Published in final edited form as:

Sports Med Arthrosc. 2016 September ; 24(3): 100–107. doi:10.1097/JSA.0000000000000121.

Biomechanical Perspectives on Concussion in Sport

Steven Rowson, PhD,

Biomedical Engineering and Mechanics, Virginia Tech

Megan L. Bland, BS,

Biomedical Engineering and Mechanics, Virginia Tech

Eamon T. Campolettano, BS,

Biomedical Engineering and Mechanics, Virginia Tech

Jaclyn N. Press, BS,

Biomedical Engineering and Mechanics, Virginia Tech

Bethany Rowson, DVM,

Biomedical Engineering and Mechanics, Virginia Tech

Jake A. Smith, BS,

Biomedical Engineering and Mechanics, Virginia Tech

David W. Sproule, BS,

Biomedical Engineering and Mechanics, Virginia Tech

Abigail M. Tyson, MS, and

Biomedical Engineering and Mechanics, Virginia Tech

Stefan M. Duma, PhD

Biomedical Engineering and Mechanics, Virginia Tech

Abstract

Concussions can occur in any sport. Often, clinical and biomechanical research efforts are disconnected. This review paper analyzes current concussion issues in sports from a biomechanical perspective and is geared towards Sports Med professionals. Overarching themes of this review include: the biomechanics of the brain during head impact, role of protective equipment, potential population-based differences in concussion tolerance, potential intervention strategies to reduce the incidence of injury, and common biomechanical misconceptions.

Keywords

Biomechanics; Concussion; Helmet; Acceleration; Prevention

Introduction

Concussions can occur in any sport. There is widespread concern of the potential neurodegenerative processes that might result from a history of concussion or chronic exposure to head impact.^{1,2} Historically, clinical and biomechanical research efforts on concussion have been disconnected. Researchers in each discipline publish in different journals and present at different conferences. Addressing the concussion issue in sports requires a truly interdisciplinary approach. This paper is geared towards increasing awareness of the biomechanical research associated with concussion among Sports Med professionals. Below, we present a list of questions and review the relevant biomechanical literature.

What happens to the brain during head impact?

When the head is impacted, the skull accelerates while the brain lags behind due to its own inertia, resulting in relative motion at the skull-brain interface. This causes strains and pressure gradients within the brain tissue, which can lead to injury if tolerable limits are exceeded. Characterizing the immediate strain response of the brain to impact would help improve understanding of the functional and anatomical changes that result, but unfortunately this response is very difficult to quantify during impact, especially *in vivo*.³ Several early attempts to observe brain motion during impact have been made using cadaveric and primate specimens,⁴⁻⁶ but these studies generally only utilized qualitative measures or involved substantial compromise of the skulls of the specimen, limiting interpretation of the findings.³ A more recent study by Hardy et al.^{7,8} used neutral density technology and high-speed biplane x-ray to measure brain displacement and deformation during concussive-level impacts in human cadaveric heads with intact skulls. It was found that, as the severity of the impact increases, relative brain motion and intracranial pressure also increase, with a maximal movement of the brain relative to the skull of 7 mm. This result demonstrates that only very minimal brain motion and deformation are actually involved in concussive impacts, and that the brain does not “slosh around” inside the skull as is commonly described.

Kinematic characteristics of a head impact are thought to be indicative of the nature of the strain experienced by the brain. Traditionally, both linear and rotational skull accelerations, are the primary kinematic parameters related to brain injury. The two types of acceleration are thought to result in two different injury mechanisms:^{3,9} linear acceleration is thought to cause transient intracranial pressure gradients resulting in more focal injury, while rotational acceleration is thought to cause shear strain from relative motion at the skull-brain interface resulting in more diffuse injury.^{10,11} Focal brain injuries typically include hematoma and contusion, while diffuse brain injuries include diffuse axonal injuries, concussion, and swelling. However, most injuries are actually a result of both types of acceleration, as real-world head impacts always involve both.¹² The type of injury that occurs depends on the combination of these loading types as well as their severity.

Is it linear or rotational acceleration that causes concussion?

The biomechanics of concussive injury is often assessed using kinematic parameters of the head during impact, as these parameters are thought to reflect the inertial response of the brain.¹³ Two input parameters in particular are traditionally used to characterize injury mechanisms: linear acceleration and rotational acceleration. The roles of these two variables in producing brain injury have historically been studied independently of each other, as each tends to be associated with different injury mechanisms. Linear acceleration is thought to cause injury via transient intracranial pressure gradients, while rotational acceleration is thought to cause injury through shear strain in the neural tissue from motion of the brain relative to the skull.^{3,9} It is still debated among scientists as to whether concussive injury is more attributable to linear or rotational head acceleration. This debate is complicated by the complex nature of studying concussion in a laboratory setting, as concussive injury manifests itself in a weakly-understood physiologic response that many experimental models struggle to reproduce, and there are different levels of physiologic response depending on the severity of the brain injury.¹⁴

Early research supporting linear acceleration as a primary indicator for concussion was based on the theory that skull deformation and intracranial pressure gradients were the main correlates to brain injury. Studies focused on direct head impacts to animals and cadavers, which related the resulting linear accelerations to injury tolerance. From these data, the Wayne State Tolerance Curve was developed, which now serves as the basis for several kinematic-based injury metrics in industry safety standards.^{15–18} This curve is primarily based around skull fracture, but is thought to correlate with severe brain injury. Research supporting rotational acceleration as the primary indicator for concussion stemmed from a theory postulated by Holbourn in 1943 that only rotational motion could cause the diffuse tensile and shear strain involved in concussive injury due to the incompressible nature of the brain.¹⁹ Studies of rotational acceleration and injury tolerance have involved exposing primates or rats to sudden rotation using inertial or non-contact loading, as direct contact is a primary contributor to linear acceleration.^{14,20–26} Several of these studies pointed to rotation alone as being responsible for injury.

In actuality, all real-world impacts involve both linear and rotational acceleration,¹² and thus both likely contribute to injury risk.¹⁴ In a study of 400 fatally injured road users, McLean found that there were no cases of brain injury without head impact.²⁷ This is further supported by research conducted by Ommaya et al., who showed that twice the rotational velocity was required to produce concussion in primates when direct impact was absent,²⁸ and theorized that rotation accounts for about half of the potential for brain injury, with contact phenomena contributing to the rest.²⁹ Furthermore, Gennarelli et al. found that concussion could only be produced in primates when a combination of linear and rotational motion was applied compared to linear motion alone.^{10,11} Rotational motion alone is practically impossible to evaluate *in vivo*, even with inertial loading apparatuses, as head rotation is pivoted around the neck and thus involves both linear and rotational components of acceleration. The knowledge that both linear and rotational acceleration play a significant role in concussive injury emphasizes the importance of implementing industry safety measures that are designed around mitigating both types of acceleration.

