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Improving bicycle and motorcycle helmet design to prevent traumatic brain injury. A review

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ABSTRACT

Traumatic brain injury (TBI) from bicycle and motorcycle-related accidents continues to be a major medical and financial burden in the United States. The complex management and debilitating consequences of TBI demand greater attention to its prevention, of which much relies on helmet use and structure. Conventional helmets today rely on an expanded polystyrene (EPS)-liner, which works to mitigate the linear acceleration experienced by the brain during impact. However, recent evidence suggests that it is not the linear acceleration but the rotational acceleration of the impact that most contribute to TBI development. This has led to the development of novel helmet designs that aim to mitigate rotational kinematics in addition to linear kinematics. The objective of this study was to overview limitations in current helmet design and discuss two of the most well-studied novel prototypes: WaveCels and Multi-Directional Impact Protection Systems (MIPS). Though both ultimately reduce the rotational acceleration of injury, they differ in mechanism and efficacy. Given the importance of helmet structure in the prevention of TBI, we find that more work is needed directly comparing these and other new designs.

INTRODUCTION

Bicycle and motorcycle injuries remain amongst the most common causes of traumatic brain injury (TBI) in the United States [20]. From 2009 to 2018, head injury from bicycle accidents accounted for almost 600,000 diagnoses of a concussion or a TBI in the emergency department [33]. Of all demographics, younger children are at greater risk of head injuries from biking accidents compared to adults [37]. Medical costs for pediatric bicycle-related TBIs reached 200 million in 2003, and have only increased since [34]. Helmets have long been championed as the ultimate protective mechanism against TBI. According to a Cochrane review, helmets can reduce the risk of head injury by up to 88% [37]. One study found that helmets lower the risk of severe TBI by 51% compared to non-helmeted bicycle riders [21]. Mortality and morbidity in TBI from bike-related accidents appear to be negatively correlated with helmet use, though some suggest that those who wear helmets are simply fundamentally different from those who do not, and generally practice safer biking practices and less risk taking behavior [15, 29]. Despite the controversy, studies show the structural features of helmets can help prevent axonal shearing and linear components upon impact, thus reducing the severity of neurologic injury [13]. Helmets also reduce the incidence of skull fractures, meningeal bleeds, and parenchymal bleeds: common characteristics of more severe TBIs [14]. They decrease the likelihood of facial injuries, impaired consciousness, and the need for neurosurgical intervention as well.

Increased public awareness of the benefits of wearing a helmet have led to greater helmet use among cyclists [22]. Yet, despite this trend, traumatic brain injury (TBI) still remains the most common cause of death and admissions to hospitals from bike-related injuries, and has increased in prevalence over the past two decades [37]. Helmets are meant to manage all the energy transferred to the head during impacts. However, most of the helmets currently approved by the Consumer Product and Safety Commission (CPSC) have only been proven to reduce linear head acceleration, while angular acceleration is less tested [39]. In recent years, it is angular acceleration of the head that has shown to be a major source of axonal shear strain in TBI and concussions [3].

Novel helmet designs have now begun to target rotational head acceleration from oblique impact for greater protection against TBI. Among them are the Multi-Directional Impact Protection System (MIPS), which uses a slip liner mechanism, and WaveCels, composed of a collapsible cellular liner [4]. While both these prototypes have shown to greatly enhance impact mitigation performance, few studies exist directly compiling and comparing their benefits. Thus, in the following paper, we overview the management and biomechanics of TBI, the limitations of current helmets, and discuss these novel designs aimed at reducing TBI risk.

