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The Effect of Normal Helmet Degradation In Division I Football Players Over the Period of One Half of a Competitive Season

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THE EFFECT OF NORMAL HELMET DEGRADATION IN DIVISION I FOOTBALL PLAYERS OVER THE PERIOD OF ONE HALF OF A COMPETITIVE SEASON

by

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Abstract

The purpose of this thesis is to evaluate the effect of normal helmet use by athletes from a Division I football team over the period of the first half of a competitive season upon the impact performance characteristics as measured by peak g values obtained through the application of the NOCSAE drop impact testing protocol. The goal of this research is to determine if one half of a season is enough time exposure to result in a significant decrease in a helmet's performance quality. This study tracks changes in performance in overall function, as well as the function of each individual location on the helmet, by comparing mean peak g during the preseason to the mean peak during the midseason. Due to degradative processes associated with normal end-use of football helmets, differences in the performance of the helmet between the preseason and the midseason may be present. Using standards provided by the National Operative Committee on Standards for Certified Equipment, eleven large Riddell® Revo Speed football helmets were tested for the 2016-17 season. Test results showed that half of a football season was not enough time exposure to affect the overall performance quality of the helmets. However, the Front Boss location showed a significant increase in peak g (decline in performance) and the Rear Boss location showed a significant decrease in peak g (increase in performance), indicating that performance changes from impacts vary according to the location of the helmet.

Dedication

To my family and friends, for always being there for me throughout my college career.

Acknowledgements

First and foremost, I would like to acknowledge my advisor, Dr. Scott Piland. Throughout your mentorship, I have been challenged to become a better writer and student. Your guidance during this journey is greatly appreciated, as I would not be to this point of my Honors College experience if it were not for you. Thank you.

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Chapter 1

Introduction

Mandated in 1939 by the National Collegiate Athletic Association and in 1940 by the National Football League, helmets are synonymous with the collision sport of American football [1]. However, this has not always been the case. The earliest football game, played in 1869, saw athletes from Rutgers and Princeton equipped with little to no protective equipment. This was the original design for the game to which it adhered for approximately thirty-four years. However, as the game became more intertwined with American culture, it gained in popularity and underwent an evolution. The game became more violent and risk for sustaining injuries increased. From 1869-1905, eighteen deaths and 159 serious, life altering injuries occurred while playing the sport [2]. Most of these deaths were attributed to catastrophic injuries to the head. Skull fractures and traumatic brain injuries were so pronounced during this time, that, in 1903, President Theodore Roosevelt intervened and held a meeting of experts at the White House. He threatened to place a complete ban on the sport. To avoid this action, rules to govern play were placed into effect and protective equipment began to be applied to the sport. The football helmet was not invented to decrease the vigorous nature of play, but rather to minimize the potential for resulting catastrophic injuries, namely, skull fractures. Throughout the years, the structure of the helmet has changed dramatically to facilitate its intent to protect.

In 1893, Admiral Joseph Mason Reeves became the first player to wear a helmet in a football game. A Navy doctor informed Admiral Reeves that additional blows to the head due to football would kill him. Thus, a shoemaker was charged with the creation of headgear that would allow the Admiral to participate in the Army-Navy game. It was not until 1940 that a plastic shell helmet was invented by John T. Riddell at his company in Chicago. With improvements in materials, technology, cost, and manufacturing procedures, helmet designs evolved with these preliminary attempts informing the system that is utilized on today's football field. Modern helmets are composed of four main parts: a hard outer shell (ABS plastic, polycarbonate plastic, or carbon fiber), inner lining of pads (foam, engineered plastic structures, or air-filled bladders), facemask, and chinstrap.

Football helmets were designed to prevent the occurrence of catastrophic head injuries, which indeed has been almost completely accomplished. However, in order to reach that goal, it was imperative to install some form of standardization and oversight to assure the consumer that the purchased headgear would perform as intended. Thus, the National Operating Committee on Standards for Athletic Equipment (NOCSAE) was formed in 1969 with the mission of establishing standards for equipment that would ideally result in the reduction of catastrophic injuries in sport. The committee sought to develop a standard that guaranteed safe and reliable equipment. In 1973, NOCSAE completed the standard specific to football headgear, which today is referred to as the Standard Test Method and Equipment Used in Evaluating the Performance Characteristics of Headgear/Equipment NOCSAE DOC ND 001- 15m17. This standard utilizes a twin-wire gravity assisted drop tower, which is set up with an instrumented human surrogate headform. The headform has a tri-axial accelerometer attached to its center of mass in order to measure the force of gravity exerted to the headform as it is dropped from various heights. The data that is received from the instrumented headform as it falls reflects the change in acceleration resulting from an abrupt impact to a rubber flat-surfaced anvil. This change is represented as peak g (g), which is the maximum force of gravity upon impact. This value, along with the time it takes for the impact event to occur, allows for the calculation of Severity Index (SI). SI is a calculation of the force time curve resulting from the drop impact event. Given the fact that the NOCSAE standard was established to prevent a catastrophic injury to a helmeted athlete, both values are set below the basic threshold for a skull fracture (~300g and <1200SI respectively), leading to a requirement of new, evaluated helmets to fall below a peak g of 150 and SI of 1200. These thresholds for skull fracture were established in the mid-1950s from data that are now known as the as the Wayne State Tolerance curves [3].

The creation of the NOCSAE Football Helmet Standard in 1973, and the requirement of the players in the National Collegiate Athletic Association (NCAA) to adopt the standard in 1978, led to a significant reduction in head injury fatalities, with a downward trend initially noted in 1985. In addition, for the first time since fatalities were recorded in 1931, zero deaths occurred during the 1990 season [4]. While the decline of deaths resulting from impacts to the head is an enormous accomplishment for the sport of American football, a threat of brain injury remains. Not fully understood or recognized in the 1970s, the brain injury of concussion, like the catastrophic brain injury, results from direct or indirect impacts to the head. However, such impacts are of a lower magnitude than those resulting in catastrophic injuries. It is a common consensus that the brain injury of concussion, defined as a transient metabolic injury to the brain resulting from a direct or indirect biomechanical force, is an epidemic in America [5]. It has been reported that approximately 3.8 million concussions occur each year in sports played in the United

States [6]. Concussion is a highly complicated and not fully understood injury, resulting from not only linear forces, but also rotational forces. Unlike skull fractures, there are currently no known injury thresholds to determine how much force is required to elicit the injury; therefore, no helmet can be designed with the intention of prevention. However, it is postulated that performance standards need to fall far below those set by the current NOCSAE testing standard. Hence, helmet manufacturers are attempting to develop designs that will improve current performance characteristics with the hope they will achieve adequate enough energy mitigation to reduce or prevent concussion.

