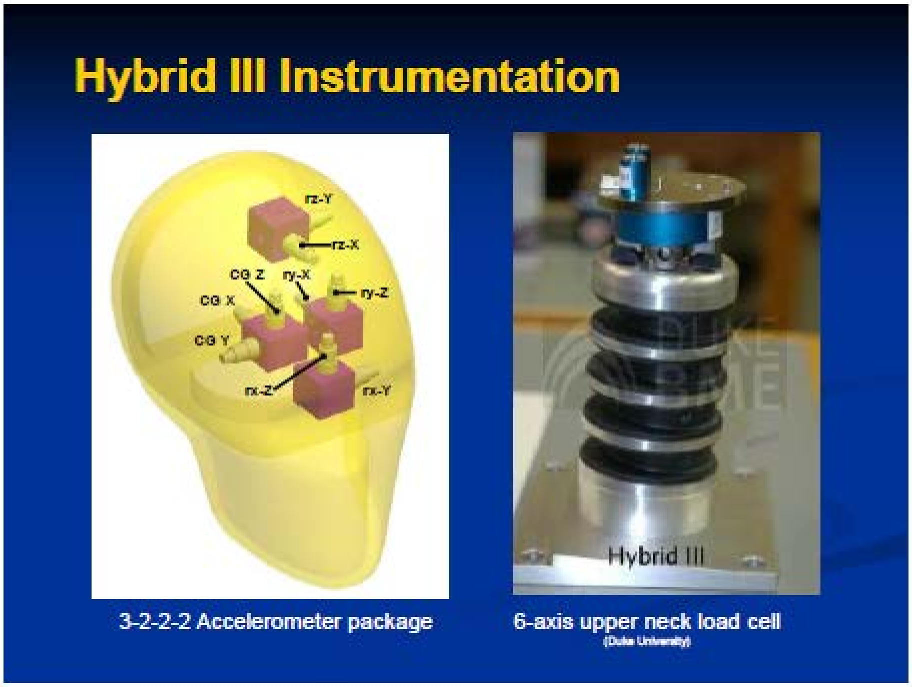
Test Matrix

	Ambient temp 75 F					
Faceguard	A'		7.4			
	A	5.5	7.4	9.3		
Faceguard-Shell	B		7.4	9.3		
	UT		7.4	9.3		
Shell	F	5.5	7.4	9.3	11.2	
	C	5.5	7.4	9.3	11.2	
	D		7.4	9.3		
	R		7.4	9.3		
	Elevated temp 100 F					
Faceguard	A			9.3		
Shell	F			9.3		
	C			9.3		
	total	**3**	**8**	**10**	**2**	**= 23 tests**



Instrumentation

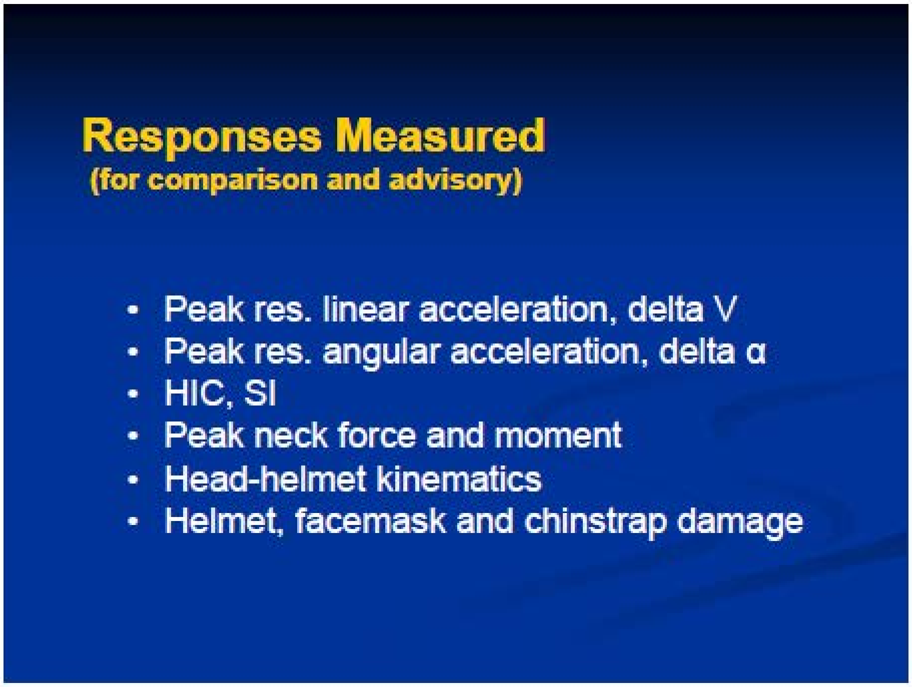
- Hybrid III 50% head and neck
- 3-2-2-2 accelerometer configuration
  - 10 kHz; CFC180
- upper neck 6-axis load cell
  - 10 kHz; CFC600
- 1000 fps video