ASSESSMENT AND TREATMENT OUTCOMES OF TBI

Traumatic brain injuries (TBI) occur when a sudden trauma, such as from a bike collision or whiplash, causes deformation and destruction of brain tissue [31]. The severity of TBI can be evaluated by the Glasgow Coma Scale and is categorized into mild, moderate, or severe [8]. Secondary injuries following TBIs can lead to impairment of cerebral oxygenation or autoregulation, which manifests as swelling and hematoma that compress brain structures and sagittally shift the brain [31]. An ideal neuromonitoring system for TBIs is continuous, noninvasive, appropriate for bedside and field environments, and affordable [30]. Thus, noninvasive monitoring, such as near-infrared spectroscopy (NIRS), is used to track the condition of the brain. Parameters used to assess brain conditions include cerebral perfusion pressure (CPP), an indicator for cerebral blood flow (CBF), mean arterial pressure (MAP), and intracranial pressure (ICP) [40]. An obstruction in CSFs generating a hydrocephalus and a blockage of arteries lead to reduced blood perfusion in the brain [31]. Initial management of patients with TBIs trauma is identical to typical trauma protocol — management of airway, breathing, and circulation with a rapid neurologic exam and prevention of hypothermia [11]. The neurologic exam involves examination of pupillary activity, assessment of lateralizing signs from increased ICP, and a GCS score calculation [31]. After resuscitation, patients undergo a non-contrast head CT, if possible, to better analyze the brain condition. As primary injuries of TBIs cannot be reversed, most subsequent management strategies prioritize preventing secondary injury through increasing MAP and/or decreasing ICP to prevent hypoxia and hypotension [12].

Given the serious and debilitating consequences of TBI, prevention is vital. Evidence indicates that many TBIs are caused primarily by acceleration loading during impact, as the brain suddenly decelerates while moving [32]. This acceleration can be either linear or rotational in nature. Linear acceleration is composed of the simple straight line forces the brain experiences in response to the deceleration, while rotational acceleration is more complex: the head moves differently relative to the neck and torso, causing the brain to “rotate” rapidly. Linear acceleration is more commonly associated with skull fractures, which can, in some cases, lead to more severe injury like epidural bleeding [26]. Although both linear and rotational acceleration ultimately contribute to TBI, one computational model estimated that 90% of total tissue strain was derived from rotational kinematics alone [42]. Given its complexities, the biomechanics of TBI should be an important factor when considering the design of effective helmets.

CURRENT MOTORCYCLE / BICYCLE DESIGN

Conventional bicycle helmets are composed of 3 layers: a polycarbonate outer shell, an expanded polystyrene (EPS) liner, and an inner layer for padding [23]. The protective properties of the helmet depend on the cracking of the polycarbonate shell and compression of the liner [9]. When a force impacts the helmet, the cracking of the outer plastic shell and subsequent compression of the EPS liner help decrease the impact energy transferred to the head. The slow compression of the EPS liner specifically allows for increased duration of the impact, which results in both the depletion of the initial impact energy and decrease of the acceleration delivered to the head [23]. The process by which conventional bicycle helmets work to protect the brain from TBI is further illustrated in Figure 1.

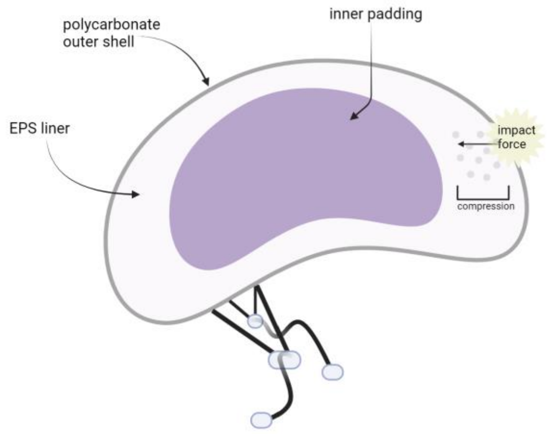

Figure 1. Conventional helmet design and function. Conventional helmets adjust to force impacted first through the cracking and damage to the outer plastic shell, followed by the expanded polystyrene (EPS) liner compressing. Impact energy gets converted into heat, which is a by-product of plastic deformation and results in the cracking of the polycarbonate layer. Compression of EPS liner increases duration of the impact, which decreases the peak acceleration delivered to the head [9].