Addressing the issue of protecting against concussion is rife with challenges. Helmets are created using materials that are known to undergo degradation processes when exposed to UV light, thermal stresses and repetitive impacts [7]. Helmets are often stored in thermally uncontrolled environments and are constantly utilized in outdoor facilities under intense sunlight. An individual helmet can be exposed to each of these factors throughout its normal end-use lifespan, which is set by manufacturers and National Athletic Equipment Reconditioners Association (NAERA) to be 10 years. It has been reported that the typical helmet undergoes approximately 2200 impacts per season [7]. Further, the effect of a year of normal use of a helmet results in pronounced degradation to the external aesthetics that are easily observed. In fact, most manufacturers require that a helmet undergo a process to be reconditioned once every two years that is intended to regain product aesthetics and gross performance.

Reconditioning is regulated by the National Athletic Equipment Reconditioners Association (NAERA). This association, which was created in 1976, has provided a list of standards and steps that the reconditioning facility must take in order for the helmets to be approved for use again. These steps consist of scraping or sanding the paint off of the outer shell, removing the pads, pressure washing the pads with high temperature water, replacing the pads if any are cracked, sandblasting the outer shell to even out deformities, and finally reassembling the helmets and applying a fresh coat of paint. With such potential for material degradation to occur both during the normal season and following reconditioning period, and in the absence of known performance criteria in which a helmet should perform to prevent concussion, it is imperative to gain a clear understanding of the potential effect of material degradation upon the impact characteristics of a modern football helmet system.

Purpose

The purpose was to evaluate the effect of normal helmet use by athletes from a Division I football team over the period of the first half of a competitive season upon the impact performance characteristics as measured by peak g values obtained through the application of the NOCSAE drop impact testing protocol. Due to degradative processes associated with normal end-use of football helmets, differences in the performance of the helmet between the preseason and the midseason may be present, which would lead to a rejection of the null hypothesis.

Research Questions

RQ1: Is there a difference in energy mitigation, using the overall average peak g as measured according to the NOCSAE testing protocol lower velocity, in new helmets following half a season of normal use?

RQ2: Is there a difference in energy mitigation, using the overall average peak g as measured according to the NOCSAE testing protocol higher velocity, in new helmets following half a season of normal use?

RQ3: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol lower velocity, in the front location of new helmets following half a season of normal use?

RQ4: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol higher velocity, in the front location of new helmets following half a season of normal use?

RQ5: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol lower velocity, in the side location of new helmets following half a season of normal use?

RQ6: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol higher velocity, in the side location of new helmets following half a season of normal use?

RQ7: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol lower velocity, in the front boss location of new helmets following half a season of normal use?

RQ8: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol higher velocity, in the front boss location of new helmets following half a season of normal use?

RQ9: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol lower velocity, in the rear boss location of new helmets following half a season of normal use?

RQ10: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol higher velocity, in the rear boss location of new helmets following half a season of normal use?

RQ11: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol lower velocity, in the rear location of new helmets following half a season of normal use?

RQ12: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol higher velocity, in the rear location of new helmets following half a season of normal use?

RQ13: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol lower velocity, in the top location of new helmets following half a season of normal use?

RQ14: Is there a difference in energy mitigation, using average peak g as measured according to the NOCSAE testing protocol lower velocity, in the top location of new helmets following half a season of normal use?

Hypotheses

H_1 There will be no difference in the energy mitigating capacity, as measured by overall average peak g from the lower velocity, in new helmets following half of a season of normal use.

H_2 There will be no difference in the energy mitigating capacity, as measured by overall average peak g from the higher velocity, in new helmets following half of a season of normal use.

H_3 There will be no difference in the energy mitigating capacity, as measured by average peak g from the lower velocity, in the front location of new helmets following half of a season of normal use.

H_4 There will be no difference in the energy mitigating capacity, as measured by average peak g from the higher velocity, in the front location of new helmets following half of a season of normal use.

H_5 There will be no difference in the energy mitigating capacity, as measured by average peak g from the lower velocity, in the side location of new helmets following half of a season of normal use.

H_6 There will be no difference in the energy mitigating capacity, as measured by average peak g from the higher velocity, in the side location of new helmets following half of a season of normal use.

H_7 There will be no difference in the energy mitigating capacity, as measured by average peak g from the lower velocity, in the front boss location of new helmets following half of a season of normal use.

H_8 There will be no difference in the energy mitigating capacity, as measured by average peak g from the higher velocity, in the front boss location of new helmets following half of a season of normal use.

H_9 There will be no difference in the energy mitigating capacity, as measured by average peak g from the lower velocity, in the rear boss location of new helmets following half of a season of normal use.

H_{10} There will be no difference in the energy mitigating capacity, as measured by average peak g from the higher velocity, in the rear boss location of new helmets following half of a season of normal use.

H_{11} There will be no difference in the energy mitigating capacity, as measured by average peak g from the lower velocity, in the rear location of new helmets following half of a season of normal use.

H_{12} There will be no difference in the energy mitigating capacity, as measured by average peak g from the higher velocity, in the rear location of new helmets following half of a season of normal use.

H_{13} There will be no difference in the energy mitigating capacity, as measured by average peak g from the lower velocity, in the top location of new helmets following half of a season of normal use.

H_{14} There will be no difference in the energy mitigating capacity, as measured by average peak g from the higher velocity, in the top location of new helmets following half of a season of normal use.

Significance

Due to the known fact that materials, common to football helmets, can functionally degrade over time, differences in the energy mitigating characteristics preseason to midseason are expected. However, what is not fully understood is the exact magnitude associated with these purported changes. Further, it is unclear whether these changes would result in an increased risk of the brain injury of concussion. Ultimately, concussion prevention consists of small gains over time; thus, if there is a possibility of increasing a player's safety, then these efforts are of paramount importance.

Definition of Key Terms

Polycarbonate: outer shell of a football helmet

Energy mitigation: ability of the football helmet to dissipate the energy from an impact to the helmet, reducing its influence on the head and brain

NOCSAE: National Operating Committee on Athletic Equipment

NAERA: National Athletic Equipment Reconditioners' Association

HITS: Head Impact Telemetry System

Peak g: maximum force of gravity upon impact

Accelerometer: placed inside the headform to measure acceleration and the peak g that is exerted as the headform is dropped from various heights

Concussion: a transient metabolic injury to the brain resulting from a direct or indirect biomechanical force

Chapter 2

Literature Review

History of the Helmet

The first helmet designs date back to antiquity. These helmets were crafted from animal skins and intended to protect soldiers by reducing the blow of impacts targeting the head during war [1].

Figure 1 was pulled from https://en.wikipedia.org/wiki/Football_helmet and shows a leather helmet.