Hybrid III Instrumentation

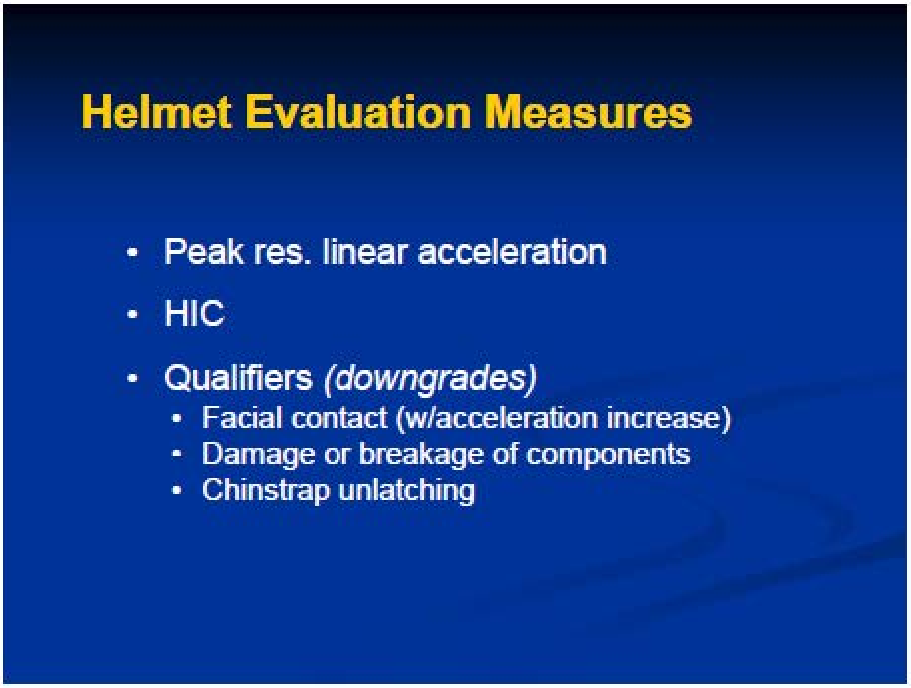
3-2-2-2 Accelerometer package

6-axis upper neck load cell
(Duke University)



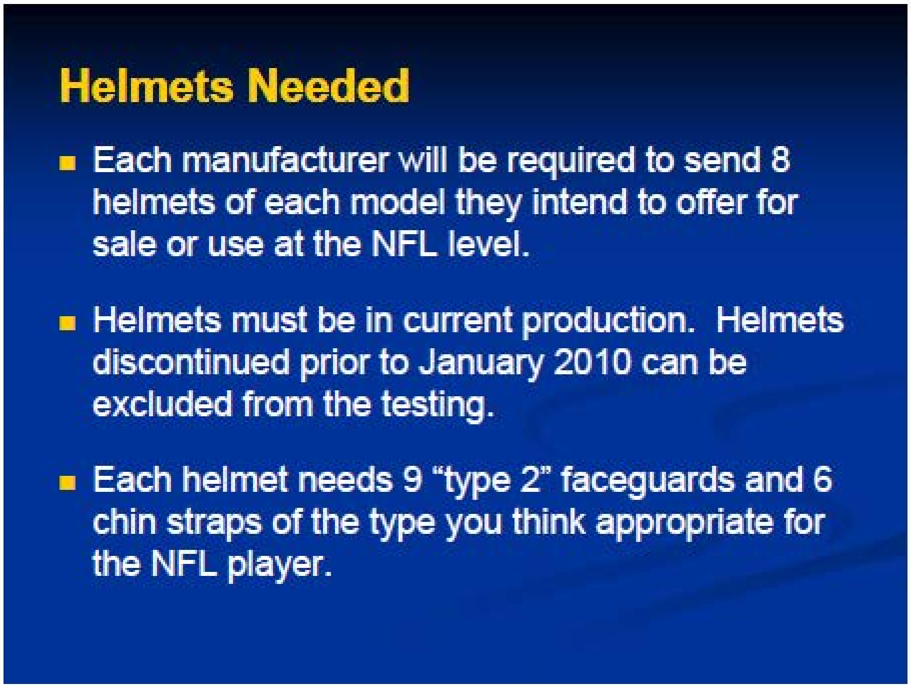
Responses Measured
(for comparison and advisory)