In the United States, bicycle helmets must endure testing by the US Consumer Product Safety Commission in order to demonstrate efficacy and safety. For example, helmets are required to undergo impact attenuation testing, where helmets are dropped vertically onto a horizontal surface. The test establishes thresholds for peak linear acceleration, but fails to account for angular acceleration, as head surrogates during testing are constrained [39]. However, angular head acceleration from oblique impacts is known to cause TBI; in fact, most bike accidents involve oblique impacts with impact angles between 30 and 60 degrees, inducing radial and tangential forces to the head, and resulting in both linear and rotational head acceleration [27]. Studies have also shown that the typical angular acceleration experienced by a helmeted bicyclist exceeds the thresholds indicated for TBI despite linear acceleration levels remaining below such thresholds [23]. Because current standards do not include testing for angular acceleration and conventional helmets as a result do not account for angular acceleration, further research into novel helmet designs that reduce both linear and angular acceleration is being explored.

Angular, or rotational, acceleration to the head during oblique impacts results in shearing and strain to the corpus callosum and sulci of the brain [2]. The corpus callosum is the largest white matter tract connecting two hemispheres and is affected by diffuse axonal injury caused by impacts [35]. The sulci is involved in white matter injury from impacts and neurodegenerative disease [17]. A study recently found that axonal injury post-rotational TBI was specifically concentrated between white and gray matter tracts, which can be explained by the difference in tissue elasticity at these interfaces that allows one region to slide over the other, causing shear stress [25]. Another mechanism by which rotational acceleration to the head contributes to neurotrauma is by its effects on the neuronal cytoskeleton. Accumulation of heavy neurofilament subunits in the neuronal perikarya in several brain regions such as the cerebral cortex, hippocampus, cervical spinal cord, pyramidal tract, cranial nerves and cerebellum was found after induced rotational trauma in animal models [17]. Increased amyloid-beta expression and light neurofilament subunits were also observed in cortical white matter and granule cells of the hippocampus. These findings, observed a few days after rotational trauma was induced, are also consistent with those of several neurodegenerative diseases such as Alzheimer's and amyotrophic lateral sclerosis. Therefore, because conventional bicycle helmet designs do not accommodate for angular acceleration, their utilization is more likely to result in the neurotrauma and TBI as previously described.

IMPROVED DESIGNS

Limitations in current bicycle and motorcycle helmet design underscore the need for improved prototypes. In particular, given the role of oblique impacts in the development of neurotrauma from bicycle injury, a helmet design that incorporates anti-rotational protection may be of special benefit. Many such prototypes have been introduced in the literature, though a paucity of studies compiling and comparing these designs exist. We thus overview here two such widely-used concepts that have gained recognition in their capacity to enhance impact mitigation performance: WaveCel and Multi-Directional Impact Protection Systems (MIPS). Each attempts to reduce both linear and rotational acceleration, though they both utilize notably different mechanisms to achieve this aim.

WAVECEL

Inspired by the Angular Impact Mitigation System developed by Hansen et.al, the WaveCel is a collapsible cellular structure that mimics, in part, a honeycomb [19]. Such “biomimetic” prototypes, which take inspiration from nature and progressed with the advent of new manufacturing technology, have gained popularity in recent years [23]. Indeed, the greater overall efficacy of bio-inspired designs in aspects such as energy absorption have sparked a global interest in their potential ability to prevent neurotrauma. Honeycomb structures, for example, have frequently been optimized in helmets, with their hexagonal shape allowing them to better withstand compression. In the case of WaveCels, “cells,” which are shaped like inverted “V’s,” are lined together in a honeycomb-like hierarchical arrangement [3]. They can flex against small, often frictional, forces, but if the WaveCel is met with a large enough impact, the cells collapse or crumple, elastically transmitting and redirecting the force. This process is better represented in Figure 2. The inherently collapsible nature of WaveCels give them a great advantage over traditional EPS liners by reducing helmet rigidity and therefore mitigating any potential shearing that could occur [23].

