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Recent bicycle helmet designs and directions for future research: A comprehensive review from material and structural mechanics aspects

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ABSTRACT

Cycling becomes more and more popular for recreation, exercising and commuting in many countries. Despite the popularity of cycling, it often comes with high level of risk. Conventional bicycle helmets, with expanded polystyrene foam (EPS) liners, can effectively mitigate impact by linear acceleration. However, there has been an urgent call for further improvement in bicycle helmets, as rotational acceleration has been found to be more dominant in severe head injuries. Recent advancements in manufacturing technologies have enabled various novel conceptual ideas and designs of bicycle helmets, which are previously deemed impracticable due to complexities in structures and materials, to become feasible. There are various bicycle helmet designs in terms of structures and materials used in both the helmet shell and liner, targeting at reducing both linear and rotational acceleration. Moreover, inspired by biological structures in nature, bio-inspired structures have been developed rapidly with excellent energy absorption capacity. As a piece of protective equipment, Bicycle helmet is a representative example where researchers are attempting to apply bio-inspired structures. The objective of the paper is to review the development of bicycle helmets and recent exploration for improvement. This includes the history of bicycle helmets, current test standards, designs of conventional bicycle helmets and the latest research (e.g. material replacement and novel structures), as well as application of bio-inspired structures to helmets. This review also identifies the limitations of current designs and standards, and challenges for future investigations.

1. Introduction

Cycling is a well-known choice for recreation, exercising, commuting and environmentally friendly activities around the world. In typical bicycle-friendly cities such as Amsterdam, Netherland, and Copenhagen, Denmark, the cycling participation rates are approximately 34% and 36%, respectively [1, 2], whilst local authorities in many other countries have been promoting cycling [1, 3], with the benefits of improving health, easing congestion, and reducing air and noise pollution [1]. For example, the number of people in America, who ride bicycles for commuting, increased by 61% between 2000 and 2012 [4, 5]. In the context of Australia, the federal government announced its goal to double the number of bicycle riders from 2011 to 2016 [6, 7].

Despite the popularity of cycling, it often comes with high level of risk. Head injury is the typical one with the greatest concern [8, 9], as it contributes to one-third of treatment in emergency departments and three-quarter of the deaths [10–12]. Particularly, traumatic brain injury (TBI), known as 'silent epidemic', can affect human in a delayed manner regarding thinking, emotion, sensation, etc. [13, 14]. According to the Australian statistical studies with data from local police and hospitals [15, 16], among all the motor vehicle accidents, 34% of cyclists had head injuries and 15% experienced even worse situation that was diagnosed by the hospitals [15, 16]. Moreover, it had been reported that approximately 55% of deaths result from head injury in cycling fatalities [17]. Similar situation was also found in America, with more than 30, 000 hospitalizations, and over 2 billion treatment cost associated with bicycle crashes, not mentioning the life-quality loss of the patients [18].

Bicycle helmet is the only piece of protective equipment for bicycle riders against TBI and other injuries [8]. Its use has been proved to be the most effective protection for cyclists through many case studies and research papers [19–28], and it has been demonstrated that the number of injured riders with/ without helmets in various sustained injuries (Table 1). In order to reduce the rate of cycling fatalities, mandatory helmet legislation was first introduced in Victoria, Australia, in 1990 [29]. Similar ones came into effect in the other states in the following two years [29]. These legislations for mandatory helmet wearing had been found to be greatly associated with the reduction in head injuries and severe ones, by 20% and 55%, respectively [30].

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Table 1
Number of the injured bicycle riders and the injury types with/ without helmets (Reproduced from Joseph, et al. [9]).

Variable	Helmeted (n = 1571)	Non-helmeted (n = 4696)
Severe TBI	626 (39.8%)	2630 (56.0%)
Craniotomy	22 (1.4%)	197 (4.2%)
Mortality	26 (1.6%)	150 (3.2%)
Any facial fracture	345 (22.0%)	1186 (25.3%)
Mandibular fracture	37 (2.4%)	130 (2.8%)
Malar fracture	186 (11.8%)	555 (11.8%)
Orbital fracture	219 (13.9 %)	726 (15.5%)
Nasal fracture	126 (8.0%)	416 (8.9%)
Contusions/ lacerations	345 (22.0%)	1299 (27.7%)

A typical bicycle helmet consists of the shell, the liner and the retention straps. Among these components, the liner is used to absorb most of the impact energy, and reduce the wearer's risks of sustaining head injuries [13]. The typical liner materials are either expanded polystyrene foam (EPS) or expanded polypropylene (EPP) [13]. Although high crushing stress-to-weight ratio and low manufacturing cost promote broad application of EPS, there are still some other downsides [31]. Specifically, rotational head acceleration is regarded as the predominant mechanism of head injury [13]. Previous researches [32, 33] have shown that, when brain tissues are subjected to rotational acceleration, their axons can be sheared and torn, inducing axonal injuries. These injuries cannot be prevented well by the traditional helmet liner which only attenuates the magnitude of translational acceleration. With more studies showing inadequate protection by traditional design, it is necessary to call for advanced technology to escalate the level of safety [34].

A huge number of researchers have been investigating bio-inspired designs to capture and integrate their advantages into engineering products [35]. The unique features of bio-inspired structures show the ability to surpass the man-made ones, making them much valuable in many areas such as energy absorption [35]. These innovative designs provide insights into the further optimization of the helmet liner.

The objective of this paper is to review the most recent development and research innovation for new bicycle helmet concepts and designs. Specifically, we first introduce the conventional bicycle helmets, discuss the current widely adopted testing standards for bicycle helmets, and these are subsequently followed by a detailed review of the recent innovation designs of the current commercially available bicycle helmets, and their protective performance. We will also discuss about the latest anti-rotational features in the helmet designs since rotational acceleration was found to be more dominant in terms of brain injury [36–38]. Current challenges, limitations and future directions for exploration will be identified at last.

2. Bicycle helmet overview

2.1. History of bicycle helmets

Head injury is one of the most common injuries in cycling accidents, and it can lead to severe consequences. Research on protective measures against this cycling injury can be traced back to a century ago. In the 1880s, the pith helmets were worn by high wheel cyclists [39], as pith is a crushable material best available at that time. Later, with the popularity of cycling and racing, the helmets made of strips of leather-covered padding, were used more often by bicycle racers [39]. The helmet design was then improved with hard exteriors and foam liner interiors. However, a series of problems occurred associated with excessive weight or poor efficiency. In 1975, the first real cycling helmet was developed by Bell Auto Parts, composed of a hard plastic outer shell with a foam-like liner [39, 40]. This invention marked the beginning of the modern helmet era [40]. Meanwhile, related standards were proposed to regulate the commercial helmets. By the 1970′s, a group, namely Snell Foundation, carried out comprehensive testing of commercial helmets [40]. However, almost all the helmets failed to pass [40]. In 1984, American National Standards Institution released the first helmet standard, [40]. Removing unqualified, unsafe helmets from the bicycle helmet market. Before long, expanded polystyrene was invented, becoming the most common and traditional liner [40].

Modern helmets have taken a further step, with an addition of a thin hard shell added. To date, there are numerous studies into helmet design, exploring various structures and materials for better protective capability. Despite the growing emphasis on novel bicycle helmet design, there has also been an increasing focus on the elevation of the helmet safety standard. Overviews of the helmet testing standards as well as various helmet designs are discussed in Sections 2.2 & 3, respectively.