- Peak res. linear acceleration, delta V
- Peak res. angular acceleration, delta α
- HIC, SI
- Peak neck force and moment
- Head-helmet kinematics
- Helmet, facemask and chinstrap damage



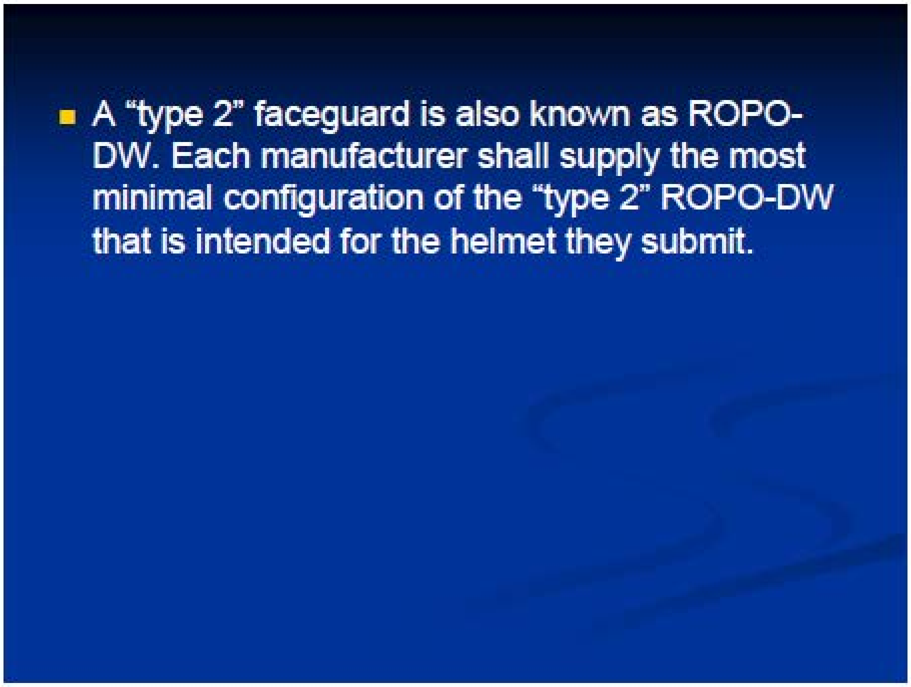
Helmet Evaluation Measures

- Peak res. linear acceleration
- HIC
- Qualifiers *(downgrades)*
    - Facial contact (w/acceleration increase)
    - Damage or breakage of components
    - Chinstrap unlatching