Do the biomechanics of concussion vary by sport?

While incidence rates of concussion vary by sport,³⁰ we do not know if population-based differences in concussion tolerance exist between athlete populations. It is reasonable to think this is true, given the ambiguity of concussion diagnosis and potential gender and age related differences in tolerance to head accelerations.

Most research on the biomechanics of concussion in athletes has focused on high school and collegiate football players, given that football is responsible for the highest incidence of concussion. At this point, there exists a fairly good understanding of the head accelerations associated with concussion in football. Concussive impacts in the NFL using crash test dummies were reconstructed based on video analysis.³¹ This research reported that concussive impacts had average head accelerations of 98 ± 28 g and 6432 ± 1813 rad/s². In addition to the impact reconstructions, researchers across the country have been instrumenting football players with helmet-mounted accelerometer arrays to collect head acceleration data for the past 13 years. Concussive impacts from these studies have yielded average head accelerations of 105 ± 27 g and 5022 ± 1791 rad/s².^{13,32} The fact that these two different methodologies have yielded similar estimates for the head accelerations associated with concussion in football reinforces the validity of these approaches.

Less research has been conducted in other athlete populations. In ice hockey, researchers have used helmet-mounted accelerometer arrays to analyze head impacts similarly to football.^{33,34} Wilcox et al. measured nine concussions in female hockey players with an average peak linear head acceleration 43 ± 12 g, and a peak rotational acceleration of 4030 ± 1435 rad/s².³⁴ In soccer, the most common mechanism of concussion is contact with another player (ie, head to head contact) although most impacts occur in heading the ball.^{35,36} Withnall et al. reconstructed head impact events in FIFA soccer matches. For the head-to-head impacts most likely associated with injury, the highest head accelerations measured had an average linear acceleration of 87 g and an average rotational acceleration of 7033 rad/s².³⁷ Concussions in baseball have been studied by recreating concussive events resulting from baseballs striking the masks of catchers and umpires.³⁸ Head accelerations generated during these ball-to-mask impacts ranged from 26 to 42 g for linear acceleration and from 1974 to 5266 rad/s² for rotational acceleration. While research is limited at this point, early evidence suggests that the head accelerations associated with concussion in these sports may be lower than what is observed in adult football players.

Two primary questions arise from these findings: 1) Are the same injuries being compared between sports? and 2) Are these differences in concussion tolerance a result of athlete population characteristics? As football players that are less tolerant to head impacts may be “weeded out” by the time they reach the college level, it is reasonable to think that the adult football players most research has focused on are a self-selected population. It is also possible that cultural differences between sports may result in varying thresholds for reporting concussion symptoms. As technology improves in wearable head impact sensors over the next few years, research can further address these questions.

Is there a difference between male and female concussion tolerance?

While there are notable differences in concussion incidence rates between male and female athletes, the reason for these discrepancies is still debated. Studies have shown that female athletes may be up to 2.6 times more likely to sustain a concussion than their male counterparts.³⁹⁻⁴⁴ This has been found for numerous sports including soccer, lacrosse, basketball, baseball/softball, and gymnastics.^{41,44} Some studies suggest that women may merely be more honest in reporting concussions because they are more concerned about the effects of an injury on their future health.^{41,45,46} Conversely, male athletes may be less likely to report a concussion due to cultural tendencies which encourage male athletes to play despite injuries.^{41,47}

Others believe that inherent anatomical differences make women more susceptible to concussions.^{41,43,44} Being that risk of concussion is directly related to the accelerations experienced during impact, less head-neck segment mass in females could predispose women to concussions.⁴⁸⁻⁵⁰ According to Newton's second law, less head mass correlates with greater head acceleration for a given applied force. Gender differences have also been noted in the ability of individuals to use their dynamic neck stabilizers for protection against head injury.⁵⁰ When these muscles are tensed, a portion of the torso's mass is recruited for impact. Weaker neck muscles in women would correlate to less recruited torso mass, which could result in increased head accelerations during an impact. Researchers suggest that women should perform head-neck segment resistance training to increase neck girth and strength, as this correlates positively with greater joint resistance to motion.⁵⁰ More research must be done to investigate these theories so that preventative measures can be taken to reduce risk for female athletes.

Are youth more susceptible to concussions?

As the brain continues to develop beyond the adolescent years, it has been suggested that youth are more susceptible to concussions than other populations. The most cited rationales for this point to myelination in the youth brain and neck strength.^{51,52} In youth, myelination is still an ongoing process, with nerve connections not fully developed. Research comparing myelinated and unmyelinated brain fibers' responses to biomechanical impulses has shown that unmyelinated fibers retain deficits even after myelinated fibers have recovered.⁵¹ This suggests pediatric populations are more vulnerable to concussions due to their unmyelinated fibers.

Further, researchers have investigated the effect of limited neck strength and stiffness in children, whose heads are nearly fully grown. Researchers posit that increased neck strength allows for greater mass recruitment, which lowers head acceleration, and thus results in a lower risk of concussion.⁵³⁻⁵⁵ Currently, only one group has found this correlation,⁵³ while other investigators have observed comparable head accelerations among players, regardless of neck strength.⁵⁵ These groups primarily looked at high school sports, however, this type of research in youth sports is nonexistent. At this point, there have only been a handful of studies investigating head impact exposure in youth sports.⁵⁶⁻⁵⁹ Compared to the research available for high school, collegiate, and even professional populations, the sample size at

the youth level is small. Still, the two head acceleration magnitudes observed for concussive impacts in youth (58 and 64 g) are within the range measured from older populations.^{49,56,60,61} Further exposure and biomechanics data are necessary to determine whether youth are more susceptible to concussions.

Can you sustain a concussion without head impact?

