

## Review

# Neurotrauma Prevention Review: Improving Helmet Design and Implementation

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**Abstract:** Neurotrauma continues to contribute to significant mortality and disability. The need for better protective equipment is apparent. This review focuses on improved helmet design and the necessity for continued research. We start by highlighting current innovations in helmet design for sport and subsequent utilization in the lay community for construction. The current standards by sport and organization are summarized. We then address current standards within the military environment. The pathophysiology is discussed with emphasis on how helmets provide protection. As innovative designs emerge, protection against secondary injury becomes apparent. Much research is needed, but this focused paper is intended to serve as a catalyst for improvement in helmet design and implementation to provide more efficient and reliable neuroprotection across broad arenas.

**Keywords:** helmet; military; sport; innovation; secondary injury

## 1. Introduction

Neurotrauma is an important, often preventable cause of morbidity and mortality. Between 180 and 250 traumatic brain injuries (TBIs) occur per 100,000 population per year in the U.S.<sup>1</sup> Helmets have been employed by humans for thousands of years and have served as a crucial instrument by which we protect ourselves from and minimize the effects of traumatic brain injury.<sup>2</sup> Substantial evidence from systematic reviews and meta-analyses points toward the protective effectiveness (often >60%) of helmets in preventing TBIs in athletes, cyclists and motorcyclists.<sup>3-6</sup> However, when stratifying TBI by severity, helmets may be less effective or even ineffective in preventing milder forms of TBI such as concussion.<sup>2</sup> Helmet design has predicated on linear acceleration as a metric corresponding to head injury.<sup>7,8</sup> This has served well in preventing catastrophic injuries. However, rotational acceleration is more likely implicated in the pathophysiology of milder brain injuries, including concussion.<sup>7</sup>

Substantial challenges exist in research involving helmets. For example, a diversity of helmet types based on sport and occupation limits statistical power for studies, along with nonuniform definitions of concussion.<sup>2</sup> Furthermore, prospective studies involving helmets are unethical, and animal models of helmets might not be comparable to those involving humans.<sup>2</sup> Materials scientist, engineer, neuroscientist, neurologist, and neurosurgeon input will be essential to design better helmets.

The following literature review aims to review helmet design in various contexts, along with necessary steps to promote better protection against neurotrauma.

## 2. Current Sports Helmet Design

The mandated use of helmets in organized sports dates back as early as the 1940's when the National Collegiate Athletic Association (NCAA) and National Football League (NFL) made helmets a requirement for players to reduce head-related injuries.<sup>9</sup> Since this time, multiple organizations have developed standards for testing and producing sports helmets (**Table #1**). While the implementation of sports helmets has successfully reduced catastrophic head-related injuries, including traumatic brain injuries (TBI) and orofacial injuries, the risk of concussive injuries remains unmitigated. This discrepancy in selective protection may be explained by how helmets are tested and certified, with the current standard for testing helmets focusing on the use of linear acceleration, which has demonstrated a reduction of TBI and skull fractures, but not concussive injury.<sup>10</sup> Research has demonstrated that the primary mechanism of injury leading to concussions in sports is the result of rotational acceleration, which is not explicitly tested for by certifying organizations.<sup>11,12</sup>

Current sports helmets are designed to protect against punches, falls, projectiles, collisions, and abrasion; and can be grossly organized into two main categories - single-impact and multi-impact helmets.<sup>13</sup> However, virtually all current sports helmets have the basic design of an inner comfort liner, an impact energy attenuating liner, a restraint system, and an outer shell.<sup>14</sup> Single-impact helmets are designed to withstand high-impact encounters only once. Examples of these include bicycle, mountaineering, and equestrian helmets. The energy attenuating liner in these helmets is typically constructed of lightweight expanded polystyrene (EPS) foam, which does well in dissipating energy, but permanently deforms after impact.<sup>9</sup> On the other hand, multi-impact helmets are designed to withstand multiple impacts and are used in US football, hockey, motorcross, and rugby. The resilience to multiple impacts is accomplished by construction with either vinyl nitrile (VN) or expanded polypropylene (EPP) foam for the energy attenuating liner. VN and EPP can return to their original form after impact; however, VN performs better with lower energy impacts than EPP, which performs better at higher energy impacts.<sup>9,15</sup> In both helmets, the outer shell functions to distribute the force of impact along the area of the energy attenuating liner. Shells are commonly constructed of polycarbonate (PC) or ABS plastic, but some helmets may have hard shells composed of composites, such as fiberglass or carbon fiber.<sup>7,16</sup>

Further variations in helmet design exist according to the dangers encountered in each sport, as well as practicality, ease of use, and aesthetics. Sports (e.g., lacrosse, hockey, and baseball) where the impact from a projectile is of concern may implement a face guard (typically either a wired frame or an extension of the helmet's shell) to protect against orofacial injuries.<sup>17,18</sup> Cycling and mountaineering helmets are often engineered to be highly aerodynamic and as light as possible to avoid hindering the player's performance.<sup>19</sup> Helmets used in motorcycle-variant sports are designed with thicker protective layers that aerodynamically encapsulate the entire head to protect against greater risks associated with high speed.<sup>20</sup> A list of sports helmet types, activities, and applicable standards may be found in **Tables #1 and #2**.