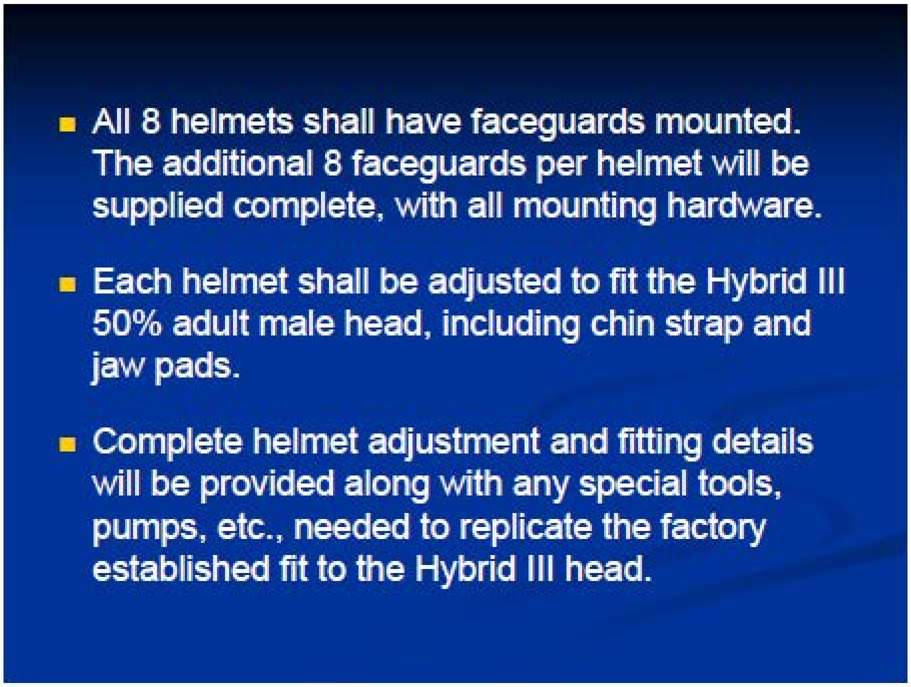


Helmets Needed

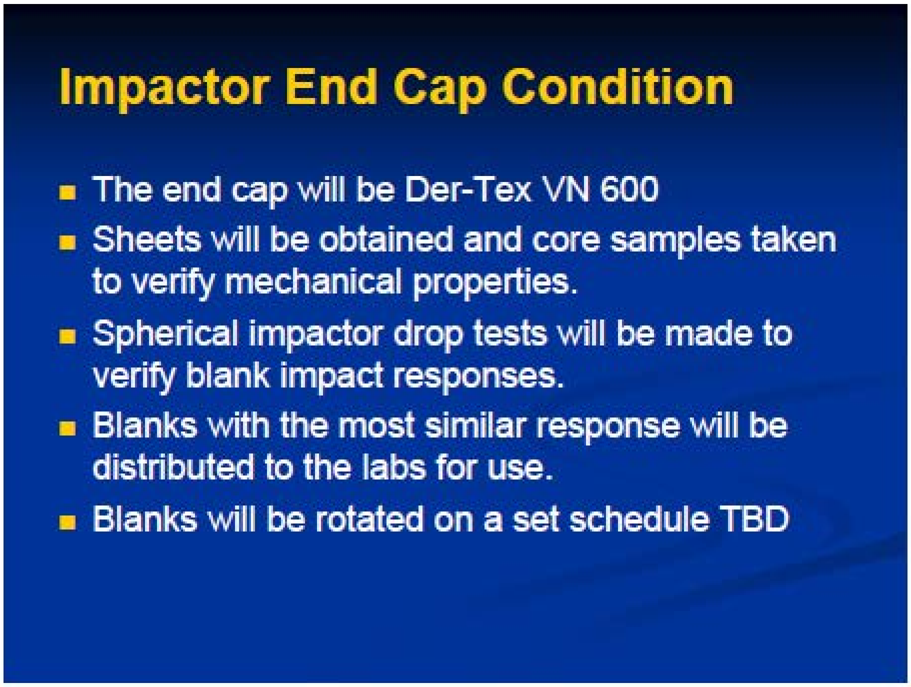
- Each manufacturer will be required to send 8 helmets of each model they intend to offer for sale or use at the NFL level.
- Helmets must be in current production. Helmets discontinued prior to January 2010 can be excluded from the testing.
- Each helmet needs 9 “type 2” faceguards and 6 chin straps of the type you think appropriate for the NFL player.



- A “type 2” faceguard is also known as ROPO-DW. Each manufacturer shall supply the most minimal configuration of the “type 2” ROPO-DW that is intended for the helmet they submit.