It is often suggested that concussion can result from a whiplash injury or a blow to the chest or back that “jars” the brain. This concept stems from the early hypothesis of Holbourn who stated that head rotation was the crucial contributor to concussions and the translational component could not produce injury.¹⁹ If this hypothesis was true, then equal concussion injuries should be produced at identical changes in rotational velocity thresholds, irrespective of head contact. However, according to Ommaya’s research on primates, twice the rotational velocity was required to produce a concussion during whiplash as opposed to a direct impact.¹⁴ This suggests that contact phenomena play a significant role in concussion thresholds. Furthermore, although brain injury during indirect loading has been observed in animal models, all research on humans has only found evidence of concussions in conjunction with a head impact.²⁷ It is important to note that whiplash injuries can result in similar symptoms to a concussion and may occur in addition to a head impact.⁶² Although the two injuries may be treated similarly due to their symptoms, a neck injury does not imply a brain injury.

Can helmets reduce concussion risk?

Helmets were originally introduced in sports to prevent catastrophic head injuries and deaths.^{63,64} Helmet safety standards are based on thresholds for skull fracture and more severe brain injuries, which leads to a common misconception that helmets are ineffective at reducing concussion risk. Studies evaluating differences in concussion rates by helmet model have mixed results.^{53,65–67} These studies define concussion rate as the number of injuries per athletic exposure, which is any game or practice an athlete participates in. Concussions per athletic exposure neglect the level of participation in practices or games as well as the number of head impacts different players are exposed to. For example, a first string linebacker would be exposed to more head impacts than a third string quarterback in a single game or practice, putting the linebacker at a higher risk for sustaining a concussion. However, both scenarios would be considered a single athletic exposure. Estimates of differences in concussion rates between helmet types are improved when head impact exposure is controlled for. Studies defining concussion rates as the number of injuries per number of head impacts found significant differences in injury rates by helmet model.^{68,69}

In addition to on-field studies, laboratory evaluations comparing different helmet models have been performed.^{32,70–73} These studies are based on the fundamental principle that helmets that lower head acceleration reduce the risk of injury. A large body of research has shown that concussive impacts are associated with higher linear and rotational accelerations than impacts that do not result in concussion.^{31,32,49,74,75} Several studies compared newer helmet models with thicker padding to older helmet models, and found that in general the newer models performed better when considering peak linear and rotational

accelerations.^{70,72,73} Relative performance ratings of football and hockey helmets have also been recently introduced to inform consumers on the ability of different helmets to reduce the risk of concussion.^{32,71} These studies found large differences in relative performance among helmets that pass minimum safety standards.⁷⁶ The NFL also recently released a list of relative rankings to assess impact performance of helmets worn by NFL players.⁷⁷ Although different methods and injury severity metrics were used, the results of both football helmet rankings were largely in agreement.

From a mechanical standpoint, differences in performance between newer and older helmet models depend on their ability to modulate impact energy transfer to the head. Older models tend to have a smaller offset with less room for padding.⁷² Thinner padding is required to be stiffer to manage high energy impacts, with the tradeoff being that it is less effective for lower energy impacts. Thicker padding can be more compliant, while still providing protection for both high and low energy impacts.

Do larger helmets increase the risk of head or neck injury?

In order to improve impact energy attenuation characteristics, helmet manufacturers have increased the size and weight of helmets.⁷² Larger helmets have led to fears that neck injuries will increase with newer helmets, especially in children due to their larger head-to-body mass ratio. Resistance to legislation mandating helmet use in activities such as motorcycle and bicycle riding has cited a potential increase in neck injuries with helmet use.⁷⁸ The concern with increasing helmet size and mass (or adding a helmet to non-helmeted sports) is that it will lead to increased torque on the neck during an impact either from the mass added to the head or an increased lever arm if the force is directed tangentially to the helmet (i.e. a glancing blow). There is also some concern that helmets make the head a larger target, thus making head impacts more likely. However, studies have not found any statistically significant increases in neck injuries with helmet use.^{79–86} Several studies which adjusted for age did not see an increase in neck injuries with helmet use for younger populations either.^{79,80,87} Additionally, several studies of motorcycle accidents revealed lower cervical spine injury rates with helmet use.^{78,88}

In laboratory evaluations of different types of football helmets, it was found that newer helmet models performed better than older models^{70,72,73,89}. One study also noted a reduction in neck injury metrics with newer helmets.⁷⁰ When comparing between sports, football helmet padding is generally 2–3 times thicker than hockey helmet padding, resulting in a substantially lower risk of concussion.⁷¹ Although it is possible that there are changes in neck dynamics with larger, heavier helmets, it is unlikely that these changes are clinically relevant. These changes are also most likely outweighed by improvements in head injury protection.

Is helmet fit more important than helmet performance?

When choosing a helmet, fit is often pointed to as the most important factor. However, there is no published evidence of this being the case. While no biomechanical studies have investigated helmet fit, various studies have analyzed helmet fitting errors. Parkinson et al.

reported that only 4% of children or their parents were able to correctly fit a bicycle helmet.⁹⁰ In addition, Rivara et al. collected data from children admitted to the hospital due to injuries from action sports. From this data collection, it was found that the difference between helmet width and head width might be the most important factor contributing to poor fit.⁹¹ They hypothesized that the increased distance between the head and the helmet might allow the head to accelerate during a crash before it comes into contact with the padding, and helmets that are too large in any dimension might be more likely to move out of the correct position during a crash, leaving portions of the head unprotected. While the latter is most likely the case, this might not apply for helmets that have a larger coverage of the skull such as football helmets. McGuine et al. reported that out of 3403 players evaluated, 1671 (49%) had fitting errors.⁹² However, it is unclear as to how this might affect concussion risk in football players. From a biomechanical standpoint, fit will affect the resulting head accelerations from impact, but the mechanical properties of the helmet and padding will dominate the impact response as long as the helmet remains secured to the head.

Should soccer players wear headgear?

There has been very little comprehensive testing on the efficacy of soccer headgear in reducing head accelerations, despite the fact that there are multiple brands available for purchase and use. In 2003, Naunheim et al. propelled soccer balls at a standard magnesium headform and compared peak head accelerations with and without the use of protective headgear finding no measurable protection.⁹³ In 2005, Withnall et al. performed a combination of head-to-head dummy impacts, ball-to-head dummy impacts, and volunteer ball heading with and without the use of protective headgear.⁹⁴ This study also found that headgear provided no measurable protection during ball impacts, but did provide an overall 33% reduction in impact response during head-to-head tests.

