5-2022

Impacts of Methods and Pose on Performance of Two Modern American Football Helmets

Ta'Quoris Newsome
The University of Southern Mississippi

Impact of Methods and Pose on Performance of Two Modern American Football Helmets

by

Ta’Quoris Newsome

A Thesis
Submitted to the Honors College of
The University of Southern Mississippi
in Partial Fulfillment
of Honors Requirements

May 2022

Approved by:

Scott G. Piland, Ph.D. ATC, Professor & Director
Thesis Advisor
School of Kinesiology and Nutrition

Sabine Heinhorst, Ph.D., Dean
Honors College

ABSTRACT

The standardization of American football helmets began with the development of the National Operating Committee for Safety in Athletic Equipment (NOCSAE). The organization successfully developed a certification that quantifies a helmet's ability to mitigate blunt force to prevent skull fractures; however, the ability to assure the same level of protection against concussion has been elusive. Regardless, The National Football League (NFL) and Virginia Tech University (VT) have developed blunt and rotational impact testing methodologies that aim to provide consumers with the effectiveness and safety of American football helmets through their respective ranking system. These ranking systems are intended to aid consumers in making informed purchasing decisions. The defined impact location between the two methodologies, however, differs, thus leading to performance variations across different helmet designs. Where one helmet design may perform better than another depending upon the methodology applied. In this study, a linear pneumatic impacting device was used to strike a Schutt F7 LTD and Xenith Shadow XR helmet. Each helmet was impacted at four NFL and VT designated locations using the specific pose of each methodology. Each location was impacted four times (32 total impacts per helmet) at a velocity just above 7.5 m/s. The results highlighted no statistical differences in performance between the two tested helmets. However, substantial differences were found to exist between impact performances between the two applied methods. This leads to the conclusion that the ranking of helmets is not necessary if helmets display insignificant differences in performance upon insult. Also, the performance of helmets is likely linked to testing methodology and not helmet design.

Keywords: Concussion, Pose, Protective headgear

ACKNOWLEDGMENTS

This research was funded in part by the Department of Defense and US Army Award #W911NF-18-2-0061. DEVCOM ARL and the School of Kinesiology and Nutrition at the University of Southern Mississippi. The researcher also acknowledges Mrs. Elizabeth Edwards and Ms. Tiffany Landrey for their excellent technical support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ABBREVIATIONS

NFL	National Football League
NFLPA	National Football League Players Association
NOCSAE	National Operating Committee for Safety and Athletic Equipment
VT	Virginia Tech University

CHAPTER I: Introduction

American football is currently the least deadly that it has ever been. In its earliest days, football had the reputation of being a violent sport. This reputation was merited, as the sport of football was responsible for a consistent death rate up until the 1970s. Though still an injurious sport, football is far safer today than when it was founded. This evolution towards being less life-threatening was produced through a combination of rule and game-play changes, along with advancements in equipment. During the first part of football's hundred-plus-year history, the addition of and advancement in protective headgear served to circumvent the deadly macroscopic brain traumas that were plaguing the sport, such as skull fractures and brain bleeds.

It was in the late 1800s when the role of protective headgear began to permeate the sports world. Skull fractures and traumatic brain injuries were leading to permanent disability and death for many athletes. Head-to-head contact occurring during high speed was the injurious mechanism. The initial effort, made by a few at first, was the creation of the leather helmet. These helmets had no facemasks and provided little to no cushioning on the interior(Bartsch et al., 2012). This was hardly an effective solution, as the same macro traumatic injuries were continuing to arise. However, the players were typically manufacturing these devices themselves and were only able to access the materials that were available to them, which were certainly limited by the technologies of the day. Tinkerers and industrious inventors began to see the need for protective gear, and through the time-tested tradition of trial and error, devices were constructed and began making their way onto the football field. In 1939, John T. Riddell designed and sold the first hard-plastic helmet(Bartsch et al., 2012). This design was adopted by both the

National Collegiate Athlete Association (NCAA) and the National football League (NFL) around 1940. It was not until the 1960s, with the invention of Makrolon® (more commonly known as Polycarbonate) that plastic materials were strong enough to endure multiple impacts without fracturing, which was the largest problem with Riddell's initial creation (Bartsch et al., 2012). The adoption of a hard-shell durable helmet was an improvement, but death rates continued to soar. Though skull fractures were less likely, the typical helmet of the day did not dissipate energy through a soft linear system but was simply a hard shell from which a focused impact was dispersed across a larger area of the head (Rowson et al., 2014). Because of this, officials began to take notice of techniques and tackling strategies of the day. It was through rule changes and technique adjustments where more protective gains were found.

Through the 1960-1970s our understanding of the mechanisms that lead to catastrophic injuries improved. Post-World War II, the United States saw a boom in the growth of the automotive industry. Not only had our understanding of skull fracture and traumatic brain injury improved as a direct outcome of world events, but people were also buying cars and driving became a way of American life. Therefore, automotive crashes were becoming common. With no safety restraints, crumple zones, or advanced materials, automotive accidents drove the science behind our understanding of blunt impact mechanics (Cobb et al., 2016). Much of this work and knowledge was organically transferred to the football field. In the mid 1970's an organization called the National Operating Committee on the Safety of Athletic Equipment (NOCSAE) was founded, and a basic performance standard was established for the American football helmet. (Bartsch et al., 2012). The primary goal of the standard was to prevent skull fractures to the head.

Along with a simple rule change made across the NCAA and the NFL mandating that no ramming or spearing using the top of the head be done, the new helmet standard served to eradicate skull fracture from the sport. To date, near-zero skull fractures have been reported as a result of head-to-head contact in football.

The head injury problem was thought to be nearly solved, but another ominous brain injury was still lurking behind the curtain of the skull fracture injury, concussion.

Concussion, now a common term to most Americans, was originally thought to be associated with forces that were just below skull fracture thresholds. It was also thought to be completely harmless, as it appeared to be completely transient in nature (Giza & Hovda, 2014). Athletes would appear dazed and dizzy, but these symptoms would also seem to resolve. This led to a culture of ignorance, where individuals would simply play through the injury or ignore it together. Until the mid 1990s, the life-altering effects of this injury were not at all understood(Mckee & Daneshvar, 2015). However, in the late 90s and early 2000s, research scientists began to make headway in realizing the casual mechanisms and deleterious effects of concussion.

Skull fracture, which results from the focused impact energy from a linear or direct (in-line) impact to the head, was addressed by actively reducing the chance of such impacts through rule changes and by creating helmets that could disperse such energies across a greater surface area (Giza & Hovda, 2014). This made a focused energy less focused. Concussion, in-line, was thought to also result from the same mechanism. However, researchers began to recognize that rotational kinematics also played an integrated role, producing stresses to the brain itself. (Rowson et al., 2012). Linear acceleration refers to the translation of the head in one plane; it is related to compressive forces that the brain tissue is able to withstand relatively well (Hoshizaki et al., 2014). Through research, linear acceleration has been used to demonstrate the amount of force tolerable to the skull without resulting in a fracture. Angular acceleration and angular velocity, however, are related to how quickly the head rotates relative to a fixed point. These measures are related to shear forces, and brain tissue has a low affinity to withstand these types of forces (Hoshizaki et al., 2014). Therefore, rotational kinematics has been identified as being closely related to the onset of concussion itself, as it contributes mostly to the microscopic injury of the brain tissue.