**Table 1.** Sports helmet standards ('x' indicates standard)<sup>14,21</sup>.

Sport Category	ASTM	AS/NZS	CSA	DOT	EN (incl. BSI, DIN NSAI)	FIFA, FIS, IIHF, IRB	NOCSAE	ISO	Snell
American Football	x						x		
Animal Riding	x								
Baseball	x						x		
Cricket		x			x (BSI)				
Cycling Sports	x	x	x		x				x
Football	x								
Ice Hockey			x		x		x	x	
Lacrosse							x		
Motorized Sports				x					x
Mountaineering					x				x
Pole Vaulting	x								
Polo							x		
Rugby						x (IRB)			
Skateboard Sports	x								x
Snow Sports	x			x					x
Water Sports					x				

AS/NZS, Standards Australia/New Zealand Standards; ASTM, ASTM International; BSI, none; CSA, Canadian Standards Association; DIN, Germany Industry Standards; DOT, Department of Transportation; FIFA, Federation International Football Associations; FIS, International Ski Federation; IIHF, International Ice Hockey Federation; IRB, International Rugby Board; ISO, International Standards Organization; NOCSAE, National Operating Committee on Standards for Athletic Equipment; NSAI, National Standards Authority Ireland; Snell, Snell Memorial Foundation

**Table 2.** Sport helmets categorized by activity<sup>14,21</sup>.

Helmet Type	Activity	Applicable Standards
American Football	American Football	NOCSAE ND002, ND006; ASTM F717
Baseball Batter's	Baseball	NOCSAE ND022
Baseball Catcher's	Softball	NOCSAE ND024
	T-Ball	
Bicycle	Bicycling	ASTM F1447, F18981; Snell B-90A, B-95, N-94; CPSC
	Kick Scooter Riding	
	Roller Skating - Recreational	
BMX	BMX Cycling	ASTM F2032; CPSC
Bull Riding	Bull Riding	ASTM 2530
Canoeing/White Water	Canoeing/Kayaking	EN 1385
Cricket	Cricket	BSI BS7928 <sup>22</sup>
Downhill	Downhill Mountain Bike Racing	ASTM F1952; CPSC
Equestrian	Horseback Riding	ASTM F1163; Snell E-2001
Football	Football	ASTM F2439-06 <sup>23</sup>
Hockey	Ice Hockey	NOCSAE ND030; ASTM F1045
Lacrosse	Lacrosse	NOCSAE ND041
Motorcycle	Motorcycling	Snell M-2005, M-2010, CMS/CMR 20073; DOT FMVSS 218
Motorcycle	Power Boating	Snell M-2005, M-2010, CMS/CMR 2007; DOT FMVSS 218
Motorcycle or Karting	Karting/Go-Karting	Snell K-98, M-2005, M-2010, CMS/CMR 2007; DOT FMVSS 218
Motorcycle or Moped	Moped Riding	Snell L-98, M-2005, M-2010, CMS/CMR 20073; DOT FMVSS 218
	Motorized Bicycling	
	Powered Scooter Riding	
Motorcycle or Motocross	ATV Riding	Snell M-2005, M-2010, CMS/CMR 2007; DOT FMVSS 218
	Dirt- and Mini-Bike Riding	
	Motocrossing	
	ROV/Side by Side/UTV Riding	
Mountaineering	Rock- and Wall-Climbing	EN 12492; Snell N-94
	Spelunking	
Pole Vaulting	Pole Vaulting	ASTM F2400
Polo	Polo	NOCSAE ND050
Skateboard	Longboarding	ASTM F1492; Snell N-94
	Roller Skating - Trick	
	Skateboarding	
Ski	Skiing	ASTM F2040; CSA Z263.1; Snell RS-98, S-98
	Snowboarding	
	Snow Tubing	
Snowmobile	Snowmobiling	Snell M-2005, M-2010, CMS/CMR 2007; DOT FMVSS 218

3. Current Military Helmet Design

The current issue military helmet for combat use is the advanced combat helmet (ACH), and previously was the personnel armor system for ground troops (PASGT) in the late 1990’s and early 2000’s.<sup>24</sup> Prior work has highlighted the blunt impact standard limitation to linear head acceleration,<sup>25</sup> with the need to focus on rotational head motion, the likely mechanism contributing to diffuse axonal injury (DAI).<sup>25-28</sup> Military-specification (mil-spec) requires a blunt impact acceleration limit testing for pass/fail criteria of the ACH, but does not require a rotational component testing.<sup>27</sup> Blast induced TBI (BTBI) is also a mechanism of combat induced diffuse axonal injury where blast waves cause rotational forces on the brain to induce DAI.

The ACH is equipped with high-strength Kevlar 129 fibers, housed in a 7.8 mm thick composite shell.<sup>2,29</sup> Previous literature has highlighted the efficacy of the ACH head protection in reduced likelihood of blast-induced mild TBI (mTBI), where levels of protection increase with peak blast exposure,<sup>27</sup> as well as protection against blast-induced intracranial pressure (ICP) increases and brain strains.<sup>30,31</sup> Although there is increased overall protection against blast exposures, helmet design still has limitations. For example, Zhang et

al.<sup>30</sup> demonstrated that blast waves could directly penetrate through the gap between the forehead and the helmet, causing further deformation of padding.

Warfighters who engage in parachute combat rather than ground combat are twice as likely to sustain any form of TBI<sup>32</sup> and are three times more likely to sustain a mild form of a TBI wearing the PASGT combat helmet compared to the ACH.<sup>32</sup> This is likely due to the higher velocity impacts sustained in parachute jumping and a suspension system that is not as advanced as the ACH. The current ACH uses a suspension padding system that offers protection against axonal shearing, but the preclinical models are still limited regarding how effective these padding systems are in humans.<sup>26</sup>

Thus, slight modifications to the ACH and/or future helmet design mil-spec testing may reduce incidence of DAI and the prevalence of military-related TBI for warfighters. Preclinical animal models may provide further adequate preliminary evidence of the need to address diffuse rotational injury associated with warfighters.

