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Brain Injuries in American Football: Understanding the Injury, Difficulty in Helmet Optimization, and Current Communication Practices – A Narrative Review

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ABSTRACT

Background: Over 2.7 million people suffer traumatic brain injuries (TBIs) annually in the United States. TBI involves the application and generation of external forces and impulse loads respectively to the head whereby the brain moves relative to the skull. Despite numerous studies, further understanding of TBIs is necessary, requiring consistent attention. **Objective:** The purpose of this article is to investigate the history of American football helmets and provide an academic and practitioner review as it relates to TBIs. This study is a literature review that also considers perspectives from an autoethnographic frame. **Method:** An extensive literature review was performed to assess the history of TBI as it relates to American football. This article evaluates helmet design optimization and American football safety as well as an exploration into the sports' education methods for players and staff alike. **Results:** Despite developing helmet designs that can better attenuate impact forces, reducing linear and rotational movement, the skull and brain move very differently relative to one another. Helmet designs and tools for measuring forces require further validation techniques to determine resultant forces and movement for the brain. Current biomechanics research lacks sufficient methodology for defining TBI thresholds, making helmet optimization difficult. **Conclusion:** According to past research, no helmet can eliminate all TBI risk; however, processes are in place lead by the National Football League (NFL) and NFL Players Association to educate players, coaches, and staff at all levels of competition of the protective capabilities of available helmet options.

Key words: United States Football, Traumatic Brain Injuries, Brain Concussion, Biomechanics, Safety Management, Athletics Injuries

INTRODUCTION

Sports-related concussions are estimated to account for an average of 2.7 million or 20% of the traumatic brain injuries (TBI) reported in the United States annually (Daneshvar, Nowinski, McKee, & Cantu, 2011; Manoogian, McNeely, Duma, Brolinson, & Greenwald, 2006; Saulle & Greenwald, 2012). Yet, this statistic has been regarded as a gross underestimate due to the prominence of people neglecting to seek out medical attention following mild to moderate TBI or concussions (Bartsch, Benzel, Miele, & Prakash, 2012; Daneshvar et al., 2011; McKeithan, Hibshman, Yengo-Kahn, Solomon, & Zuckerman, 2019; Saulle & Greenwald, 2012). TBI is categorized by a clinically-derived severity scale, the Glasgow coma scale (GCS), which assigns points to basic functional and mental deficits related to visual, eye, and motor responses (Teasdale & Jennett, 1974). The scale is broken down into mild, moderate, and severe ratings, where minimal mental status changes characterize mild TBI (mTBI) and amnesia or extended period of unconsciousness discern severe TBI (McKeithan et al., 2019; Teasdale & Jennett, 1974).

Sport Related Brain Injuries

TBI involves the application of an external force to, or transmitted to, the head that generates an impulse load whereby the brain moves relative to the skull (Lloyd & Conidi, 2016; McKeithan et al., 2019). Though the terms are commonly used interchangeably, concussions are a subset of mTBI and clinically describe the symptoms imposed by a mTBI (McCrory et al., 2017; McKeithan et al., 2019). Symptomatically, mTBI relates to a plethora of behavioral, physical, somatic and cognitive changes which include signs such as dizziness, headaches, sleep disturbance, slowed reaction time, and irritability (Bartsch et al., 2012; Daneshvar et al., 2011; Emery et al., 2017). These symptoms characteristically commence rapidly following the injury and resolve spontaneously within 2-3 weeks, which often allows these

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injuries to go unrecognized by coaches, trainers, and even the athlete (Daneshvar et al., 2011; McKeithan et al., 2019). Approximately 53% of these football-related concussions occurring at the high school level go unreported, feeding into the already prominent underestimation for annual sports-related TBIs (Bartsch et al., 2012; Daneshvar et al., 2011). Additionally, defining a concussion by the general grouping of symptoms previously mentioned presents a major flaw, in that it does not provide any insight into varying severities, mechanism of impairment or prominent functional abnormalities (McCrory et al., 2017). Perhaps even more worrisome, is that the acute injury, being concussive or repeated sub-concussive impact, may not result in any observable signs for which a diagnosis can be made (Ford et al., 2018). In fact, loss of consciousness, one of the most easily recognizable and diagnosable consequences of concussion, does not even occur in 90% of sports-related concussions and serves as no indication for the severity of the injury (Broglio, Surma, & Ashton-Miller, 2012).