Common battle strategies of the day warranted hand-to-hand combat; therefore, protective headgear was deemed advantageous. However, weaponry in battle became much more advanced and leather helmets were rendered useless, as they could no longer serve to protect soldiers from high velocity projectiles. Thus, in the absence of appropriate materials and manufacturing processes, helmets were completely neglected from the battle dress of warfighters. Eventually, material innovation grew and metallurgist and manufacturers were enabled to mass-produce more advanced helmets, made from iron, bronze and eventually hi-tensile steel. Each material offers increasing abilities to protect against ballistic threats. Such headgear eventually became a standard issue for soldiers [1]. Due to adoptions of headgear for such protective applications, especially the importance and necessity of head protection, helmets soon transitioned from usage by soldiers to more common applications, namely work environments and sports

Helmets in Football

As popularity of, and participation in, sports has grown, there has been a concomitant rise in the risk of injury. Thus, the need for better protective gear became more and more relevant to American football. The number of deaths was significant in early football, with 109 fatalities recorded from 1945 to 1954, 138 fatalities recorded from 1955 to 1964, and an all-time high of 204 fatalities recorded from 1965-1974 [8]. In 1968 alone, thirty-two fatalities were recorded [4]. Thus, the NOCSAE was formed in 1969. This committee was formed with the sole purpose of designing a safety standard that sought to stop the deaths that were occurring from head injuries in football. In 1973, NOCSAE accomplished this goal by publishing the first ever set of standards. By 1978, the National Collegiate Athletic Association issued a requirement that all players must wear a NOCSAE certified helmet [4]. High school teams followed suit in 1980 and implemented NOCSAE certified helmet use as well [9]. As a result, football became a much safer sport, exemplified in 1990, which marked the first year with zero deaths in a competitive season since the beginning of fatality records [4].

Football Helmet Design

Modern football helmets are a significant advancement from original leather helmets donned by athletes in the early 1900s. Today, football helmets are composed of four main components: the outer shell, inner liner, faceguard, and a retention system. The outer shell provides the first layer of defense against the initial force of an impact. The rigid polymer of the shell provides the toughness and stability that is demanded in protection against the high velocity impacts that football entails. It also serves to distribute the energy from these impacts and transfer it to the inner liner. [10]. In turn, the inner liner absorbs the energy of the impact. Resiliency is required at this point as there is a finite amount of space in which the head can decelerate and stop before the energy is transferred to the brain. Foams are used to "dissipate energy over a broad area, sustain repetitive high-intensity impacts, and quickly return to their original shape" [10]. Next, the facemask, usually made from steel or titanium, provides face protection from fractures and lacerations by shielding the eyes, chin, and mouth. Finally, the retention system consists of a chinstrap, which provides a firm security that allows the helmet to remain secure on the head [10].

Figure 2 was pulled from the study of Gale A *et al*, performed in 1985 and shows an American football helmet with the outer polycarbonate shell component shown in red and the inner lining of the pads and foams shown in white.

Football Helmet Standards

As previously mentioned, NOCSAE developed a new set of standards to evaluate football helmets in 1973. Today the standard that is used is the Standard Test Method and Equipment Used in Evaluating the Performance Characteristics of Headgear/Equipment NOCSAE DOC ND 001- 15m17. Designed to protect against impacts related to football, procedures based on the NOCSAE standards attempted to duplicate the helmet-to-helmet impacts that occur in football [11]. To do this, a helmet is positioned on a headform and dropped onto an anvil at certain velocities from various locations of the helmet. An accelerometer that is placed inside the headform records the instantaneous acceleration, which can be used to calculate the resultant acceleration of Severity Index (SI), and the peak g, which is a good indicator of the amount of velocity that a helmet will be able to withstand upon impact. The SI value is defined by the formula [12]:

$$SI = \int_{0}^{T} A^{2.5} dt$$

A = is the instantaneous resultant acceleration
dt = time in seconds
T = duration

In order to receive NOCSAE certification and be approved for use, the SI value needs to fall below 1200 and the peak g needs to fall below 150g. These values assure the wearer that a skull fracture is not likely to occur. Furthermore, the Summation of Tests for the Analysis of Risk (STAR) system was implemented in 1911 in order to rank the performance of a helmet so that the consumer may know the quality of the helmet being purchased. The STAR system utilizes the NOCSAE protocol for twenty-four drops (four different locations from six different heights) and then creates the STAR value using the specific formula [13]:

$$STAR = \sum_{L=1}^{4} \sum_{H=1}^{6} E(L,H) \times R(a)$$

L = impact location
H = drop height
E = head impact exposure
R = injury risk
a = peak g

Head Injury in Football

With the development of the NOCSAE standards, there has been a steep decline in the amount of skull fractures, with the number of fatalities decreasing by 74% since their inception [14]. In fact, the standards were so successful, that a study designed and conducted with the assertion that they were not accurate, actually strengthened their validity. The study was performed with the hypothesis that the NOCSAE standard does not hold true because they cannot relate to true competitive play. The NOCSAE standards require that each location on the helmet be impacted only four times, when, in reality, a single location may experience a considerable number of impacts throughout a typical season. Therefore, the study targeted each location on a single helmet 100 times from a height of sixty inches, the most severe impact utilized in NOCSAE testing. Despite increasing the number of impacts required by NOCSAE standards twenty-five fold and using the highest NOCSAE velocity level, the results showed only a slight decline in performance, but not one significant enough to prevent the helmet from performing under the skull fracture threshold. It did, however, cause the helmet to fall into the above 80% risk of concussion value, solidifying that NOCSAE standards are designed to protect a player from a skull fracture, rather than from a concussion. However, it should be noted that the test was performed in the most extreme circumstances from the greatest velocities which rarely occur in football, as most impacts are of the subconcussive nature [15]. Furthermore, NOCSAE standards are not designed to prevent concussions due to the complexity of the head injury and the lack of a known threshold at which they occur.

Concussions are the most common sport-related brain injury to date, with a prevalence of as many as 3.8 million incidences in the United States per year [6]. They occur when the helmet cannot absorb or distribute the force of an impact, causing the brain to move within the cranial vault both linearly and rotationally [16]. This action of the brain can result in the spontaneous activation of neural synapses resulting in a depolarization of neurons, which produces an uncontrollable metabolic shift in brain function. This shift can produce a multitude of symptoms such as loss of memory, balance, and cognitive functions [6]. Concussions are especially dangerous in that they are sometimes considered a “silent injury” [17], with studies estimating that up to 53% of concussions may go unreported [18]. In addition, concussions do not simply have to occur from a single, high velocity impact. Subconcussive impacts have become of great concern because, if repetitive, they can potentially impair cerebral functions without leading to any observable signs or symptoms [19]. Subconcussive impacts can also cause damage to the central nervous system by having the capability of transferring a high degree of linear and rotational acceleration to the brain [19]. In fact, continuous subconcussive impacts to the head may inflict the same, if not more, damage than a single concussive impact, as demonstrated in a study testing the adverse effects that occurred from the ball to head impacts in soccer players [20]. The danger of repetitive subconcussive impacts is evident, with studies stating that a single football player will sustain around 6.3 impacts per practice and 14.3 impacts per game, with anywhere from 1400 up to 2200 head impacts in a single season [7,15]. Unfortunately, as it is unclear how many and to what intensity subconcussive impacts need to occur in order to lead to a concussion, reducing the threat is more challenging. In fact, concussions are such a complex head injury that concussive thresholds from a single impact are yet to be discovered. If such knowledge did exist, then players could be closely monitored in order to reduce their risk for concussions [19].