**Table 3.** Military Helmets.

Standard Issue Helmet	Material	Efficacy
Advanced Combat Helmet (ACH)	ballistic fabrics (Kevlar®) k129, composite shell, suspension system	Evidence of reduced ICP brain stain/limited research on diffuse TBI efficacy <sup>27</sup>
Personnel Armor System for Ground Troops (PASGT)	ballistic fabrics (Kevlar®) K29, suspension system	Penetration protection against .22 caliber and lower tolerance to blast compared to k129 fibers <sup>33,34</sup>

**4. Current Construction Helmet Design**

In the United States, the construction industry is responsible for the largest portion of industrial injuries and induces an estimated healthcare and economic burden of \$11.5 billion in direct medical costs and lost wages, as last investigated in 2002.<sup>35</sup> The United States Bureau of Labor Statistics reports that falls in the construction industry account for 62.9% of all fatal falls.<sup>36</sup> Industrial workers 65 years of age and older are at the greatest risk for more severe outcomes after TBI, including death. In addition, this age group has a higher incidence of falls, and within the construction industry, these workers have the highest (57%) frequency of fall-related injuries, including TBIs. This increased risk for injury demonstrates the importance of proper personal protective equipment (PPE), such as helmets. PPE is defined as a control measure used in hazardous situations where the hazard cannot be eliminated or controlled to an acceptable level through engineering design or administrative actions.<sup>37</sup> According to Occupational Safety and Health Administration (OSHA) and the United States Army Corps of Engineers (USACE) regulations, all employees and visitors to a construction site must wear a provided hard hat.<sup>37</sup> These industrial safety helmets are required in conditions where objects might fall from above and strike workers on the head, workers may bump their heads against objects, or there is possible contact with electrical hazards. The American National Standards Institute (ANSI) regulates hard hats by setting performance and requirement testing standards. Type I and II helmets reduce force to the top of the head, while type III classified helmets can reduce impact to the top and sides of the head. Industrial safety helmets have a suspension design that is intended to reduce the force of impact and penetrations of small objects. Furthermore, a study was performed to assess their effectiveness against larger objects and found these helmets were capable of reducing the force and linear acceleration for vertical impact.<sup>36-38</sup> They also reduced the likelihood of skull fracture and severe injury, further supporting the importance of industrial safety helmets.

Construction-related injuries to the head can result in skull fractures and localized underlying brain injury, closed head injuries, neck injuries, and rotational injuries leading to diffuse axonal injury.<sup>39</sup> A study was performed to assess the impact of hard hats during varied neck movements utilizing surface electromyography sensors on the upper

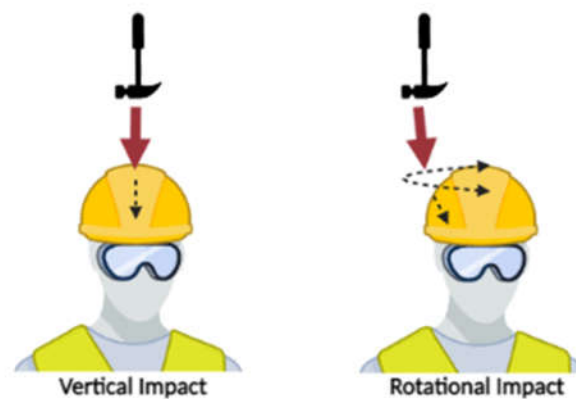
trapezius muscles of volunteer subjects.<sup>40</sup> The researchers demonstrated that muscle activity and fatigue were not increased while wearing an industrial hard hat, suggesting that this protective equipment is not causing further detriment to workers' neck strain.<sup>40</sup> Vertical impact occurs in 36% of falling object cases, yet most injuries include a rotational injury.<sup>39</sup> Though industrial safety helmets are required PPE in the construction industry, these helmets have suspension designs that primarily protect against vertical impact. This design may be beneficial for many types of possible injury at a construction site, but it does not protect the wearer during a fall or when faced with a rotational injury (**Figure #1**).

Models for assessing helmet design often utilize crash dummies with a rigid spine and do not allow for realistic evaluations of vertical impact on neck injury. Improvements in performance testing have resulted from the use of flexible neck dummies that can better emulate neck compression and rotational impact.<sup>39</sup> These measures should be considered in the development of new safety helmets.<sup>39</sup> Finite element analysis is a numerical analysis technique utilized to assess the engineering and design of helmets by mathematically modeling physical contributions such as force. This mathematical modeling utilizes a scoring system such as the head injury criteria (HIC) score, incorporating acceleration and time, where a score of 1000 is considered a safe limit.<sup>41</sup> This widely used score has been utilized to improve and test different helmet materials such as Carbon Fiber and Polyethylene.<sup>42</sup> In addition, finite element analysis can be utilized to assess diffuse axonal injury computationally via von Mises stress.<sup>38</sup> A study evaluating simulation-based impact on construction helmets indicated that a 2 kg cylinder vertical impact has a 50% chance of causing mild diffuse axonal injury, which increases in severity as impact speed increases. However, this study was limited by the lack of modeling any elements of rotational acceleration.<sup>38</sup> This testing provides classifications for helmets for one-time impact, yet industrial helmets regularly endure multiple impacts. One study evaluated the damage and vulnerability induced by repeated impacts on the helmets' shock absorption performance.<sup>43</sup> An endurance limit was determined for each helmet, where cumulative damage from multiple impacts degraded the shock absorption performance when the impacts were greater than the endurance limit.

The largest challenge with construction-related safety is workers wearing the industrial safety helmet. Industrial safety helmets have been accused of being too heavy and uncomfortable to wear while working; thus, many workers often choose not to wear helmets when possible. One initiative for promoting wearing helmets on construction sites has been artificial intelligence technology for safety helmet recognition.<sup>44</sup> While improvements in industrial helmet design are needed for comfort and protection against rotational injury, the use of these safety helmets is still effective in protecting the wearer from injury. An analysis of work-related injuries demonstrated that safety helmets meeting current OSHA and ANSI requirements more effectively prevented intracranial injury in comparison to no helmet at all.<sup>45</sup>

While helmets can effectively dissipate and reduce impact and acceleration-deceleration forces, they do not entirely prevent energy transfer and the risk of concussion. The pathophysiological consequences to single or repeated concussions while wearing a helmet are needed but present challenges when adapting experiments to translational TBI models. Helmets are designed for human heads and impact based on bipedal kinematics, where common TBI animal models introduce varied head and brain shapes and quadrupedal movement that can change the fundamental dynamics of applied forces, where the temporal and spatial profile of physiological alterations, diffuse axonal injury, and secondary injury sequelae can be influenced.

In conclusion, industrial safety helmets are beneficial for preventing head injury, but there is a large gap in work-related injury research. Mechanistic understanding and appropriate injury models, including rotational acceleration, are required to develop more protective helmets for work-related traumatic brain injuries.



**Figure 1.** Industrial safety helmets have a suspension design that prevents injury from vertical impact. These helmets are not designed to prevent injury from side or rotational impacts that would increase injury severity and diffuse axonal injury.