The aforementioned NOCSAE emerged in 1973 and has since played a pivotal role in the development of the first standardized testing protocol. NOCSAE has become so important in American football that protective headgear cannot be sold or worn for use in the sport unless it is certified by the organization. The pioneering impact testing protocol created by the organization has directly aided in the reduction of skull fractures and traumatic brain injury in American football. However, the understanding of the mechanistic causes of concussion, along with the short and long-term effect of this injury, have been very slow to generate. A concussion is a multi-faceted problem, of which protective headgear is only a single piece. In the 2010s, concussion was identified by the Center for Disease Control (CDC), as the silent epidemic. With high profile athletes and their careers being impacted, along with a fear of the unknown long-term effects of the injury, led to a large public interest in the injury. Consumers were now paying attention to things like equipment, and product manufacturers were paying attention to the consumers. With this, concussion became a “buzzword” and manufacturers began to try and create products to address the perceived needs. With this attention, a greater number of products began to arrive to the market and design-cycles for manufactures for new product lines became reduced. Product claims of concussion prevention became commonplace, but research to back those claims was not being produced at the same rate. The solution to prevent a concussion is dependent upon the base understanding of the injury. This lack of science-based understanding prevented NOCSAE from updating its linear skull fracture-specific standard to include measures and performance criteria for rotational forces. Thus, a void existed between need and scientific understanding. To fill this gap for consumers, one university and the NFL began to create their own individual assessment protocols, both of which served to produce annual reports which serve to rank (good, better, best) helmet products. These efforts were accomplished outside of NOCSAE's own test standard developments. In 2022, we have an updated NOCSAE standard which includes measures of rotation, the National Football League Players Association (NFLPA) annual helmet testing report, and the Virginia Tech Star rating system for football helmets. Glaring similarities exist between all three protocols, but only the NFLPA and the VT methodologies serve to address the link between helmet performance and concussion reduction. This is important, as there are distinct variations in the actual points of impact where the specimen helmet is tested, along with variations in the position and orientation (pose) of each anthropomorphic test device (ATD) headform and neck set-up.

It is understood that results of impact tests are sensitive to and can vary between impact location and how the ATD is positioned/oriented so that the particular positions can be impacted. Because ATD headform impact responses can be influenced by position and pose, and helmet performances are now ranked to fuel consumption and end-user decisions, it is important to gain a better understanding of these two variables across the current private testing methodologies. Specifically, there exists two helmets, both reported upon by the two available consumer metrics where one helmet is ranked as a higher performer over the other in one method and is inverted in the other. Therefore, the purpose of this study was to investigate the effect of variability in impact location and pose between the NFL and Virginia Tech methodologies on the performance (impact response) of two modern football helmets. Based on the data obtained from the study, implications regarding whether helmets perform differently under identical and varying parameters, which leads to the relevancy of helmet ranking, can be established. The research questions of this study are as follows:

Research Question 1: Do the impact characteristics of two, 5-star rated American Football Helmet designs differ from each other using impact locations from the VT testing methodology?

Research Question 2: Do the impact characteristics of two, recommended American Football Helmet designs differ from each other using impact locations from the NFLPA testing methodology?

Research Question 3: Is there a difference in the impact characteristics of the Schutt F7 LTD helmet between the VT and NFLPA Side Impact Pose?

Research Question 4: Is there a difference in the impact characteristics of the Xenith XR helmet between the VT and NFLPA Side Impact Pose?

The follow-up Hypotheses to each of these questions are as follows:

H1: There will be no difference in the impact performance of two high-rated helmets designs when assessed using the VT pose methods.

H2: There will be no difference in the impact performance of two high-rated helmets designs when assessed using the NFLPA pose methods.

H3: There will be no difference in the impact performance of the Schutt F7 LTD design between the VT and NFLPA methods.

H4: There will be no difference in the impact performance of the Xenith XR design between the VT and NFLPA methods.

CHAPTER II: Literature Review

Concern about sport-related concussion, causal mechanisms, diagnosis, management, long-term effects, and equipment design has been consistently growing over the past twenty years. A succinct and predictable understanding of these low-grade transient disabilities is not yet available. As a collegiate football athlete who depends upon a protective helmet, I share this concern and am motivated to gain a more thorough understanding of how forces from blunt impacts are mitigated by protective equipment. Specifically, my interest revolves around how these forces are measured so that protective helmets can be deemed safe. Currently, all American football helmets must undergo testing to align with the impact testing standard established by the Nation Operating Committee for Safety in Athletic Equipment (NOCSAE). Before any American football helmet can be sold in the United States, it must be assessed and pass this blunt and rotational impact test. Though recently updated, the NOCSAE certification standard has been in effect for American football since 1973. More recently, two independent organizations have developed blunt and rotational impact testing methodologies aimed at providing consumers with performance information from which to make informed purchasing decisions. In alignment, these three testing methodologies use similar approaches to assess helmet performance. However, the defined location of impact are not identical, thus variations in performances could be elicited as a result of testing methodology instead of helmet design.

Concussion

Concussion, a form of mild traumatic brain injury (mTBI) has been identified in humans for several thousands of years (McCrory, 2005), but a scientific understanding has only come into focus over the past 25 years, with the first scientific definition coming into existence in 2004. Investigations on sport-specific concussions began to permeate into the global scientific literature in the mid-1990's. Since that time, there has been an explosion of activity which has led to a scientific definition of the injury and partial understanding of its mechanism. Studies in rat models demonstrate that upon insult, there is an ionic flux and hyperacute indiscriminate glutamate is released. Potassium exits the neuron while sodium and calcium flow into the neuron, and this cascade is partially responsible for the post-concussive impairments experienced (Giza and Hovda 2014). To get a full understanding of the phenomena of concussion, one must have a fundamental understanding of neurons and action potentials. A neuron is simply a nerve cell, and an action potential can be described as the impulse of electrical activity due to the depolarization of the membrane potential of a neuron. Neurons have dendrites that receive signals from other neurons and transfer the action potential down an axon. An axon has a special thick fatty coating known as myelin sheath that allows for the propagation of the action potential down the axon at an accelerated rate. The action potential does not actually travel along the surface of this myelin sheath, rather it "jumps" to the space that exists between the myelin sheath known as the Nodes of Ranvier. As the action potential reaches the axon of the terminal, there are several inhibitory or excitatory neurotransmitters, such as acetylcholine, that are put into vesicles and pushed to the end of the cell where the neurotransmitters are released into the synapse and reach the post-synaptic dendrites. Under normal circumstances, this process continues between neurons to communicate a signal that causes a response within the body. When concussion occurs, however, the neurotransmitters are "spilled" into the synapse prematurely, leading to a state in which there are not enough available receptors to bind the neurotransmitters. This leads to physical symptoms of disorientation and other impairments that are recognized and associated with concussion. Researchers have also discovered that the duration of the post-concussive impairments is related to the time it takes neurotransmitters in the synaptic cleft to be "cleaned up" after the TBI caused them to go in a state of overdrive and be released into the synaptic cleft (Giza and Hovda, 2014). Researchers are realizing that the injury is a progressive process rather than an acute injury. Because the understanding and knowledge have increased, there are now tests and scales used to identify the severity of TBI. The three most common ways to assess a concussion are by using the Glasgow Coma Scale score, measuring the duration of a loss of consciousness, and examining the post-traumatic amnesia (McKee and Daneshvar, 2015). Scores of these tests have been linked to long-term issues, whether it be physical, emotional, behavioral, and/or cognitive decline, potentially affecting a person's ability to carry out normal, routine activities (McKee and Daneshvar, 2015).