2.2. Bicycle helmet test standards

Bicycle helmet standards regulate criteria to be met through specific laboratory tests in a reproducible manner [41]. These criteria often

Table 2
Key features of bicycle helmet standard (modified from Towner, et al. [41]).

Standard	*Country of Origin*	*Status*	*Anvils*	*Drop Apparatus*	*Impact Velocity/ Energy*	*Acceleration Threshold*	*Roll-off Test*	*Retention System Strength*
CPSC	USA	Took effect since 1999	Flat, hemisphere and curbstone	Guided free fall	6.2 m/s (flat anvil) 4.8 m/s (hemisphere and curbstone anvils)	<300 g	Yes	Force applied dynamically. Helmet supported on head form
EN 1078	Membership of CEN (EU and EEA)	Took effect since 1997	Flat and curbstone	Guided free fall	5.42-5.52 m/s (flat anvil) 4.57-4.67 m/s (curbstone anvil)	<250 g	Yes	Force applied dynamically. Helmet supported on head form
AS/NZS 2063	Australia and New Zealand	Took effect since 1996	Flat	Twin wire drop rig	1.45-1.80 m free-fall height	<200 g for 3 ms; <150 g for 6 ms	Yes	Force applied statically
CSA-D113.2-M89	Canada	Took effect since 1996	Flat and cylindrical	Twin wire drop rig	5.7 m/s (flat anvil) 4.7 m/s (cylindrical anvil)	It depends on different situations (ranging from 150 g to 250 g)	Yes	Force applied dynamically.
GB 24429-2009	China	Took effect since 2010	Flat and curbstone	Guided free fall	6.2 m/s (flat anvil) 4.8 m/s (curbstone anvil)	<300 g	Yes	Force applied dynamically.

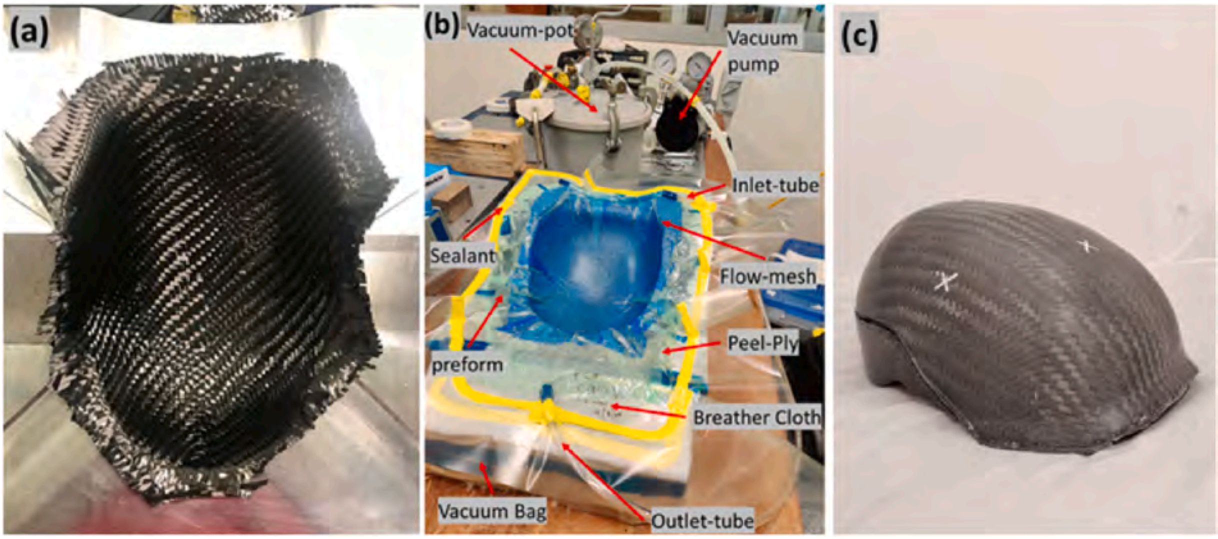

Fig. 1. (a) Preform placement into the mold (b) Bagging setup of the infusion process for the helmet shells (c) manufactured composite helmet shell (Reproduced from Gohel et al. [50]).

include impact energy absorption under defined conditions, the strength and effectiveness of the retention system, etc. [41]. However, there are also a few factors not mentioned in the standards. For example, employment of new materials or structures are not restricted in the standards, as long as manufacturers or designers can guarantee that the helmet is protective and is able to pass the tests [41].

Towner et al. [41] had also listed and compared a few bicycle helmet standards from several countries (Table 2). Through comparison, they provided the following summaries that help people understand the standards in a general way.

- These national test standards certified by individual countries, are largely similar in methodologies and principles, except that the impact energy thresholds vary depending on the drop height.
- All these bicycle helmet test standards aim to ensure a uniform standard of safety testing for bicycle helmets in individual countries, so that all the tested helmets are sufficiently safe to prevent any severe head injuries in any unfortunate event of accident.
- All the certified helmets should have the capability of preventing any penetrating injuries to the head, reducing the relative motion between the skull and brain, as well as keeping biomechanical injury indicators (such as head injury criteria (HIC)) resulted from any unavoidable impacts, within the range of human injury tolerance.
- In terms of the sample tests, the Australia/ New Zealand standard requires the same sample to pass all the tests, while both the European EN1078 and US's CSPC standards allow using different samples to be tested for different tests.

Despite the continuous improvement in the past three decades, there are still issues being neglected by these widely adopted standards. In particular, the test standards solely consider the linear kinematics of the head without taking the rotational acceleration into account. However, it is generally believed that rotational acceleration is more dominant in terms of damaging intracranial injuries, such as diffuse axonal injury (DAI) caused by shearing of brain tissues, as well as tearing of parasagittal bridging veins [36–38, 42]. As doubted by Stigson [43], current bicycle helmets tested under these standards, may not have the capability in reducing rotational acceleration. Stigson [43] also argued that the linear acceleration threshold could be relatively high, as research demonstrated that a lower value of linear acceleration (i.e. from 250 g to 180 g) would lead to a lower risk of skull fracture [44]. Therefore, researchers in the field are proposing various advanced test methods for bicycle helmet, taking into account the translational and rotational effects [37]. These newly proposed tests will still need further improvement and standardizations before being considered mandatorily in all the certified bicycle helmet testing standards by legislative regulations.

Overall, although the bicycle helmet test standards have been developed and amended for better performance of helmets and a better regulated market, it is evident that some critical factors are missing. Mitigation of rotational head acceleration should be considered mandatorily in all the certified bicycle helmet testing standards by legislative regulations.

3. Helmet design

Despite the improvement made in the past few decades, there is ongoing research on helmet design, with particular focuses on the material and structural aspects of the helmet shell and the liner. Combining the properties of each component will lead to expected functions (e.g. reducing the deceleration of skull, managing the impact, and preventing forces being concentrated on a specific small area) [41]. Besides, helmets are required to provide adequate protection and comfort in all conditions, yet with lesser materials to achieve lightweight [41].

In this paper, we will discuss about various designs of the helmet shell and liner in terms of the choices of materials and structures.