Ball-to-head impacts rarely generate the high-level head accelerations that normally cause concussions.^{49,95–98} Because the ball is much more compliant than the head, the ball deforms greatly during impact (almost ten times more than the thickness of the headband) and modulates most of the energy transfer to the head. Therefore, it would be unlikely for headgear to have a clinically relevant effect for these types of impacts. There is much more potential in reducing the larger accelerations that result from player-to-player contact.^{94,95} Further research must be done to quantify which currently available headgear types are the best at reducing concussion risk.

Is heading soccer balls dangerous?

From the few studies that have measured head accelerations during active heading of a soccer ball, average peak linear accelerations range from 12 to 55g with an average of 27 ± 12 g.^{93,95,97,98} Average peak rotational accelerations range from 732 to 3003 rad/s² with an average of 1966 ± 879 rad/s².⁹⁵ This correlates to a concussion risk that is well below 1%.⁴⁹ For context, the average concussion in football occurs around 100g and 5000 rad/s².^{13,32} From a mechanical standpoint, the ball is a low mass, highly compliant object. This results in the ball deforming greatly upon impact and managing most of the energy transfer.

Therefore, when the player strikes the ball, resulting accelerations are low and acute injury from this activity is unlikely.

Heading is very common in soccer and a single player might head the ball over 200 times in a single season.³⁶ This unique aspect of the game has led researchers to investigate the effects of cumulative sub-concussive head impacts. This area is not yet well-understood, as findings in the current literature are mixed. Many studies have compared neurocognitive test performance between soccer players and control groups, with the majority finding no significant differences.^{99–104} There is a small subset of studies, however, which have found inverse relationships between the number of ball impacts and certain neurocognitive performance scores in categories such as verbal learning, attention, strategic planning, and visual processing.^{105–107} The reliability and accuracy of neurocognitive tests should be taken into consideration when interpreting these findings, as they are often limited in their ability to control for compounding factors that might influence the outcome of such tests.¹⁰³

Can mouthguards reduce risk of concussion?

Mouthguards were originally developed in the late 19th century for boxers to prevent lip lacerations.¹⁰⁸ Since then, various mouthguards have been developed to help prevent oral injuries, with some being marketed as being able to reduce concussion risk. Various studies have attempted to investigate the effects of mouthguards on concussion risk. Hollis et al. observed 3000 rugby players, tracking concussion incidence along with mouthguard use, and reported no conclusive evidence supporting a reduction in concussions.¹⁰⁹ A review conducted by Benson et al. found no evidence that a mouthguard reduces concussions in football, rugby, ice hockey, and basketball.¹¹⁰ Mihalilk et al. investigated how mouthguards might decrease the symptoms of concussion and found that mouthguard use does not reduce the severity of concussion symptoms.¹¹¹ In addition to these clinical studies, Viano et al. performed a biomechanical study to investigate the effect mouthguards have on head accelerations by impacting a modified dummy head with an articulating mandible. It was found that mouthguards lowered mandible forces, but had little reduction in the response of the head.¹¹² While the literature has shown that mouthguards do not affect concussion risk, the use of mouthguards should continue to be recommended as they are effective in the prevention of oral injuries.¹¹¹

Are wearable head impact sensors valuable?

If wearable head impact sensors were validated to portray accurate head acceleration and those reading the data understood how to use it, then this technology could be extremely valuable for both consumers and researchers. Many commercially available sensors are limited by inaccurate and unrepeatable measurements due to poor coupling with the head. Some sensors are adhered directly to the helmet shell, even though helmet accelerations can be up to 10 times greater than head accelerations.¹¹³ Others are worn as a skin patch or headband, but these both move with the skin and produce unrealistically high linear and rotational accelerations.^{36,114} Sensors that produce better coupling with the skull include those worn in the mouth or ear canal.¹¹⁴

Even with perfect accuracy, the sensor measurements will not be diagnostic. There is no concussive threshold for head acceleration since injury is also likely dependent on other factors such as impact location, contact phenomena, pre-existing conditions, genetics, and stage of development.⁶¹ Some employ thresholds for alerting medical staff, but any threshold used by the sensor systems simply represents a generalized risk for a population of people. Some individuals will exhibit higher tolerances to head impact than others. However, sensors do provide additional information on the field that can help identify severe impacts that may otherwise go unnoticed. Once a high magnitude impact is identified and an injury is suspected, medical staff should still evaluate the athlete for the signs and symptoms of concussion.

Head impact sensors also provide researchers with a unique opportunity to shed light on the biomechanics of concussion in differing athlete populations. While helmet-mounted accelerometer arrays have been extensively used in football,¹¹⁵ very little research has been performed on youth athletes,⁵⁷ and even less on female athletes.³⁶ As head impact sensor technology continues to advance, we are hopeful that these devices can be used to help better understand concussion in sports.

Are all concussions preventable?

Concussions will never be eliminated from sports. Even if all head impacts were removed, incidental head impacts would still occur. In these situations, the head would accelerate, the brain would experience transient pressure gradients and strains, and some people would experience injury. Individuals have different tolerances to injury, so there will always be some vulnerable subset of sports participants. With that in mind, a multifaceted approach that includes rule changes, teaching proper technique, and safer equipment would best minimize the incidence of injury.

Researchers have investigated the biomechanics of concussion in sports with the goal of characterizing head impact exposure and mitigating the risk of concussion. Head impact exposure data from high school and collegiate populations has shown that football players can experience as many as 1000 impacts in a season.^{116,117} Daniel et al. instrumented youth football players for one season and observed that practices accounted for 75% of all impacts for the season.⁵⁷ High magnitude impacts were almost exclusively associated with practice sessions. This research led Pop Warner to mandate alterations aimed at limiting contact in practice. In a comparative study between teams following the mandate and those not, nearly a 50% reduction in head impacts was observed for teams who limited contact.⁵⁶ Limiting head impacts through rule changes can reduce the risk of concussion.¹¹⁸

In addition to rule changes, proper technique must be taught in order for maximum effect and increased player safety. USA Football instituted the Heads Up Football program in 2012 to educate players and coaches on proper tackling technique. Similar to the study comparing the success of the Pop Warner mandate, Kerr et al. instrumented teams that utilized the Heads Up Football protocol as well as ones that did not.¹¹⁹ On average, players on teams using the Heads Up Football program experienced one-third fewer head impacts than those

on teams that did not. Teaching proper technique can be effective at limiting head impacts and reducing the risk of concussion for athletes.

