Helmet efficacy against concussion and traumatic brain injury: a review

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Helmets are one of the earliest and most enduring methods of personal protection in human civilization. Although primarily developed for combat purposes in ancient times, modern helmets have become highly diversified to sports, recreation, and transportation. History and the scientific literature exhibit that helmets continue to be the primary and most effective prevention method against traumatic brain injury (TBI), which presents high mortality and morbidity rates in the US. The neurosurgical and neurotrauma literature on helmets and TBI indicate that helmets provide effectual protection against moderate to severe head trauma resulting in severe disability or death. However, there is a dearth of scientific data on helmet efficacy against concussion in both civilian and military aspects. The objective of this literature review was to explore the historical evolution of helmets, consider the effectiveness of helmets in protecting against severe intracranial injuries, and examine recent evidence on helmet efficacy against concussion. It was also the goal of this report to emphasize the need for more research on helmet efficacy with improved experimental design and quantitative standardization of assessments for concussion and TBI, and to promote expanded involvement of neurosurgery in studying the quantitative diagnostics of concussion and TBI. Recent evidence summarized by this literature review suggests that helmeted patients do not have better relative clinical outcome and protection against concussion than unhelmeted patients.

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KEY WORDS helmet efficacy; concussion; traumatic brain injury; review

The most prevalent method of preventing or minimizing traumatic brain injury (TBI) is helmet use. Helmets are one of the earliest and most enduring methods of personal protection in the history of human civilization. They provide protection from head trauma by absorbing the impact energy and diffusing and displacing peak impact and pressure gradient to a greater surface area of the head, rather than to a localized region.76

History of Pre-20th–Century Helmets

Since the helmet’s inception, the vast majority have been designed for ceremonial uses and for the purpose of personal protection during military engagements. Early military helmets were used by Sumerians in Mesopotamia around 2500 BCE.113 Circa 2450 BCE, Eannatum, king of the Sumerian city Lagash, defeated the neighboring city Umma after a border dispute and commissioned the Stele of the Vultures to record his triumph (http://www.louvre.fr/en/oeuvre-notices/stele-vultures). The upper registers of the stele depicted helmeted soldiers carrying spears and marching in formation behind their king, Eannatum.109 These helmets were composed of copper and were most likely padded with leather underneath, as is evident from the bodies excavated from the Royal Cemetery at Ur, now in modern-day Iraq.113 The Standard of Ur from the Royal Cemetery also depicts similar helmets to those that appear on the stele (http://www.britishmuseum.org/research/collection_online/collection_object_details.aspx?objectId=368264&partId=1). Sumerian helmets indicated the first major advancement in personal defense in military conflicts.

Since then, helmets have been used throughout the Bronze Age, the Roman Empire, the World Wars, and...
presently. Ancient combat helmets were typically made of stiffened leather, bronze, or iron. Notable examples include the bronze helmets of the ancient Greeks (Fig. 1). Steel came into prevalent use in helmets of later eras, especially those of European origin (Fig. 2). There are countless accounts of helmet use in battle throughout human history, but literature specifically written on helmet protection against TBI in both civilian and military spheres did not come into prevalence until the 19th century. According to a book published by Jeffreys in 1858, a new helmet design was presented for protection of British soldiers against the sun and TBI.46 The book asserted that the helmet design “would render it proof against injury from ordinary accidents, as falls or pressure” and provided “protection from sword-cuts.”36 The Tuson helmet was composed of a steel wire frame padded with cork and cloth.36,46 In 1889, in the British Medical Journal, Foulis corroborated that the Tuson helmet design is “to a great degree, swordproof.”36 Erichsen wrote a case report in 1875 about a lieutenant colonel who fell from horseback and hit his head on the hard road on September 4, 1872, near Poonah, India.39 According to the report, the lieutenant colonel’s skull was not fractured due to his helmet, but he was temporarily paralyzed. Another case report in the American Journal of the Medical Sciences, published in 1882, describes a head injury patient who was hit over the parietal bone by a shot from an arquebus firearm while wearing a helmet.54 The report states that the ball indented the helmet and did not penetrate the scalp, but the patient died after 6 days of coma.

History of the 20th Century and Modern Helmets

Military and civilian helmets in the 1940s were typically composed of a solid steel shell and a plastic and cotton fiber liner. Steel M1 helmets were used by the US Armed Forces during World War II in both the European and Pacific Theaters (Fig. 3). The surgical and neurosurgical literature during World War II reported that the government-issued steel helmets reduced the impact of TBI and allowed soldiers to withstand certain blows to the head that otherwise would have been fatal.18,34,45 Studies on civilian head trauma during the 1940s examine the efficacy of motorcycle crash helmets against TBI.17,19 One study of 106 patients concludes that crash helmets are effective in reducing localized head trauma.19 Another study in which 8 cases were observed advocates the use of crash helmets but states that there is no conclusive evidence in favor of motorcycle crash helmets.17

Modern combat helmets generally use a combination of synthetic polymers and fibers that provide better protection than steel shells such as the M1 helmet. This is most evident in the Advanced Combat Helmet (ACH) of the US Armed Forces (Fig. 4). The ACH is composed of a Kevlar and phenolic-resin composite shell and a polyurea suspension padding system.20 The ACH provides some degree of protection against mild TBI (mTBI).46 Modern helmets for civilian purposes, such as cycling, also use synthetic polymers, foam, and fibers for better protection against head trauma (Fig. 5). There has been a general trend in the modern era for both civilian and military helmets, in which the focus has shifted from protection against lethal, penetrating TBI toward protection against the more frequently incurred blast injury and concussion.50,109

Protection Against Severe Injuries

Literature evidence relevant to TBI clearly demonstrates that helmet use provides effective protection against severe and lethal intracranial injuries like penetrating TBI that require neurosurgical intervention.22–24,37,84,102 In the Vietnam War, although combat helmets were not effective against bullets, they provided significant protection against shell fragments.20 Improvements in helmet design and the development of sophisticated fiber materials like Kevlar by the time of the Iraq and Afghanistan Wars reduced the frequencies of penetrating TBI among active-duty soldiers.84,93 Retrospective studies on the Iraq and Afghanistan campaigns provide evidence that Kevlar helmets were efficacious against penetrating head injuries.93,111 Studies on motorcyclists and bicyclists also demonstrate that helmet use was associated with reduced frequency of sustaining severe TBI in a vehicular accident.24 Helmet efficacy against severe and penetrating TBI in both civilian and military aspects is generally well accepted.