## 5. Secondary Injury Prevention

While there are likely a plethora of factors that influence TBI, linear and rotational acceleration are two of the most significant. Linear acceleration is believed to produce focal trauma at both coup and contrecoup locations within the brain.<sup>46</sup> Examples of focal injuries include epidural hematomas, skull fractures, and cerebral contusions.<sup>46,47</sup> Conversely, rotational acceleration produces more diffuse trauma within the brain through shearing forces.<sup>46,48</sup> For years, reducing linear acceleration has been one of the primary goals of helmet design. However, it was not until 2018 that the National Operating Committee for Standards in Athletic Equipment updated the criteria to include rotational acceleration in the design of new helmets.<sup>49</sup> In a 2020 evaluation of combat helmets released by the US Army Combat Capabilities Development Command, they demonstrated that while, on average, the Army Advanced Combat Helmet (ACH) produced a statistically significant reduction in linear acceleration compared to no helmet. However, it failed to produce a statistically significant average reduction in rotational acceleration and even increased rotational acceleration at higher force impacts.<sup>50</sup> Consequently, helmet designs in sports and combat have historically neglected to consider rotational acceleration and the resultant more mild traumatic brain injuries (mTBI) such as concussion and subconcussion.<sup>7,51</sup>

Rotational acceleration produces axonal shearing, obstructing axonal function, and causing an accumulation of amyloid-beta precursor protein that peaks after 24-48 hours.<sup>52-54</sup> In addition, shearing and mechanical forces produce plasma membrane instability resulting in potassium leakage and neuronal depolarization.<sup>55,56</sup> As a result, the excitatory neurotransmitter glutamate is released and binds NMDA receptors, generating a cycle of potentially neurotoxic hyperexcitation.<sup>54,57-59</sup> This drastically elevates intercellular calcium and sodium concentrations and destabilizes mitochondrial function as a vital calcium buffer system within the cell.<sup>60-62</sup> As a result, calcium-dependent proteases and lipases are activated and reactive oxygen species production increases, causing oxidative stress within the cell.<sup>63,64</sup> Mitochondrial dysfunction downregulates ATP production and contributes to a global metabolic crisis.<sup>61,65-68</sup> Elevated oxidative stress within the cell is believed to promote perturbation within the endoplasmic reticulum (ER) and a subsequent accumulation of unfolded proteins. As a result of the activation of several signal pathways including inositol requiring enzyme 1 (IRE1), activating transcription factor 6 (ATF6), and protein kinase R-like ER kinase (PERK), the ER upregulates the unfolded protein response (UPR) pathway.<sup>69-71</sup> The UPR initially functions to resolve ER stress through inhibition of protein synthesis and proteolysis of misfolded or unfolded proteins.<sup>71,72</sup> With a failure of

ER stress resolution over time, the ER UPR pathway ultimately upregulates caspases and pro-apoptotic pathways, promoting cell death.<sup>71,73-75</sup> These functions can be exacerbated with repeated injury, requiring improved innovation in helmet design.

## 6. Innovations in Helmet Design

While the outward appearance of many helmets may not change with safety innovations, the internal design continues to dramatically transform with each new development. The NFL launched its Helmet Challenge in November 2019, with the top-performing prototypes being announced in 2021.<sup>76</sup> The NFL awarded grants to Kollide, Xenith, and Impressio based on prototype NFL lab performance testing that surpassed the current NFL top-performing helmet.<sup>76</sup> Kollide used a 3D printed helmet containing a 95 pad mesh liner.<sup>77</sup> The 3D printed design allowed for unique customization to the shape of each player's head.<sup>78,79</sup> Xenith combined a 3D printed polymer lattice with fitted foam inserts.<sup>76</sup> Impressio's helmet prototype contains liquid crystal elastomers housed within 3D printed columns.<sup>77,80</sup> Liquid crystal elastomers combine the self-organization of the liquid crystal-line phase with the elasticity of an elastomer, offering an innovative and potentially superior approach to absorbing impact energy.<sup>81-83</sup> All three companies incorporated 3D printing into their design with an increased focus on the customization of helmet fit for each individual. Experimental evaluation is ongoing.

The overall benefit of impact sensors (accelerometer and gyroscope) in helmets has been widely debated, as numerous studies have highlighted the significant error in data measurement and consequently limited clinical utility.<sup>84,85</sup> The 2017 Berlin Concussion in Sport Group concluded that head impact sensors did not offer any beneficial information in diagnosing a concussion.<sup>86</sup> More recent research into developing more accurate impact sensors in helmet and mouthpieces have offered some insight into the duration, direction, magnitude of head motion, and impact.<sup>87</sup> One study examining the use of fiber optics sensors coupled with a machine learning model could accurately predict ( $R^2 \sim 0.90$ ) blunt-force trauma magnitude and direction from novel impacts not yet experienced by the system.<sup>88</sup> When examining angular acceleration and velocity, using a sensor patch placed against the neck has shown some promise in the prediction of head rotational kinematics ( $R^2 > 0.9$ ).<sup>89</sup> Such a device could be used in conjunction with a helmet sensor to reduce measurement error. Unfortunately, many helmets and patch impact sensors tend to overpredict linear and rotational acceleration with false positive high acceleration impacts.<sup>90</sup> Without visual confirmation of the motion to support the recorded data, this high false positive rate limits the benefit of current impact sensors in practice. As technology advances in the field of impact sensors and analysis of kinetic data, helmet, patch, and mouthpiece sensors may offer valuable information to future clinicians.