Concussion incidence is also dependent on protective headgear worn by athletes. Helmets are certified to prevent skull fracture, not concussion; but have been shown to vary in their ability to reduce risk of concussion.^{32,69,71,76} While some argue that helmets serve as a weapon and should be eliminated from sports, this is the case only when proper technique is not taught or enforced. The combination of better protective equipment, rule changes, and player education plays an important role in reducing the risk of athletes sustaining a concussion.^{118,120} Ultimately, head impacts in both helmeted and unhelmeted sports are unavoidable and risk of concussion is inherent with participation in sports.

Acknowledgments

Research reported in this publication was supported by the National Institute of Neurological Disorders And Stroke of the National Institutes of Health under Award Number R01NS094410. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

References

1. Omalu BI, DeKosky ST, Minster RL, Kamboh MI, Hamilton RL, Wecht CH. Chronic traumatic encephalopathy in a national football league player. *Neurosurgery*. 2005; 57(1):128–34. [PubMed: 15987548]
2. Talavage TM, Nauman EA, Breedlove EL, et al. Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *J Neurotrauma*. 2014; 31(4):327–38. [PubMed: 20883154]
3. King AI, Yang KH, Zhang L, Hardy W, Viano DC. Is head injury caused by linear or angular acceleration? IRCOBI Conference. 2003:1–12.
4. Hodgson VR, Thomas LM, Gurdijan ES, Fernando OU, Greenberg SW, Chason JL. Experimental skull deformation and brain displacement demonstrated by flash x-ray technique. *J Neurosurg*. 1966; 25(5):549–52. [PubMed: 5926321]
5. Nusholtz GS, Lux P, Kaiker P, Janicki MA. Head impact response – skull deformation and angular accelerations. SAE Technical Paper Series. 1984; 841657
6. Pudenz RH, Sheldon CH. The lucite calvarium – a method for direct observation of the brain ii. Cranial trauma and brain movement. *J Neurosurg*. 1946; 3(6):487–505. [PubMed: 20279145]
7. Hardy WN, Foster CD, Mason MJ, Yang KH, King AI, Tashman S. Investigation of head injury mechanisms using neutral density technology and high-speed biplanar x-ray. *Stapp Car Crash J*. 2001; 45:337–68. [PubMed: 17458753]
8. Hardy WN, Mason MJ, Foster CD, et al. A study of the response of the human cadaver head to impact. *Stapp Car Crash J*. 2007; 51:17–80. [PubMed: 18278591]
9. Unterharnscheidt FJ. Translational versus rotational acceleration: Animal experiments with measured inputs. *Proceedings of the 15th Stapp Car Crash Conference*. 1971 SAE 710880.
10. Gennarelli T, Ommaya A, Thibault L. Comparison of translational and rotational head motions in experimental cerebral concussion. *Proc 15th Stapp Car Crash Conference*. 1971:797–803.
11. Gennarelli TA, Thibault LE, Ommaya AK. Pathophysiologic responses to rotational and translational accelerations of the head. SAE Technical Paper Series. 1972; 720970:296–308.
12. Rowson S, Brolinson G, Goforth M, Dietter D, Duma SM. Linear and angular head acceleration measurements in collegiate football. *J Biomech Eng*. 2009; 131(6):061016. [PubMed: 19449970]
13. Rowson S, Duma SM, Beckwith JG, et al. Rotational head kinematics in football impacts: An injury risk function for concussion. *Ann Biomed Eng*. 2012; 40(1):1–13. [PubMed: 22012081]
14. Ommaya, AK. Biomechanics of trauma. Appleton-Century-Crofts; 1985. Biomechanics of head injuries: Experimental aspects.

15. Gadd CW. Use of a weighted-impulse criterion for estimating injury hazard. Proceedings of the 10th Stapp Car Crash Conference. 1966 SAE 660793.
16. Gurdjian E, Lissner H, Evans F, Patrick L, Hardy W. Intracranial pressure and acceleration accompanying head impacts in human cadavers. *Surg Gynecol Obstet.* 1961; 113:185. [PubMed: 13709837]
17. Lissner HR, Lebow M, Evans FG. Experimental studies on the relation between acceleration and intracranial pressure changes in man. *Surg Gynecol Obstet.* 1960; 111:329–38. [PubMed: 14417481]
18. Versace J. A review of the severity index. SAE Technical Paper Series. 1971 SAE 710881.
19. Holbourn AHS. Mechanics of head injury. *Lancet.* 1943; 242(6267):438–41.
20. Davidsson J, Angeria M, Risling MG. Injury threshold for sagittal plane rotational induced diffuse axonal injuries. IRCOBI Conference. 2009:43–56.
21. Gennarelli TA. Head injury in man and experimental animals: Clinical aspects. *Acta Neurochir Suppl (Wien).* 1983; 32:1–13. [PubMed: 6581696]
22. Gennarelli TA, Thibault LE, Adams JH, Graham DI, Thompson CJ, Marcincin RP. Diffuse axonal injury and traumatic coma in the primate. *Ann Neurol.* 1982; 12(6):564–74. [PubMed: 7159060]
23. Margulies SS, Thibault LE. A proposed tolerance criterion for diffuse axonal injury in man. *J Biomech.* 1992; 25(8):917–23. [PubMed: 1639835]
24. Margulies SS, Thibault LE, Gennarelli TA. Physical model simulations of brain injury in the primate. *J Biomech.* 1990; 23(8):823–36. [PubMed: 2384494]
25. Ommaya AK, Gennarelli TA. Cerebral concussion and traumatic unconsciousness. Correlation of experimental and clinical observations of blunt head injuries. *Brain.* 1974; 97(1):633–54. [PubMed: 4215541]
26. Ommaya AK, Hirsch AE, Flamm ES, Mahone RH. Cerebral concussion in the monkey: An experimental model. *Science.* 1966; 153(3732):211–2. [PubMed: 4957321]
27. McLean AJ. Brain injury without head impact? *J Neurotrauma.* 1995; 12(4):621–5. [PubMed: 8683613]
28. Ommaya AK, Hirsch AE, Martinez JL. Proc 10th Stapp Car Crash Conference. The role of whiplash in cerebral concussion. 1966:314–24. SAE 660804.
29. Ommaya A, Hirsch A. Tolerances for cerebral concussion from head impact and whiplash in primates. *J Biomech.* 1971; 4(1):13–21. [PubMed: 5001829]
30. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *J Athl Training.* 2007; 42(2):311–9.
31. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF. Concussion in professional football: Reconstruction of game impacts and injuries. *Neurosurgery.* 2003; 53(4):799–812. [PubMed: 14519212]
32. Rowson S, Duma SM. Development of the star evaluation system for football helmets: Integrating player head impact exposure and risk of concussion. *Ann Biomed Eng.* 2011; 39(8):2130–40. [PubMed: 21553135]
33. Mihalik JP, Guskiewicz KM, Marshall SW, Blackburn JT, Cantu RC, Greenwald RM. Head impact biomechanics in youth hockey: Comparisons across playing position, event types, and impact locations. *Ann Biomed Eng.* 2012; 40(1):141–9. [PubMed: 22012083]
34. Wilcox BJ, Beckwith JG, Greenwald RM, et al. Biomechanics of head impacts associated with diagnosed concussion in female collegiate ice hockey players. *J Biomech.* 2015; 48(10):2201–4. [PubMed: 25913243]
35. Kirkendall DT, Jordan SE, Garrett WE. Heading and head injuries in soccer. *Sports Med.* 2001; 31(5):369–86. [PubMed: 11347686]
36. Press JN, Rowson S. Quantifying head impact exposure in collegiate women's soccer. *Clin J Sport Med.* 2016
37. Withnall C, Shewchenko N, Gittens R, Dvorak J. Biomechanical investigation of head impacts in football. *Brit J Sport Med.* 2005; 39(Suppl 1):49–57.