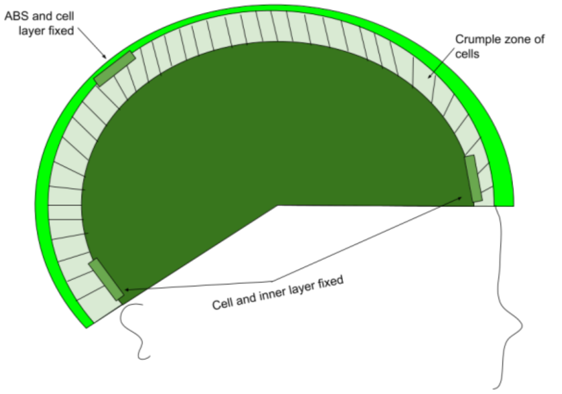

Figure 2. WaveCel design and function. Simple schematic of conventional WaveCel designs. A crumple zone of inverted “V” cells is suspended between an outer and inner layer, with key fixation points allowing for elasticity. Acrylonitrile butadiene styrene (ABS) is used most frequently in the outer shell of traditional helmets.

In one study, though the results were mixed for peak rotational acceleration, WaveCels were found to be superior to EPS helmets in lowering peak rotational velocity [4]. WaveCels were also noted as significantly reducing risk of head injury. This finding was corroborated by other work, which suggested that WaveCels performed better than conventional helmets in mitigating rotational kinematics as well as possible head injury [3]. Interestingly, the data available on WaveCels in regards to linear acceleration is not clear. One study suggested that WaveCels were no different than EPS in protecting against linear kinematics, while others have found that WaveCels performed significantly better than traditional helmets in mitigating linear acceleration [19]. The ambiguity surrounding WaveCels and their effects on linear kinematics warrants further study and exploration. However, what is ultimately clear from the literature is the notable anti-rotational properties of WaveCels, a characteristic that is demonstrably crucial to the etiology of neurotrauma [42].

Multi-Directional Impact Protection Systems (MIPS)

MIPs, meanwhile, do not utilize a collapsible cellular structure, but rather are considered “slip layer” designs [4]. In this prototype, a low-friction thin “slip” liner is attached to an outer liner by rubber straps. An impact causes this slip liner to slide across the outer layer, dampening impact energy and allowing sliding between the head and the helmet, reducing rotational acceleration. A schematic in Figure 3 depicts this more clearly.

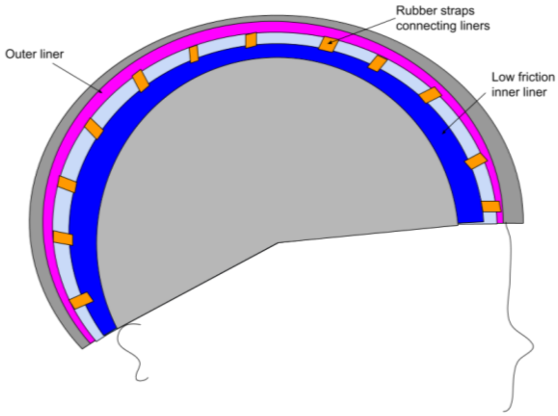

Figure 3. MIPS design and function. Simple schematic of conventional MIPS designs. Rubber straps join the low friction inner liner with the outer liner, allowing it to slide past the layer.

MIPs are thought to be quite effective in protecting against oblique impacts, and in one study reduced rotational acceleration up to 56% [1]. Other work has similarly shown that although MIPS and control EPS-lined helmets performed the same in terms of linear acceleration, rotational kinematics were substantially mitigated with MIPS [41]. Compared to the EPS standard, MIPS also dramatically lowered neuronal strain from impact injury [2].

MIPS is perhaps more clear than WaveCels in regards to its effects on linear acceleration. In general, most work found that MIPS was no different than conventional helmets in terms of linear kinematics [6]. Interestingly, the effects of MIPs on even rotational kinematics are highly variable, with noted dissimilarites in the magnitudes of results across different MIPS studies. It has been suggested that this may be due to the impact mitigation performance of MIPS being contingent on certain factors, such as velocity of impact or headform type, but the reason for this ambiguity has yet to be made clear [7].