Protection Against Concussion

Although the general consensus is to encourage the use of helmets for head protection, it is unclear according to
the literature whether helmets are effective against concussion. There is a general lack of published studies specifically on the relationship between helmets and concussion. Studies that have provided data on helmet protection from head trauma have focused on head injury as one aggregate group, confounding results specifically about concussion. The literature on head trauma that focuses on helmet protection either has found that the data are inconclusive or has provided disparate conclusions.

Optimization of helmets to maximize protection against concussion is complicated by the limited understanding on the biomechanics of concussion. There is significant evidence in the literature that concussion is primarily caused by inertial forces, or acceleration. However, little research and understanding have been developed on the specific roles of linear and angular head acceleration in concussion. More recent literature has provided evidence that angular, or rotational, acceleration plays a large role in the biomechanics of concussion. Furthermore, extensive research has been conducted on the biomechanics of impact-induced TBI, but not on blast-induced TBI. The protective mechanism of helmets, especially combat helmets, in response to blast events is relatively unknown in the literature. Another factor contributing to the complexity of the data on helmet protection from concussion is the varying, inconsistent standard for helmet development. It is difficult to balance the needs for maximum protection against concussion with appropriate design for the specific sport or use, affordability, low weight, and comfortable fit, and still develop an effective helmet.

Epidemiology of TBI

Maximizing helmet efficacy against concussion and other forms of TBI is important because TBI is a major public health issue in the US, with very high occurrence, morbidity, and mortality rates. Approximately 1.7 million people in the US sustain TBI annually, in which there are 275,000 hospitalizations and 52,000 fatalities. Traumatic brain injury is a contributing factor to 30.5% of all injury-related deaths, and it is also the leading cause of mortality and disability in young individuals in developed countries. There is a recent shift in the incidence of TBI toward older individuals, with falls as the primary cause of TBI. Hospitalizations and mortality rates due to TBI incurred in geriatric patients by falling have risen since 2000 and are expected to continue to increase. The epidemiology of pediatric TBI in North America, Europe, Australia, and New Zealand indicates that the leading mechanism of injury in children under the age of 5 years is also by falling, whereas the mechanism of injury in children over the age of 15 years is by motor vehicle accidents. The annual mortality rates of moderate and severe TBI, defined as a GCS score of 13–15, moderate TBI is defined as a GCS score of 9–12, and severe TBI is defined as a GCS score of 8 or less. Another way in which TBI is distinguished is by the location of the intracranial injury. The injury can be extraaxial, such as with epidural hematoma and subdural hematoma (SDH) or hemorrhage, or the injury can be intraaxial. Primary injury in TBI is neuronal damage at the moment of impact, whereas secondary injury is neuronal damage caused by consequent physiological response to the initial injury. Acute severe TBI with intracranial hemorrhage (ICH) or intracerebral contusions may lead to death.

Clinical Definitions of TBI

There are various forms and severities of TBI. These injuries can be categorized into closed TBI (blunt force trauma), penetrating (open) TBI, and blast TBI. The severity of TBI has historically been most frequently evaluated with the Glasgow Coma Scale (GCS). Mild TBI is defined as a GCS score of 13–15, moderate TBI is defined as a GCS score of 9–12, and severe TBI is defined as a GCS score of 8 or less. Another way in which TBI is distinguished is by the location of the intracranial injury. The injury can be extraaxial, such as with epidural hematoma and subdural hematoma (SDH) or hemorrhage, or the injury can be intraaxial. Primary injury in TBI is neuronal damage at the moment of impact, whereas secondary injury is neuronal damage caused by consequent physiological response to the initial injury. Acute severe TBI with intracranial hemorrhage (ICH) or intracerebral contusions may lead to death.

The most common type of TBI is concussion, which accounts for up to 75% of all TBI cases. The term concussion has often been used interchangeably with mTBI in various publications, but there is a recent trend to recognize concussion and mTBI as different injuries.
There is little consensus on the definition and diagnosis standards of concussion or mTBI, and it has also been found that highly trained physicians often disagree on the diagnosis of blast-related mTBI. The biomechanics of concussion are also disputed and very little understood. The American Congress of Rehabilitation Medicine (ACRM) defines concussion as having “any alteration of mental state at the time of the accident (dazed, disoriented, or confused),” and the WHO Task Force defines the mental state at the time of injury as characterized by disorientation and confusion. The ACRM definition also states that the focal neurological signs of mTBI may or may not be transient, whereas the WHO definition of mTBI describes the focal neurological signs as transient.

Concussion is prevalent in both civilian and military life. Sports-related concussions (SRCs) and recreation-related concussions are increasing epidemiological concerns, with annual estimates increasing from 300,000 in 2001 to nearly 4 million in 2011. Some of this increase is probably due to the increased awareness of the condition. American football players are thought to be at an especially high risk of sustaining concussions. Concussion and blast-related TBI account for a significant number of injuries in the military, with incidences in deployed soldiers ranging from 14.9% to approximately 20%, and up to 22%. It is difficult to identify and diagnose concussion because this injury can be asymptomatic in its lower limits, and there are no structural abnormalities present on conventional neuroimaging.