3.1. Helmet shell design

Potential areas of improvement for helmet design have been focused on the helmet constituents. The outer shell, typically made of thermoplastic materials (e.g. acrylonitrile–butadiene–styrene (ABS), polycarbonate (PC)) or composite materials, is the first and hardest layer, to prevent penetration from foreign objects [45]. The outer shell is [45]:

- To spread the impact load over a large area so that the concentrated stresses at the impact site would be reduced. The distributed energy will then be absorbed by the inner liner.
- To prevent penetration of the helmet by a sharp object to avoid punctured skull and penetrating brain tissue injuries.
- To absorb the initial shock as the first layer of protection [46].
- To provide a structure for helmet liner to ensure that the liner will not disintegrate by penetration.

Table 3
Summary of the shell materials.

Material	Advantages	Drawbacks
Carbon/ Glass/ Kelvar fabric reinforced polyester [48]	Absorb larger amounts of energy by the failure of composite materials.	High stiffness hinders large deformation and further energy absorption.
Carbon/Elium® (WEL) [50]	Show better ductility and less catastrophic damage compared to the conventional shell	Manufacturing process of composite material may be complex and expensive
Coconut shell [51]	Eco-friendly and show great results in static and thermal analysis	No prototype fabrication or experiments have been conducted with the natural material

3.1.1. *Materials for helmet shell*

Hansen et al. [47] collected the data of injury levels of people with no bicycle helmet, no-hard-shell helmets and hard-shell helmets. They found that, when compared to the other two categories, hard-shell bicycle helmets could provide better protection, highlighting the importance of the hard helmet shell. That awareness of the helmet shell contribution motivates researchers to improve the helmet design. One popular solution is the use of composite materials. For example, Kostopoulos et al. [48] used finite element (FE) simulations to evaluate the performance of helmet shells with different woven fabric materials (namely, carbon, Kevlar and glass) and a glass mat ply for reinforcement. It was concluded that all the composite materials can help to reduce peak accelerations of the head, and the Kevlar sample outperformed others due to its low shear strength and stiffness. Although the investigation was based on a motorcycle helmet, the results are still valid for bicycle helmets, since both the injury mechanisms are similar. Meanwhile, Cernicchi et al. [49] explored the feasibility of a fiber-reinforced shell helmet by using both numerical and experimental means. Further application of composite materials can be seen in Gohel et al. [50]'s study, in which a woven carbon/Elium® (WEL) bicycle shell helmet was fabricated (as depicted in Fig. 1) and tested with drop tests according to CPSC 1203 helmet certification. Effect of various anvil shapes were examined. Based on the post-test analysis on the high-speed camera images, Gohel et al. argued that the proposed carbon/Elium® (WEL) bicycle shell showed less catastrophic damage, as well as improved head injury criteria (HIC) value due to the composite's ductility. It was also concluded that most of the energy was directly absorbed by the composite shell, whereas less amount of energy was transferred to the liner foam. Totla et al. [51] thought that the helmet shell, no matter made by thermoplastics or composites, was not eco-friendly. Instead, they proposed a novel coconut shell made of natural coconut material. A 3D FE model was developed, and a series of simulations were carried out for the helmets with a coconut shell, an ABS shell and a semi-synthetic shell. They concluded that, despite the similar stress levels in a static analysis, there was a significant difference of deformation between the coconut and the ABS. A further thermal analysis showed that coconut material could be an excellent insulator.

Table 3 summarizes the aforementioned materials, compared to the conventional shell. Despite the many positive findings of implementing composite materials in helmet shell, the doubt that whether they can thoroughly replace the conventional thermoplastic shell, still remains questionable. Pinnoji and Mahjan [46] argued that the composite shell failed to absorb sufficient impact energy which is transferred to the head under high-speed impact. Moreover, the higher raw material and manufacturing costs make it less appealing solely for commercial cost-effectiveness.

3.1.2. *Anti-rotational design on shells*

It is well known that rotational force is a dominant factor causing brain injury, but meanwhile, it is still ignored by the current employed bicycle helmet standards [36–38]. Therefore, there are a paucity of studies exploring in the design of an anti-rotational helmet. The Multi-directional Impact Protection System, acronymed as MIPS (MIPS® AB, Taby, Sweden), is a good example showing the continuous effort in reducing rotational acceleration experienced by the head. MIPS is regarded as an advanced slip-plane technology to reduce rotational forces [52]. An extra low-friction layer is fitted in the helmet and

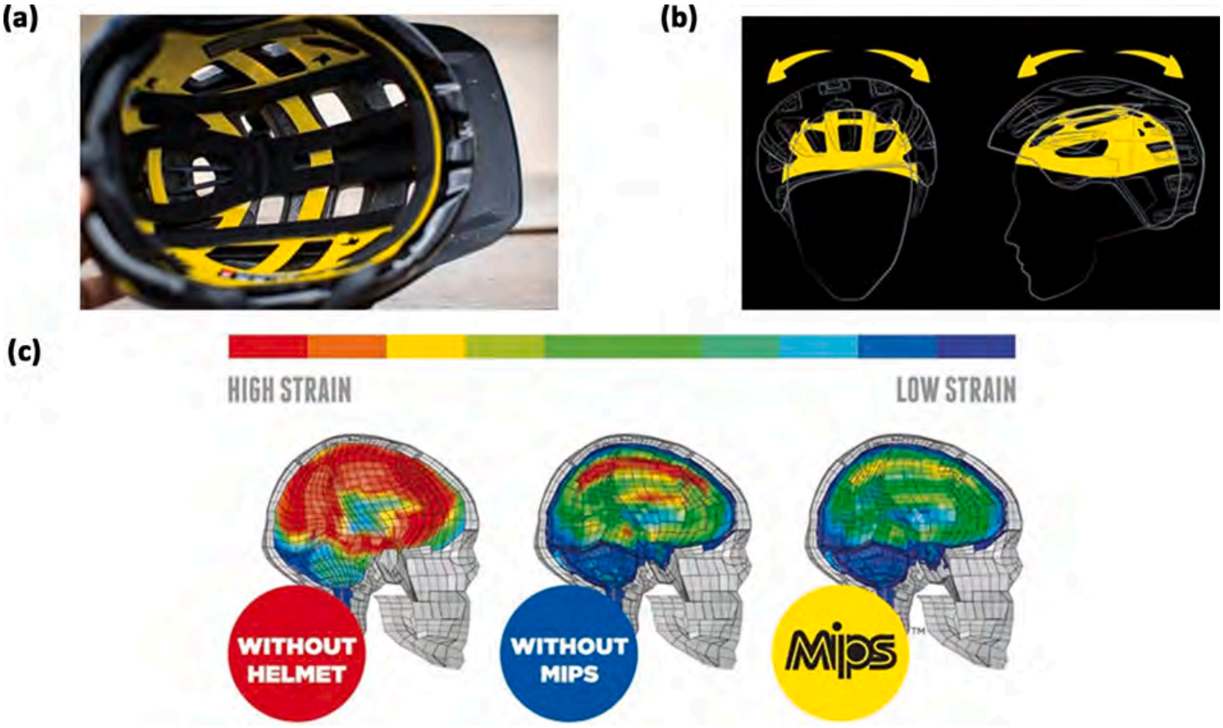

Fig. 2. MIPS Helmet (a) MIPS layer in a helmet (Modified from MIPS [56]); (b) Mechanism of MIPS (Reproduced from Vilaboy [53]);); (c) Comparison of MIPS helmets compared to the brain strains when the head is equipped with no helmet, conventional helmets and MIPS helmets (Reproduced from Feldmeir [54]).