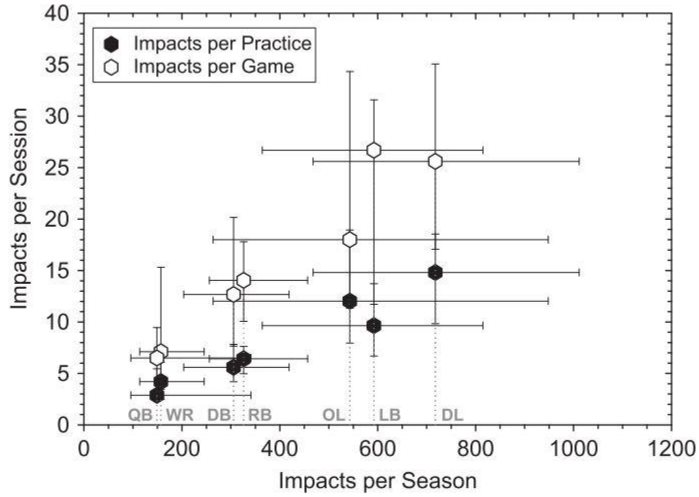
As many variables factor into the causes for concussion, determining the threshold is challenging. Common examples of these factors include the frequency, magnitude, and location of the impact placed upon the helmet [21]. These factors are impossible to determine through observation of the naked eye; thus, technology may aid in the calculation of these measurements and hopefully reducing the risk of concussion by providing insights into the mechanical forces applied to the brain during typical impacts.

Head Impact Telemetry System

The Head Impact Telemetry System (HITS), coupled within the Sideline Response System, is a wireless system that was created to help identify moments in which a player has received an impact to the head that results in concussive injury To from either linear or rotational impacts [6]. Two main components of HITS allow it to develop this calculation: an encoder placed inside the football helmet and a computer located on the sideline. The computer receives the data from the encoder and determines the location and magnitude of the impact [22]. Since the HITS system is capable of measuring frequency, magnitude, and location of the impact without interfering with the normal play of the game, studies can be conducted in real time in order to gain further knowledge on concussions [23]. The system is incorporated into only Riddell® produced products, namely the Riddell Revo Speed® and Speedflex® helmets.

Impacts by Position

A study done by Crisco *et al* utilized the HITS system to observe the frequency, magnitude, and location of impacts based on position of the football player. The study observed 314 players from the collegiate level, categorized into seven different positions: defensive line, linebacker, defensive back, offensive line, running back, wide receiver, and quarterback. In the study, five measures were calculated: practice impacts, game impacts, impacts per season, impacts per practice, and impacts per game. Four locations were also measured: front, side, back, and top. By the end of the study, a total of 286,636 impacts had been analyzed from fifty practices and twelve games. The positions of defensive line, linebacker, and offensive line received the highest frequency of impacts in a season, while the positions of wide receiver and quarterback received the lowest frequency of impacts in a season. Running backs received the greatest magnitude of impacts, while the offensive and defensive line, though receiving the greatest frequency, received the lowest magnitude of impacts. For impacts to the front of the helmet, the frequency was highest for offensive line and the magnitude was greatest for running back. For the side location, the magnitude was the greatest for the running backs, while the offensive line actually received the fewest and smallest magnitude of impacts in relation to other positions. For the top of the helmet, impacts occurred with the least frequency but the highest magnitude among players of all positions, with the position of running back experiencing the most. For the back of the helmet, the magnitude and frequency of impacts was the greatest in quarterback and wide receiver. The results of this study demonstrated that the position of the player did indeed play a significant role in the magnitude, frequency, and location of impacts throughout a season of play [21].



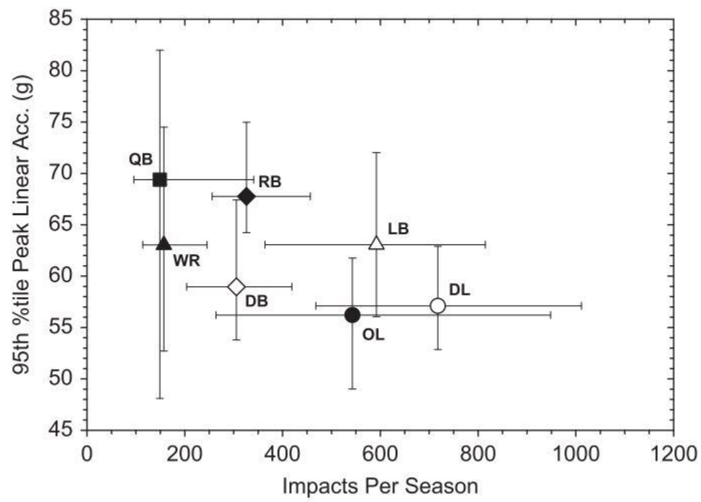


Figure 3 (top) and Figure 4 (bottom) was pulled from the results of a study done by Cisco *et al* and that shows impacts and acceleration by position.

Impact Location in Normal Football Play

Research conducted by Guskiewicz and Mihalik shows that the most common concussion comes from the head down position, which occurs when an athlete lowers his head before being tackled, causing the head and neck to absorb most of the energy from the impact [6]. This finding is consistent with the conclusion of the previous study on impacts based on position of the player, affirming that the top position of the helmet receives the greatest magnitude of impacts. The head down position increases the mass of the athlete that delivers the hit by 67% through coupling the torso into the impact, causing the transfer of a greater amount of momentum into the athlete receiving the hit [6]. Another study, performed on high school football players, found that the front of the helmet experienced the greatest number of impacts that resulted in concussions, but the top location of the helmet resulted in the greatest amount of unconsciousness associated with the concussions [24]. The findings from all of these studies further suggests that, in competition, the front of the helmet receives the greatest frequency of impacts, while the top location receives the greatest magnitude of impacts, which could lead to increased degradation at these locations.