Protective Headgear

Protective headgear in sports began to draw mainstream attention as the 19th century was ending in response to the devastating injuries occurring in American college football. Leather helmets arrived on the scene of athletics as an attempt to stop these injuries. These leather helmets possessed no facemask and were equipped with minimal cushioning on the inside, offering little protection. The head and neck injuries that continued to be sustained required neurosurgical attention, and athletes were still losing their life as a result (Hoshizaki et al. 2014). American football began to earn a reputation of violence, and the deaths of 19 collegiate football athletes in 1905 contributed to this while adding more pressure to make the game safe. The prevalence of cranial fractures and death from participation in college football finally evoked a response from President Theodore Roosevelt who held a meeting at the White House to discuss rule implementations to make the game safer for athletes involved (Hoshizaki et al. 2014). In 1906, the forward pass was legalized to provide the offense with an additional way to advance the ball down the field in an effort to reduce the physicality of the game (Bartsch et al., 2012). Facemasks were added to the helmets in 1935, which aided directly to the reduction of nose fractures. However, helmets were not officially mandated by the National Collegiate Athletic Association (NCAA) or the National Football League (NFL) until 1940 when the first hard-plastic helmet equipped with a facemask was patented by Riddell (Bartsch et al., 2012). The 1940s was the decade that pilot studies began that attempted to view the relationship between head impact tolerance and cerebral concussion related to linear acceleration began to rise. During this time, the definition of concussion was in reference to direct insult to the skull and brain which resulted in macroscopic injury. This is a key difference from the present-day generally accepted definition of concussion, which recognizes injury that does not cause visible skull or brain surface injury (Bartsch et al., 2012). The first theories linking braining tissue straining and shearing to dysfunction began to permeate in 1966. For the first time, linear and rotational kinematics were identified as cofounding variables that are affected upon insult, thus affecting injury mechanism (Bartsch et al., 2012). Within this same year, the first head injury severity index was developed based on the acceleration to the head area upon insult, known as the Gadd Severity Index (GSI). Two years later in 1968, a reported 38 football-related injuries persisted, and this shocking statistic was enough to invoke a response similar to that of earlier President Theodore Roosevelt, resulting in the formation of NOCSAE. Following the creation of the organization, the first of its kind football testing standard was born, using the GSI. The development of the testing standard made helmets and the game of American football safer than they had ever been. It was outstanding and led directly to rule changes in the game through the ’70s and ’80s, such as the penalizing of the initiation of blocking and tackling head-first and additional restrictions being placed on initiating contact with the head, neck, and face. Players were also penalized for striking these areas of their opponents (Bartsch et al., 2012). The protective headgear itself has been manipulated minimally since the turn of the 21st century. This is in line with data generated by impact testing on helmets, which illustrates similar force data upon insult from helmets in the early 2000s to the current helmets. The original intent behind protective headgear, more specifically American football helmets, was to circumvent the onset of catastrophic brain injuries, and helmets have done an astonishing job at doing this. However, the success in preventing skull fractures has not been linear to the prevention of concussion, as it is still a major topic and area of concern in American football.

Impact Testing of Helmets

Though there are a variety of ways the head can be impacted while competing in American football, helmet-to-helmet contact accounts for roughly 61% of the impacts that leads to concussion (Hoshizaki et al., 2014). Counterintuitively, the type of testing required for the certification of helmets in American athletics uses a drop rig method, which would be representative of an athlete contacting the ground with linear acceleration as the main variable (Hoshizaki et al., 2014). Linear acceleration, which is the translation of the head, has historically been used as the primary variable in testing. A linear acceleration between 200g and 300g was identified as the range at which best predicts the risk of skull fracture, which led to impacts between 250g and 300g being above the threshold that allows for a helmet to pass the NOCSAE certification (Hoshizaki et al., 2014). Again, this threshold was effective in the reduction of skull fracture and traumatic injury to the brain, but poorly addressed the incidence of concussion. The severity of the rotational acceleration of the head has been linked to the shearing of the brain tissue, thus leading to a concussion. The shearing of brain tissue is directly related to the physical properties of the brain tissue itself; the tissue happens to have a low resistance to the forces associated with rotation but high resistance to forces associated with compression, which is related to linear translation (Hoshizaki et al., 2014). Damage score is another quantifiable metric that estimates the strain that is placed upon the brain when an impact occurs. This strain is directly related to the mechanism of head rotation. This explains the importance of considering rotational kinematics when impact testing because shear forces are likely to have the most profound effect that contributes to the mechanism of concussion.

NFL and Virginia Tech methodology

With the transient changes to brain metabolism (and, by default, brain function) which occur after blunt impact, it has become a focus of scientists to better understand the role that a protective helmet can play in the mitigation of the transmitted forces leading to this injury. Ways to decrease the incidence of a concussion continue to be under investigation, and testing methodologies play a significant role in determining the impact responses of a helmet. An area exists within the field that could be pursued intricately, particularly regarding the differences in the specific impact locations utilized in the NFLPLA and Virginia Tech testing methodologies and how this corresponds to differences in their rating system of helmets. The STAR and NFLPLA rating systems use different impact locations to test for the performance of a given helmet; differences in impact location between the STAR system and NFLPLA, no matter how subtle, can influence the resultant magnitude and location of mTBI (Hoshizaki et al., 2014). The Virginia Tech protocol uses the NOCSAE head form while the NFLPLA methodology uses the Hybrid III anthropometric testing device (ATD). A characteristic flaw with the NOCSAE head form is it was developed specifically to withstand blunt force linear acceleration. The Hybrid III ATD head form was originally used in the automobile industry for the crash dummy heads. Because of the difference in their original intent and design, the two head forms differ in shape, material composition, instrumentation, and inertial properties, all of which can impact the measurable kinematic responses of each head form. A primary difference seen between the NOCSAE and Hybrid III head forms exists at the base of the skull and neck area. This area primarily dictates the characteristics of a head upon impact, meaning differences observed at the base of the skull and neck can lead to the severity index of a given methodology to be more stringent, ultimately affecting a rating assigned to a helmet and fed to consumers. While the helmet is critical in modulating the capacity at which energy is dispersed and transferred to the head upon impact, it is essential that an appropriate head form is used that most resemble a human head to ensure data created in the laboratory has relevance to what occurs on the field. The creation of the Varsity Football STAR Rating System was motivated by the altruistic desire to feed consumers information about the way specific helmets perform upon insult. It acknowledges and incorporates the NOCSAE ideology; however, it takes it a step further by formulating an equation that calculates injury risk. The STAR system has impact locations at the front, front boss, side, and back of the helmet using low, medium, and high impact velocities, where the highest impact energies are meant to resemble an impact that may lead to a concussive state. These locations are struck by a nylon-capped impactor to replicate helmet-to-helmet contact using a pendulum system. The NFLPLA methodology was created in response to the output of misinformation regarding the deficits seen in diagnosed concussed athletes at the high school and collegiate levels. Ironically, the data reported showed no deficits in NFL athletes diagnosed with a concussion. This misinformation led the NFL to attempt to save face by funding and pushing for the passage of the Zackery Lystedt law in 2009 in Washington State. This was the first national law that specifically addressed concussions in youth athletics (Bartsch et al., 2012). The Zackery Lystedt law eventually led to the initiation of bills in the Senate and House of Representatives in 2011 that directly acknowledged the safety of youth and adult helmets and essentially forbade the use of deceptive advertising related to helmets role in protecting from concussion (Bartsch et al., 2012). The NFLPLA was the NFL's response to its athletes to show their investment and dedication to their safety. The NFL incentivized researchers by allowing the research with the most prolific findings to be funded and used as the official methodology to test the protective headgear. The current NFLPLA testing methodology employs a linear impacting system that uses compressed air to accelerate a nylon-capped impactor with the Hybrid III head form equipped with sensors to record impact responses as they occur. The helmet has impact locations at the side upper, oblique front, oblique rear, side, facemask side, and facemask central oblique. The NFL protocol is unique in its own right because it presents the data of the top-ranking helmets in regard to whether the helmets are significantly different or not. If a helmet is significantly different from the top-performing headgear, it is put in a "red zone," indicating the unsafety of the helmet. However, helmets that are not significantly different are placed in a green zone that is graphically ambiguous, misleading consumers to believe one helmet is better than the next when in actuality they perform the same, mathematically. The protocol uses linear and angular data. Data generated using a primarily linear impacting system can be misleading because a head form has a high affinity to withstand compressive forces; therefore, an impact with a large linear force alone may not be enough to result in a concussive state. When rotational acceleration is considered, the coupled forces can result in such a state. Existing literature presents research using human participants that suggests it is difficult to obtain a true threshold that results in a concussive state while looking at linear acceleration independently of rotational acceleration since a linear force that leads to a concussive state for one individual may be surpassed by another individual without the result of concussion (Rowson et. al, 2012). The inability to truly identify the exact mechanics that cause the transient injury has troubled scientists; however, significant work has been done indicating tolerable blunt forces for humans. This work gives an estimate of the tolerance that humans have for rotational acceleration, illustrating a rotational acceleration of 5,260 rad/s^2 produced an injury risk of 10% while 7,483 rad/s^2 had an injury risk of 90% (Rowson et. al, 2012). This further highlights the fact that a particular amount of acceleration and velocity that may exceed the threshold for an individual to withstand on a personal level may not be enough to cause injury in another individual. The details regarding this study are critical because they illustrate how independently looking at linear and/or rotational kinematics is not truly representative of what is occurring in competition; therefore, the testing methodology must incorporate impacts that are representative of on-field competition into the laboratory setting as best as possible.