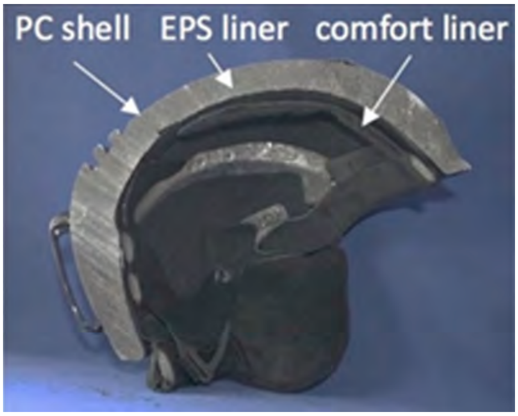

Fig. 3. EPS-foam in a bicycle helmet (Modified from DiGiacomo et al. [60]).

connected to the shell with rubber straps between the shell and the inside liner, to help the outer shell slide slightly (normally 10–15 mm) when there is any rotational force, as shown in Fig. 2 (b) [53]. This mechanism, which mimics the human head's own natural protection system (i.e. the cerebrospinal fluid (acronymed as CSF) surrounding the brain), aims to avoid shearing force resulting in severe rotational acceleration-induced injuries. Although the MIPS helmet looks similar to a traditional one, many studies have shown that it manages to reduce rotational force experienced by the head. Fig. 2 (c) [54]. By 2019, 14.2 million MIPS helmets had been sold and used by over 100 helmet brands all over the world [55].

Knight [57] also considered how to reduce rotational force transmitted to the head by introducing three layered helmet shells, which are made of various materials. Elastomeric trusses or energy dampening fluid were applied between the layers. The elastomeric trusses were arranged diagonally to connect to the outer shell and middle shell in one direction, and the middle and the inner shell in another direction. In some cases, conical structures can also be employed to separate the middle and inner shell. With the elastic and multi-directional property, the multilayered structure can deform in the shell's tangential direction when rotation occurs, so that it is capable of attenuating a portion of the rotational force.

Apart from the consideration of impact loading from various directions, researchers also strive to solve problems related to thermal comfort, proper fit, and other factors. For instance, Jordan Klein and David Hall, the founders of the Park & Diamond, Inc., came up with the idea of a collapsible baseball cap-alike bicycle helmet [58], which is a multilayered foldable helmet with an optimized 3D mesh fabric, EVA foam, a polycarbonate shell, and a composite layer. Despite being ultra-lightweight, the founders claimed that it still has equivalent impact energy dissipation capacity. In addition to this innovative foldable design, other researchers have been focusing on thermal comfort with fluid dynamics, proper fit by analyzing anthropometric data, etc. [59, 60].

3.2. *Helmet liner design*

As only a limited amount of impact energy (6.87 % by the PC shell [61]) is absorbed and dispersed by the outer shell, the main purpose of the helmet liner is to attenuate the majority of the remaining energy from the impact (82.8 % by the EPS liner [61]) [45]. The liner is supposed to absorb the impact energy by allowing more deformation, increasing the impulse duration and lowering the peak forces [45].

The most common helmet liner is expanded polystyrene (EPS) foam (shown in Fig. 3), which is a cellular material with excellent shock absorption capacity and desirable cost-benefit ratio [62]. Related manufacturing techniques have been developed for more than half a century, enabling manufacturers to create variable density foams as layers in the helmet [63]. EPS liner is now widely applied in commercially available bicycle helmets, motorcycle helmets, and other sports protection systems. Furthermore, the lightweight property and the relative low cost of EPS helmet lead to its popularity in the market.

Although EPS foam exhibits excellent energy absorption capacity, the capacity becomes much poorer after its first impact with limited elastic recovery [45, 64]. More importantly, a strong link between rotational acceleration and TBI has been found, which has promoted awareness of the anti-rotational capacity of bicycle helmets. Studies by Aare and Halldin [65], Mills and Gilchrist [66], Pang et al. [67], Hansen et al. [68] have demonstrated that, even though a helmet can pass a linear impact test, the value of its angular acceleration can still exceed the desired value of angular acceleration. While rotational acceleration is one of the leading risk factors in brain injury, researchers have been investigating various mechanisms of the helmet liner for anti-rotational protection.

3.2.1. *Existing helmet liner materials*

As the liner is the main energy absorber in a helmet, continuous research efforts have been paid on exploring alternatives and optimization of helmet liners in the past decades. Vanden Bosche et al. [69] suggested that polyethersulfone (PES) foam have the potential to replace EPS liner. Similar to the traditional EPS liner, PES also has a low-density characteristics and good energy absorption capacity. PES liner is expected to perform well in terms of both the anti-linear and the anti-rotational systems due to its anisotropic property. Vanden Bosche et al. [69] conducted quasi-static compression and shear tests on cubic samples, as well as oblique impact tests on the helmets. With the equipped PES liner, peak linear and rotational accelerations decreased by around 37% and 40%, respectively. Fernandes et al. [70] employed agglomerated cork to replace the traditional EPS liner. Cork is a natural cellular material with great crashworthiness. Moreover, cork can recover after compression and can be used in multi-impact scenarios [70], and its energy absorption capacity was also identified by other researchers [71, 72]. Fernandes et al. [70] generated a new FE model and employed to conduct a parametric study by varying the thickness of the material and removing some parts of the liner. The results indicated that cork was a good material as the liner, and the total mass of the helmet could be controlled by modifying the thickness of the liner in some regions.

Employing the same type of material with various properties is another alternative to optimize the liner's performance. For example, studies have indicated that functionally graded foam is a good choice as an energy absorber. Di Landro et al. [62] employed EPS foam with different densities in a helmet. It was found that density is a crucial parameter that influences deformation behavior, failure and energy absorption capacity [62]. Higher-density EPS foam could absorb more energy during impact, but it could also transfer higher acceleration. On the other hand, lower-density foam could decrease acceleration level, but to absorb the same amount of energy, increased thickness is required. Therefore, by controlling the density gradient in a graded foam, the performance of the liner could be improved further. Inspired by the functions of graded foam, Gupta [73] developed four-layered synaptic foams, with each foam being made of the same material, but with different densities. They concluded that 300–500% more energy can be absorbed by the functionally graded structure, as compared with the foam with a uniform density. Later on, Rueda et al. [74] also discovered liner optimization by comparing two types of foams; one was a conventional EPS foam with a uniform density, whereas the other was three layered EPS foam with different densities. Various combinations of layered liners and uniform liners were tested under different conditions of impact speed and angles. Rueda et al. [74] argued that with additive manufacturing, layered liner is a promising method to improve the performance of helmets, because each layer can be targeted separately depending on locations. Meanwhile, another study by the same group [75] focused on the effect of the foam density using numerical means.