For military paratroopers and civilian parachute enthusiasts, parachute opening shock has been associated with the incidence of neck and back injuries.<sup>91</sup> Wing loading, referring to the ratio of weight carried by the individual to the area of the parachute canopy, is believed to affect head acceleration responsible for these injuries.<sup>91</sup> NASA has worked to reduce water landing neck injuries by developing an Orion helmet support assembly (HSA) to mitigate dynamic loading on the neck.<sup>92,93</sup> Their preliminary design was composed of a rigid HSA secured to the helmet with a metal bar braced behind the shoulders.<sup>92</sup> The metal bar was fixed in place by shoulder straps.<sup>92</sup> With dynamic impact testing, this rigid HSA design demonstrated overall increased upper neck loading with an elevated neck injury metric.<sup>92</sup> This data led to the development of a flexible HSA consisting of steel wires attached to both the front and back of the helmet.<sup>92</sup> These interconnected steel wires were bent to fit the chest and back of the wearer, with a shoulder harness attached to the helmet.<sup>92</sup> Overall, NASA's flexible HSA design demonstrated reduced neck loading and neck injury metrics with testing across various body types.<sup>92</sup> This data suggests that a helmet neck support system may reduce neck injuries in astronauts and potentially paratroopers, while an overly rigid HSA could induce further injury. While protection typically comes with a trade-off of lost mobility, this study indicates that limited mobility may provide some benefit in the reduction of injury.

## 7. Conclusion

Considering the effectiveness of helmets in preventing catastrophic TBIs, efforts can be made to promote greater helmet usage and awareness. For example, in India, which has a large number of TBIs related to road accidents, public efforts to promote helmet usage and improved prehospital EMS care resulted in plateauing of road traffic deaths.<sup>94</sup> A systematic review of helmet laws found helmet laws to increase compliance and decrease road traffic-related head injuries and fatalities.<sup>95</sup> This is an important consideration in low-income nations, where many people, including pediatric populations, rely on motorcycles, scooters, and bicycles.<sup>95</sup> Certain sports, such as equestrian-related sports, feature low helmet usage and high rates of TBI, so increasing awareness and promotion of helmet use and mandatory helmet laws could also prevent TBIs by up to 50%.<sup>96,97</sup>

Nonetheless, as described in this review, current helmets may not be effective in preventing concussions or mild TBIs.<sup>2,7</sup> This has promoted the development of various new helmets incorporating rotational acceleration testing and rotational damping technology that may decrease concussion incidence or magnitude.<sup>98,99</sup> For example, Hoshizaki et al.<sup>98</sup> employed drops onto a 45° anvil to simulate the rotational dynamics of head impacts, showing that two helmets fitted with rotational damping technologies better mitigated rotational acceleration compared to a standard helmet. DiGiacomo et al.<sup>99</sup> similarly used drops onto a 45° anvil to show that rotational damping-based snow helmets significantly reduce rotational acceleration and concussion probability compared to standard helmets. More testing of the different rotational damping helmets is necessary to see which provides the most effective protection against concussions. Further examination of impact location can inform optimization of padding placement to minimize rotational angular acceleration in more vulnerable locations.<sup>100</sup> For example, Fanton et al.<sup>100</sup> found mandibular impacts to be the most significant.

Now that rotational acceleration is becoming a vital consideration of helmet testing, further testing and models to correlate head kinematics (particularly rotational acceleration) with brain strain will be important.<sup>101,102</sup> For example, Ghazi et al.<sup>103</sup> developed a convolutional neural network that approximates brain strain and demonstrated significant variations in brain strains between 23 football helmet models, suggesting continued room for improvement in helmet design. Future helmets might use such data to initiate warnings in helmets when concussion is probable.<sup>7</sup> Other efforts to reduce concussions and improve helmets include standardizing definitions of concussion by using protocols involving eye-tracking assessments and/or serum biomarkers, like total tau, to better analyze and differentiate data in future helmet studies.<sup>2</sup> Perhaps helmet selection will evolve to increased selection based on multiple contexts and sports-related risks due to technological innovations and assessment of impact kinematics. Nonetheless, more helmet research considering rotational acceleration will likely advance the field.

## Reference

1. Bruns J, Jr., Hauser WA. The epidemiology of traumatic brain injury: a review. *Epilepsia*. 2003;44(s10):2-10.
2. Sone JY, Kondziolka D, Huang JH, Samadani U. Helmet efficacy against concussion and traumatic brain injury: a review. *J Neurosurg*. 2017;126(3):768-781.
3. Donnan J, Walsh S, Fortin Y, et al. Factors associated with the onset and progression of neurotrauma: A systematic review of systematic reviews and meta-analyses. *Neurotoxicology*. 2017;61:234-241.
4. Thompson DC, Rivara FP, Thompson R. Helmets for preventing head and facial injuries in bicyclists. *Cochrane Database Syst Rev*. 2000;1999(2):Cd001855.
5. van den Brand CL, Karger LB, Nijman STM, Valkenberg H, Jellema K. Bicycle Helmets and Bicycle-Related Traumatic Brain Injury in the Netherlands. *Neurotrauma Rep*. 2020;1(1):201-206.
6. Thompson DC, Rivara FP, Thompson RS. Effectiveness of Bicycle Safety Helmets in Preventing Head Injuries: A Case-Control Study. *JAMA*. 1996;276(24):1968-1973.
7. Hoshizaki TB, Post A, Oeur RA, Brien SE. Current and Future Concepts in Helmet and Sports Injury Prevention. *Neurosurgery*. 2014;75(Supplement 4):S136-S148.
8. Gurdjian ES, Webster JE, Lissner HR. Observations on the mechanism of brain concussion, contusion, and laceration. *Surg Gynecol Obstet*. 1955;101(6):680-690.
9. Cantu RC. *Neurologic athletic head and spine injuries*. Saunders; 2000.
10. Post A, Hoshizaki TB. Mechanisms of brain impact injuries and their prediction: A review. *Trauma*. 2012;14(4):327-349.