Measuring concussion severity in a patient is also challenging because diagnoses and treatments may be based on subjective clinical complaints. Objective assessments for concussion are numerous, but no single test has been validated as the gold-standard diagnostic. One internationally accepted method of clinically measuring the severity of concussion is the Sport Concussion Assessment Tool, 3rd edition (SCAT3) test. These difficulties are problematic at the public health and epidemiological level because concussion is often underdiagnosed and can easily be overlooked.
Methods

A literature search on PubMed was conducted using key phrases such as “helmet protection against concussion” or “helmet efficacy in traumatic brain injury” within the years 2010–2015 to identify all recent relevant articles. Reference lists of relevant publications and literature reviews were searched and used to find additional sources. Studies that were not directly related to finding helmet effectiveness in protecting against concussion were eliminated from the PubMed searches.

Results

The PubMed search terms “helmet” and “concussion” in all fields yielded 137 results, from which 125 were excluded and 12 qualified for the literature review. Of the 12 publications under the search terms “helmet” and “concussion,” 5 articles were impact or in silico laboratory tests, 3 were neurocognitive evaluations, and 4 were clinical studies based on incidence reports. The PubMed search terms “helmet” and “head injury” in all fields initially resulted in 640 publications, from which 8 articles were selected. Of the 8 studies, 3 were impact or in silico tests, and 5 were clinical incidence report studies. The PubMed search terms “concussion” and “incidence” in the title provided 12 results, and 1 incidence report study was selected. Four articles qualified for the review under the search terms “eye tracking” and “concussion.” Some publications were found under multiple sets of search terms. The 25 publications were located outside of PubMed searches.

Impact Simulation of Concussion

Ten studies examined helmet efficacy against concussion through in simulacra and in silico impact tests. These studies are summarized in Table 1. Two of the 10 studies observed military helmet efficacy against concussion and blast injury in the ACH. Using an in silico parametric study, Sarvghad-Moghaddam et al. found that the effectiveness of the ACH against explosive blasts was direction-dependent. Although the study did not specifically discuss concussive injuries, it showed that fully protected and helmeted systems were most effective against front and top blasts but resulted in adverse effects from bottom blasts, by measuring intracranial pressure (ICP) changes, shear stress, and principal strain on the brainstem. Unhelmeted systems had more adverse effects from front, back, and top blasts, but less adverse effects from bottom blasts than fully protected and helmeted systems. Nyein et al. investigated the stress intensity of blasts by measuring the pressure, associated with hydrostatic or volumetric tissue deformation, and the equivalent stress, which is associated with isochoric distortions in the tissue, through in silico blast simulations. The study revealed that the existing model of the ACH does not significantly contribute to either mitigating or worsening blast effects to the head.

Of the 10 publications, 8 articles examined the efficacy of civilian helmets against concussion and head injury; 2 of those studies examined football helmets’ effectiveness against concussion. Lloyd and Conidi conducted 330 drop tests on 10 popular football helmets at repeated impacts of 12 mi/hr by using sensor-installed crash test dummy head and neck systems. The study found that football helmets reduced the risk of skull fracture by 60%–70%, and the risk of focal brain contusion by 70%–80%, but the risk of concussion was only reduced by 20%. The study also showed that football helmets were effective against linear acceleration impacts, but not rotational acceleration im-
TABLE 1. Impact testing and in silico studies observing helmet efficacy against concussion and TBI

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Method</th>
<th>Study</th>
<th>Helmet Type</th>
<th>No.*</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>McIntosh et al., 2013</td>
<td>Impacts</td>
<td>ERM</td>
<td>Bicycle</td>
<td>66</td>
<td>Unhelmeted subjects had concussion at minimal impact; helmeted subjects had concussion at ≥1-m drop, 0–25 km/hr horizontal impacts</td>
</tr>
<tr>
<td>Rousseau et al., 2014</td>
<td>Impacts</td>
<td>ERM</td>
<td>Ice hockey</td>
<td>15</td>
<td>Ice hockey helmets were ineffective at reducing concussion risk below 50% for puck impacts at velocity of ≥23 m/sec</td>
</tr>
<tr>
<td>Lloyd &amp; Conidi, 2014</td>
<td>Impacts</td>
<td>ERM</td>
<td>Football</td>
<td>330</td>
<td>Football helmets reduced concussion risk by only 20% and were ineffective against rotational acceleration impacts</td>
</tr>
<tr>
<td>Bartsch et al., 2012</td>
<td>Impacts</td>
<td>ERM</td>
<td>Football</td>
<td>195</td>
<td>Leather football helmets were comparable or better in head-impact doses and TBI risks than modern helmets</td>
</tr>
<tr>
<td>Post et al., 2015</td>
<td>Impacts</td>
<td>ERM</td>
<td>Baseball</td>
<td>84</td>
<td>There was a high concussion risk for subjects regardless of which MLB helmet model was used for protection</td>
</tr>
<tr>
<td>Karton et al., 2014</td>
<td>Impacts</td>
<td>ERM</td>
<td>Multiple</td>
<td>84</td>
<td>Speed skating, bicycle, and ice hockey helmets had ≥50% risk of concussion in rotational acceleration impacts</td>
</tr>
<tr>
<td>O’Sullivan et al., 2013</td>
<td>Impacts</td>
<td>ERM</td>
<td>Taekwondo</td>
<td>32</td>
<td>Headgear not protective against low-energy (50 g) and high-energy (150 g) impacts that can induce concussion</td>
</tr>
<tr>
<td>McIntosh &amp; Lai, 2013</td>
<td>Impacts</td>
<td>ERM</td>
<td>Motorcycle</td>
<td>52</td>
<td>Unhelmeted subjects had concussion at minimal impact; helmeted subjects had concussion at ≥1-m drop, ≥25 km/hr horizontal impacts</td>
</tr>
<tr>
<td>Nyein et al., 2010</td>
<td>In silico</td>
<td>ERM</td>
<td>ACH</td>
<td>NA</td>
<td>In silico ACH has no significant effect on mitigating or worsening blast effects to head</td>
</tr>
<tr>
<td>Sarvighad-Moghaddam et al., 2015</td>
<td>In silico</td>
<td>ERM</td>
<td>ACH</td>
<td>NA</td>
<td>In silico ACH fully protected against front and top blasts and was more effective than no helmet; bottom blasts showed less adverse effect with no helmets</td>
</tr>
</tbody>
</table>

ERM = experimental repeated-measures study; MLB = Major League Baseball; NA = not applicable.