38. Beyer JA, Rowson S, Duma SM. Concussions experienced by major league baseball catchers and umpires: Field data and experimental baseball impacts. *Ann Biomed Eng.* 2012; 40(1):150–9. [PubMed: 22012084]
39. Covassin T, Swanik CB, Sachs ML. Sex differences and the incidence of concussions among collegiate athletes. *J Athl Training.* 2003; 38(3):238–44.
40. Delaney JS, Lacroix VJ, Leclerc S, Johnston KM. Concussions among university football and soccer players. *Clin J Sport Med.* 2002; 12(6):331–8. [PubMed: 12466687]
41. Dick RW. Is there a gender difference in concussion incidence and outcomes? *Brit J Sport Med.* 2009; 43(Suppl 1):46–50.
42. Fuller CW, Junge A, Dvorak J. A six year prospective study of the incidence and causes of head and neck injuries in international football. *Brit J Sport Med.* 2005; 39(Suppl 1):3–9.
43. Tierney RT, Higgins M, Caswell SV, et al. Sex differences in head acceleration during heading while wearing soccer headgear. *J Athl Training.* 2008; 43(6):578–84.
44. Zuckerman SL, Kerr ZY, Yengo-Kahn A, Wasserman E, Covassin T, Solomon GS. Epidemiology of sports-related concussion in ncaa athletes from 2009–2010 to 2013–2014: Incidence, recurrence, and mechanisms. *Am J Sport Med.* 2015; 43(11):2654–62.
45. Llewellyn T, Burdette GT, Joyner AB, Buckley TA. Concussion reporting rates at the conclusion of an intercollegiate athletic career. *Clin J Sport Med.* 2014; 24(1):76–9. [PubMed: 24157468]
46. Torres DM, Galetta KM, Phillips HW, et al. Sports-related concussion: Anonymous survey of a collegiate cohort. *Neurol Clin Pract.* 2013; 3(4):279–87. [PubMed: 24195017]
47. Granito VJ Jr. Psychological response to athletic injury: Gender differences. *J Sport Behav.* 2002; 25(3):243.
48. Queen RM, Weinhold PS, Kirkendall DT, Yu B. Theoretical study of the effect of ball properties on impact force in soccer heading. *Med Sci Sport Exer.* 2003; 35(12):2069–76.
49. Rowson S, Duma SM. Brain injury prediction: Assessing the combined probability of concussion using linear and rotational head acceleration. *Ann Biomed Eng.* 2013; 41(5):873–82. [PubMed: 23299827]
50. Tierney RT, Sitler MR, Swanik CB, Swanik KA, Higgins M, Torg J. Gender differences in head-neck segment dynamic stabilization during head acceleration. *Med Sci Sport Exer.* 2005; 37(2):272–9.
51. Choe MC, Babikian T, DiFiori J, Hovda DA, Giza CC. A pediatric perspective on concussion pathophysiology. *Curr Opin Pediatr.* 2012; 24(6):689–95. [PubMed: 23080130]
52. Reeves TM, Phillips LL, Povlishock JT. Myelinated and unmyelinated axons of the corpus callosum differ in vulnerability and functional recovery following traumatic brain injury. *Exp Neurol.* 2005; 196(1):126–37. [PubMed: 16109409]
53. Collins CL, Fletcher EN, Fields SK, et al. Neck strength: A protective factor reducing risk for concussion in high school sports. *J Prim Prev.* 2014; 35(5):309–19. [PubMed: 24930131]
54. Viano DC, Casson IR, Pellman EJ. Concussion in professional football: Biomechanics of the struck player—part 14. *Neurosurgery.* 2007; 61(2):313–27. [PubMed: 17762744]
55. Caswell SV, York M, Ambegaonkar JP, Caswell AM, Cortes N. Neck strengthening recommendations for concussion risk reduction in youth sport. *IJATT.* 2014; 19(6)
56. Cobb BR, Urban JE, Davenport EM, et al. Head impact exposure in youth football: Elementary school ages 9–12 years and the effect of practice structure. *Ann Biomed Eng.* 2013; 41(12):2463–73. [PubMed: 23881111]
57. Daniel RW, Rowson S, Duma SM. Head impact exposure in youth football. *Ann Biomed Eng.* 2012; 40(4):976–81. [PubMed: 22350665]
58. Daniel RW, Rowson S, Duma SM. Head impact exposure in youth football: Middle school ages 12–14 years. *J Biomech Eng.* 2014; 136(9):094501. [PubMed: 24950298]
59. Young TJ, Daniel RW, Rowson S, Duma SM. Head impact exposure in youth football: Elementary school ages 7–8 years and the effect of returning players. *Clin J Sport Med.* 2013
60. Broglio SP, Surma T, Ashton-Miller JA. High school and collegiate football athlete concussions: A biomechanical review. *Ann Biomed Eng.* 2012; 40(1):37–46. [PubMed: 21994058]