Every TBI severity classification has been documented in American football injuries spanning the last decade (Boden, Tacchetti, Cantu, Knowles, & Mueller, 2007; Daneshvar et al., 2011; Forbes et al., 2013). Severe or catastrophic injuries result in macroscopic lesions to the brain inclusive of subdural hematomas, diffuse brain edema, aneurysm and skull fractures (Bartsch et al., 2012; Boden et al., 2007; Forbes et al., 2013; Lloyd & Conidi, 2016). A review covering reported catastrophic injuries among high school and collegiate football players from 1989 to 2002, found that 9% of these athletes died as a result of the catastrophic injury and 51% of them suffered a permanent neurological injury (Boden et al., 2007). In the last decade or so, growing interest has evolved around concussive and sub-concussive impacts due to their potential role in long-term neurological deficits and onset for neurodegenerative disease (Ford et al., 2018; Goriely et al., 2015; Mckee, Abdolmohammadi, & Stein, 2018; McKee et al., 2010). The progressive neurodegenerative disease hypothesized to initiate from the accumulation of concussive and sub-concussive impacts, is termed chronic traumatic encephalopathy (CTE) (Mckee et al., 2018; McKee et al., 2010). CTE has been most notably studied in former professional boxers and National Football Players (NFL) and shares many of the same initial symptoms of concussions but, as the disease progresses, symptoms further resemble both Alzheimer's and Parkinson's disease (Mckee et al., 2018; McKee et al., 2010). Despite increased research efforts, the exact pathophysiological mechanisms for CTE and all mTBI injuries are inadequately understood (McCrory et al., 2017; Mckee et al., 2018; McKee et al., 2010).

History of TBI in American Football

Football has implemented many changes over the years to support player safety including mandates for certain protective gear as well as more rules and guidelines for gameplay in the sport (Bartsch et al., 2012; Levy, Ozgur, Berry, Aryan, & Apuzzo, 2004). However, the path to creating these changes has been quite gruesome. The use of helmets and ever-evolving designs is unfortunately due to the hundreds of fatalities American football has generated over the years (Bartsch et al., 2012; Boden et al., 2007; Levy et al., 2004; Lloyd & Conidi, 2016). Many of these fatalities were a direct cause of catastrophic TBI's, namely being skull fractures (Bartsch et al., 2012; Campolettano, Gellner, & Rowson, 2018; Levy et al., 2004; Lloyd & Conidi, 2016).

The incorporation of the first leather helmet occurred in 1890s and further progressed into plastic and shelled designs beginning in the 1930s (Bartsch et al., 2012; Levy et al., 2004; Lloyd & Conidi, 2016). With the initial implementation of helmets in the late 1930s through the early 1940s, head injuries actually increased due to the heightened occurrence of head-to-head collisions (Bartsch et al., 2012; Levy et al., 2004; Lloyd & Conidi, 2016). In the 1970s, upon formation of the National Operating Committee on Standards for Athletic Equipment (NOCSAE), a governing body mandating adequate helmet standards based on linear accelerations tolerances of impact, catastrophic TBI's declined by a notable 74% (Levy et al., 2004). However, catastrophic injuries only account for macroscopic consequences. There are also the neurologic deficits from concussions that continue to significantly increase and have even been referred to as the "silent epidemic" (Collins et al., 2016; Greenhill et al., 2016). Additionally, although the involvement of NOCSAE generated an almost immediate decline in catastrophic injuries in the 1970s, several researchers have remarked that catastrophic injuries are at a 30-year high, highlighting that the yearly incidence of these injuries increased by 238% when comparing reports from 2008-2012 to those from 1998-2002 (Forbes et al., 2014, 2013; Levy et al., 2004). Just as there is little understanding of the mechanisms for TBI, the reason for increases in TBI over the years is also unknown (Forbes et al., 2013).