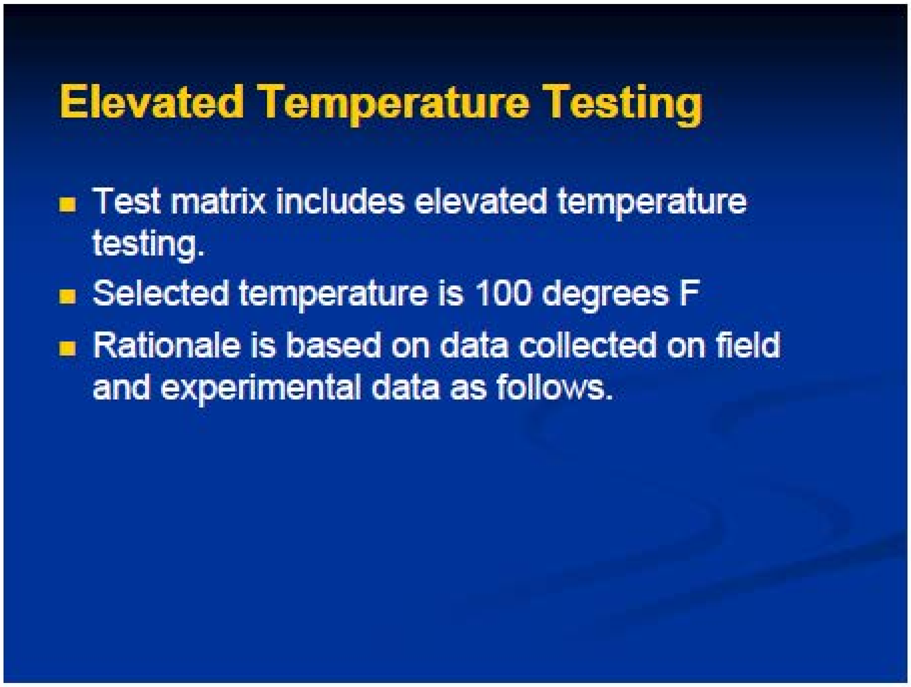


- All 8 helmets shall have faceguards mounted. The additional 8 faceguards per helmet will be supplied complete, with all mounting hardware.
- Each helmet shall be adjusted to fit the Hybrid III 50% adult male head, including chin strap and jaw pads.
- Complete helmet adjustment and fitting details will be provided along with any special tools, pumps, etc., needed to replicate the factory established fit to the Hybrid III head.



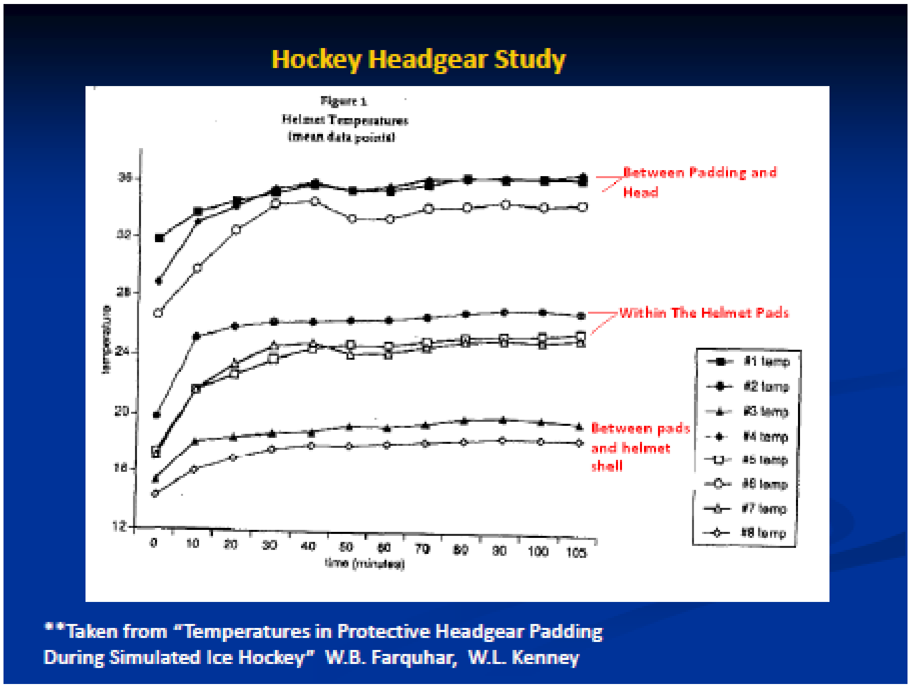
Impactor End Cap Condition

- The end cap will be Der-Tex VN 600
- Sheets will be obtained and core samples taken to verify mechanical properties.
- Spherical impactor drop tests will be made to verify blank impact responses.
- Blanks with the most similar response will be distributed to the labs for use.
- Blanks will be rotated on a set schedule TBD