* Throughout the tables, the heading “No.” refers to values that are either patient sample sizes or number of drops, depending on the study design.

The protective efficacy of other sports helmets. Ice hockey, baseball, and speed skating helmets were all shown to have significant risks of concussion by impact velocities or acceleration directions.67,89 Karton et al. found that bicycle, ice hockey, and speed skating helmets all consistently presented a greater than 50% probability of players wearing these helmets sustaining a concussion at the mean peak rotational accelerations.57 From striking-pendulum impact tests, O’Sullivan et al. showed that standard Taekwondo helmets do not protect against low-energy (50-g) and high-energy (150-g) head impacts that can induce concussion.

Four of the 8 studies on civilian helmet efficacy examined the protective efficacy of other sports helmets. Ice hockey, baseball, and speed skating helmets were all shown to have significant risks of concussion by impact velocities or acceleration directions.67,89 Karton et al. found that bicycle, ice hockey, and speed skating helmets all consistently presented a greater than 50% probability of players wearing these helmets sustaining a concussion at the mean peak rotational accelerations.57 From striking-pendulum impact tests, O’Sullivan et al. showed that standard Taekwondo helmets do not protect against low-energy (50-g) and high-energy (150-g) head impacts that can induce concussion.

In traffic injury literature, 2 studies from McIntosh and associates tested the efficacy of motorcycle and bicycle helmets.58,60 In the motorcycle helmet test, 52 impact tests on 4 helmets were conducted at conditions of 0.5-, 1.0-, and 1.5-m drop heights; 0, 25, and 35 km/hr horizontal striker plate speeds; occipital, lateral, and visor impact orientations; and loose, “2-fingers tight” chin strap adjustments in 10 front center impacts.58 In the bicycle helmet test, drop heights of 0.5, 1.0, and 1.5 m, horizontal striker plate speeds of 0, 15, and 25 km/hr, and occipital and lateral head impact orientations were assessed with and without helmets.59 Both studies found that unhelmeted subjects were prone to concussion in the least severe impact, and helmeted subjects presented risk of concussion at impacts equivalent to a drop height at or above 1 m, and horizontal velocity of 0–25 km/hr for bicycle helmets, and at least 25 km/hr for motorcycle helmets.

Neurocognitive Evaluations on Concussion

Two studies in the neurosurgical literature and 1 study in the sports medicine literature examined neurocognitive symptoms and scores in helmeted and unhelmeted patients with concussions.58,77,116 Studies on neurocognitive evaluation are summarized in Table 2. In 1 retrospective study of 40 patients with postconcussion syndrome, participants were matched by age and sex to patients with SRC, and neurocognitive evaluations of both acute and subacute phases were completed using the Post-Concussion Symptom Scale.77 The study showed that no bivariate associations were found between acute-phase and subacute-phase Post-Concussion Symptom Scale scores and postconcussion syndrome development, and that helmet use, loss of consciousness (LOC), amnesia, over-the-counter or narcotic pain reliever use, and initial consultation with a health care provider did not predict postconcussion syndrome.

A retrospective study of motocross riders (n = 139) found that 136 (98%) reported “always” wearing a helmet while riding, 67 (48%) reported experiencing at least 1 concussion symptom from riding or racing, 52 of those 67 riders (78%) sought treatment from a health care professional for their symptoms, and 46 of 139 riders (33%) reported multiple episodes of concussion symptoms from any source during the season.58 The study concluded that although almost all riders wore helmets, it was not enough to prevent concussion symptoms after collisions.

A third retrospective cohort study matched age, sex, number of previous concussions, and days to postconcussion test to examine acute neurocognitive symptom changes and outcomes after SRC in 138 helmeted and unhel-
TABLE 2. Neurocognitive symptoms studies evaluating helmet efficacy against concussion and TBI

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Method</th>
<th>Helmet Type</th>
<th>No.</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morgan et al., 2015</td>
<td>Neuro RCS, Multiple 40</td>
<td>Helmet use, amnesia, LOC, and over-the-counter or narcotic analgesic use did not predict postconcussive symptoms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zucker-man et al., 2015</td>
<td>Neuro RCS, Multiple 138</td>
<td>No differences between helmeted and unhelmeted groups in ImPACT scores after head injury</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luo et al., 2015</td>
<td>Neuro RCS, Moto-cross 139</td>
<td>Motocross helmet use was not enough to prevent concussion symptoms after collisions involving head injuries</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Neuro = neurological evaluation; RCS = retrospective case-control study; RCS = retrospective cohort study.

Neurocognitive symptoms studies evaluating helmet efficacy against concussion and TBI

Results are interpreted with caution because variability in comparison groups was impossible to control and helmet quality and mode for use was similarly heterogeneous. Despite these limitations, the study shows that helmets are not fully protective against concussion as quantitated with SCAT3 or eye tracking.