11. Bain AC, Meaney DF. Tissue-level thresholds for axonal damage in an experimental model of central nervous system white matter injury. *Journal of Biomechanical Engineering*. 2000;122(6):615-622.
12. Forero Rueda MA, Cui L, Gilchrist MD. Finite element modelling of equestrian helmet impacts exposes the need to address rotational kinematics in future helmet designs. *Computer Methods in Biomechanics and Biomedical Engineering*. 2011;14(12):1021-1031.
13. Hoshizaki T, Brien S. The Science and Design of Head Protection in Sport. *Neurosurgery*. 2004.
14. McIntosh AS, Andersen TE, Bahr R, et al. Sports helmets now and in the future. *British Journal of Sports Medicine*. 2011;45(16):1258-1265.
15. Post A, Hoshizaki TB, Brien S. Head Injuries, Measurement Criteria and Helmet Design. In: Hong Y, ed. *Routledge Handbook of Ergonomics in Sport and Exercise*. London: Routledge Publishers; 2012.
16. Bustamante MC, Bruneau D, Barker JB, Gierczycka D, Coralles MA, Cronin DS. Component-Level Finite Element Model and Validation for a Modern American Football Helmet. *Journal of Dynamic Behavior of Materials*. 2019;5(2):117-131.
17. Tuna EB, Ozel E. Factors Affecting Sports-Related Orofacial Injuries and the Importance of Mouthguards. *Sports Medicine*. 2014;44(6):777-783.
18. Ranalli DN, Demas PN. Orofacial Injuries from Sport. *Sports Medicine*. 2002;32(7):409-418.
19. Underwood L, Jermy M, Eloi P, Cornillon G. Helmet position, ventilation holes and drag in cycling. *Sports Engineering*. 2015;18(4):241-248.
20. Gibson TJ, Thai K. Helmet protection against basilar skull fracture. Australian Transport Safety Bureau; 2007.
21. Which Helmet for Which Activity? *US Consumer Product Safety Commission*.
22. International Cricket Council.
23. Standard Specification for Headgear Used in Soccer.
24. Scharine AA, Binseel MS, Mermagen T, Letowski TR. Sound localisation ability of soldiers wearing infantry ACH and PASGT helmets. *Ergonomics*. 2014;57(8):1222-1243.
25. York S, Edwards ED, Jesunathadas M, et al. Influence of Friction at the Head-Helmet Interface on Advanced Combat Helmet (ACH) Blunt Impact Kinematic Performance. *Mil Med*. 2022.
26. Bradfield C, Vavalle N, DeVincentis B, et al. Combat Helmet Suspension System Stiffness Influences Linear Head Acceleration and White Matter Tissue Strains: Implications for Future Helmet Design. *Mil Med*. 2018;183(suppl\_1):276-286.
27. Terpsma R, Carlsen RW, Szalkowski R, et al. Head Impact Modeling to Support a Rotational Combat Helmet Drop Test. *Mil Med*. 2021.
28. Begonia M, Humm J, Shah A, Pintar FA, Yoganandan N. Influence of ATD versus PMHS reference sensor inputs on computational brain response in frontal impacts to advanced combat helmet (ACH). *Traffic Inj Prev*. 2018;19(sup2):S159-s161.
29. Grujicic M, Bell WC, Pandurangan B, Glomski PS. Fluid/Structure Interaction Computational Investigation of Blast-Wave Mitigation Efficacy of the Advanced Combat Helmet.
30. Zhang L, Makwana R, Sharma S. Brain response to primary blast wave using validated finite element models of human head and advanced combat helmet. *Front Neurol*. 2013;4:88.
31. Nyein MK, Jason AM, Yu L, et al. In silico investigation of intracranial blast mitigation with relevance to military traumatic brain injury. *Proc Natl Acad Sci U S A*. 2010;107(48):20703-20708.
32. Ivins BJ, Crowley JS, Johnson J, Warden DL, Schwab KA. Traumatic brain injury risk while parachuting: comparison of the personnel armor system for ground troops helmet and the advanced combat helmet. *Mil Med*. 2008;173(12):1168-1172.
33. Tham C, Tan V, Lee H-P. Ballistic impact of a KEVLAR® helmet: Experiment and simulations. *International Journal of Impact Engineering*. 2008;35(5):304-318.
34. Kadir Bilisik A, Turhan Y. Multidirectional stitched layered aramid woven fabric structures and their experimental characterization of ballistic performance. *Textile Research Journal*. 2009;79(14):1331-1343.
35. GM W, XS D, T M, E H, Y M. Costs of occupational injuries in construction in the United States. *Accident; analysis and prevention*. 2007;39(6).
36. U.S. Bureau of Labor Statistics. 2022; <https://www.bls.gov/>.
37. 1926.100 - Head protection. | Occupational Safety and Health Administration. 2022; <https://www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.100>.
38. J L, J Y, Z L, D L. Simulation-based assessment for construction helmets. *Computer methods in biomechanics and biomedical engineering*. 2015;18(1).
39. Hume A, N. J. Mills, and A. Gilchrist. Industrial head injuries and the performance of the helmets. 1995.
40. S M, DA A, T S, S R, D G. Are hard hats a risk factor for WRMSD in the cervical-thoracic region? *Work (Reading, Mass)*. 2020;66(2).
41. JZ W, CS P, BM W, CL R. Finite element simulations of the head-brain responses to the top impacts of a construction helmet: Effects of the neck and body mass. *Proceedings of the Institution of Mechanical Engineers Part H, Journal of engineering in medicine*. 2017;231(1).
42. P.Naresh DMK, A.V.Hari Babu, P.Hussain. Design And Analysis Of Industrial Helmet. *International Journal of Mechanical Engineering Research*. 2022.
43. Wu JZ, Pan, Christopher S., Wimer, Bryan M. Evaluation of the shock absorption performance of construction helmets under repeated top impacts | Elsevier Enhanced Reader. *Engineering Failure Analysis*. 2022.
44. Wei L, Cheng M, Feng M, Lijuan Z. Research on recognition of safety helmet wearing of electric power construction personnel based on artificial intelligence technology - IOPscience. 2020.