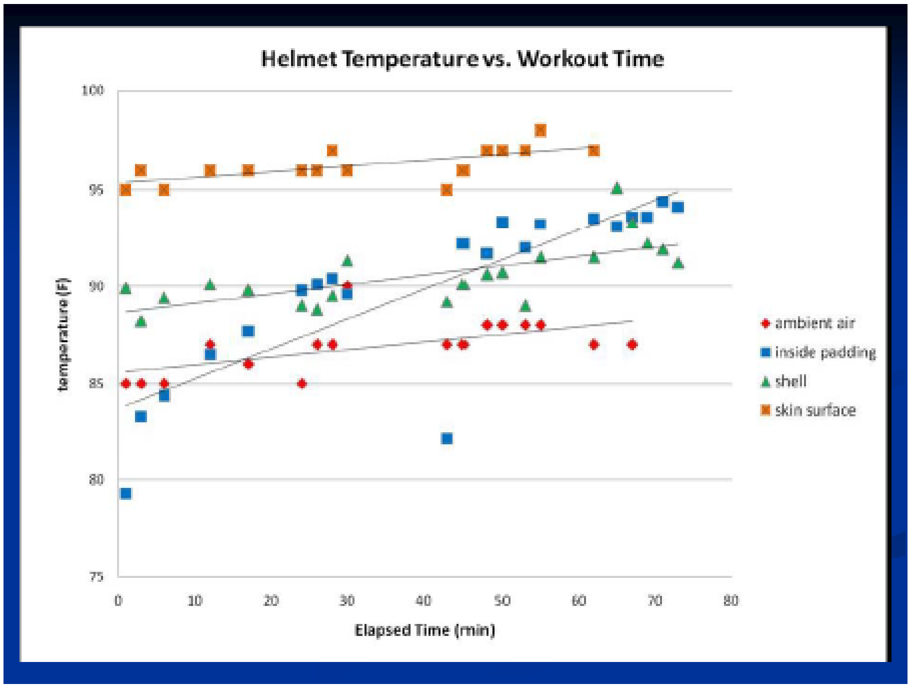
Elevated Temperature Testing

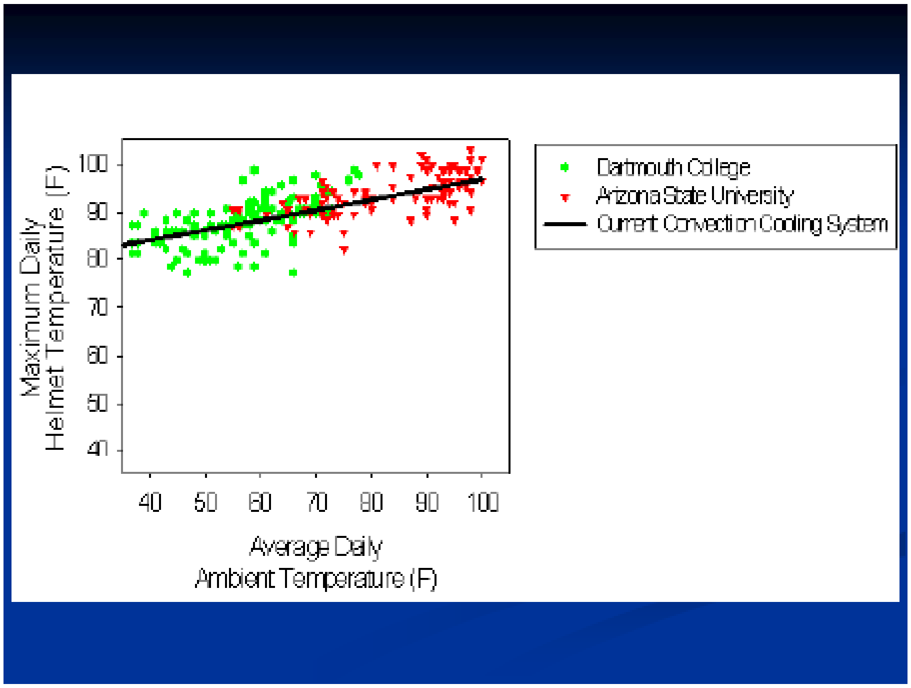
- Test matrix includes elevated temperature testing.
- Selected temperature is 100 degrees F
- Rationale is based on data collected on field and experimental data as follows.