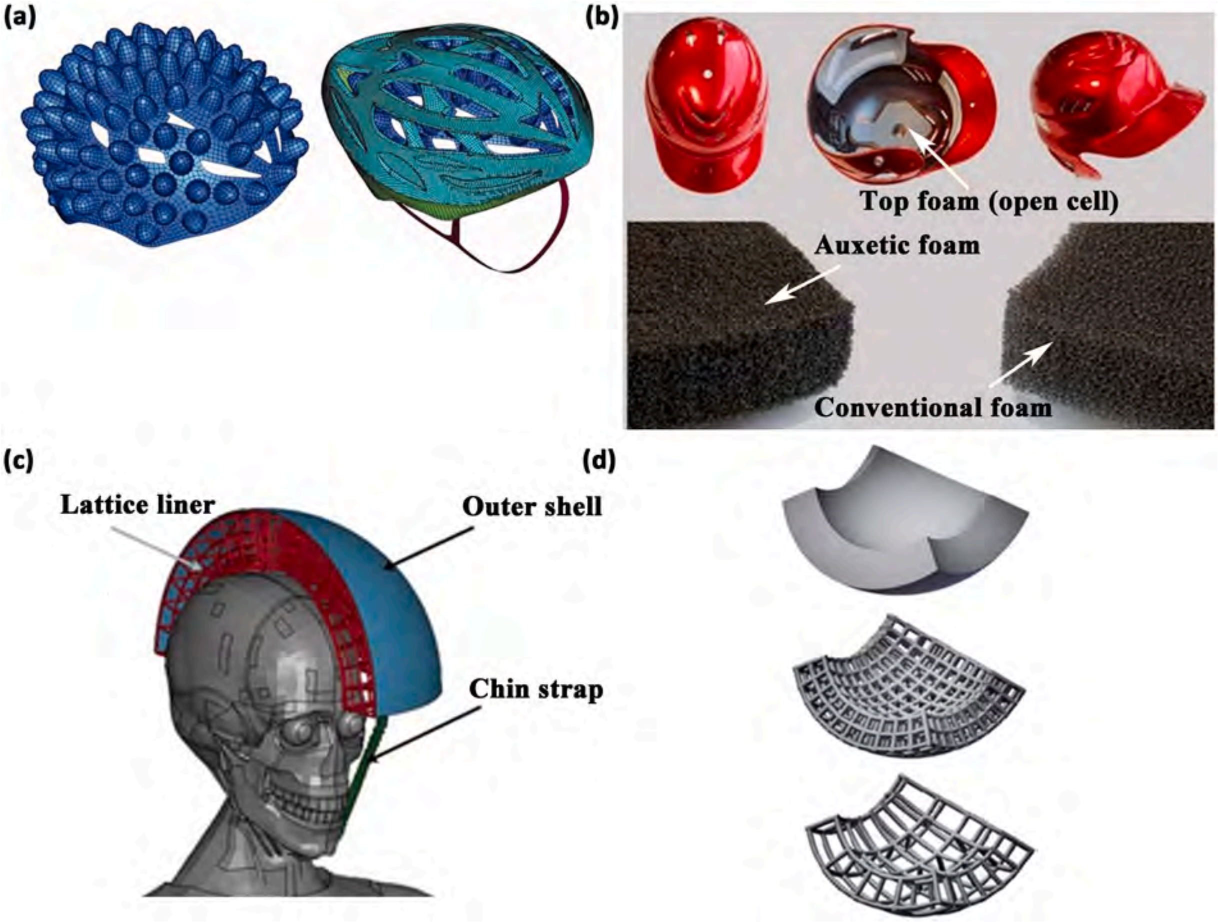

Fig. 4. (a) Cone liner in helmet model (Reproduced from Teng et al. [78]); (b) Auxetic foam liner (Modified from Foster et al. [79]); (b) The helmet model with the lattice liner (Reproduced from Khosroshahi et al. [81]); (d) Cellular liner by TPE (Reproduced from Soe et al. [82]).

The numerically simulated results indicated that the performance could be improved more by increasing density difference between layers. In their further research [76], a graded foam was developed with the same average density as that of the uniform one, and it was shown that, by applying liners with varying densities through the thickness, the safety level of the helmet could be improved further. However, Cui et al. [76] claimed that due to the difficulty of manufacturing, producing functionally graded EPS foam on a large scale remained challenging and was the key barrier to the commercial use.

3.2.2. *Existing helmet liner structural designs*

Recent research focuses on exploring novel structures for the liner. For example, Blanco et al. [77] utilized the energy absorbing capability of a deformable cone-shaped structure via a combinations of folding and collapsing of the cone, and developed a conceptual idea of a helmet liner comprising an Acrylonitrile butadiene styrene (acronymed as ABS) plastic lamina with multiple cone-shaped structures on its top. It was claimed that the main advantage of such a liner over the conventional EPS liners is that, it allows a better optimization of energy absorption for different impact sites and configurations. A similar idea of a cone-shaped helmet liner was further investigated by Teng et al. [78], who fabricated the liner with ABS material (Fig. 4 (a)) and performed a series of drop tower tests according to EN 1078 standard. Various impact velocities (4.57 m/s and 5.42 m/s) and anvil types, namely the curbstone and flat types, were used in these tests. It was found that the HIC values of the helmet with the novel structure were all better than those of the conventional one in crown, frontal, rear and lateral impact locations. Moreover, with the intention of exploring other advanced materials, Foster et al. [79] evaluated the performance of open-cell polyurethane auxetic foams as the liner, as depicted in Fig. 4 (b). Auxetic structure is a type of structure with negative Poisson's ratio, which displays unique properties and better energy absorption capacity when impacts occur [79, 80]. Foster et al. [79] employed this structure in a sports helmet and compared it with the traditional counterpart via drop tower tests. They concluded that auxetic liner could effectively reduce the peak linear acceleration and attenuate more impact energy transmission to the head. Although they used auxetic structure in the sports helmet, it still has the potential to be utilized in bicycle helmets.

Khosroshahi et al. [83] employed topology optimization in the design of their lattice liner structure, and used nylon as the additive manufacturing material for the fabrication of their hierarchical lattice liner (Fig. 4 (c)) as it can absorb relatively high energy with its plastic deformation during buckling [83]. Results from both FE simulations and experimental tests indicated that the structure could be an option for the next generation helmet liner due to its better energy absorption ability. Further parametric study was conducted [81] by adjusting its relative density and topology (prismatic versus tetrahedral unit cell), the prismatic unit cell with 6% relative density was found to be the best configuration, which reduced peak linear and rotational accelerations by 48% and 37%, respectively. Specifically, their analyses of the prismatic unit cell provide further insight into the mechanism of rotational energy absorption. A similar cellular structure as depicted in Fig. 4 (d) was proposed by Soe et al. [82], where a laser sintering (LS) process was employed to fabricate the structure using thermoplastic elastomer (TPE). Soe et al. [82] evaluated their cellular structure by both numerical and experimental means, and concluded that this additive-manufactured cellular structure was able to absorb more energy, showing immense potential for enhanced helmet safety.