45. SC K, YS R, SD S, JY K. Preventive Effects of Safety Helmets on Traumatic Brain Injury after Work-Related Falls. *International journal of environmental research and public health*. 2016;13(11).
46. Tierney G. Concussion biomechanics, head acceleration exposure and brain injury criteria in sport: a review. *Sports Biomechanics*. 2021;1-29.
47. Kleiven S. Why Most Traumatic Brain Injuries are Not Caused by Linear Acceleration but Skull Fractures are. *Frontiers in Bioengineering and Biotechnology*. 2013;1.
48. Rowson S, Bland ML, Campolettano ET, et al. Biomechanical Perspectives on Concussion in Sport. *Sports medicine and arthroscopy review*. 2016;24(3):100-107.
49. Trotta A, Ní Annaidh A, Burek RO, Pelgrims B, Ivens J. Evaluation of the head-helmet sliding properties in an impact test. *Journal of Biomechanics*. 2018;75:28-34.
50. Neice R, Plaisted T. *Evaluation of a Combat Helmet Under Combined Translational and Rotational Impact Loading*. Oak Ridge Associated Univ.; 2020/12/01/ 2020.
51. McKeithan L, Hibshman N, Yengo-Kahn AM, Solomon GS, Zuckerman SL. Sport-Related Concussion: Evaluation, Treatment, and Future Directions. *Medical Sciences*. 2019;7(3):44.
52. Jamjoom AAB, Rhodes J, Andrews PJD, Grant SGN. The synapse in traumatic brain injury. *Brain*. 2020;144(1):18-31.
53. Pavlovic D, Pekic S, Stojanovic M, Popovic V. Traumatic brain injury: neuropathological, neurocognitive and neurobehavioral sequelae. *Pituitary*. 2019;22(3):270-282.
54. Romeu-Mejia R, Giza CC, Goldman JT. Concussion Pathophysiology and Injury Biomechanics. *Current Reviews in Musculoskeletal Medicine*. 2019;12(2):105-116.
55. Keating CE, Cullen DK. Mechanosensation in traumatic brain injury. *Neurobiology of Disease*. 2021;148:105210.
56. Wofford KL, Grovola MR, Adewole DO, et al. Relationships between injury kinematics, neurological recovery, and pathology following concussion. *Brain Communications*. 2021;3(4):fcab268.
57. Tehse J, Taghibiglou C. The overlooked aspect of excitotoxicity: Glutamate-independent excitotoxicity in traumatic brain injuries. *European Journal of Neuroscience*. 2019;49(9):1157-1170.
58. Guerriero RM, Giza CC, Rotenberg A. Glutamate and GABA Imbalance Following Traumatic Brain Injury. *Current Neurology and Neuroscience Reports*. 2015;15(5):27.
59. Wofford KL, Loane DJ, Cullen DK. Acute drivers of neuroinflammation in traumatic brain injury. *Neural Regeneration Research*. 2019;14(9):1481-1489.
60. Hubbard WB, Joseph B, Spry M, Vekaria HJ, Saatman KE, Sullivan PG. Acute Mitochondrial Impairment Underlies Prolonged Cellular Dysfunction after Repeated Mild Traumatic Brain Injuries. *Journal of Neurotrauma*. 2019;36(8):1252-1263.
61. Cheng G, Kong R-h, Zhang L-m, Zhang J-n. Mitochondria in traumatic brain injury and mitochondrial-targeted multipotential therapeutic strategies. *British Journal of Pharmacology*. 2012;167(4):699-719.
62. Verweij BH, Muizelaar JP, Vinas FC, Peterson PL, Xiong Y, Lee CP. Impaired cerebral mitochondrial function after traumatic brain injury in humans. *Journal of Neurosurgery*. 2000;93(5):815-820.
63. Ismail H, Shakkour Z, Tabet M, et al. Traumatic Brain Injury: Oxidative Stress and Novel Anti-Oxidants Such as Mitoquinone and Edaravone. *Antioxidants*. 2020;9(10):943.
64. Kumar Sahel D, Kaira M, Raj K, Sharma S, Singh S. Mitochondrial dysfunctioning and neuroinflammation: Recent highlights on the possible mechanisms involved in Traumatic Brain Injury. *Neuroscience Letters*. 2019;710:134347.
65. Signoretti S, Marmarou A, Tavazzi B, et al. The protective effect of cyclosporin A upon N-acetylaspartate and mitochondrial dysfunction following experimental diffuse traumatic brain injury. *Journal of Neurotrauma*. 2004;21(9):1154-1167.
66. Signoretti S, Marmarou A, Tavazzi B, Lazzarino G, Beaumont A, Vagnozzi R. N-Acetylaspartate reduction as a measure of injury severity and mitochondrial dysfunction following diffuse traumatic brain injury. *Journal of Neurotrauma*. 2001;18(10):977-991.
67. Vagnozzi R, Signoretti S, Tavazzi B, et al. Hypothesis of the postconcussive vulnerable brain: experimental evidence of its metabolic occurrence. *Neurosurgery*. 2005;57(1):164-171; discussion 164-171.
68. Vagnozzi R, Tavazzi B, Signoretti S, et al. TEMPORAL WINDOW OF METABOLIC BRAIN VULNERABILITY TO CONCUSSIONS: MITOCHONDRIAL-RELATED IMPAIRMENT—PART I. *Neurosurgery*. 2007;61(2):379-389.
69. Tan H-P, Guo Q, Hua G, Chen J-X, Liang J-C. Inhibition of endoplasmic reticulum stress alleviates secondary injury after traumatic brain injury. *Neural Regeneration Research*. 2018;13(5):827-836.
70. Krajewska M, Xu L, Xu W, et al. Endoplasmic reticulum protein BI-1 modulates unfolded protein response signaling and protects against stroke and traumatic brain injury. *Brain Research*. 2011;1370:227-237.
71. Brady RD, Bird S, Sun M, et al. Activation of the Protein Kinase R-Like Endoplasmic Reticulum Kinase (PERK) Pathway of the Unfolded Protein Response after Experimental Traumatic Brain Injury and Treatment with a PERK Inhibitor. *Neurotrauma Reports*. 2021;2(1):330-342.
72. Scheper W, Hoozemans JJM. The unfolded protein response in neurodegenerative diseases: a neuropathological perspective. *Acta Neuropathologica*. 2015;130(3):315-331.
73. Krishnamurthy K, Laskowitz DT. Cellular and Molecular Mechanisms of Secondary Neuronal Injury following Traumatic Brain Injury. In: Laskowitz D, Grant G, eds. *Translational Research in Traumatic Brain Injury*. Boca Raton (FL): CRC Press/Taylor and Francis Group; 2016.
74. Hetz C, Axten JM, Patterson JB. Pharmacological targeting of the unfolded protein response for disease intervention. *Nature Chemical Biology*. 2019;15(8):764-775.