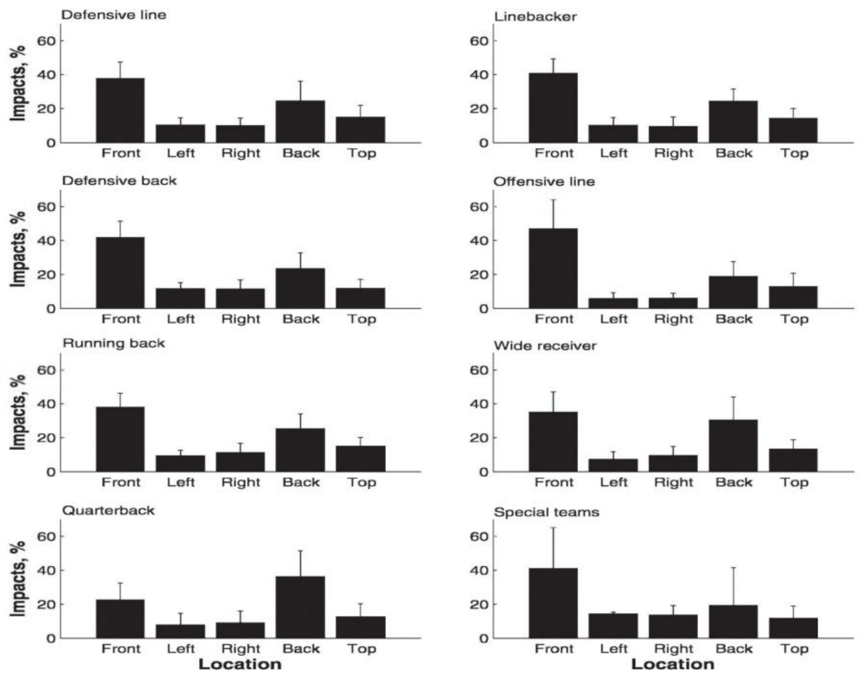


Figure 5 was pulled from a study done by Crisco *et al* in 2012 and indicates the percent of impacts that each individual location received for each position.

Football Helmet Degradation, Reconditioning, and Life Cycle

Based upon the known life cycle of the most common outer-shell material, Polycarbonate, NAERA has placed a ten-year lifespan on football helmets in 2011 [25]. The extent to the amount of degradation that occurs relative to time is unclear. It is certain, however, that over time, a helmet is faced with many challenges, as its materials are exposed to a variety of conditions resulting in degradation. The repetitive impacts, along with environmental factors, including temperature, ultraviolet light, moisture, and humidity, cause a decline in the helmet's performance quality [7]. The continuous application of stress by the numerous impacts on the helmet can change the way its material absorbs energy, more commonly referred to as material fatigue [15]. While the helmets may still pass NOCSAE test protocols by registering below the threshold for a skull fracture, degradation of the helmet still leaves players at a higher risk for concussions [10].

Reduction in the capacity of the helmet to provide protection led to the formation of a process with the sole purpose of maintaining the initial performance of a new American football helmet [10]. This process is monitored by the NAERA, previously mentioned, which is licensed by NOCSAE. According to the NAERA, over time and throughout multiple seasons, the safety properties of a football helmet may slowly degrade and result in an increased risk of head injury to athletes, which demands the existence of a reconditioning process to return the helmets to NOCSAE standards once again [10]. It is an extensive process that consists of completely disassembling a helmet, pressure washing it, examining it, cleaning it, and, if need be, repairing it [10].

Figure 6 was pulled from http://legacy.wkyc.com/story/news/health/concussions/2014/04/30/interactive--helmet-reconditioning/8522687/ and shows the effect that reconditioning has on a helmet

NAERA suggests that a football helmet be reconditioned every one or two years in order to minimize material fatigue. Therefore, as one season may be capable of causing enough degradation and decline in performance of the helmet to warrant intervention, our study takes it a step further by suggesting that one half of a season causes enough degradation in football helmets to warrant intervention.

Chapter 3

Methodology

Participants

Eleven players from a southern NCAA Division I football team were equipped with large Riddell® Revo Speed football helmets at the start to the 2016-17 season. These players were broken down into three Defense Backs, two Running Backs, two Tight Ends, two Quarterbacks, one Defensive Line, and one Linebacker. Though no human subject data was collected, each player was made aware that his helmet had been tested according to the standard NOCSAE testing protocol and that the helmets would also undergo continued testing throughout the season. Before receiving the helmet for use, each participant read and signed an informed consent document approved through the University's Institutional Review Board.

Instrumentation

NOCSAE testing protocol was performed at the School of Kinesiology Applied Biomechanics Laboratory.

Figure 7 was a picture taken of the inside of the facility.

A Cadex Twin-Wire Drop Testing Machine was used with an instrumented, triaxial accelerometer NOCSAE headform.

Figure 8 was a picture taken the Cadex twin wire machine that was used for testing.

Figure 9 was a picture taken of the headform that was dropped onto the anvil during testing.

NOCSAE Standard Testing Protocol

Prior to placing the helmet onto the headform, calibrations were performed for the front, side, and top positions. A three-inch MEP calibration pad, as per the protocol, was used. When impacted in congruence with certain velocities (17.55 ft/s for front, 16.95 ft/s for side, and 15.57 ft/s for top), the headform must achieve 1200 SI ± 2%.

Figure 10 was pulled from NOCSAE standards and shows the calibration of the headform before the helmet is placed on it.

Once the calibration of the headform was achieved, the half-inch MEP testing pad replaced the calibration pad and a system check was performed. The system check consisted of pre-calibration performed before testing and post-calibration performed after testing. Variation between the two must be 7% or less. For the pre-calibration, the headform was placed in the front boss position and dropped three times from a height of eighteen inches. The Cadex Software system was used to record the average SI and peak g.

After pre-calibration was performed, the actual testing of the helmets began. The headgear was placed on the headform and dropped from the various six positions of front, side, front boss, rear boss, rear, and top.

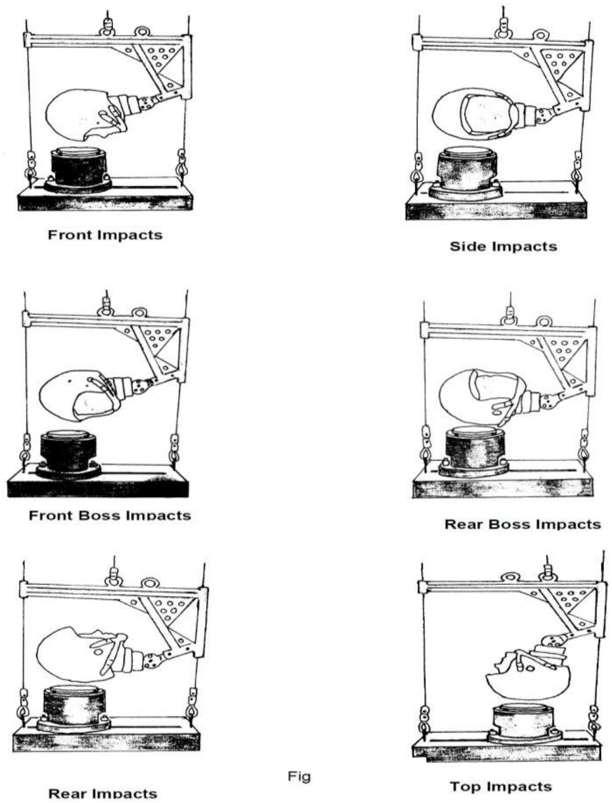


Figure 11: depicts the different types of angles that were utilized in the processing of dropping the head form, with the football helmet, onto the anvil.