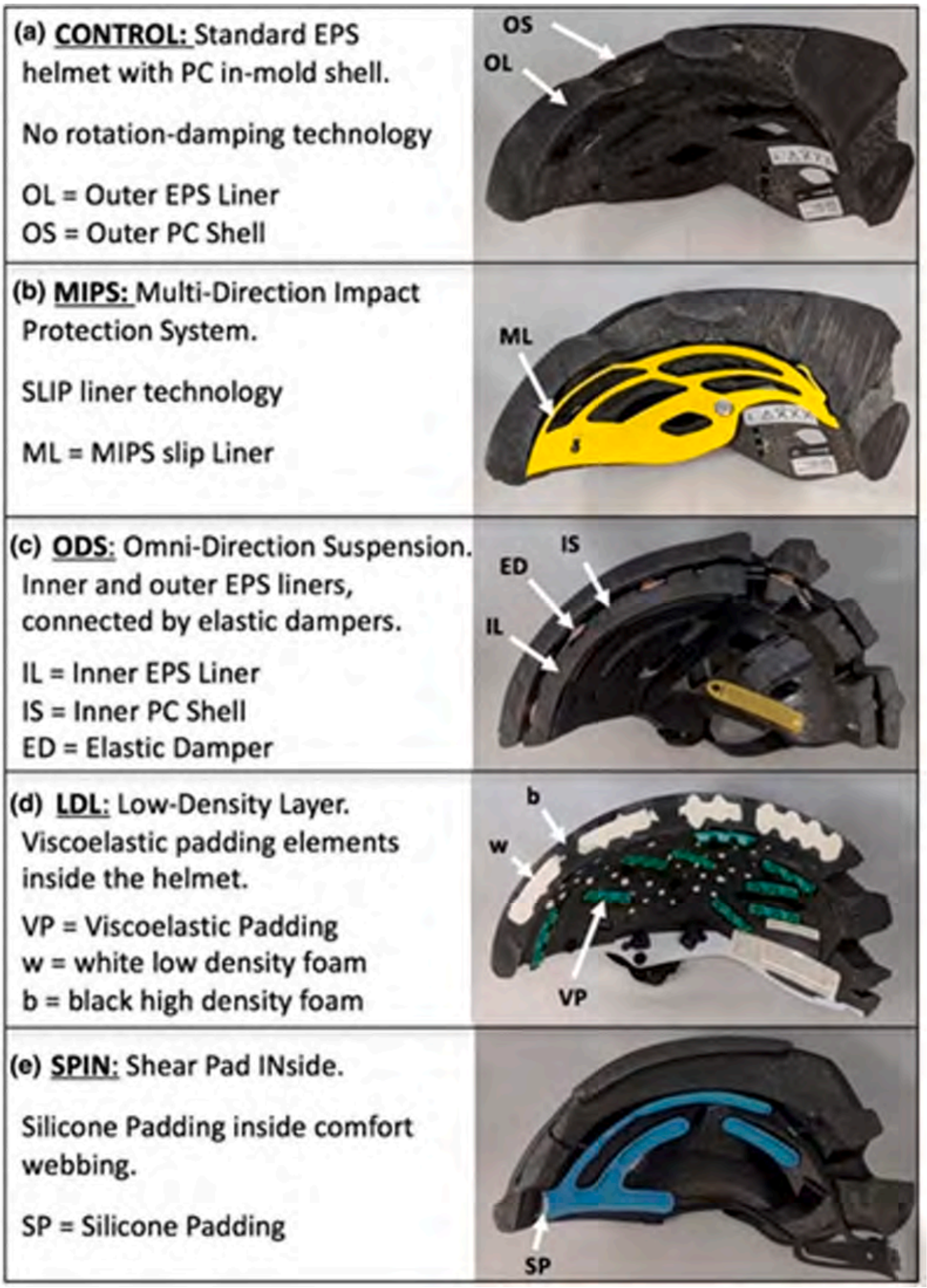

Fig. 5. Cross sections of (a) EPS helemt; (b) MIPS helmet; (c) ODS helmet; (d) LDL helemt; and (e) SPIN helmet (Reproduced from Bottlang, et al. [87]).

Instead of replacing the whole helmet liner, some researchers attempted to modify the current structure. Stewart et al. [84] incorporated Vinyl Nitrile (VN600) fluid channels into the traditional liner to improve its energy absorption ability. With the introduction of VN600, both the fluid and the elastically deformable channels could prevent head injury. Experimental evaluation showed that compared to EPS material, the modification led to better energy absorption and significantly lower Head Injury Criterion (HIC) value. Caserta et al. [85] replaced parts of the liner in critical regions by hexagonal aluminum honeycombs. Experimental results demonstrated that the proposed liner showed a better performance when impacted by a curbstone anvil. However, for the impact by a flat anvil, the improvement of energy absorption was limited, indicating that there is still room for further adjustment.

3.2.3. Anti-rotational helmet liner designs

Despite the ongoing focus on the energy absorption capacity of the helmet liner, little effort had been dedicated to the significance of mitigation of angular acceleration. In recent years, the increased awareness of the connection between rotational acceleration and TBI has sparked an intense investigation of the anti-rotational mechanism. Based on the various mechanisms, existing anti-rotational systems can be generally divided into two groups [5]. The first group employs a head-shaped slip layer (or interface) inside the helmet besides the