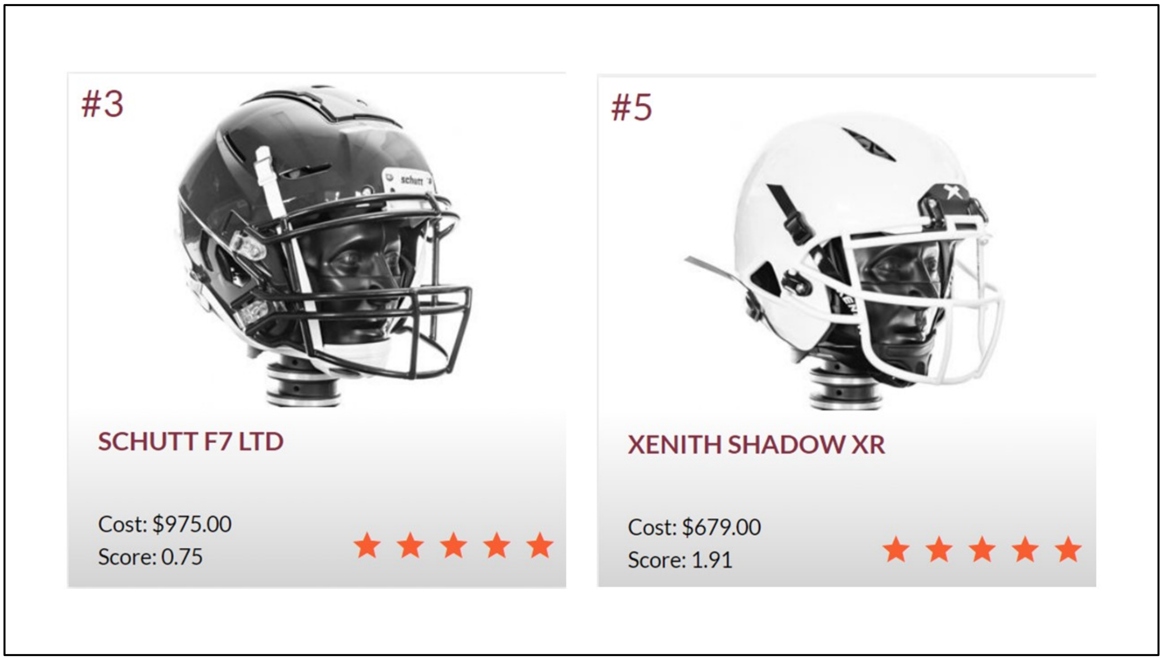
As previously mentioned, the Varsity Football STAR Testing Methodology uses four specific impact locations for testing: front, front boss, side, and back of the helmet. Each of the impact locations is characterized by a specific set of parameters in reference to the NOCSAE head form translation and rotation on the linear slide table that the head rests. The front impact location of the helmet is defined by a linear displacement of the slide table for the Y-plane displacement of 0 cm and Z-plane displacement of +5.3 cm. The rotational displacement is -20 degrees in the Y-plane and 0 degrees in the Z-plane. The front boss impact location is defined by a linear displacement of the slide table of 0 cm and +2.3 cm Y and Z-plane, respectively, and a rotational displacement of -25 degrees and +67.5 degrees for the respective Y and Z-plane. The side impact location is defined by a linear displacement of the slide table of -4 cm and +5.8 cm in the Y and Z-plane, respectively, and a rotational displacement of -5 degrees and -100 degrees in the Y and Z-planes. Finally, the impact location recognized as the back is specified as a linear translation of 0 cm and +4.5 cm for the Y and Z-planes, respectively, and a rotational displacement of 0 degrees and -180 degrees in the Y and Z-planes. The NFLPLA uses six impact locations: side upper, oblique front, oblique rear, side, facemask side, and facemask central oblique. To determine these locations, the protocol first calls for the Hybrid III head form to be set in the appropriate reference position. This is accomplished by first positioning the neck vertical with the right side of the head form facing the impactor. The table must then be adjusted accordingly so that the center of gravity marks on the head form has the centerline of the impactor running directly through it. A 90-degree head rotation brings the face of the head form towards the impactor, and the specific impact locations are then able to be determined using rotational and translational displacements of the table from the reference position as well as the center of gravity of the head form in the Y-Z plane, which is the plane that the axis of the impactor travels. The side upper impact site is defined by the table translational displacement of 1mm and -18mm in the Y and Z plane, respectively, rotational table displacement of θ =90 degrees and β= 25 degrees, and a head form center of gravity position of 1 mm in the Y axis and -47 mm in the Z axis. The oblique front impact site has a translational table displacement of 35 mm and -31 mm in the Y and Z plane, respectively, rotational table displacement of θ = -45 degrees and β= 25 degrees, and a center of gravity position of the head form at 12 mm and -64 mm. Oblique rear has a table translational table displacement of 27 mm and -2 mm in the Y and Z axis, rotational table displacement of θ = -157 degrees and β= 11 degrees, and a center of gravity position of the head form at 8 mm in the Y plane and -5 mm in the Z plane. The side impact location has a table translational displacement at 27 mm and -2 mm in the Y and Z planes, a rotational table displacement of θ = -95 degrees and β= 11 degrees, and a head center of gravity position of 0 mm in the Y plane and -7 in the Z plane. The facemask side has a translational table displacement of -63 mm in the Y plane and 38 mm in the Z plane, rotational table displacement of θ = 70 degrees and β= 15 degrees, and a head form center of gravity position of -64 mm and 26 mm in the Y and Z planes, respectively. Finally, the facemask central oblique impact location is defined by a table translational displacement of 13 mm in the Y plane and 35 mm in the Z plane, a rotational table displacement of θ = -20 degrees and β= -5 degrees, and a head form center of gravity position of -5 mm and 35 mm in the Y and Z planes, respectively. The mechanical responses that arise from the specific impact locations vary between the VT testing and NFLPLA since each impact location is achieved via different poses. The NFLPLA and the Varsity Football STAR systems both adequately describe the pose and impact locations. However, the description provided is ambiguous and leaves open interpretation for end-users across laboratories. The Devavit-Hartenberg (DH) Convention defines the coordinate plane of each piece of the testing apparatus and would serve as a great universal standardization mechanism that clearly defines pose and impact location as proposed by Jesunathadas et al., 2020. The implementation of the DH convention into impact testing would provide a common way across laboratories to express the pose of a head form relative to the base frame. The techniques of the DH convention have been successfully utilized in the field of robotics for several decades to accurately define the positions of objects in space, and this would be an effective way to define pose ATD impact testing to reduce variability across labs (Jesunathadas et al., 2020). Because there is variability in pose between different methodologies, the VT test defines a side impact based on its specific set of parameters, and the NFLPLA has a similar but different set of parameters to define its side impact. Both methodologies recognize their respective side impact as true; however, I am interested in observing if differences that arise between the two protocols at specific sites are statistically different. If there are significant differences, this will allow for the assessment as to which helmet performs better and its relationship to the ranking of helmets. Insignificant differences will allow for the determination of whether helmet ranking is even relevant, as it can be ambiguous for unlearned consumers. I intend to determine which impact gives a more severe mechanical blow, and this will ultimately lead to me fulfilling my inquiry regarding how specific impact locations affect the rating designated to helmets.