For this experiment, the helmets were dropped from the minimum and maximum heights according to NOCSAE standard protocol, which approximates both twenty-five inch and sixty-one inch drop heights, thus achieving 11.34 ft/s and 17.94 ft/s respectively. Each helmet was dropped from the two heights three times for each position, with the time between drops being within 75 ± 15 seconds. Upon impact to the anvil, the triaxial accelerometers measured the change to acceleration. The resultant acceleration was used to find the Severity Index (SI) and the peak g's via an internal algorithm within the cadex system [26]. According to NOCSAE standards, to ensure safety to the players, each impact must be well below 1200 SI and 150 g. Also, for the helmet to meet NOCSAE standards, the impact velocity in the last forty millimeters of the free fall must be within the NOCSAE limits [Standard]. If the measurements do not fall within the limits, then the experiments must be repeated until the correct value is found multiple times or until it is certain the helmet will not meet the standards and is thrown out. Using the data collected from the sensor embedded within the head form, peak acceleration (g) was calculated. After testing the helmets from each of the impact locations, the post-calibration system check was performed. This step was identical to the pre-calibration and required that the variation be within 7%. If not, the data was disregarded.

After baseline NOCSAE testing was completed in the preseason, the helmets were returned to the Southern Miss football team. Then, halfway through the season the same NOCSAE experiments were performed on the same eleven helmets. The findings were then charted, separating the helmets by position and recording the average g for each impact location. The results of the drops from the different angles were observed and analyzed to see if there was a significant difference in the preseason versus the midseason.

Data Analysis

The data was analyzed using the Statistical Package for the Social Sciences (SPSS: IBM Corp. Version 22). All descriptive statistics are presented as measures of central tendencies. Potential differences in mean scores were evaluated by a paired sample *t*-test using a Bonferroni correction (0.05/ # of pairs) to avoid a Type I error in outcomes interpretation. Type I error rate was set *a priori* at 0.05, with 0.003 after the application of the Bonferroni correction.

Chapter 4

Results

Velocity Measurement Across Locations

All peak g's recorded were accepted in alignment with the NOCSAE's Standard Test Method and Equipment Used in Evaluating the Performance Characteristics of Headgear/Equipment NOCSAE DOC ND 001- 15m17. Measurements show the mean peak g of helmets impacted in each location, from the lower and higher velocities, at the preseason and at the midseason. In addition, the overall average of all the helmets and all of the locations is reported.

Table 1. Preseason and midseason mean peak g by impact location at lower velocity

Helmet Location	Impact Velocity (ft/s)	Preseason Mean Peak g (g)	Midseason Mean Peak g (g)
Front	11.34	62.291	64.300
Side	11.34	63.764	64.491
Front Boss	11.34	62.300	71.936
Rear Boss	11.34	53.382	52.773
Rear	11.34	52.145	52.318
Top	11.34	49.991	48.482
Overall	11.34	57.312	59.050

- The preseason and midseason peak g values listed are a mean of the eleven tested football helmets

Table 2. Preseason and midseason mean peak g by impact location at higher velocity

Helmet Location	Impact Velocity (ft/s)	Preseason Mean Peak g (g)	Midseason Mean Peak g (g)
Front	17.942	119.645	125.900
Side	17.942	118.964	111.736
Front Boss	17.942	111.582	118.918
Rear Boss	17.942	109.345	100.973
Rear	17.942	94.500	94.455
Top	17.942	108.609	103.627
Overall	17.942	110.441	109.268

- The preseason and midseason peak g values listed are a mean of the eleven tested football helmets

Comparison of Preseason and Midseason

In order to determine if the differences in preseason to midseason from any of the impact locations and velocities listed in the table above were of significant value, a paired sample *t*-test, with the Bonferroni correction, was applied.

Table 3. Paired sample t-test of preseason vs. midseason at lower velocity

Helmet Location	Impact Velocity (ft/s)	t-score	Degrees of freedom	*p*-value
Front	11.34	-0.487	10	.637
Side	11.34	-0.710	10	.494
Front Boss	11.34	-6.158	10	.000
Rear Boss	11.34	0.549	10	.595
Rear	11.34	-0.135	10	.895

Top	11.34	2.496	10	.032
Overall	11.34	-1.693	10	.121

* a negative sign denotes a decrease in performance quality

* the values displayed represent a difference in the preseason and midseason values

Table 4. Paired sample t-test of preseason vs. midseason at higher velocity

Helmet Location	Impact Velocity (ft/s)	t-score	Degrees of freedom	*p*-value
Front	17.942	-2.639	10	.025
Side	17.942	2.656	10	.024
Front Boss	17.942	-4.075	10	.002
Rear Boss	17.942	5.836	10	.000
Rear	17.942	0.016	10	.988
Top	17.942	2.532	10	.030
Overall	17.942	0.883	10	.398

* a negative sign denotes a decrease in performance quality

* the values displayed represent a difference in the preseason and midseason values

Significant Differences

A significant difference from the preseason to the midseason is denoted by a *p*-value less than 0.003, due to the Bonferroni correction. Three conditions resulted in statistically significant differences between the mean peak g of the two time points (preseason testing to midseason testing). These conditions were the front boss location from both the highest velocity (17.492 ft/s) and lowest velocity (11.34 ft/s) impacts and the rear boss location from the highest velocity impact (17.492 ft/s) as shown in Table 5.

Table 5. Bar graph revealing significant differences

- a lower peak g value represents a better performance value

Chapter 5

Discussion

The goal of this study was to determine if one half of a competitive season of normal use results in any meaningful changes in impact characteristics of an American football helmet. The null hypothesis stated that there would be no difference in the energy mitigating capacity, as measured by peak g from the lower and higher velocities, for overall and each individual location in new helmets following half of a season of normal use. Materials common to football helmets are known to degrade over time; thus, differences between the preseason (when the helmets were brand new) and the midseason were expected.

Preseason vs. Midseason from a Lower Velocity

Following the NOCSAE testing standard, each helmet was dropped at six locations from one of two fixed heights. The first resulted in an impact velocity of approximately 11.34 ft/s. This impact velocity is equivocal to a very low magnitude, but highly typical, impact event that occurs throughout football play. In preventing head injury from football impacts, the role of the helmet system is to receive the blow to the outer shell and disperse the focal energy across a broader surface area. The force then transmits into the inner liner, which serves to provide a resistant counterforce that dissipates the energy as heat. This liner system has a fixed design height within the shell, which approximates up to 1.5 inches. As the impact event is underway the liner collapses, working to mitigate the force in order to elongate the time it takes for the entire event to occur. The result of this elongation of time is that the peak g is lowered. If the impact force is too high, the energy will not be fully mitigated prior to full compression of the liner system, which results in focal forces being transmitted directly into the head. Lower velocities do not utilize the full thickness of the liner and energy is more easily mitigated. Overall differences in peak g performances varied bi-directionally across testing sites. It was expected that peak g would increase (decline in performance) if degradation had occurred. For the Front Boss location we observed a statistically significant increase in peak g (9g or 9 times the force of gravity exerted to the brain). However, most differences were menial at best and two locations demonstrated an observable, though not statistically significant, decrease in peak g (improvement in performance). It is becoming better understood that impacts to the Front and Top of the helmet are among the most common and intense from the perspective of magnitude. During the first half of the season, it is postulated that the Front Boss of the helmets experienced a different history (frequency and/or magnitude of impacts) than other areas, which resulted in some level of liner breakdown, leading to a poorer performance at midseason testing. As alternate locations of the helmet performed differently, it can be assumed that underlying materials underwent a period of "breaking in." This transition from a post-production stiffness to a more useable pliability resulted in variation of performance.