Concussion and Head Injury Incidence Studies

There is significant accumulating evidence through studies on incidences of TBI and concussion that helmets do not provide the necessary protection against concussion or even sometimes more severe forms of TBI. Eleven articles examined helmet efficacy through injury reports of head injury and concussion. The incidence and eye movement–tracking studies are summarized in Table 3. Of the 11 articles, 3 studies retrospectively examined ski or snowboard helmet efficacy based on patient diagnosis and treatment reports. Baschera et al. showed through logistic regression analysis of 245 subjects that helmeted and unhelmeted alpine skiers had no significant differences in TBI with respect to helmet use, and although there was an increase in helmet use from 2000–2001 to 2010–2011, there was no decrease in TBI cases. Another study of 678 youth skiers and snowboarders with documented helmet status presented through a 95% CI that concussion risk was not associated with helmet use. Although Rughani et al. did not specifically study helmet use with concussion risks, their study showed that in a retrospective data set of 57 skiers and snowboarders, there was a correlation between reduced skull fractures and helmet use but no significant difference in the incidence of epidural hematoma and SDH, intraparenchymal hemorrhage, subarachnoid hemorrhage (SAH), or contusion between helmeted and unhelmeted patients.

Two studies on amateur boxing presented significant evidence recommending against headgear use. One article observed that mandatory headgear use was associated with a decrease in referee-stop-contest (RSC) injury (stopping the match due to a nonhead injury) and increases in RSC head injury (stopping the match due to a head injury) and RSC injuries overall, ultimately suggesting implementation of the traditional no-headgear rule. Preliminary, unpublished research sponsored by the medical commission of the International Boxing Association—which was originally named the Association Internationale de Boxe Amateur (AIBA)—suggested that removal of headgear was associated with reduced concussion rates in amateur boxers. That is, 7352 rounds with headgear use presented a concussion rate of 0.38%, whereas 7545 rounds without headgear use resulted in a lower concussion rate of 0.17% (Butler et al., unpublished data, 2013).

Of the 11 publications based on injury reports, 2 studies evaluated bicycle helmet use regarding concussion and TBI rates. Castle et al. studied the effects of the mandatory helmet law in California starting in 1994 by observing age, sex, race, GCS score, Injury Severity Score, presence of TBI, presence of abdominal injury, and helmet use. The study found that there were no significant changes in the rate of helmet use and the rate of TBI in 1684 bike-related traumas with helmet use between 1992 and 2009. Although there were more unhelmeted subjects with TBI than helmeted subjects, the difference was not significant.
Another retrospective cohort study on pediatric bicyclists reported a concussion rate of 19.4% in helmeted patients and a concussion rate of 37.4% in unhelmeted patients, but the difference was not statistically significant between the 2 patient groups \( (p = 0.0509) \). The reduced incidences of skull fractures and ICH in helmeted pediatric subjects were statistically significant \( (p = 0.0408, p = 0.0079) \).

The literature on other sports and recreational helmet efficacy based on concussion incidences consistently showed that helmets did not fully protect against concussion and its risks. A retrospective population-based cohort study of 60 cases of TBI in pediatric motocross accidents observed a significantly high TBI incidence (57 cases with LOC, pathological findings on CT scans in 10 patients) despite helmet use \( (43 \text{ of 60 cases, } 71.6\%) \). One descriptive epidemiology study observing SRC in 12 different high school sports with 2651 concussion incidences from 1997–1998 to 2007–2008 showed in a 95% CI that helmeted sports had a higher increase in and nearly twice the concussion rate as in unhelmeted sports. Such studies are limited by bias in that helmeted sports are more likely to require contact and collisions.

Two studies of football helmets examined protective efficacy between different types of helmets but not between helmeted and unhelmeted players. In 1 cohort study with 2081 athletes and 134,437 football exposures, 206 players \( (9\%) \) sustained 211 SRCs \( (1.56/1000 \text{ exposures}) \). That study showed that no significant difference in SRC incidence existed between players wearing Riddell \( (1171 \text{ helmets, } 9.1\% \text{ incidence } [95\% \text{ CI } 7.6\%–11.0\%]) \), Schutt \( (680 \text{ helmets, } 8.7\% \text{ incidence } [95\% \text{ CI } 6.7\%–11.1\%]) \), or Xenith \( (436 \text{ helmets, } 9.2\% \text{ incidence } [95\% \text{ CI } 6.7\%–12.4\%]) \) type helmets. However, another retrospective analysis in the neurosurgical literature showed conflicting results. Rowson et al. examined head impacts and concussion incidences of 1833 collegiate football players who wore either a Riddell VSR4 or a Riddell Revolution helmet, using a 95% CI. In their study, 3.34% of all players sustained concussions, 4.47% of players in VSR4 helmets sustained concussions, and 2.82% of players in Revolution helmets sustained concussions. The difference in concussion incidences between VSR4 and Revolution helmets was found to be statistically significant \( (\chi^2 = 4.68, p = 0.0305) \).

**Discussion**

In this review of helmet efficacy against TBI and concussion, we report that helmets do not fully protect against concussion. The majority of studies showed that helmet use did not result in a statistically significant reduction in conc-

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**TABLE 3. Eye movement tracking and incidence report studies on helmet efficacy against concussion and TBI**