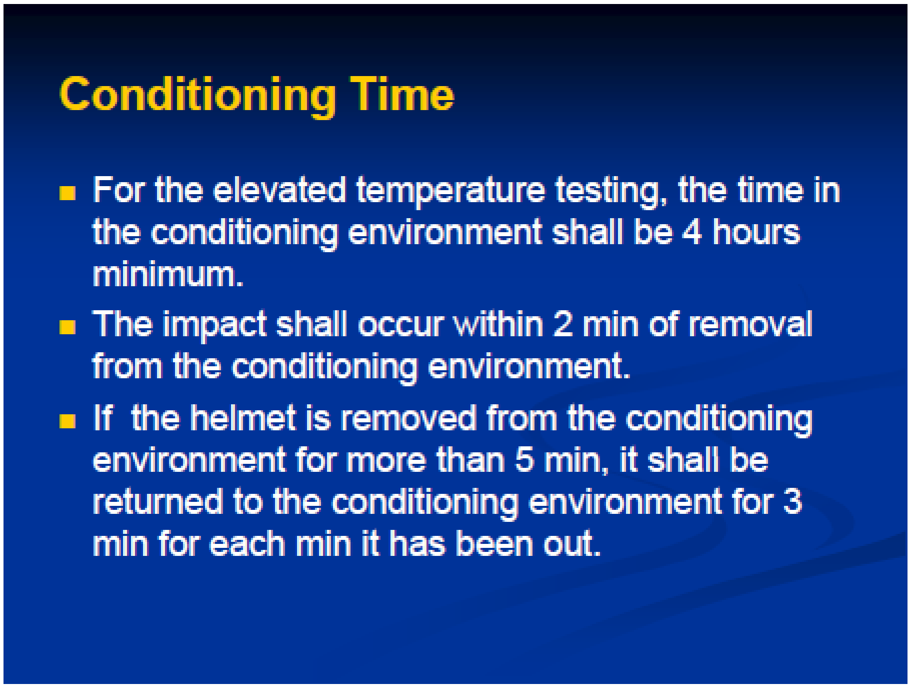


Hockey Headgear Study

**Taken from "Temperatures in Protective Headgear Padding During Simulated Ice Hockey" W.B. Farquhar, W.L. Kenney

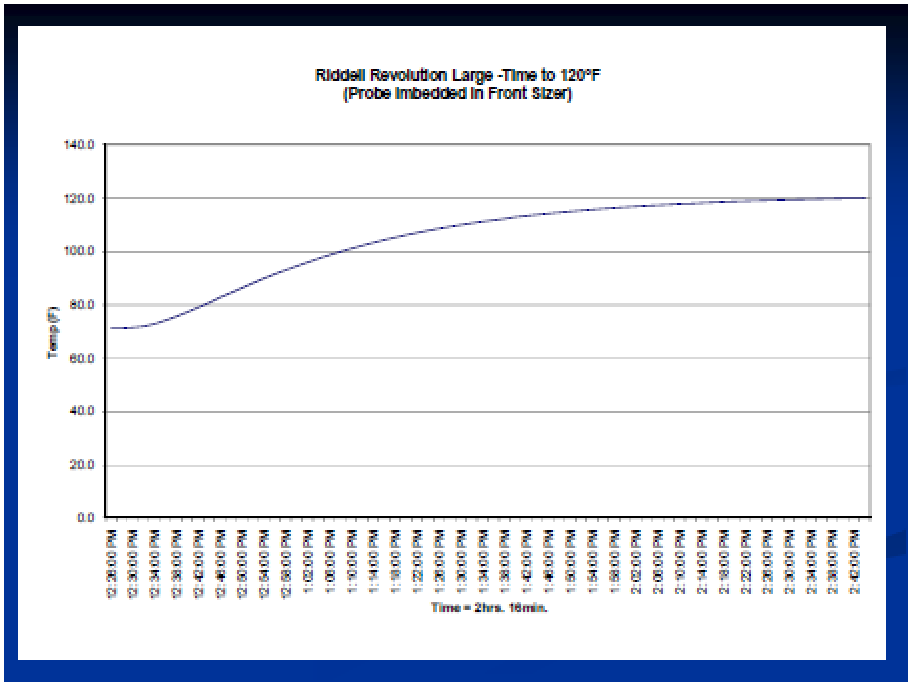






Conditioning Time

- For the elevated temperature testing, the time in the conditioning environment shall be 4 hours minimum.
- The impact shall occur within 2 min of removal from the conditioning environment.
- If the helmet is removed from the conditioning environment for more than 5 min, it shall be returned to the conditioning environment for 3 min for each min it has been out.