Preseason vs. Midseason from a Higher Velocity

Following the NOCSAE testing standard, identical tests were run on each of the six impact locations, but dropped from a fixed height that resulted in an impact velocity of 17.942 ft/s. This impact velocity is equivocal to a very high magnitude, but atypical, impact event that occurs throughout football play. This high magnitude impact is more likely to require utilization of the full thickness of the liner when compared to the lower magnitude impact. This can result in the risk of the time elongation period not being sufficient enough to fully mitigate the energy of the force before being transmitted to the head. Overall differences in peak g performances varied bi-directionally across testing sites for the higher velocity as well. It was expected that peak g would increase (decline in performance) if degradation had occurred. For the Front Boss location we observed a statistically significant increase in peak g (7g or 7 times the force of gravity exerted to the brain). For the Rear Boss location, we observed a statistically significant decrease in peak g (8g or 8 times the force of gravity exerted to the brain). However, the results for the higher impact velocities were perhaps even more menial than the lower impact velocities, with only two locations demonstrating an increase in peak g, regardless of statistical significance. During the first half of the season, it is postulated that the Front Boss and the Rear Boss of the helmets experienced very different histories (frequency and/or magnitude of impacts) than other areas. The liner of the Front Boss location resulted in some level of breakdown and decline in performance quality, whereas the liner of the Rear Boss location underwent a highly effective period of "breaking in," as improvement in performance quality not only increased, but significantly increased.

Overall Performance of Helmets

Differences in the overall performances of the helmets from the preseason (new) to the midseason were negligible, with the change in mean peak g from the lower impact velocity and higher impact velocity being a 1g increase (decline in performance) and a 1g decrease (improvement in performance), respectively. Since we expected to see some level of decline in performance in helmets that experienced degradation, it is postulated that one half of a season is not enough time exposure for helmets to experience such degradation. It is understood that the two major effects on helmet degradation are environmental factors and repetitive impacts. Circumstances such as exposure to sunlight and storage in thermally uncontrolled environments play major roles in the environmental degradation. However, given that the length of this study consists of just one half of a season, it is reasonable to assume that no environmental degradation will occur. Therefore, repetitive impacts were the main component of helmet degradation that was analyzed in these results. At this time, there is no data in the available scientific literature to fully disclose the amount of repetitive impacts required to result in a decline in impact mitigation performance. This study observed half a season of college football season, with expectations of approximately twenty to thirty practices and six games taking place. During this period, based on the Cournoyer *et al* (2016) theory that 6.3 impacts occur per practice and 14.3 impacts occur per game, it is reasonable to expect anywhere from 211-275 impacts to occur. As there was very little overall difference in the mean peak g, it is clear that this amount of impacts was not enough to cause significant degradation in our study group. This evidence may help provide clarity in determining the amount of impacts resulting in degradation.

Although testing of the overall performance of the helmet is important, analysis of potential degradation in individual locations of the helmet is crucial as well. As previously mentioned, each location of the helmet has its own unique history relative to its anatomy and impact frequency and/or magnitude. The anatomy of the head and neck accounts for the difference in peak g values among the various locations of the helmet (*e.g.* Rear and Top locations tend to record lower peak g values than Front and Side). The movement of the neck and the shape of the head are two main components that cause the difference in the characteristics of the various locations of the helmet. The six movements that the neck can perform are flexion (lowering of the chin to the chest), extension (raising of the head to the ceiling), lateral rotation (rotating the head to the left or right), and lateral flexion (moving the head left or right, bringing the ear to the shoulder). Each of these different movements contains a different, limited range of motion. Typically, flexion consists of 80 to 90 degrees of motion, extension consists of 70 degrees of motion, lateral rotation consists of 90 degrees of motion, and lateral flexion consists of 20 to 45 degrees of motion [27]. This affects peak g because the greater the range of motion, the more time the head has to absorb the force of the impact. For example, when the Rear location of the helmet is impacted, the neck provides the head with 90 degrees of forward flexion, giving the head more time to absorb the force of the impact. Alternatively, the neck only provides the head with 70 degrees of extension to absorb an impact to the Front location of the helmet. This accounts for the lesser values of peak g seen in the Rear location compared to the Front location. The shape of the head affects peak g by way of mass and surface area. For example, the posterior portion of the head consists of a large mass (relative to the rest of the head) concentrated over a small surface area, accounting for better resistance against the force of impacts. Alternatively, the anterior portion of the head has a smaller mass distributed over a larger surface area, accounting for the lesser resistance against the force of impacts. Similarly, in comparing the side of the head to the top of the head, the top has a larger mass concentrated in a small surface area versus the side of the head having a smaller mass distributed over a larger surface area. These different shapes in the various locations on the head may account for the variation in peak g observed in tests (the Front and Side locations result in higher peak g values than the Top and Rear locations). In addition, it has become better understood that the Front area of a helmet (Front and Front Boss locations) is impacted the greatest in terms of frequency and the Top area of a helmet is impacted the greatest in terms of magnitude. This makes sense in comparison to normal play, as impacts typically occur from a head-on collision of two players running in opposite directions. Proper tackling form dictates that, as two players are about to collide, they slightly turn their heads to the side. This results in impacts that target the Front Boss location of the helmet. Therefore, degradation would be expected to occur sooner and to a greater extent in the Front Boss location. The expected outcome occurred as results showed a significant increase in peak g for the Front Boss location. On the other hand, the Top location of the helmet experienced a slight, but not significant, decrease in peak g. Although impacts to the top of the helmet typically result in a higher magnitude when compared to impacts to other areas of the helmet, they are not common in normal play. In fact, they are highly frowned upon as they would typically occur during a tackle utilizing the, now illegal, "head-down" form. The rare occurrence of impacts to the Top location of the helmet may account for the improvement in performance, as just enough impacts targeted the Top location to result in the "break in" of the inner foam.

Therefore, our study demonstrated that significant degradation of overall function does not occur in only one half season of football, but that certain locations of the helmet do vary in performance due to the difference amount of impacts that each receive throughout normal play. For example, there was a significant improvement in the performance of the Front Boss location of the helmet and a significant decrease in performance of the Rear Boss location of the helmet. These findings may serve to assist future studies that seek to observe the same research questions, extended over a longer period of time.