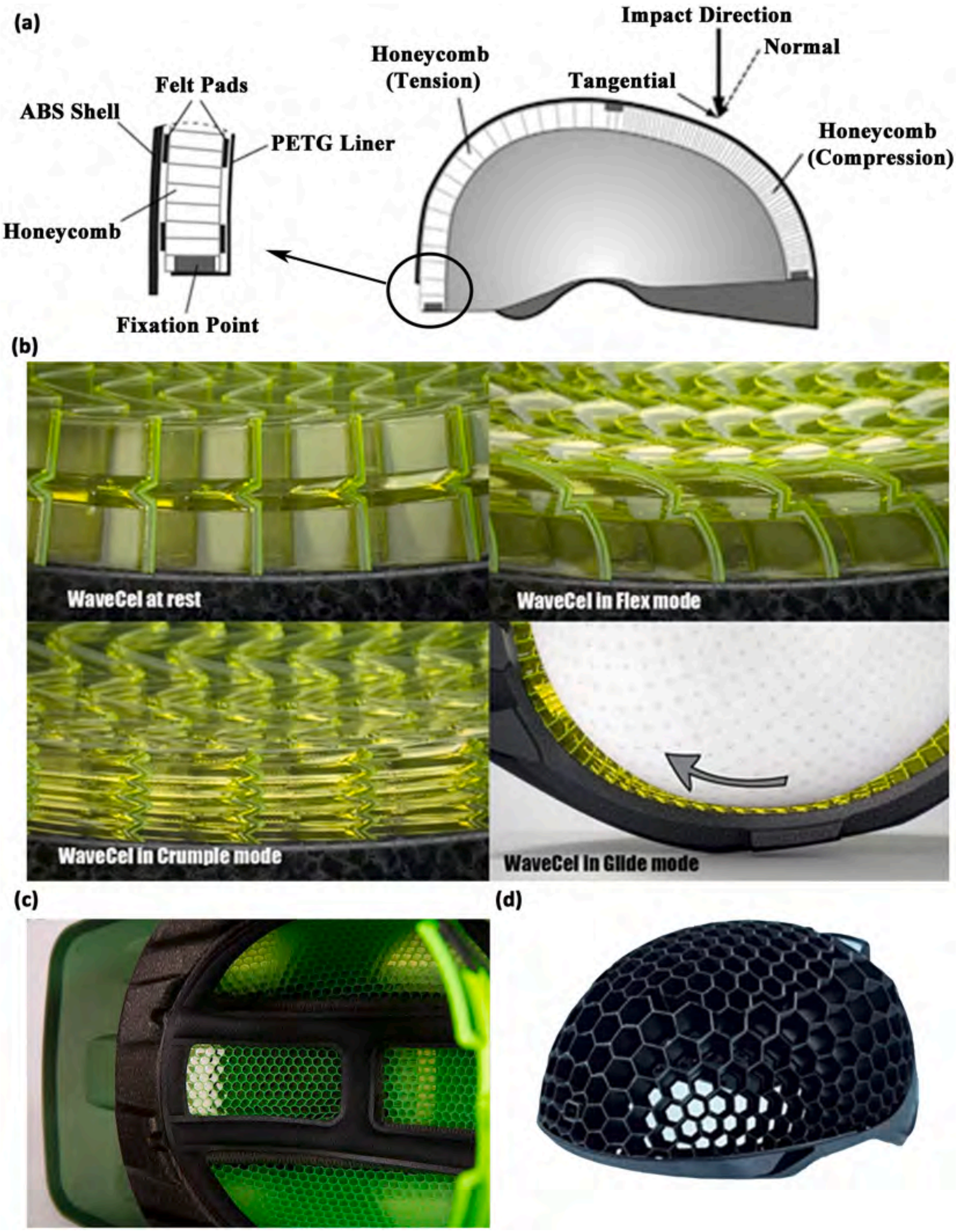

Fig. 6. (a) AIM system & its mechanism (Reproduced from Hansen et al. [68]); (b) Mechanism of WaveCel helmet (Reproduced from Edwards [93]); (c) Koroyd helmet liner (Reproduced from Owen [94]); (d) HEXR helmet with 3D printed honeycomb liner (Reproduced from HEXR [92]).

traditional layers [5] and is presented in Section 3.2.3.1. The second group uses collapsible structures in helmets and is presented in Section 3.2.3.2.

3.2.3.1. Slip-layer designs. A typical example is the Multi-Directional Impact Protection System (MIPS® AB, Taby, Sweden), as mentioned in the previous section. In this helmet, a thin slip liner is equipped with a low-friction property, which is connected to the other outer layer through rubber straps. The connected rubber straps allow this layer to slide approximately 10–15 mm, seeking to mitigate rotational acceleration. To assess the performance of the MIPS helmet, an oblique impact test was undertaken by Aare and Halldin [65]. A custom-made impact rig was proposed for the experiment, with a Hybrid III head anthropomorphic test device equipped with accelerometers. They concluded that compared to conventional helmets, MIPS helmet could reduce rotational acceleration by up to 56% in all impact scenarios (i.e. various velocities and impact locations).

Similar mechanism was employed by Knight and his team [57], who proposed a multi-layered helmet connected by elastomeric trusses or energy dampening fluid between each layer. This configuration enables each layer to slide towards the shearing direction at different impact velocities, which prevents the rotational impacts from fully transferring to the human head to a large extent. Idea of sliding was also employed in 'ATB-1T EVO' helmet by 6D Helmet [86] named after Omni-Directional Suspension (ODS) system, as shown in Fig. 5 (c). Double layers of EPS liners were applied in the helmet, connected by an array of elastomeric

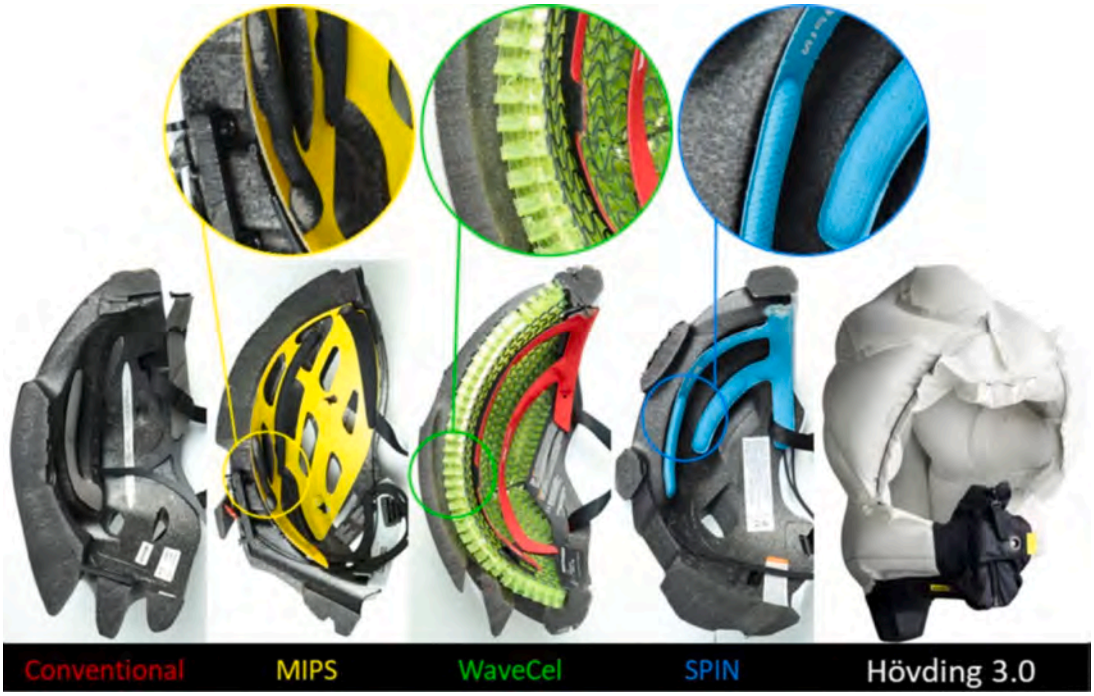

Fig. 7. Tests of Hövding helmet compared to other helmets (Reproduced from Abayazid et al. [96]).

dampers [87]. Unlike the aforementioned helmets, Fig. 5 (e) represents another type of bicycle helmets ('AURIC SPIN' helmet) that place the silicone padding inside the comfort webbing in the comfort fit system [87, 88].

3.2.3.2. Collapsible structure design. Collapsible structures are utilized to amend or replace the EPS liner, attempting to reduce the stiffness of shearing in the bicycle helmet [5, 68]. For example, Hansen et al. [68] developed an Angular Impact Mitigation (AIM) system using an elastically suspended aluminum honeycomb liner to deal with rotational forces (Fig. 6 (a)). To evaluate its performance, a conventional bicycle helmet and the novel prototype were used in a normal impact test for linear acceleration and an oblique test for rotational acceleration. By comparison, they concluded that the novel helmet liner led to 14%, 34% and 22% - 32% reduction in peak linear, rotational acceleration and neck loading, respectively. While EPS-based helmet may not be optimized further to reduce rotational acceleration, AIM-system-based liner becomes an alternative.

Inspired by the AIM system, Bliven et al. [13] proposed a novel bicycle helmet, named as WaveCel Helmet. It was equipped with a collapsible cellular structure to mitigate the rotational acceleration, as shown in Fig. 6 (b). The unique cellular structure can crumple and flex to absorb both linear and rotational impact. To assess the efficiency of the novel helmet, drop tower tests with oblique impacts were conducted under several conditions (4.8 m/s and 6.2 m/s impact velocities and 30°, 60° and 90° impact angles respectively). Meanwhile, linear acceleration, rotational acceleration, head form and neck loads were recorded correspondingly. They found that this structure manages to reduce rotational acceleration by 34% to 73%. WaveCel Helmet currently has been widely applicable in the market. Besides the cellular structure's compressive capability in attenuating impact energy, the whole liner can also glide towards the direction of shearing.