Current literature suggests that the NOCSAE head form may be the superior model to use for testing as it allows the least bit of rotation, which means its tolerance for intracranial pressure and brain strain may be more realistic than that of a human subject. Existing literature also expresses the continuing effort to find the most effective testing methodology that accurately replicates impacts experienced during competition to help give consumers the best indication of how helmets will perform before purchasing the equipment. With my research, I aim to look directly at the differences in the impact locations between the two testing methods. I will investigate the difference in data that is generated by the four impact sites that are recognized as the same for each methodology. For instance, the NFLPLA has six impact locations while the VT testing methodology only has four impact locations. Therefore, I will replicate the tests for each protocol at the locations that both protocols reference as the front, front boss, side, and back; the two additional impact sites do not need to be accounted for because they have nothing in which they can be compared. I intend to test the head form in a helmeted condition, which will allow me to extract data regarding the severity index of each test and obtain an estimate of brain strain, having a direct correlation to concussion risk. Directly comparing the helmets under each protocol will give implications as to how the slight variation in impact locations affects the damage and severity index of the protective headgear under equal circumstances, indicating which testing method provides a harsher impact assessment. The interpretation of the data will lead to a better understanding of how the specific helmet impact locations lead to the rating given to a helmet based on the VT STAR rating system and NFLPLA. Parallels can be drawn between helmet impact locations and ratings assigned to a helmet because if a particular protocol produces data that has harsher numbers at every impact site, this will ultimately mean this helmet will not be ranked as well in accordance with that specific methodology relative to the opposing protocol. This may lead to an implication that a helmet going through a more stringent assessment has a predisposition to a lower rating. This research will provide consumers with a better idea of the performance of a given helmet relative to the methodology which it had to undergo as it relates to safety and mitigation of minor traumatic brain injury. While I do understand concussions will never be eradicated from American football, detailing the protocols to know which testing methodology is more severe between the NFLPLA and VT STAR rating system allows consumers to make informed decisions when purchasing helmets based on assigned ratings to possibly assist in lowering the incidence of concussion.

CHAPTER III: Methods

A Xenith Shadow XR (Xenith Inc., Detroit, MI) sized large, and Schutt F7 LTD (Schutt Sports Inc., Litchfield, IL.), sized large, American football helmets (see Figure 1) were fit to a Hybrid III 50^{th} percentile male head outfitted with a 6 degrees of freedom (DOF) angular rate and triaxial linear accelerometer system mounted at the center of gravity. Each helmet was impacted at a velocity just above 7.5 m/s using a pneumatic linear impactor with an integrated femur load cell. A NOCSAE anvil was utilized for the bareheaded impacts during the pre and post-checks. The precheck and post checks were conducted and were within the 7% accepted tolerance of each other for peak resultant linear acceleration, peak resultant angular acceleration, and peak resultant angular velocity. Once the precheck was completed, the NOCSAE anvil was taken off and replaced by the NFL large radius nylon anvil, which was utilized for both protocols. The Virginia Tech STAR Rating Method was completed prior to the NFL protocol; once the methodology had been completed for the Virginia Tech protocol, the helmets were inspected for damage, and chinstraps were adjusted, as necessary. Both helmets were impacted four times at each location for each protocol. Between each hit, each helmet was readjusted using the helmet position index (HPI). The HPI is a device that measures the distance between the brim of the helmet and a determined location on the head form. In this study, the determined location was the base of the nose on the head form. The HPI was used for consistency in impact location for every recorded hit. Acceleration signals were resolved into peak resultant linear, peak angular accelerations, and peak angular velocity (PLA, PAA, and PAV) using MATLAB software to remove baseline shifts and filter. Angular rate signals were differentiated to obtain angular accelerations about each axis. Resultant linear and angular accelerations along with angular velocity were calculated, and peak values were extracted for analysis. Statistical analyses were performed on the difference scores.

Figure 1: Schutt F7 LTD and Xenith Shadow XR, VT rated list



Locations

Following the guidelines provided withing the NFL Helmet Test Protocol (Biocore Consulting and Research, LLC. Charlottesville, VA) and Virginia Tech STAR Rating Methodology (Rowson et, al., Virginia Tech), we impacted each helmet specimen at the following locations for the NFLPA: Oblique Front, Side Upper, Oblique Rear, and Side (see Figure 2), and the following locations from the VT method: Front Boss, Front, Rear, and Side (see Figure 3). Locations from each protocol were selected based upon their relativity to each other and their lack of inclusion of the facemask. The NFLPA protocol has 6 impact locations, but 2/6 contact the facemask. These were eliminated as facemask interaction is outside of the scope of this work. The VT protocol also employs a total of 6 locations, but we only used the impact locations which generally approximated those found in the NFLPA methods.

Figure 2: NFLPA Impact locations and POSE

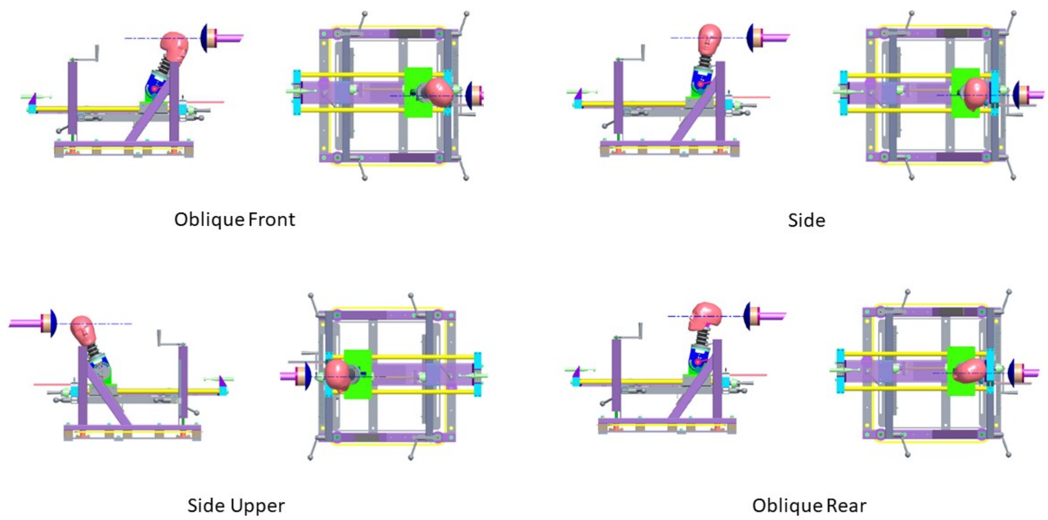
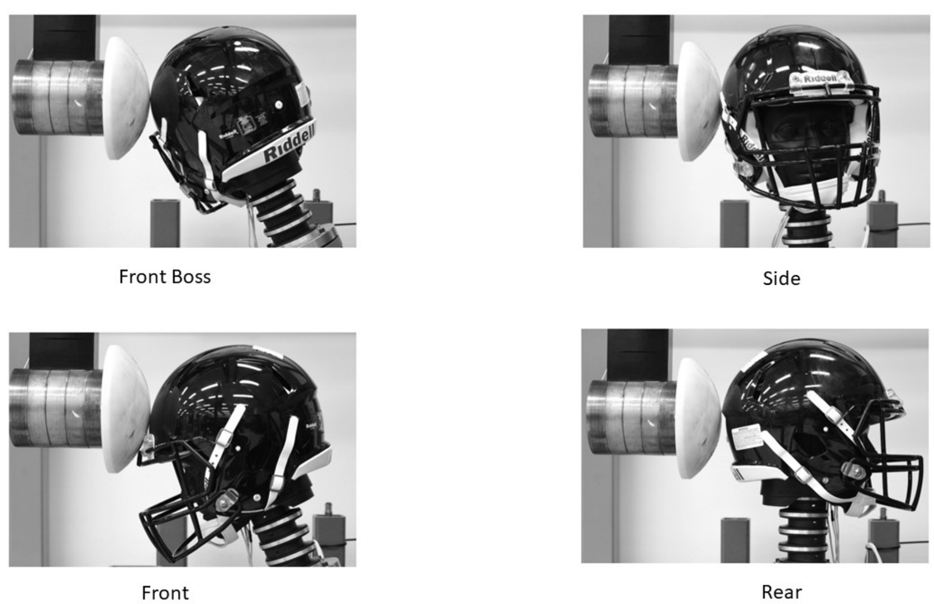


Figure 3: VT Impact locations and POSE



Measures of central tendency are provided in tabular form and each comparison employed a Welch's t-test, a simple two sample assessment which assumes unequal variance, for statistical analysis. We set our p value at $p \leq 0.05$. Results are placed in tables and discussed.