61. Guskiewicz KM, Mihalik JP. Biomechanics of sport concussion: Quest for the elusive injury threshold. *Exerc Sport Sci Rev.* 2011; 39(1):4–11. [PubMed: 21088602]
62. Hynes LM, Dickey JP. Is there a relationship between whiplash-associated disorders and concussion in hockey? A preliminary study. *Brain injury.* 2006; 20(2):179–88. [PubMed: 16421067]
63. Hoshizaki TB, Brien SE. The science and design of head protection in sport. *Neurosurgery.* 2004; 55(4):956–66. [PubMed: 15458605]
64. Mertz HJ, Prasad P, Nusholtz G. Head injury risk assessment for forehead impacts. *International Congress and Exposition.* 1996 SAE 960099.
65. Collins CL, McKenzie LB, Ferketich AK, Andridge R, Xiang H, Comstock RD. Concussion characteristics in high school football by helmet age/recondition status, manufacturer, and model: 2008–2009 through 2012–2013 academic years in the united states. *Am J Sport Med.* 2016
66. McGuine TA, Hetzel S, McCrea M, Brooks MA. Protective equipment and player characteristics associated with the incidence of sport-related concussion in high school football players: A multifactorial prospective study. *Am J Sport Med.* 2014; 42(10):2470–8.
67. Zemper ED. Analysis of cerebral concussion frequency with the most commonly used models of football helmets. *J Athl Training.* 1994; 29(1):44–50.
68. Rowson S, Duma SM. The virginia tech response. *Ann Biomed Eng.* 2012; 40(12):2512–8.
69. Rowson S, Duma SM, Greenwald RM, et al. Can helmet design reduce the risk of concussion in football? Technical note. *J Neurosurg.* 2014; 120(4):919–22. [PubMed: 24484225]
70. Pellman EJ, Viano DC, Withnall C, Shewchenko N, Bir CA, Halstead PD. Concussion in professional football: Helmet testing to assess impact performance–part 11. *Neurosurgery.* 2006; 58(1):78–96. [PubMed: 16385332]
71. Rowson B, Rowson S, Duma SM. Hockey star: A methodology for assessing the biomechanical performance of hockey helmets. *Ann Biomed Eng.* 2015; 43(10):2429–43. [PubMed: 25822907]
72. Viano DC, Halstead D. Change in size and impact performance of football helmets from the 1970s to 2010. *Ann Biomed Eng.* 2012; 40(1):175–84. [PubMed: 21994057]
73. Viano DC, Pellman EJ, Withnall C, Shewchenko N. Concussion in professional football: Performance of newer helmets in reconstructed game impacts–part 13. *Neurosurgery.* 2006; 59(3):591. [PubMed: 16823324]
74. Broglio SP, Schnebel B, Sosnoff JJ, et al. Biomechanical properties of concussions in high school football. *Med Sci Sport Exer.* 2010; 42(11):2064–71.
75. Guskiewicz KM, Mihalik JP, Shankar V, et al. Measurement of head impacts in collegiate football players: Relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery.* 2007; 61(6):1244–53. [PubMed: 18162904]
76. Rowson, S.; Duma, SM. National impact database – adult football helmet ratings – may 2012. 2012. <http://www.sbes.vt.edu/nid.php>
77. 2015nfl health and safety report. www.nflhealthplaybook.com.
78. Crompton JG, Bone C, Oyetunji T, et al. Motorcycle helmets associated with lower risk of cervical spine injury: Debunking the myth. *J Am Coll Surg.* 2011; 212(3):295–300. [PubMed: 21227720]
79. Bridges EJ, Rouah F, Johnston KM. Snowblading injuries in eastern canada. *Brit J Sport Med.* 2003; 37(6):511–5.
80. Hagel BE, Russell K, Goulet C, Nettel-Aguirre A, Pless IB. Helmet use and risk of neck injury in skiers and snowboarders. *Am J Epidemiol.* 2010; 171(10):1134–43. [PubMed: 20406762]
81. Moskal A, Martin JL, Laumon B. Helmet use and the risk of neck or cervical spine injury among users of motorized two-wheel vehicles. *Inj Prev.* 2008; 14(4):238–44. [PubMed: 18676782]
82. Mueller BA, Cummings P, Rivara FP, Brooks MA, Terasaki RD. Injuries of the head, face, and neck in relation to ski helmet use. *Epidemiology.* 2008; 19(2):270–6. [PubMed: 18277163]
83. Rivara FP, Thompson DC, Thompson RS. Epidemiology of bicycle injuries and risk factors for serious injury. *Inj Prev.* 1997; 3(2):110–4. [PubMed: 9213156]
84. Rowland J, Rivara F, Salzberg P, Soderberg R, Maier R, Koepsell T. Motorcycle helmet use and injury outcome and hospitalization costs from crashes in washington state. *Am J Public Health.* 1996; 86(1):41–5. [PubMed: 8561240]