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Method</th>
<th>Study Type</th>
<th>Helmet Type</th>
<th>No.</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samadani et al., 2015</td>
<td>Eye tracking</td>
<td>PCSS</td>
<td>Multiple</td>
<td>55</td>
<td>Helmeted subjects had relative deficits in eye-tracking metrics and SCAT3 scores; there were no significant differences in CT scan results, admission rate, LOS, or SCAT3 scores between helmeted and unhelmeted groups</td>
</tr>
<tr>
<td>Baschera et al., 2015</td>
<td>Incidence</td>
<td>RCS</td>
<td>Ski</td>
<td>245</td>
<td>From seasons 2000–2001 to 2010–2011, helmet use increased from 0% to 71.4%, but there were no significant differences in TBI rate, severity, and treatment methods between helmeted and unhelmeted patients</td>
</tr>
<tr>
<td>Rughani et al., 2011</td>
<td>Incidence</td>
<td>RCS</td>
<td>Ski, snow-board</td>
<td>57</td>
<td>Helmet use had more favorable trend in hemorrhage, hematoma, contusion, cervical spine injury, need for neurosurgical intervention, and LOS, but was not statistically significant</td>
</tr>
<tr>
<td>Butler et al., 2013</td>
<td>Incidence</td>
<td>Prelim data</td>
<td>Boxing</td>
<td>14,897</td>
<td>7352 rounds with headgear had 0.38% concussion rate; 7545 rounds without headgear had 0.17% concussion rate</td>
</tr>
<tr>
<td>Bergmann et al., 2016</td>
<td>Incidence</td>
<td>RCCS</td>
<td>Ski, snow-board</td>
<td>678</td>
<td>LOS, admission, and discharge rates were similar between helmeted and unhelmeted groups; unhelmeted subjects were more likely for ICU admission, but it was not statistically significant</td>
</tr>
<tr>
<td>Bergenstal et al., 2012</td>
<td>Incidence</td>
<td>RCS</td>
<td>Bicycle</td>
<td>NA</td>
<td>Helmeted concussion rate was 19.4%, and unhelmeted rate was 37.4%; it was not significant; helmeted patients had fewer skull fractures, ICHs</td>
</tr>
<tr>
<td>Castle et al., 2012</td>
<td>Incidence</td>
<td>RCS</td>
<td>Bicycle</td>
<td>1684</td>
<td>Implementation of a mandatory helmet law had no significant changes in rates of TBI and helmet use</td>
</tr>
<tr>
<td>Bianco et al., 2013</td>
<td>Incidence</td>
<td>RCS</td>
<td>Boxing</td>
<td>29,357</td>
<td>Headgear use was associated with increased RSC and RSC head injury, and decreased RSC injury; study recommended no headgear use</td>
</tr>
<tr>
<td>McGuine et al., 2014</td>
<td>Incidence</td>
<td>DES</td>
<td>Multiple</td>
<td>2651</td>
<td>Helmeted sports had a higher increase than, and 2 times the SRC rate, as unhelmeted sports</td>
</tr>
<tr>
<td>Daniels et al., 2015</td>
<td>Incidence</td>
<td>RCS</td>
<td>Motocross</td>
<td>248</td>
<td>High TBI rates after pediatric motocross/motorbike accidents were observed despite predominant helmet use by riders</td>
</tr>
<tr>
<td>Rowson et al., 2014</td>
<td>Incidence</td>
<td>RCS</td>
<td>Football</td>
<td>1833</td>
<td>Revolution helmet model had a significantly lower SRC rate than VSR4 model, at 2.82% vs 4.47%, respectively</td>
</tr>
</tbody>
</table>

DES = descriptive epidemiological study; PCS = prospective cohort study; PCSS = prospective case-series study; Prelim = preliminary.
cussion incidence and symptoms. Wide varieties of helmets were unable to protect against the impacts of simulated directional forces that would induce concussion in human subjects. Patients who wore helmets at the time of head injury accidents and collisions presented concussive and postconcussive symptoms in neurological examinations after the injury. Although eye movement tracking has shown its effectiveness in quantitatively measuring the severities of concussion and TBI, eye-tracking metrics did not provide significant differences between helmeted and unhelmeted patients admitted to the hospital. In addition, TBI and concussion incidence reports presented that high rates of helmet use were not associated with low concussion incidence and favorable changes in concussion incidence following the implementation of mandatory helmet use regulations. Some studies indicated efficacy and a favorable trend of helmet use in reducing TBI as an aggregate group or in reducing TBI with pathological findings on CT scans, such as traumatic SAH or SDH. However, there were no articles reporting that helmeted patients presented statistically significantly reduced rates of concussion or better clinical outcomes of concussion than unhelmeted patients. Earlier literature reviews have presented similar findings on helmet efficacy against TBI and concussion; that is to say, helmets do not provide the necessary protection from such traumatic intracranial injuries.62,70

Older Literature on Helmet Efficacy

Studies published between 2000 and 2009 also presented consistent evidence that helmets are limited or ineffective in their protection against concussion. Three studies on rugby players in the sports medicine literature showed that the use of headgear did not reduce the rates of concussion or head injury, or result in any statistically significant differences between helmeted and unhelmeted groups.62,70,71 A cluster randomized controlled trial with a control group (n = 1493), a standard headgear group (n = 1128), and a modified headgear group (n = 1474) found that incidence rate ratios for the standard headgear group referenced to controls were 0.95 and 1.02 for game and missed-game injuries, whereas ratios for the standard headgear group referenced to the unhelmeted group were 1.11 and 1.10.71 A prospective cohort study on rugby players in Dunedin, New Zealand, found no evidence of a statistically significant efficacy of helmet use against concussion in a 95% CI.62 A pilot study involving 15 rugby unions showed similar evidence that the use of headgear in rugby was not associated with statistically significant improvement in protection against concussion compared with the players who did not wear helmets.69 However, 1 study on the use of helmets in football (soccer) in the sports medicine literature suggested that use of protective headgear was associated with a reduction in the risk of head injuries such as concussion.71

Limitations to Helmet Efficacy in Studies and Practical Aspects

There are several major limitations to the current studies and their experimental designs regarding helmet efficacy, which in turn impose limitations on their literature reviews. These limitations are also shared by any literature reviews on concussion. 1) There is a definite lack of standardization for a definition of concussion. As delineated in the introduction to our review, the WHO and the ACRM have discrepancies in their definition of concussion.88,91 Furthermore, the interchangeability between the definitions of mTBI and concussion are still debated, although there is a trend to distinguish them as separate intracranial injuries.13,33,64,65,100,108 This lack of standardization creates inconsistent clinical comparisons between different studies, inhibiting a clear consensus on the injury and its outcomes. 2) There is also a lack of standardization in examining helmet efficacy. This also stems from the lack of a standardized definition for concussion, which creates inconsistent comparisons of the helmets’ efficacy against the specific head injury. Additionally, although most studies focus on cranial pathology, some studies will include patients sustaining neck injury, vestibular dysfunction, or other noncranial pathology. Although these inclusions do not necessarily detract from the strength of the evidence on helmet efficacy, they can shift the focus of helmet efficacy away from concussion and other head injuries.