Riddell Revolution Large -Time to 120°F
(Probe Imbedded in Front Sizer)
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Temp (F)
12:26:00 PM
12:30:00 PM
12:34:00 PM
12:38:00 PM
12:42:00 PM
12:46:00 PM
12:50:00 PM
12:54:00 PM
12:58:00 PM
1:02:00 PM
1:06:00 PM
1:10:00 PM
1:14:00 PM
1:18:00 PM
1:22:00 PM
1:26:00 PM
1:30:00 PM
1:34:00 PM
1:38:00 PM
1:42:00 PM
1:46:00 PM
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2:14:00 PM
2:18:00 PM
2:22:00 PM
2:26:00 PM
2:30:00 PM
2:34:00 PM
2:38:00 PM
2:42:00 PM
Time = 2hrs. 16min.

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ABSTRACT

FOOTBALL HELMET FITMENT AND ITS EFFECTS ON HELMET PERFORMANCE

by

RONALD JADISCHKE

May 2012

Advisor: Dr. Albert King

Major: Biomedical Engineering

Degree: Master of Science

A method and system to objectively quantify helmet fitment was designed and developed. It measures the pressure between the energy-absorbing material in the helmet and the athlete's head. This system is also capable of measuring surface pressure during impact events. A volunteer-based field study was conducted to quantify how helmets were fitting athletes in a real-life setting. The helmets fit athletes in varying degrees of tightness and evenness. Most athletes (59%) had the highest pressures in the frontal area and 29% had the highest pressure in the occipital area. A large-sized helmet on the Hybrid III headform represented how most helmets fit the athletes in the field.

Impact testing was also conducted to assess the effects of helmet fitment. Four impact locations were selected (F, UT, C and D). Two fit variations were analyzed: loose vs. tight (and more uniform). Overall, the tight-fitting condition resulted in higher linear acceleration-related response parameters (HIC - $p=0.26$), (GSI - $p=.088$), (a_{peak} -

$p=0.097$); however, there were significantly lower angular accelerations ($p=0.003$) and lower angular velocity ($p=0.081$). Results were significant (95% C.I.) for 3 of the 4 impact locations. Generally, a tighter and more evenly fitting helmet resulted in more of a linear response of the headform and less angular acceleration. The tighter (and more uniform) fitting helmet resulted in the surface pressure being distributed over a larger area.

The helmet used for the impact testing was equipped with the Head Impact Telemetry (HIT) System. The reported response parameters from the HIT System were compared to the Hybrid III headform data. The headform data was considered to be the accurate measurement. No correlation could be found between the HIT System data versus the Hybrid III headform data. Relative error of the HIT System was significantly different than the headform data for HIC ($p =0.001$), GSI ($p <0.001$), Peak Linear Acceleration ($p =0.013$) and Peak Angular Acceleration ($p <0.001$). Absolute error and relative error of the HIT System was also calculated for each of the response parameters.

AUTOBIOGRAPHICAL STATEMENT

EDUCATION

B.A.Sc. Mechanical Engineering (Honors-Automotive Option), University of Windsor, 2002.

M.S. Biomedical Engineering (Impact Biomechanics), Wayne State University, Detroit, MI. May 2012.

PROFESSIONAL MEMBERSHIPS & AFFILIATIONS

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Society of Automotive Engineers (SAE)

EXPERIENCE

Mr. Jadischke has always been involved in athletics including a variety of contact and non-contact sports. He played a substantial amount of hockey and continues to be an active participant. His interest in concussion research has grown due to his involvement in contact sport and his exposure to concussions.

He is currently employed with McCarthy Engineering Inc. in Windsor, Ontario, and began there in 2005. He specializes in motor vehicle accident reconstruction, vehicle fitness inspections, seat belt investigations, impact biomechanics, evaluating driver perception/response times, and accident avoidance. He is also a partner at Vehiclemetrics Inc. wherein they have developed a method and process to acquire vehicle systems parameters for use in automobile collision simulations. They also acquire geometric data for occupant modeling.

Prior to joining McCarthy Engineering Inc., Mr. Jadischke was employed as a Mechanical Engineer at Behr America Inc., in Troy, Michigan (2002-2005). He was the design team leader in charge of the design, development, simulation, and validation of vehicle heating and air conditioning components and their integration into the heating and air conditioning systems. He has also obtained a variety of automotive related research and development, design and manufacturing experience while enrolled in the University of Windsor's Co-operative Engineering Program.