Limitations and Future Research

A sample size of n=11 limited the ability to divide the helmets into positions to see if the position of the athlete would have an effect on the ability of the helmet to maintain its energy mitigation properties. As previous studies have found that the position of football players does have an effect on concussions, future studies would need to be performed in order to see if certain positions receive more degradation than others from one half of a competitive season. Utilization of the HITS system was beyond the scope of this study, but could be utilized for future investigations analyzing real time effects of impacts on helmet performance, including data based on player position. Further knowledge on helmet degradation variation in position could lead to the development of helmets unique to each position, based on the information found on the extent of degradation to each specific location.

Chapter 6

Conclusion

Research on concussions is being conducted at an all-time high. The seriousness of the injury and the need to prevent it has resulted in a better understanding of concussions, but robust advances towards prevention have been quite elusive. The set of standards established by NOCSAE in 1973 was intended to diminish the occurrence of skull fractures, but do not address the parameters required for concussion prevention. While it is understood that they fall below that of a skull fracture, the lack of a set threshold leads to uncertainty in the ability to design a helmet that reduces the incidence of concussions. With the only understanding of concussive thresholds being that they exist below the skull fracture threshold and the knowledge that a lower peak g value denotes a safer helmet, the only possible reduction in risk factors is achieved through designing a helmet with the lowest peak g value possible. Therefore, the negative effects of helmet degradation pose a threat to the safety of a football player. The repetitive impacts and environmental factors that a helmet is exposed to throughout its competitive use leads to a decrease in its energy mitigation capability. While the helmet may still meet NOCSAE standards for preventing a skull fracture, a higher peak g value increases the risk for a concussion. In addition, reconditioning was designed to ensure that a helmet remains within NOCSAE certification standings, but not to prevent concussions. The aim of this study, therefore, was determined if there is significant degradation in the effect of normal helmet use during the first half of a competitive season, as measured by peak g values.

There was no significant difference in the overall mean peak g for all eleven helmets from the preseason to the midseason. However, the mean peak g for impacts to the Front Boss location did experience a significant increase in peak g. This finding is consistent with the research that states that most of the impacts from competitive football play occur to the front of the helmet (Front Boss included). Furthermore, with degradation of helmet requiring the existence of a ten-year lifespan and a reconditioning process (typically every two years), future research is highly recommended. The connection between high frequency impacts to the Front Boss location and the degradation in the Front Boss location is an important step in bridging the gap that exists in preventing concussions and hopefully will provide a stepping-stone into the development of future research.

References

1. Hoshizaki TB and Brien SE. The Science and Design of Head Protection in Sport. *Congress of Neurological Surgeons* 2004, *55*(4): 956-967.
2. A Brief History of the Game. Alameda High School. 2015. www.hornetfootball.org
3. Gurdjian ES, Lange WA, Patrick LM, et al. Impact injury and crash protection. Thomas CC, editor. Springfield, Illinois. 1970.
4. History and Purpose. National Operating Committee on Standards for Athletic Equipment. www.nocsae.org.
5. Traumatic Brain Injury & Concussion. *Centers for Disease Control and Prevention*, 2017. www.cdc.gov
6. Guskiewicz KM and Mihalik JP. Biomechanics of Sport Concussion: Quest for the Elusive Injury Threshold. *Exercise and sport sciences reviews*, 2011. 39(1): 4-11.
7. Krzeminski DE, Fernando D, Gould TE, et al. Quantifying the effects of accelerated weathering and linear drop impact exposures of an American football helmet outer shell material. *Sports Engineering and Technology*, 2014. 228(3): 171-187.
8. Mueller FO. Fatalities from head and cervical spine injuries occurring in tackle football: 50 years' experience. *Clin J Sports Med* 1998, 17(1): 169-182.

9. Hodgson, VR. National Operating Committee on Standards for Athletic Equipment football certification program. *Medicine & Science in Sports* 1975, 7(3): 225-231.

10. Gould TE, Piland SG, Krzeminski DE, et al. Textiles for Sportswear. *Protective Headgear for Sports,* 2015: 213-244.

11. Viano DC and Halstead D. Change in Size and Impact Performance of Football Helmets from the 1970s to 2010. *Biomedical Engineering Society*. 2011: 175-184.

12. NOCSAE ND001-15m17. Standard Test Method and Equipment Used in Evaluating the Performance Characteristics of Headgear/Equipment. National Operative Committee on Standards for Athletic Equipment 2017.

13. Rowson S and Duma SM. Development of the STAR Evaluation System for Football Helmets: Integrating Player Head Impact Exposure and Risk of Concussion. *Biomedical Engineering Society*, 2011.

14. Levy ML, Ozgur BM, Berry C, et al. Birth and Evolution of the Football Helmet. *Oxford Academic- Neurosurgery*, 2004. *55*(3).

15. Cournoyer J, Post A, Rousseau P, et al. The Ability of American Football Helmets to Manage Linear Acceleration With Repeated High-Energy Impacts. *Journal of Athletic Training*, 2016. 51(3): 258-263.

16. Vetter L, Vanderby R, and Broutman LJ. Influence of Materials and Structure on Performance of a Football Helmet. *Polymer Engineering and Science*, 1987. 27(15).

17. Kirkwood MW, Yeates KO, Taylor HG, et al. Management of Pediatric Mild Traumatic Brain Injury: A Neuropsychological Review from Injury Through Recovery. *NCBI*, 2008. 22(5): 769-800.

18. McCrea M, Hammeke T, Olsen G, et al. Unreported concussion in high school football players: implications for prevention. *Clin J Port Med*, 2004. 14(1): 13-7.

19. King D, Hume P, Gissane C, et al. The Influence of Head Impact Threshold for Reporting Data in Contact and Collision Sports: Systematic Review and Original Data Analysis. *Sports Med*, 2016. 46: 151-169.

20. Webbe F, Barth J. Short-term and long-term outcome of athletic closed head injuries. *Clin Sports Med* 2003, 22(3): 577-92.

21. Crisco JJ, Wilcox BJ, Beckwith JG, et al. Head impact exposure in collegiate football players. *Journal of Biomechanics*, 2011. 44: 2673-2678.

22, Broglio SP, Sosnoff JJ, Shin S, et al. Head Impacts During High School Football: A Biomechanical Assessment. *Journal of Athletic Training*, 2009. 44(4): 342-349.

23. Rowson S, Duma SM, Beckwith JG, et al. Rotational Head Kinematics in Football Impacts: An Injury Risk Function for Concussion. *Annals of Biomedical Engineering*, 2012. 40(1): 1-13.

24. Kerr ZY, Collins CL, Mihalik JP, et al. Impact Locations and Concussion Outcomes in High School Football Player-to-Player Collisions. *Pediatrics*, 2014. 134(3): 489-

25. Fisher E. 10-Year Helmet Reconditioning Policy. *National Athletic Equipment Reconditioners Association*, 2011.

26. *Standard Test Method and Equipment Used in Evaluating the Performance*

Characteristics of Headgear/Equipment. NOCSAE DOC ND 001-13m15c. Prepared by NOCSAE. Modified: June 2015.

27. Singh AP. Range of Motion of Cervical Spine. *Bone and Spine*, 2016. www.boneandspine.com