CHAPTER IV: Results

Linear Acceleration:

Measures of central tendency are provided in Tables 1-4 for all assessments. Results for Linear Acceleration (Peak g) are provided in Figure 4. We found that all research questions related to peak g performance were statistically significant. Specifically, the Helmet type by helmet method pose showed that when employing the VT testing methods, the Schutt F7 LTD manages the linear force better than the Xenith XR ($t = -2.91$, $df = 19$, $p \leq .05$). This is also the case for peak g when the helmets were evaluated using the NFLPA poses ($t = -3.71$, $df = 30$, $p \leq .05$). When evaluating the specific differences presented by side poses, the VT side pose produced lower peak g results across both helmet designs ($t = -2.85$, $df = 5$, $p \leq .05$ & $t = -5.77$, $df = 6$, $p \leq .05$ for the F7 design and XR design respectively).

Angular Acceleration:

Measures of central tendency are provided in Tables 1-4 for all assessments. Results for Angular Acceleration are provided in Figure 5. We found that all, but one comparison, were statistically insignificant. The comparison between the Side poses of the two methods showed a significant difference when employed upon the F7 helmet ($t = 3.54$, $df = 4$, $p \leq .05$). The NFLPA side pose produced a lower angular acceleration to the helmet compared to the VT side pose.

Angular Velocity:

Measures of central tendency are provided in Tables 1-4 for all assessments. Results for Angular Velocity are provided in Figure 6. Again, we found that all, but one comparison, were statistically insignificant. The comparison between the Side poses of the two methods showed a significant difference when employed upon the F7 helmet ($t = -2.58$, $df = 6$, $p \leq .05$). The VT side pose produced a lower angular velocity to the helmet compared to the NFLPA side pose.

DAMAGE score:

Measures of central tendency are provided in Tables 1-4 for all assessments. Results for DAMAGE score are provided in Figure 7. We found statistically significant difference in two of four comparisons. The VT side pose resulted in a lower DAMAGE scores across both helmet designs ($t = -3.67$, $df = 6$, $p \leq .05$ & $t = -3.66$, $df = 5$, $p \leq .05$ for the F7 design and XR design respectively).

Table 1: Overall Comparison Between Helmets using VT Pose.

Combined Locations	Schutt F7 LTD	Xenith XR VT
Linear Acceleration (g)	55.26 (9.64)	61.49 (7.96)
Angular Acceleration (rad/s^2)	3,700.67 (642.15)	3233.92 (774.32)
Angular Velocity (rad/s)	33.38 (1.62)	34.79 (3.07)
Damage	0.23 (0.05)	0.23 (0.04)

Table 2: Overall Comparison Between Helmets using NFLPA Pose.

Combined Locations	Schutt F7 LTD	Xenith XR VT
Linear Acceleration (g)	51.76 (4.75)	58.14 (4.96)
Angular Acceleration (rad/s^2)	3473.34 (905.19)	3392.58 (285.37)
Angular Velocity (rad/s)	32.97 (2.76)	34.58 (4.18)
Damage	.24 (.04)	.23 (.04)

Table 3: Comparison between SIDE pose locations on Schutt F7 LTD

Schutt F7 LTD Side Location	VT STAR	NFLPA
Linear Acceleration (g)	53.78 (1.32)	57.79 (2.47)
Angular Acceleration (rad/s^2)	4610.73 (414.79)	3844 (123.4)
Angular Velocity (rad/s)	33.22 (1.03)	35.39 (1.31)
Damage	.23 (.01)	.26 (.01)

Table 4: Comparison between SIDE pose locations on Xenith XR

Xenith XR Side Location	VT STAR	NFLPA
Linear Acceleration (g)	56.92 (1.79)	63.54 (1.42)
Angular Acceleration (rad/s^2)	3918.35 (826.92)	3553.78 (258.68)
Angular Velocity (rad/s)	37.52 (3.90)	39.24 (2.24)
Damage	.21 (.01)	.26 (.02)

Figure 4: Evaluation of Linear Acceleration (Peak g): red outline (sig.)

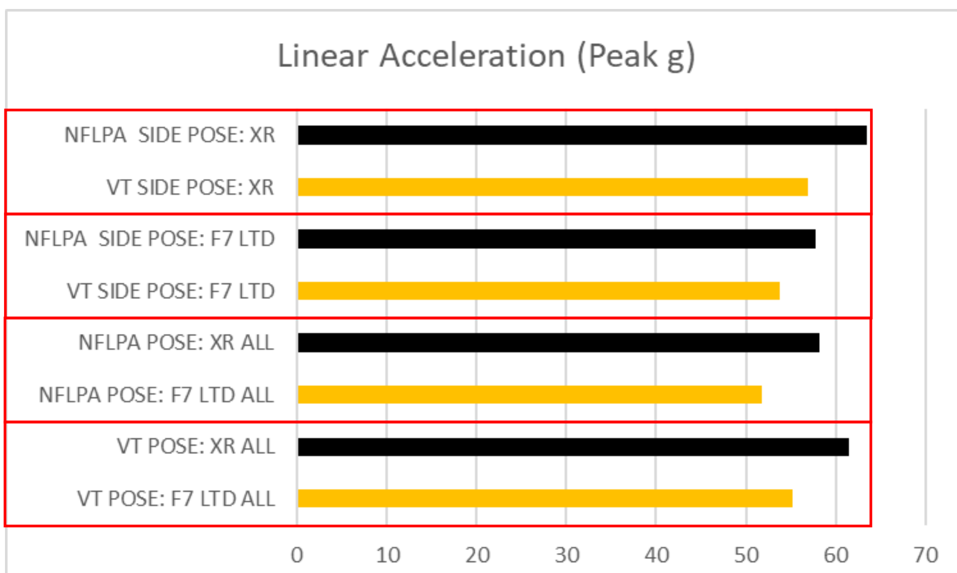


Figure 5: Evaluation of Angular Acceleration (rad/sec^2): red outline (sig.)

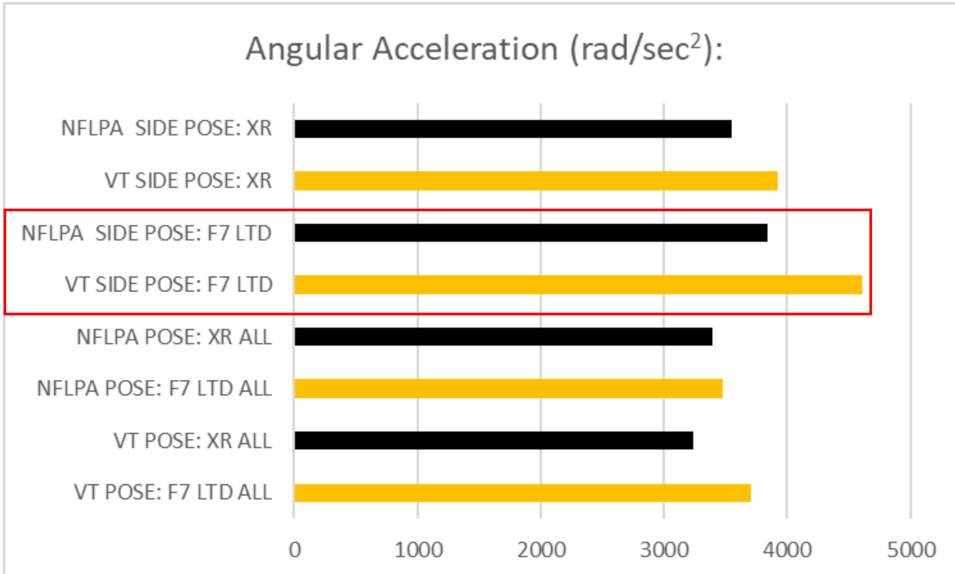


Figure 6: Evaluation of Angular Velocity (rad/sec): red outline (sig.)