75. Kim I, Xu W, Reed JC. Cell death and endoplasmic reticulum stress: disease relevance and therapeutic opportunities. *Nature Reviews Drug Discovery*. 2008;7(12):1013-1030.
76. NFL Helmet Challenge Raises the Bar for Helmet Technology and Performance, Awards \$1.55 Million in Grant Funding to Help New Models Get on Field Faster. *NFL.com*.
77. Video: Meet the Awardees of the NFL Helmet Challenge. *NFL.com*.
78. 3 Ingenious innovations from the NFL's Helmet Challenge. *Digital Trends*. 2022.
79. KOLLIDE : A 3D REVOLUTION IS COMING. *KOLLIDE*.
80. Chatham L. Protection & Testing. *ImpressioTech*.
81. Hussain M, Jull EIL, Mandle RJ, Raistrick T, Hine PJ, Gleeson HF. Liquid Crystal Elastomers for Biological Applications. *Nanomaterials*. 2021;11(3):813.
82. Luo C, Chung C, Traugott NA, Yakacki CM, Long KN, Yu K. 3D Printing of Liquid Crystal Elastomer Foams for Enhanced Energy Dissipation Under Mechanical Insult. *ACS applied materials & interfaces*. 2021;13(11):12698-12708.
83. Jeon S-Y, Shen B, Traugott NA, et al. Synergistic Energy Absorption Mechanisms of Architected Liquid Crystal Elastomers. *Advanced Materials (Deerfield Beach, Fla)*. 2022;34(14):e2200272.
84. O'Connor KL, Rowson S, Duma SM, Broglio SP. Head-Impact-Measurement Devices: A Systematic Review. *Journal of Athletic Training*. 2017;52(3):206-227.
85. Cummiskey B, Schiffmiller D, Talavage TM, et al. Reliability and accuracy of helmet-mounted and head-mounted devices used to measure head accelerations. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*. 2017;231(2):144-153.
86. Wu L. Sports concussions: can head impact sensors help biomedical engineers to design better headgear? *British Journal of Sports Medicine*. 2020;54(7):370-371.
87. Gabler LF, Dau NZ, Park G, Miles A, Arbogast KB, Crandall JR. Development of a Low-Power Instrumented Mouthpiece for Directly Measuring Head Acceleration in American Football. *Annals of Biomedical Engineering*. 2021;49(10):2760-2776.
88. Zhuang Y, Yang Q, Han T, et al. Fiber optic sensor embedded smart helmet for real-time impact sensing and analysis through machine learning. *Journal of Neuroscience Methods*. 2021;351:109073.
89. Dsouza H, Pastrana J, Figueroa J, Gonzalez-Afanador I, Davila-Montero BM, Sepúlveda N. Flexible, self-powered sensors for estimating human head kinematics relevant to concussions. *Scientific Reports*. 2022;12:8567.
90. Eitzen I, Renberg J, Færevik H. The Use of Wearable Sensor Technology to Detect Shock Impacts in Sports and Occupational Settings: A Scoping Review. *Sensors*. 2021;21(15):4962.
91. Rooks TFMS, Novotny BLMS, McGovern SMBS, Winegar A, Shivers BLP, Brozoski FTMS. Evaluation of Head and Body Kinematics Experienced During Parachute Opening Shock. *Military Medicine*. 2021;186(11-12):e1149-e1156.
92. Suhey J, Gohmert D, Jacobs S, Baldwin MA. Development of a Novel Helmet Support Assembly for NASA Orion Crew Survival Suit. Paper presented at: International Conference on Environmental Systems; 2019/07/07/, 2019.
93. Jacobs S, Tufts D, Gohmert D. Space Suit Development for Orion. 2018.
94. Veerappan VR, Nagendra B, Thalluri P, Manda VS, Rao RN, Pattisapu JV. Reducing the Neurotrauma Burden in India—A National Mobilization. *World Neurosurgery*. 2022;165:106-113.
95. Du RY, LoPresti MA, García RM, Lam S. Primary prevention of road traffic accident-related traumatic brain injuries in younger populations: a systematic review of helmet legislation. *Journal of Neurosurgery: Pediatrics PED*. 2020;25(4):361-374.
96. Winkler EA, Yue JK, Burke JF, et al. Adult sports-related traumatic brain injury in United States trauma centers. *Neurosurgical Focus FOC*. 2016;40(4):E4.
97. Zuckerman SL, Morgan CD, Burks S, et al. Functional and Structural Traumatic Brain Injury in Equestrian Sports: A Review of the Literature. *World Neurosurgery*. 2015;83(6):1098-1113.
98. Hoshizaki T, Post AM, Zerpa CE, Legace E, Hoshizaki TB, Gilchrist MD. Evaluation of two rotational helmet technologies to decrease peak rotational acceleration in cycling helmets. *Sci Rep*. 2022;12(1):7735.
99. DiGiacomo G, Tsai S, Bottlang M. Impact Performance Comparison of Advanced Snow Sport Helmets with Dedicated Rotation-Damping Systems. *Ann Biomed Eng*. 2021;49(10):2805-2813.
100. Fanton MG, Sganga JA, Camarillo D. Vulnerable locations on the head to brain injury and implications for helmet design. *J Biomech Eng*. 2019.
101. Bian K, Mao H. Mechanisms and variances of rotation-induced brain injury: a parametric investigation between head kinematics and brain strain. *Biomechanics and Modeling in Mechanobiology*. 2020;19(6):2323-2341.
102. Gabler LF, Crandall JR, Panzer MB. Development of a Second-Order System for Rapid Estimation of Maximum Brain Strain. *Annals of Biomedical Engineering*. 2019;47(9):1971-1981.
103. Ghazi K, Begonia M, Rowson S, Ji S. American Football Helmet Effectiveness Against a Strain-Based Concussion Mechanism. *Annals of Biomedical Engineering*. 2022.