PREVIOUS RESEARCH (BIOMECHANICS OF TBI)

Biomechanics encompasses several fields, all focused on brain injuries but approaching the problem from different perspectives. In particular, biomechanics is heavily involved in understanding the mechanisms of injury and the brain's response to impact at the macroscopic and microscopic levels, while utilizing various mechanical concepts to characterize tolerances for these impacts (Zhang, Yang, & King, 2001). Though biomechanics is generally engineering-based, the study of brain biomechanics relies heavily on the interplay of advancements in clinical, biochemical, and biomechanical fields. However, the scope of this review focuses on the several approaches in biomechanical methodology for influencing helmet design optimization.

Brain Tissue Mechanics

To tackle the concept of TBI, understanding the extensive variability in anatomical structures, relative cellular distributions, cellular morphologies and biochemical processes involved in the normal and altered function of the brain are inherently important factors. However, understanding this dynamic process requires dissecting the problem in more controlled testing environments which, is generally done via the use of surrogate models. While some surrogate models for TBI involve *in vivo* animal studies to mainly derive pathophysiological-related responses, *in vivo* and *ex vivo* studies can also be employed to acquire material properties of brain tissue (Bayly, Black, Pedersen, Leister, & Genin, 2005; Budday, Ovaert, Holzapfel, Steinmann, & Kuhl, 2019; Goriely et al., 2015; Petraglia et al., 2014; Risling et al., 2019).

The ubiquitous saying in the biochemical realm goes, “structure determines function.” While this statement holds true for many proteins interactions and chemical reactions that describe nearly every process in existence, this relationship is also key to the hypothesized mechanisms of TBI. Though highly biochemically complex, there has been a great deal of progress made in defining the mechanical characteristics of brain tissue, which subsequently allows researchers to understand the mechanisms of TBI.

The brain is comprised of both gray and white matter, two tissues that hold very different material properties and consequently, provide very different but necessary functions (Budday et al., 2019). Both macroscopically and microscopically, the brain is quite heterogenous. The outer layer of the brain is comprised of gray matter while the white matter is more centrally located. Of additional importance, the gray layer houses many of the cell bodies of neuronal cells. These cells have lengthy extensions, called axons, that extend from the gray regions, deep into the central white regions allowing the brain to transmit messages to the entire body. Due to the material property mismatch at the gray-to-white matter transition sites, these axons are highly susceptible to damage when exposed to external loads, like those from TBI (Bain & Meaney, 2000; Budday et al., 2019; Goriely et al., 2015; Merchant-Borna et al., 2016). During TBI, the brain endures dynamic loading involving the tension, compression and shearing of anatomical components simultaneously (Bartsch et al., 2012; Budday et al., 2019; Merchant-Borna et al., 2016; Zhang et al., 2001). Many studies have focused on the effects from each of these loading applications, across a variety of strain rates and strain levels (Cater, Sundstrom, & Morrison, 2006; Chatelin, Constantinesco, & Willinger, 2010). The stress—strain relationships from the tissue, microscopic characterizations of fiber alignment, and application of many other mechanical properties allow for a greater overall understanding of normal as well as imposed dysfunctional characteristics caused from TBI. Though this a promising field to couple with impact kinematics for defining damage thresholds more reliably in football helmet design, findings in this field require more methodological refining before definite conclusions can be made from these measures.

Human Studies and Kinematic Measurements

There is no better model for the human body than the human body. Though there are heightened restrictions on the procedures that researchers can carry out in human studies, many research groups have managed to acquire kinematic data from middle school, high school, collegiate and professional-level games and practices. Most of these studies utilized accelerometers whether mounted atop or within the helmet, or embedded into mouthguards and patches that can be placed behind the athletes ear (Campolettano et al., 2018, 2019; Campolettano, Rowson, & Duma, 2016; Crisco et al., 2010, 2011; Daniel, Rowson, & Duma, 2014; Duma et al., 2005; Elkin, Gabler, Panzer, & Siegmund, 2019; Ford et al., 2018; Kelley et al., 2017; Kuo et al., 2018; Manoogian et al., 2006; Merchant-Borna et al., 2016; Mihalik et al., 2017; O’Connor, Rowson, Duma, & Broglio, 2017; Reynolds et al., 2016; Rowson et al., 2019; Schmidt et al., 2018; Urban et al., 2013; Viano, Casson, & Pellman, 2007; Viano & Pellman, 2005). Other researchers made use of videogrammetry, motion trackers or a combination of methods to acquire kinematic data (Bailey et al., 2018; Campolettano et al., 2018; Crisco et al., 2011; Kelley et al., 2017; Kuo et al., 2018; Viano et al., 2007; Viano & Pellman, 2005).