The quality of the acquired data in the studies is often a major limitation to the examination of helmet efficacy against concussion and TBI. Several studies examined by this review were limited by their study designs as retrospective, self-reporting, or nonrandomized in helmet use. Some studies also presented some selection bias in acquiring data on helmeted and unhelmeted patients. It is difficult to overcome the selection bias for acute concussive injuries and especially more severe forms of TBI for several reasons. 1) Acute head injuries are typically examined by the on-site or nearest health care provider to ensure the patient’s safety and the data’s accuracy. Prospective studies involving SRC and helmet efficacy typically use on-site health care providers who assess the concussive symptoms.50,66,90 This is especially true for more severe forms of TBI because such injuries entail high risks of morbidity and mortality, and it is essential for the patient to receive immediate care. These necessities limit the injured subject groups to smaller, sometimes underpowered cohorts specific to the sport and region. 2) Helmets and their efficacy are also specific to the occupation or sport, requiring separate subgroups and preventing randomization across the different helmet types. These limitations decrease the statistical power and favor smaller, localized cohorts in the studies. The inability to perform truly blinded, randomized prospective trials of helmeted versus unhelmeted subjects due to ethical considerations and the knowledge that helmets prevent TBI-induced death is another critical limitation in studies examining helmet efficacy. The inability to conduct a blinded study also stems from the fact that the health care provider for the TBI needs to know about helmet use for proper neurological assessment. It is also difficult to acquire TBI subjects for the unhelmeted group because many occupations and sports require helmet use as part of safety regulations. Furthermore, animal model studies cannot supplant human subjects for prospective blinded randomized trials because 1) the helmet designs worn by humans may not necessarily be reproducible or scalable at a rodent model scale, and 2) the neurological evaluations of rodent models are not directly comparable to human subject evaluations.

The efficacy of helmets against concussion and TBI
faces many limitations beyond studies, experimental design, and literature reviews. Bias in personality and risk-taking behavior can result in preferences toward or against helmet use. The bias in personality also affects the likelihood that the patient will seek a physician after the potential head injury and ensure sufficient postinjury care. The quality, condition, and proper fit of the helmet used by an individual cannot necessarily be controlled to optimize helmet efficacy, even though such factors are crucial for protection against concussion and TBI. It is expected that researchers fail to demonstrate efficacy against concussion (which is difficult toquantitate) because it is already difficult to demonstrate efficacy against the need for neurosurgical intervention, due to the fact that most studies are significantly underpowered and difficult to balance because of the limitations described in this section.

Current Implications of Helmet Efficacy

Evidence continues to indicate that helmets are significantly protective against death due to brain injury, more severe forms of TBI, skull fractures, and traumatic ICHs. Therefore helmet use is recommended for sports, activities, and occupations that entail risks of intracranial injury. Helmets may be less effective against concussion than against more severe forms of TBI due to the inherently different biomechanics of these injuries. 1) Concussion is induced by low-energy linear and rotational accelerations that cause more diffuse, distributed impact loading and peak ICP than the brain tissue can tolerate, resulting in damage to the microscopic structures of the brain and temporary onset of neurological impairment. 2,25,102 2) More severe forms of TBI are typically caused by high-energy focal forces loading onto a localized region of the brain, resulting in injuries such as penetrating TBI and depressed skull fractures. 2,25 3) Closed types of severe TBI are induced by distributive impacts that result in macroscopic lesions and inflammation, such as DAI. 55 It is more difficult to design helmets and component materials that can safely reduce the low-energy directional accelerations and peak pressures that are distributed throughout the brain than to make helmets that can absorb severe diffuse impacts or stop externally localized forces strong enough to penetrate the dura mater or damage the skull.

Implications for Helmet Efficacy in the Future

Modern helmets for civilian and military purposes have begun to focus more on protection against concussion and blast injuries. This review highlights the fact that the lack of helmet efficacy against such intracranial trauma is a growing medical and public health concern due to the epidemic prevalence of TBI and concussion and their increasingly recognized morbidity and mortality. 27,80 Because the most effective method of protection against concussion and TBI is prevention, reconsideration of helmet design and efficacy is crucial to reducing incidences of concussion, TBI, secondary neuronal damage, and chronic neurocognitive disability at clinical and epidemiological levels. The importance of materials engineering for helmets should be further promoted and emphasized, because new synthetic materials comprising the helmets are critical to reducing the acceleration and shock of concussive impacts. Improved helmet efficacy and design against concussion and TBI may also lead to a reduced neurosurgical burden regarding preventable deaths and perioperative complications due to the pathophysiology of TBI and concussion. Examination of studies on helmet efficacy within the neurosurgical literature is summarized in Table 4.

Beyond the redesign of helmets, additional studies should be conducted to further examine helmet efficacy against concussion with simulated impact tests and assessment of physiological function, with eye tracking, neurocognitive outcomes, and epidemiological studies. To improve the understanding of whether helmets are effective against concussion, these studies would ideally emphasize larger sample sizes of differently helmeted subjects and would incorporate better study designs that are prospective, randomized, and controlled for confounding factors. As described previously, ethical considerations place significant limitations on prospective, randomized, and controlled study designs for examining helmet efficacy. It may be possible to conduct prospective, randomized controlled trials with helmeted and unhelmeted groups in sports that incorporate optional helmet use, such as rugby union, without violating ethical concerns. However, randomization may be difficult, and selection bias may thus still exist. Prospective randomized trials may also be possible with different brands of helmets. This type of study would improve helmet efficacy by examining which helmet has greater protection and recommending the safer helmet to the general population. The disadvantages of such a study design are that 1) there are no unhelmeted subjects, and 2) a substantially large sample size of TBI is needed to ensure equal and statistically significant data for different helmets.