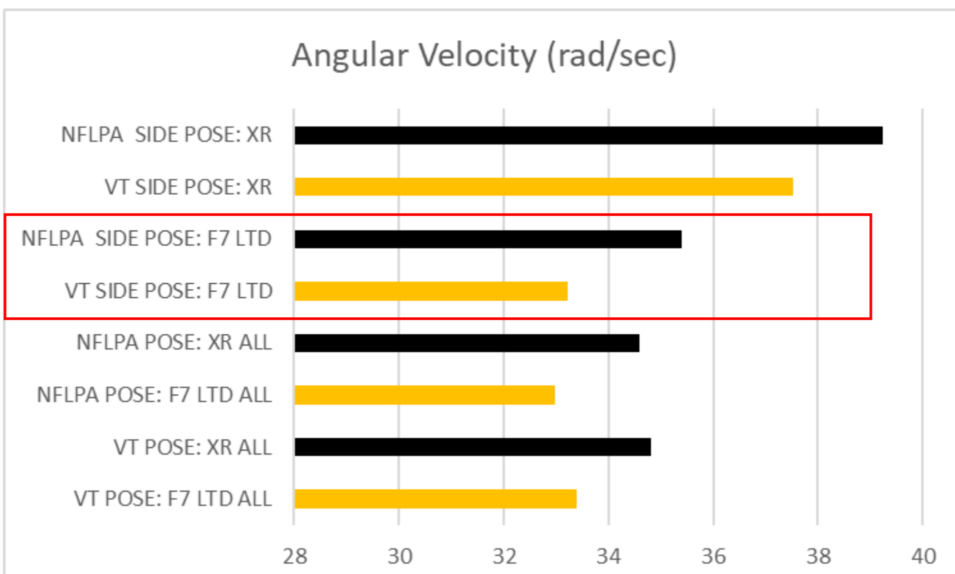
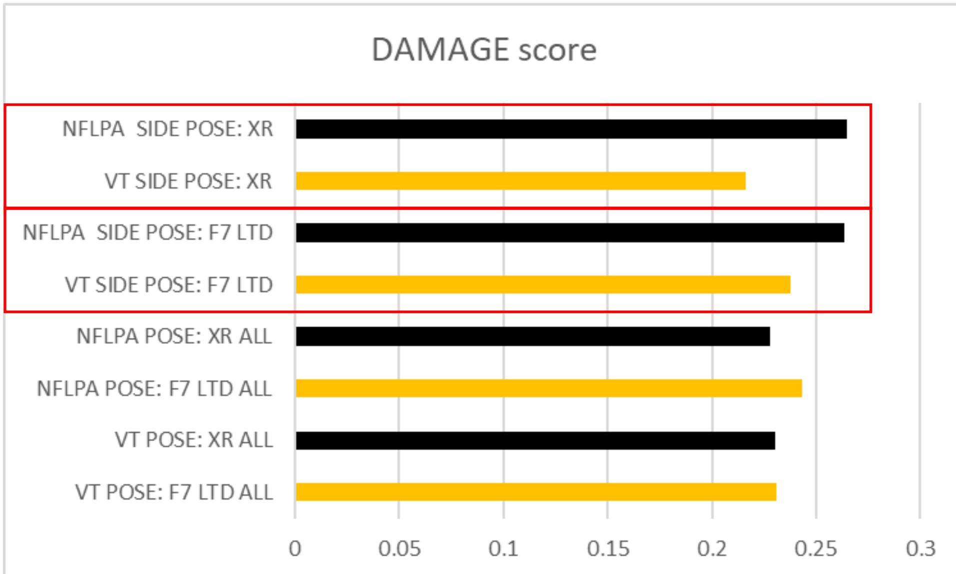


Figure 7: Evaluation of DAMAGE score: red outline (sig.)



CHAPTER V: Discussion

For greater than 3 years, two organizations, one private and the other affiliated with a research university, have provided an assessment of current helmet designs for the general consumer and end-user. This is done with the intention of providing consumers with the ability to make informed choices. Though this is altruistic, the methodologies differ in how they not only perform impact assessments, but also in how they link those performances to injury, namely concussion. The latter aspect is beyond the scope of this study, but the differences in methodologies provide our focus.

In recent results, the VT STAR rating system (Duma, S. et al., 2022)ranks the Schutt F7 LTD as its 3rd best performing helmet design compared to the 5th rated Xenith Shadow XR design. In total, 27 specific designs are assessed and ranked. For the same year, the NFLPA helmet laboratory testing results (Crandall, J. et al., 2022) rank the Xenith design as better than the Schutt. This juxtaposition can be, and is often, confusing to consumers. This gives rise to our concerns that variation in results could be connected to variations in the pose and ultimate impact locations identified by the testing methodologies. Thus, we employed an experiment that evaluated the two aforementioned designs utilizing the most common impact sites across the two provided methodologies to identify if testing methodology variations, specific to impact locations and pose, lead to variation in design performance. Therefore, the purpose of this study was to investigate the effect of variability in impact location and pose between the NFLPA and Virginia Tech STAR methodologies on the performance (impact response) of two modern football helmets.

Our results show no significant difference in damage score between the Schutt F7 LTD and Xenith Shadow XR across all impacted sites. This result was the same whether using the VT method impact locations and pose or the NFLPA method impact locations and pose. These findings demonstrate that the outcome of an impact to the head is the same between both helmet designs. In simple terms these two designs serve to manage the blunt impact energies equally.. The damage score is an important variable to use for analysis because it serves as an estimation of the amount of stress and strain placed upon the brain during the impact event. Damage scores have been shown to correlate to simulation models of human brains, with lower scores equating to less threatening stresses to the tissue. The damage score algorithm relies upon information from the two measures of angular kinematics, angular acceleration and angular velocity. We found no differences between these two measures across testing methods for the composite impact sites for each design. Rotational kinematics are related to shear forces that are placed upon the brain upon impact. A lack of difference existing in either rotational kinematics, and ultimately damage score estimates, means the risk of concussion is virtually the same for the end-user when utilizing either helmet. This means both helmets are equally effective in the mitigation of the rotational kinematic responses sustained by the head upon impact through the dissipation of the forces. Thus, helmet rankings become less important if two helmets are displaying equal performance based on kinematic responses. If significant differences were to be seen with damage scores, this argues for the relevancy of helmet rankings because the characteristics of the brain tissue would differ upon insult. Whichever helmet produces the significantly lower damage score would represent the lower injury (concussion) risk. This would be important information to be shared with consumers. However, there was no difference in overall performance between the two helmets, so there should not be a difference in ranking. We expect that the variation in rankings of these two particular designs between the VT and NFLPA methods has to do with the other aspects of the approaches employed by each final methodology. The NFLPA takes a statistical approach which categorizes levels of performance by comparing the best performing helmet with all the others. All helmets that are not statistically different from the highest performing helmet are included in the top ranked category, but they are graphically ranked for display. Their approach is scientifically read to mean that all top performing helmets are identical in ability to protect, but them providing a graphical ranking may drive a consumer to make a choice for one brand over the other based upon this, instead of something like comfort. Comfort is important for player satisfaction. The concern is that rankings create a false idea for consumers to believe that one helmet is performing better than the other when this is not correct at all. Allocating stars to a helmet is acceptable as this clears up ambiguity and provides consumers with digestible information that clearly conveys helmet performance. The findings mentioned above answers the first two research questions. The impact characteristics of two, 5-star rated football helmets do not differ from each other when using impact locations from either the VT or NFLPA testing methodologies. The findings also support the hypotheses given for these two questions, as no difference in impact performance was seen when assessed through either testing methodology.