85. Russell K, Christie J, Hagel BE. The effect of helmets on the risk of head and neck injuries among skiers and snowboarders: A meta-analysis. *CMAJ*. 2010; 182(4):333–40. [PubMed: 20123800]
86. Sulheim S, Holme I, Ekland A, Bahr R. Helmet use and risk of head injuries in alpine skiers and snowboarders. *JAMA*. 2006; 295(8):919–24. [PubMed: 16493105]
87. Macnab AJ, Smith T, Gagnon FA, Macnab M. Effect of helmet wear on the incidence of head/face and cervical spine injuries in young skiers and snowboarders. *Inj Prev*. 2002; 8(4):324–7. [PubMed: 12460972]
88. Sarkar S, Peek C, Kraus JF. Fatal injuries in motorcycle riders according to helmet use. *J Trauma*. 1995; 38(2):242–5. [PubMed: 7869444]
89. Viano DC, Withnall C, Halstead D. Impact performance of modern football helmets. *Ann Biomed Eng*. 2012; 40(1):160–74. [PubMed: 22012079]
90. Parkinson GW, Hike KE. Bicycle helmet assessment during well visits reveals severe shortcomings in condition and fit. *Pediatrics*. 2003; 112(2):320–3. [PubMed: 12897281]
91. Rivara FP, Astley SJ, Clarren SK, Thompson DC, Thompson RS. Fit of bicycle safety helmets and risk of head injuries in children. *Inj Prev*. 1999; 5(3):194–7. [PubMed: 10518266]
92. McGuine T, Nass S. Football helmet fitting errors in wisconsin high school players. *ASTM Special Technical Publication*. 1997; 1305:83–8.
93. Naunheim RS, Ryden A, Standeven J, et al. Does soccer headgear attenuate the impact when heading a soccer ball? *Acad Emerg Med*. 2003; 10(1):85–90. [PubMed: 12511322]
94. Withnall C, Shewchenko N, Wonnacott M, Dvorak J. Effectiveness of headgear in football. *Brit J Sport Med*. 2005; 39(Suppl 1):40–8.
95. Hanlon EM, Bir CA. Real-time head acceleration measurement in girls' youth soccer. *Med Sci Sport Exer*. 2012; 44(6):1102–8.
96. Naunheim RS, Bayly PV, Standeven J, Neubauer JS, Lewis LM, Genin GM. Linear and angular head accelerations during heading of a soccer ball. *Med Sci Sport Exer*. 2003; 35(8):1406–12.
97. Naunheim RS, Standeven J, Richter C, Lewis LM. Comparison of impact data in hockey, football, and soccer. *J Trauma*. 2000; 48(5):938–41. [PubMed: 10823540]
98. Self BP, Beck J, Schill D, Eames C, Knox T, Plaga J. Head accelerations during soccer heading. *The engineering of sport*. 2006; 6:81–6.
99. Jordan SE, Green GA, Galanty HL, Mandelbaum BR, Jabour BA. Acute and chronic brain injury in united states national team soccer players. *Am J Sport Med*. 1996; 24(2):205–10.
100. Kaminski TW, Cousino ES, Glutting JJ. Examining the relationship between purposeful heading in soccer and computerized neuropsychological test performance. *Res Q Exerc Sport*. 2008; 79(2):235–44. [PubMed: 18664047]
101. Kaminski TW, Wikstrom AM, Gutierrez GM, Glutting JJ. Purposeful heading during a season does not influence cognitive function or balance in female soccer players. *J Clin Exp Neuropsych*. 2007; 29(7):742–51.
102. Kontos AP, Dolese A, Elbin RJ, Covassin T, Warren BL. Relationship of soccer heading to computerized neurocognitive performance and symptoms among female and male youth soccer players. *Brain Inj*. 2011; 25(12):1234–41. [PubMed: 21902552]
103. Putukian M, Echemendia RJ, Mackin S. The acute neuropsychological effects of heading in soccer: A pilot study. *Clin J Sport Med*. 2000; 10(2):104–9. [PubMed: 10798791]
104. Rutherford A, Stephens R, Fernie G, Potter D. Do uk university football club players suffer neuropsychological impairment as a consequence of their football (soccer) play? *J Clin Exp Neuropsych*. 2009; 31(6):664–81.
105. Janda DH, Bir CA, Cheney AL. An evaluation of the cumulative concussive effect of soccer heading in the youth population. *Inj Control Saf Promot*. 2002; 9(1):25–31. [PubMed: 12462161]
106. Lipton ML, Kim N, Zimmerman ME, et al. Soccer heading is associated with white matter microstructural and cognitive abnormalities. *Radiology*. 2013; 268(3):850–7. [PubMed: 23757503]
107. Rutherford A, Stephens R, Potter D, Fernie G. Neuropsychological impairment as a consequence of football (soccer) play and football heading: Preliminary analyses and report on university footballers. *J Clin Exp Neuropsych*. 2005; 27(3):299–319.

108. McCrory P. Do mouthguards prevent concussion? *Brit J Sport Med*. 2001; 35(2):81–2.
109. Hollis SJ, Stevenson MR, McIntosh AS, Shores EA, Collins MW, Taylor CB. Incidence, risk, and protective factors of mild traumatic brain injury in a cohort of Australian nonprofessional male rugby players. *Am J Sport Med*. 2009; 37(12):2328–33.
110. Benson BW, Hamilton GM, Meeuwisse WH, McCrory P, Dvorak J. Is protective equipment useful in preventing concussion? A systematic review of the literature. *Brit J Sport Med*. 2009; 43(Suppl 1):56–67.
111. Mihalik JP, McCaffrey MA, Rivera EM, et al. Effectiveness of mouthguards in reducing neurocognitive deficits following sports-related cerebral concussion. *Dent Traumatol*. 2007; 23(1):14–20. [PubMed: 17227375]
112. Viano DC, Withnall C, Wonnacott M. Effect of mouthguards on head responses and mandible forces in football helmet impacts. *Ann Biomed Eng*. 2012; 40(1):47–69. [PubMed: 21994059]
113. Manoogian S, McNeely D, Duma S, Brolinson G, Greenwald R. Head acceleration is less than 10 percent of helmet acceleration in football impacts. *Biomed Sci Instrum*. 2006; 42:383–8. [PubMed: 16817638]
114. Wu LC, Nangia V, Bui K, et al. In vivo evaluation of wearable head impact sensors. *Ann Biomed Eng*. 2015:1–12. [PubMed: 25527321]
115. Duma SM, Rowson S. Past, present, and future of head injury research. *Exerc Sport Sci Rev*. 2011; 39(1):2–3. [PubMed: 21183827]
116. Broglio SP, Sosnoff JJ, Shin S, He X, Alcaraz C, Zimmerman J. Head impacts during high school football: A biomechanical assessment. *J Athl Training*. 2009; 44(4):342–9.
117. Crisco JJ, Wilcox BJ, Beckwith JG, et al. Head impact exposure in collegiate football players. *J Biomech*. 2011; 44(15):2673–8. [PubMed: 21872862]
118. Crisco JJ, Greenwald RM. Let's get the head further out of the game: A proposal for reducing brain injuries in helmeted contact sports. *Curr Sports Med Rep*. 2011; 10(1):7–9. [PubMed: 21228645]
119. Kerr ZY, Yeargin SW, Valovich McLeod TC, Mensch J, Hayden R, Dompier TP. Comprehensive coach education reduces head impact exposure in American youth football. *Orthop J Sports Med*. 2015; 3(10):2325967115610545. [PubMed: 26779546]
120. Rowson S, Duma SM. The temperature inside football helmets during head impact: A five year study of collegiate football games. *Proceedings of the Institution of Mechanical Engineers, Part P: J Sports Eng Technol*. 2013; 227(1):12–9.