Diagnostic instruments used to measure concussion should be improved to increase helmet efficacy. More robust diagnosis and definition of concussion can lead to better helmet standards based on a refined understanding of concussion biomechanics and pathophysiology. In addition, patients who have experienced a concussion are more likely to suffer recurrent concussions, and patients with a chronic history of concussions have higher risks of developing neurodegenerative diseases such as chronic traumatic encephalopathy (CTE) and dementia. 32,43,86,105 Thus, reforming concussion diagnostics may result in not only an increase in helmet efficacy but also a decrease in epidemiological severity of recurrent concussions and neurodegenerative diseases through earlier and more comprehensive clinical management of postconcussive symptoms and stronger precautions to minimize future concussive injuries. Expanding the awareness of the general population with regard to TBI and concussion is an additional method to reduce such injuries, by increasing individual precaution in activities that entail risk of concussion and TBI and pressing for improvements in safety regulations in sports and transportation.

A Role for Physicians and Engineers in Improving Helmet Efficacy

It is incumbent on neurosurgeons, neurologists, and other neuroscientists to provide leadership and expertise for the improvement of helmet efficacy against concussion and TBI. Clinicians and scientists should collaborate with engineers in designing helmets that not only protect
against impact injuries, but also minimize the risks of DAI due to acceleration and deceleration of the head. For example, it is important to reduce the mass of the helmet because heavier helmets can potentially cause greater magnitudes of injury through greater inertia. Consider that flexion-extension of the neck during trauma may actually be exacerbated if the mass of the head is greater, resulting in greater shear injury within the brain. Engineers and clinicians need to work together to create helmets that not only protect against focal injury resulting in death or skull fracture, but also reduce shear injury.

There is also a need for greater focus on the development of objective, standardized, quantitative diagnostic assessments for concussion, TBI, and other head injuries within the neurosurgical specialty. Currently, there are numerous concussion and TBI assessment techniques under investigation, such as quantitative electroencephalography, eye tracking, and tau protein level changes in CSF and blood. Preliminary data and several studies suggest that quantitative electroencephalography measures significantly different brain activity in patients with acute SRC, chronic recovery of SRC, PCS, and posttraumatic migraine. Tau is a structural microtubule-associated protein expressed in neurons, and is especially abundant in neuroaxonal axons. The hyperphosphorylation of tau (P-tau) can form toxic neurofibrillary tangles, which are found in the brains of people with neurodegeneration such as Alzheimer disease and CTE. Total tau (T-tau) in the brains of people with neurodegeneration such as Alzheimer disease and CTE. Total tau (T-tau) in the CSF and blood plasma was found to be present in significantly higher concentrations in boxers who experienced acute repeated mTBI than in control subjects, in whom the higher T-tau levels normalized after 2 weeks. Plasma T-tau levels were also shown to be acutely higher after a single incidence of concussion in ice hockey players, in which the elevated concentrations 1 hour after the injury were associated with the time needed to resolve concussive symptoms and the time needed for recovery before returning to play. Standardizing the pathology of structural TBI and concussion with quantitative assessments is the crucial foundation for allowing studies to have stronger evidence, more clearly defined injury groups, and be directly comparable with one another. Standardization also facilitates care for concussion and TBI, reducing overall clinical burden on not only neurosurgery but also other relevant specialties.

Conclusions

There is significant evidence to support helmet use to protect against devastating intracranial injury. A considerable amount of evidence indicates that contemporary helmets are not efficacious in protecting against concussion. Further research and development on helmet design and efficacy is needed to reduce concussion in helmeted subjects.

References


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**TABLE 4. Neurosurgical literature examining helmet efficacy against concussion and head injury**

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Method</th>
<th>Study</th>
<th>Helmet</th>
<th>No.</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bartsch et al., 2012</td>
<td>Impacts</td>
<td>ERM</td>
<td>Football</td>
<td>195</td>
<td>Leather football helmets were comparable or better in head impact doses and TBI risks than modern helmets</td>
</tr>
<tr>
<td>Morgan et al., 2015</td>
<td>Neuro</td>
<td>RCS</td>
<td>Multiple</td>
<td>40</td>
<td>Helmet use, amnesia, LOC, and over-the-counter or narcotic analgesic use did not predict postconcussive symptoms</td>
</tr>
<tr>
<td>Luo et al., 2015</td>
<td>Neuro</td>
<td>RCS</td>
<td>Motocross</td>
<td>139</td>
<td>Motocross helmet use was not enough to prevent concussion symptoms after collisions involving head injuries</td>
</tr>
<tr>
<td>Rughani et al., 2011</td>
<td>Incidence</td>
<td>RCS</td>
<td>Ski, snowboard</td>
<td>57</td>
<td>Helmet use had a more favorable trend in hemorrhage, hematoma, contusion, cervical spine injury, need for neurosurgical intervention, and LOS, but was not statistically significant</td>
</tr>
<tr>
<td>Daniels et al., 2015</td>
<td>Incidence</td>
<td>RCS</td>
<td>Motocross</td>
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Disclosures
Uzma Samadani has equity in Oculogica, Inc., an eye-tracking neurodiagnostic company.

Author Contributions
Conception and design: Sone, Samadani. Acquisition of data: Sone. Analysis and interpretation of data: Sone, Samadani. Drafting the article: Sone. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Sone.

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