There were also differences in performance found in this study. The damage score for the Xenith was significantly different when assessed through the side pose for the VT testing methodology versus the side pose for the NFLPA methodology. The same holds true for the Schutt. These findings indicate pose has relevancy when assessing the characteristics and performance of a helmet upon impact. The orientation of the head and neck influences impact characteristics by either increasing or decreasing forces transmitted through the center of gravity or outside of the center of gravity of the head. This could lead to outcomes that may not best reflect on-field conditions, but more importantly, lead to the inability to compare one assessment to another. This demonstrates the importance of considering pose when extracting information such as helmet rankings because the orientation of the head and neck in one protocol may allow a helmet to perform well while displaying variation in performance when the head and neck is oriented differently. When looking at the two rotational variables, a significant difference was observed for the Schutt when assessed through the side impact of the VT testing methodology versus the NFLPA methodology for both angular acceleration and angular velocity. Again, this finding illustrates the importance and influence of pose in the generation of performance and injury risk. This finding specifically presents that pose can directly affect the way in which the properties of the brain tissue respond upon impact, contributing very heavily and directly to the concussion mechanism. Finally, a difference was observed for linear acceleration across all parameters. There was a difference when assessing the side impacts of both helmets against each testing methodology, and there was also a difference in helmet performance when compared between all impact sites. Linear acceleration is only representing translation in a single plane and is more closely associated with compressive forces, which relates to skull fractures. Information given regarding linear kinematics would inform consumers and end-users alike about the injury risk related to a skull fracture. A higher linear acceleration (quantified as peak g) is closely related to the likelihood of the onset of skull fractures. Modern helmets, however, have been designed in a manner that peak g typically are very low (below 60 G in the helmets measured in this study), so this would not necessarily be essential information to provide since the risk of skull fracture while wearing the protective headgear is already considerably low (300g is the typical threshold for skull fracture). However, this finding is still notable for the fact that it shows how there are differing impact characteristics based on the pose. Further, linear forces still play a role in the outcome of concussions. The significantly different findings provided answers to the third and fourth research questions, as there was a difference in the impact characteristics of the Schutt F7 LTD helmet between the VT and NFLPA side-impact pose. This can be seen in the angular acceleration, angular velocity, linear acceleration, and damage score. There was also a difference in impact characteristics of the Xenith Shadow XR helmet between the side pose of the two testing methodologies, as can be seen in the linear acceleration and damage score. The hypothesis for the third and fourth research questions are not supported by the data.

The findings of this study ultimately show two important things: the two helmets that are flipped in rankings by these two independent organizations perform identically and pose does influence impact characteristics of protective headgear. This leads to the discussion of whether the ranking of helmets is necessary. Ultimately, if helmets are performing the same, there should be no rankings of good, better, or best because it is misleading. Stars should be allocated to helmets based on performance; this would be clear, digestible information for both consumers and end-users. When helmets perform differently, however, it is important to categorize them relative to helmets that perform safely, meaning rankings would be relevant in this case. As mentioned before, the NFLPA ranks helmets based on a helmet's ability to reduce the head impact severity measurements that are obtained when testing. A statistical analysis is used to determine which helmets are producing data that display no statistical differences relative to the top performing helmet. Statistical analysis is also used to determine which helmets are producing statistical differences relative to the top performing helmet. Helmets that are producing no statistical differences are labeled in the green, meaning the NFLPA recommends the use of the helmets, as they have shown to be statistically identical to the top performing helmet. However, helmets that are labeled in red are outlawed from being worn in competition in the NFL because their performance represents a greater risk to an NFL athlete of being concussed. The model that the NFL uses is ideal, but it presents the information ambiguously, leading uninformed consumers and end-users to believe one helmet is performing better than another. Instead of listing helmets, a model should be taken that visually puts all helmets performing identifiably into a group or table. Helmets performing differently should be placed into a different group to clearly be identified as a non-top-performing helmet, clearing ambiguity. Based on the findings of this study coupled with the actual rankings, more research should be done that demonstrates the effects of facemask deformation on impact characteristic.

REFERENCES

Bartsch, A., Benzel, E., Miele, V., Morr, D., & Prakash, V. (2012). Hybrid III anthropomorphic test device (ATD) response to head impacts and potential implications for athletic headgear testing. *Accident Analysis and Prevention*, *48*. https://doi.org/10.1016/j.aap.2012.01.032

Bartsch, A., Benzel, E., Miele, V., & Prakash, V. (2012). Impact test comparisons of 20th and 21st century American football helmets: Laboratory investigation. *Journal of Neurosurgery*, *116*(1). https://doi.org/10.3171/2011.9.JNS111059

Beckwith, J. G., Greenwald, R. M., & Chu, J. J. (2012). Measuring head kinematics in football: Correlation between the head impact telemetry system and hybrid III headform. *Annals of Biomedical Engineering*, *40*(1). https://doi.org/10.1007/s10439-011-0422-2

Cobb, B. R., Zadnik, A. M., & Rowson, S. (2016). Comparative analysis of helmeted impact response of Hybrid III and National Operating Committee on Standards for Athletic Equipment headforms. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *230*(1). https://doi.org/10.1177/1754337115599133

Crandall, Jeffrey. (2022, April 10). National Football League Players Association Laboratory Testing. https://www.nfl.com/playerhealthandsafety/equipment-and-innovation/equipment-testing/helmet-laboratory-testing-performance-results

Crisco, J. J., Wilcox, B. J., Beckwith, J. G., Chu, J. J., Duhaime, A. C., Rowson, S., Duma, S. M., Maerlender, A. C., McAllister, T. W., & Greenwald, R. M. (2011). Head impact exposure in collegiate football players. *Journal of Biomechanics*, *44*(15). https://doi.org/10.1016/j.jbiomech.2011.08.003

Dumas, Stefan. (2022, April 10). Virginia Teach STAR rating system. https://www.helmet.beam.vt.edu

Giza, C. C., & Hovda, D. A. (2014). The new neurometabolic cascade of concussion. *Neurosurgery*, *75*. https://doi.org/10.1227/NEU.0000000000000505

Hoshizaki, T. B., Post, A., Oeur, R. A., & Brien, S. E. (2014). Current and future concepts in helmet and sports injury prevention. *Neurosurgery*, *75*. https://doi.org/10.1227/NEU.0000000000000496

Jadischke, R., Viano, D. C., Dau, N., King, A. I., & McCarthy, J. (2013). On the accuracy of the head impact telemetry (hit) system used in football helmets. *Journal of Biomechanics*, *46*(13). https://doi.org/10.1016/j.jbiomech.2013.05.030

Jesunathadas, M., Gould, T. E., Plaisted, T. A., Edwards, E. D., & Piland, S. G. (2020). Describing headform pose and impact location for blunt impact testing. *Journal of Biomechanics*, *109*. https://doi.org/10.1016/j.jbiomech.2020.109923

McCrory, P., Johnston, K., Meeuwisse, W., Aubry, M., Cantu, R., Dvorak, J., Graf-Baumann, T., Kelly, J., Lovell, M., & Schamasch, P. (2005). Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. *British Journal of Sports Medicine*, *39*(4). https://doi.org/10.1136/bjsm.2005.018614

McKee, A. C., Daneshvar, D. H., Alvarez, V. E., & Stein, T. D. (2014). The neuropathology of sport. In *Acta Neuropathological* (Vol. 127, Issue 1). https://doi.org/10.1007/s00401-013-1230-6

McKee, A. C., & Daneshvar, D. H. (2015). The neuropathology of traumatic brain injury. In *Handbook of Clinical Neurology* (Vol. 127). https://doi.org/10.1016/B978-0-444-52892-6.00004-0

Rowson, S., & Duma, S. M. (2011). Development of the STAR evaluation system for football helmets: Integrating player head impact exposure and risk of concussion. *Annals of Biomedical Engineering*, *39*(8). https://doi.org/10.1007/s10439-011-0322-5

Rowson, S., Duma, S. M., Beckwith, J. G., Chu, J. J., Greenwald, R. M., Crisco, J. J., Brolinson, P. G., Duhaime, A. C., McAllister, T. W., & Maerlender, A. C. (2012). Rotational head kinematics in football impacts: An injury risk function for concussion. *Annals of Biomedical Engineering*, *40*(1). https://doi.org/10.1007/s10439-011-0392-4

Rowson, S., Duma, S. M., Greenwald, R. M., Beckwith, J. G., Chu, J. J., Guskiewicz, K. M., Mihalik, J. P., Crisco, J. J., Wilcox, B. J., McAllister, T. W., Maerlender, A. C., Broglio, S. P., Schnebel, B., Anderson, S., & Brolinson, P. G. (2014). Can helmet design reduce the risk of concussion in football? Technical note. *Journal of Neurosurgery*, *120*(4). https://doi.org/10.3171/2014.1.JNS13916