NOCSAE testing methods only require tolerances on helmet performance based on linear accelerations (Levy et al., 2004; Lloyd & Conidi, 2016). While this may be impactful for catastrophic injuries, as some speculate are influenced greater by linear acceleration and high velocities (Broglio et al., 2012), many studies have reflected the even greater influence of rotational accelerations on injury risk, especially in cases of mTBI (Ford et al., 2018; Hernandez, Shull, & Camarillo, 2015; Levy et al., 2004; Lloyd & Conidi, 2016; Merchant-Borna et al., 2016; Zuckerman et al., 2019). Yet, many still support the hypothesis that rotational accelerations provide a superior indication of concussion risk as well as catastrophic injury risk (Levy et al., 2004; Lloyd & Conidi, 2016).

Momentarily setting aside this pervasive debate, the accelerometer and videogrammetry techniques currently in use are able to provide data on both linear and rotational accelerations, with some methods also providing supplementary information on the magnitude of impacts a player is exposed to and where the impacts are occurring. In fact, most of the current research involving these kinematic derivations are focused on one of the following objectives: injury risk and characterization for youth versus adult football players, summative impact exposures and correlation to player position for said impacts, location of impact, or a combination of these objectives (Bailey et al., 2018; Campolettano et al., 2018, 2019, 2016; Crisco et al., 2010, 2011; Daniel et al., 2014; Duma et al., 2005; Elkin et al., 2019; Ford et al., 2018; Kelley et al., 2017; Kuo et al., 2018; Manoogian et al., 2006; Merchant-Borna et al., 2016; Mihalik et al., 2017; Reynolds et al., 2016; Rowson et al., 2019; Schmidt et al., 2018; Urban et al., 2013; Viano et al., 2007; Viano & Pellman, 2005). All of these objectives have been able to shed light on the heightened risk of adolescent impact exposure, greater number of impacts for positions such as linebackers and defensive linemen, and the greatest probability of impacts to the front of the head (Bailey et al., 2018; Campolettano et al., 2018, 2019, 2016; Crisco et al., 2010, 2011; Daniel et al., 2014; Duma et al., 2005; Elkin et al., 2019; Ford et al., 2018; Kelley et al., 2017; Kuo et al., 2018; Manoogian et al., 2006; Merchant-Borna et al., 2016; Mihalik et al., 2017; Reynolds et al., 2016; Rowson et al., 2019; Schmidt et al., 2018; Urban et al., 2013; Viano et al., 2007; Viano & Pellman, 2005). Findings of this sort are invaluable for designing helmets to attenuate more of the initial impact force.

DISCUSSION

Football Helmet Optimization

Unfortunately, there will never be a helmet that eradicates the risk of concussive and sub-concussive impacts (Levy et al., 2004; Rowson et al., 2014). As of current, there is still a lot of discrepancy and conflicting data to comment on whether a helmet will ever be able to provide even moderately increased benefits to these athletes (Rowson et al., 2014). Many tests have been performed utilizing the NOCSAE standards, in addition to newly proposed methods that can better account for rotational accelerations, to examine current and retired helmets on their ability to reduce both linear and rotational acceleration (Bailey et al., 2018; Lloyd & Conidi, 2016). In one such study, researchers tested new models of football helmets from manufacturers including Schutt, Riddell, Rawlings and Xenith with the inclusion of a few leather helmets from the 1930s (Lloyd & Conidi, 2016). While their performance scoring system ranked the Schutt Vengeance helmet as best overall, accounting for linear and rotational attenuating abilities, it cannot go unnoticed that the leather helmet actually generated the smallest magnitude of rotational acceleration among all of the helmets (Lloyd & Conidi, 2016). Similar to this study, other researchers tested the effectiveness of old leather helmets against modern Riddell, Xenith, Adams and Schutt helmets (Rowson, Daniel, & Duma, 2013). In opposition, their findings indicate significant superiority of all modern helmets relative to the old leather models (Rowson et al., 2013). However, this group only performed the NOCSAE tests for linear acceleration effects. By law, helmets must be NOCSAE tested and approved before an athlete can wear it. Therefore, this study lacks any new or valid argument for the enhancement of modern helmets.