While much is available regarding the individual efficacies of WaveCel and MIPS helmets, little exists comparing their unique advantages and disadvantages directly. One study quantifying the efficacy of the two structural strategies showed that, under a certain narrow, controlled range of impact conditions, rotational acceleration in WaveCel and MIPS helmets was significantly reduced, but was not more effective at reducing linear acceleration than EPS helmets [4]. They found that altogether, WaveCel helmets were predicted to be more effective in reducing brain injury risks from angular acceleration. Interestingly, another study found that although both WaveCel and MIPS helmets lowered strain on the corpus callosum and sulci compared to EPS, MIPS had a slightly higher effect with a lower overall strain [2]. The limited and variable results of these comparative analyses demand a deeper exploration into the differences between these different designs and mechanisms. Moreover, many of these studies were performed on anthropomorphic headforms with silicone scalp skins representing the mass and inertia of males, and so results do not perfectly emulate real-world bike crashes. These studies also often controlled for impact locations, suggesting the need for more data with variance in the locations of impact on the helmet. Currently, the only way to collect impact data from real-world head impacts is via CT scanning and collection of damage metrics to assess after the crash [18].

It is important to note as well that although MIPS and WaveCels are some of the most well-studied novel helmet designs, other such prototypes exist. The Hövding helmet, for example, mimics an airbag deployment system and releases an inflating plastic structure upon impact [38]. Several studies have found the Hövding helmet to be superior to other novel helmets in preventing both linear and rotational injury, but suggested that the duration of injury was much longer with Hövding [2]. Angular Impact Mitigation Systems (AIMS), which inspired the development of WaveCels, are also models of note, utilizing a hexagonal honeycomb structure to absorb energy of impact [23]. AIMS was found to be quite effective in mitigating linear and rotational acceleration, reducing these values by 14 and 34% respectively compared to the standard. However, little data is available comparing AIMS to other novel prototypes.

CONCLUSION

Overall, traditional EPS lined helmets have shown to be demonstrably less effective at mitigating the rotational acceleration of impacts, which recent evidence suggests is a major factor in the development of TBI [42]. The novel helmet designs of

WaveCel and MIPS both work to significantly reduce rotational components of injury, though little is known about how the exact efficacies of these mechanisms compare to each other [4]. Therefore, continued research in helmet technology is needed, and should aim for a wider range of more realistic impacts to better understand the extent of a helmet design's ability to reduce linear and rotational acceleration of the head.

However, it is important to note that future studies examining novel helmet technology and helmet efficacy in human subjects are limited by ethical considerations. For example, comparisons between helmeted versus un-helmeted individuals with the knowledge that helmets prevent TBIs and death would be unethical to conduct. A blinded study would also be difficult as healthcare providers would have to know about helmet use for proper neurological assessment. Additionally, research with rodent models is limited by the lack of reproducible helmet designs at the rodent scale and the inability to directly compare neurological evaluations of rodents to those of human subjects [36].

Although the impacts of novel helmet designs in reducing the incidence of TBI have yet to be made clear, what is obvious is the importance of helmet use [37]. Legislation and public health messaging on a larger scale continues to be necessary in the promotion of helmet use, helping the general public to distinguish between new helmet models and to understand their ultimate protective capabilities.

Abbreviations

TBI: Traumatic Brain Injury
MIPS: Multi-Directional Impact Protection System
CPSC: Consumer Product and Safety Commission
EPS: Expanded polystyrene
ABS: Acrylonitrile butadiene styrene
NIIRS: Near-infrared spectroscopy
AIMS: Angular Impact Mitigation Systems
CPP: Cerebral Perfusion Pressure
CBF: Cerebral Blood Flow
MAP: Mean Arterial Pressure
ICP: Intracranial pressure

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