As with these studies that seemed to be in moderate conflict, many researchers have also noted the bias that has been involved in many of these helmet testing and kinematic data acquisition studies (Lloyd & Conidi, 2016; McCrory et al., 2017). The Head Impact Telemetry (HIT) system, which is one of the designs and methods for accelerometer incorporation into helmets, was created by Riddell, one of the top manufacturers for American football helmets. Many of the studies using this technology had financial interest in this technology and seemingly reported glowing results from the technology (McCrory et al., 2017). However, many studies have also disputed the accuracy of the HIT system, reporting the unreliability and inaccuracy in many sensor technologies (Elliott, Margulies, Maltese, & Arbogast, 2015; O'Connor et al., 2017). While the helmet HIT system is of great debate, other sensors have generated more promising results. One such technique is the use of sensor-embedded mouthguards for the players. These mouthguards are reportedly the most accurate measurement technique for TBI exposure currently available (O'Connor et al., 2017). However, this technology is still quite new and requires further and enhanced validation (O'Connor et al., 2017).

While many researchers have focused on comparing current helmets designs to one another and subjecting them to newer testing procedures in hopes of altering NOCSAE standards; other research groups have started developing helmet designs that can better attenuate impact forces, so the head undergoes less linear and rotational movement. These researchers have highlighted the potential use of exterior padding or shells for greater attenuation with optimistic results (Nakatsuka & Yamamoto, 2014; Zuckerman et al., 2019). However, the skull and brain move very differently relative to one another. Therefore, these designs would require better validation techniques to determine resultant forces and movement for the brain as well. This very discrepancy is the reason many researchers believe there will never be a helmet capable of eliminating the risks imposed by both concussive and sub-concussive impacts (Levy et al., 2004; Rowson et al., 2014). Therefore, coaches, trainers, athletes and all the governing bodies regulating them, need to enforce and maintain stringent return-to-play rules, reductions in contact practices and other safety enhancing rules of the like to provide immediate health and safety accommodations while research on TBI mechanisms, thresholds and helmet optimization efforts proceed.

Football Equipment Room Practitioner Perspective

Given current helmet design selections available at the time of writing this review, the authors will provide no feedback regarding a single manufacturer or design that appears to work best or promote the greatest safety among football players; however, based on current testing helmet protocols, high standards are held when player safety is involved. Helmet standards are based on those reported annually by the NFL and NFL Players Association (NFLPA), who perform regular laboratory tests on current helmet designs. To understand how exactly the standards (as generated based on the previous works outlined in this narrative) relate to the communication regarding helmet selection and safety to the players themselves, an investigation of a National Collegiate Athletic Association (NCAA) Division I football program was performed. Researchers observed equipment issue room personnel and athletic training staff on current communication helmet selection procedures and were educated as the communication that occurs within the program regarding helmet standards as well as the sharing of those standards with student-athletes. While the observed Division I program is not mandated to choose only from the highest rated helmets on the NFL performance list (NFL, 2020), the director of football equipment and the associated coaching staff use this NFL and NFLPA ratings list to aid in helmet selections made for the team. Each player has their own preference regarding helmet selection which generally aligns with position-dependent needs for that player. For example, some of the offensive and defensive linemen prefer helmets with more cervical spine or neck support given that they endure more cervical spine extension during play relative to other positions. Therefore, in understanding the differences among positional needs, players are permitted to select their own helmet, as long as the helmet of their choice "is within the dark green", in regard to the helmet laboratory testing performance results chart. The dark green colored helmets at the top of the results list indicates the highest performing helmets as identified through standardized testing processes from the NFL and NFLPA (NFL, 2020). As an added safety measure for these student-athletes, the director of football equipment will fit all the helmets to the individual player's heads as a means of re-enforcing and educating the athletes how the helmet should feel and how it provides the greatest protection. While a loose-fitting helmet can be more comfortable to the player, a snug fit provides the greatest protection.

In addition to helmet safety, the coaching staff of the investigated NCAA Division I football team enforces less full-gear and tackling practices each week as well as mandatory safety awareness trainings for their student-athletes. Benefits to increased awareness and educational training surrounding items like better gameplay postures and explaining the risks imposed from play have been a result of these programs. Likewise, transparency is critical between the equipment room personnel and the student-athletes. The director of football equipment informs all new, incoming football student-athletes and their families of the serious short- and long-term consequences at stake every time they step onto the field. Transparent conversations such as these are meant to stress the fact that risks in sport hold a degree of uncertainty. While some athletes may never suffer a concussion or develop any neurological disease from their football careers, no one can assure that an injury in football—or any sport for that matter—will not occur. Additionally, the enhanced transparency with the student-athletes and their families aids in the trust building component of their team and equipment decision making. Because of heightened transparency, more of the student-athletes are comfortable discussing issues of any variety, not just equipment and safety-related ones. This open narrative between student-athletes and staff leads to quicker intervention times that will hopefully benefit the long-term health and safety of these individuals.

The practical implications of this study are to provide insight regarding (1) the current state of TBI in football, (2) the present evolution of helmets in sports, (3) the existing limitations in equipment testing, and (4) how football teams at the NCAA Division I level address communication regarding a sensitive topic—concussions—to current and future payers as well as their families. There are still many unknowns regarding TBIs and the most effective ways to test helmets such that protection confirmation is validated. However, just as the science continues to advance to keep players safer, so too does the communication around the implications of playing the sport in terms of the best options for protection and injury mitigation. There is value in understanding both sides to this problem in terms of how science views the research gaps and how the sport views the importance of education such that all involved can take part in ongoing conversations.

Limitations

The primary intent of this research was to provide a brief narrative into the current state of TBI and helmet testing and then to balance that information against communication protocols of standards within an NCAA Division I program. This was not intended to be more than a literature review with some practitioner feedback; therefore, one major limitation of this study is that there was not a comprehensive assessment of communication protocol regarding helmets and safety at the collegiate or any level for the sport of football. Through an autoethnographic frame from the authors' experience in the sport and past studies (Burch et al., 2019; Hicks et al., 2019; Luczak, Burch, Lewis, Chander, & Ball, 2019; Reid et al., 2020; Shelly et al., 2020, 2019), there is a general understanding that many Division I football programs hold similar conversations regarding health and safety with their student-athlete. However, this study focused more on the current state of TBI literature in the sport and was not intended to be a comprehensive review of practitioner communication and educational protocol.

Future Research

Future research should continue the investigation into how helmet safety is communicated to all football players at all levels of the sport to ensure consistency in the messaging as well as to learn what information best connects with the athletes. How information is communicated to players and their family is just as critical as the safety information itself. Do players have common questions and do the equipment personnel at the different levels of the sport have all the information they need to answer those questions effectively? Are there different communication styles regarding TBI and concussions across the different conferences and divisions in the sport or is everyone consistent regardless of what region of the country they are domiciled? A critical future research topic should focus on the conveying of the helmet safety itself and an assessment of player understanding and concerns so that the equipment issue room personnel are as equipped as possible to educate the players while earning the trust of the athlete and their families.

CONCLUSIONS

American football has caused an overwhelming number of TBI cases. Though the consequential type of brain injury may have progressed from namely catastrophic injuries to mTBI since the late 1800s, concussive and repeated sub-concussive loads were likely an issue throughout and only recently recognized in the last few decades. With the great deal of athletes affected, there is growing concern for more reliable technologies to accurately describe impact thresholds for the brain. Ideally, these findings will couple with knowledge of brain tissue material properties and biochemical processes to generate reliable computational models that can simulate TBI down to the individual. These models would allow helmet manufacturers to continuously refine helmet designs and reduce TBI risk. Though this level of integration for these vastly different fields is merely an idea at the moment, the path to answers and solutions truly begins when these fields start to fuse, disseminating knowledge that can strengthen the cause from all angles. In the meantime, the most effective safety measures need to be taken at the coaching levels. Increases in safety training and practices from method of tackling to fit of the helmet have provided improvements for player health. While there may never be a helmet that eradicates all concussive risk, other measures regarding training, gear, and strong player-to-coaching staff relationships may provide substantial means for reducing injury risk in the football community.

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