Koroyd helmet also makes use of cellular structure for energy absorption [89, 90]. Its liner consists of extruded, straw-like tubes with copolymer material, as depicted in Fig. 6 (c). Every six of the unit tube are welded and arranged to form a honeycomb-like structure. When impact occurs, these tubes will crumple in a consistent manner for dispersion of the impact force. It was claimed by the company that Koroyd helmet can reduce both linear and rotational acceleration with excellent air circulation.

HEXR company developed a novel helmet with 3D- printed honeycomb liner, as shown in Fig. 6 (d). By additive manufacturing technology, this novel liner provided a solution for riders who have fit problems or cochlear implants [91]. Moreover, it was claimed that the 3D-printed honeycomb improved the safety level by 30% reduction of rotational and linear acceleration [92].

3.2.3.3. Other designs. Besides the cellular structures, many other types have been investigated as well. Fig. 5 (d) represents low-density-layer (LDL) based bicycle helmet [87]. Lego-like viscoelastic padding elements are embedded inside the comfort padding. Similarly, 'Leatt Turbine' [95] was developed and employed in Leatt helmet. The unique shape enables it to become firmer when being compressed, while it can also be stretched towards shearing direction during oblique impacts, reducing rotational acceleration. Fox Fluid Inside [90] used fluid-filled pods embedded into the helmet, which mimics the movement of cerebrospinal fluid (CSF). Their technology has been applied into the product 'Rampage Pro-Carbon' helmet. Specially, Hövding helmet was proposed based on the air bag principle, as depicted in Fig. 7 (Hövding). When a crash occurs, an inflating plastic bonnet would be deployed from inside of the design. A few tests indicated that the helmet outperformed in terms of linear and rotational acceleration [43, 96], but they also argued that the time duration of the impact was longer compared to other helmets such as MIPS [96].

Table 4 represents a series of tests on the latest helmets by many researchers. General test methods, boundary conditions and results can be found in this table [43].

The range of the values refer to the results by various velocities and locations. Specific value can be achieved in the corresponding reference. Besides the experiments, FEA of oblique impacts were also conducted by researchers [101–103]. Despite the intense exploration of anti-rotational design, there are a few issues to be resolved. First, only a fraction of the technologies has been commercially available, whereas many of the rest are in early stage. Furthermore, some researchers still doubt the efficiency of some latest designs. For example, Bottlang et al. [87] carried out a series of impact tests to assess some current

Table 4
Helmet tests & performance.

Helmet	Ref.	Methods/ Boundary conditions	Peak Linear Acceleration	Peak Rotational Acceleration	AIS2*probability
MIPS	**A** [43]	Type: Normal & Oblique impact Standard: EN 1078 Headform: ISO head form & Hybrid III 50th percentile male anthropomorphic head form Boundary conditions: 1.5 m drop height; 5.42 m/s normal impact; 6.0 m/s oblique impact at three locations on 45 ° anvil Sample: Seven commercial MIPS helmets (including Bell Stoker MIPS, etc.)	Normal: 94 – 155 g; Oblique: 74 – 156 g	4.2 – 6.1 krad/s^2	N/A
	B [5]	Type: Oblique impact Standard: CPSC Headform: Hybrid III 50th percentile male anthropomorphic head form Boundary conditions: All are oblique impacts. 4.8 m/s impact on 30°, 45°, 60° anvil; 6.2 m/s impact on 45 ° anvil Sample: Twenty MIPS helmets (Scott ARX Plus, www.scott-sports.com)	83 – 86 g	3.4 -5.6 krad/s^2	~0.2 – 0.3
	C [87]	Type: Oblique impact Standard: CPSC Headform: Hybrid III 50th percentile male anthropomorphic head form Boundary conditions: 6.2 m/s impact on 45 ° anvil Sample: Scott ARX Plus (www.scott-sports.com)	85 – 95 g	5.8 - 6.4 krad/s^2	0.4 – 0.42
	D [96]	Type: Oblique impact Standard: Rotational test methods by European Committee for Standardization Working Group 11 Headform: Hybrid III 50th percentile male anthropomorphic head form Boundary conditions: 6.3 m/s impact on 45 ° anvil at three impact locations Sample: Fifteen commercial MIPS helmets (including Bell Super air R, etc.)	75 - 125 g	3.5 -7 krad/s^2	0.4 – 0.65
6D	**A** [87]	Same boundary conditions as Ref. C in MIPS Sample: ATB-1T EVO helmet (www.6dhelemt.com)	85 - 90 g	7 – 7.1 krad/s^2	0.5 – 0.505
Brain Guard	**A**	25% - 50% reduction in rotational impacts (equipped in football helmets) [97]			
AIM	**A** [68] [68]	Type: Normal & Oblique impact Standard: CPSC Headform: Magnesium alloy head form & Hybrid III 50th percentile male anthropomorphic head form Boundary conditions:2.15 m drop height; 6.2 m/s normal impact; 4.8 m/s oblique impact on 30 ° anvil Sample: Ten commercially available helmets modified by AIM system	Normal: 242 g	6.2 krad/s^2	30 % reduction of suffering concussion
WaveCel	**A** [5]	Same boundary conditions as Ref. C in MIPS Sample: Twenty commercially available helmets (Scott ARX Plus) modified by WaveCel system	53 - 64 g	1.9 – 3.2 krad/s^2	Max 0.75
	B **[96]**	Same boundary conditions as Ref. D in MIPS Sample: Bontrager specter WaveCel	80 – 105 g	3.8 – 5.5 krad/s^2	0.38 – 0.63
Koroyd	**A** [98]	Type: Normal & Oblique impact Standard: CPSC Headform: National Operating Committee on Standards for Athletic Equipment (NOCSAE) head form Boundary conditions: 5.1 m/s oblique impact at three locations on 30 ° anvil Sample: Smith Optics Overtake (SOO)	68 – 144 g	3.74 - 5.188 krad/s^2	N/A
LDL	**A** **[87]**	Same boundary conditions as Ref. C in MIPS Sample: TAVA helmet (www.bikes.kaliprotectives.com)	130 g	11.8 – 12.2 krad/s^2	0.58
SPIN	**A** **[87]**	Same boundary conditions as Ref. C in MIPS Sample: AURIC SPIN helmet (www.pocsport.com)	80 – 88 g	4.5 – 5.5 krad/s^2	0.38 – 0.39
	B **[96]**	Same boundary conditions as Ref. D in MIPS Sample: POC axion SPIN; POC tectal SPIN	100 – 110 g	5.5 – 6.5 krad/s^2	0.5 – 0.62
Leatt	**A**	Up to 30%, 40% reduction in concussion-level impacts, and rotational impacts, respectively [99]			
Fox Fluid	**A**	39% reduction in rotational forces and impacts [100]			
HEXR	**A**	Around 30% reduction in linear and rotational acceleration [92]			
Hövding	**A** **[43]**	Same boundary conditions as Ref. A in MIPS Sample: Hövding 2.0	Normal: 48 g Oblique: 27 – 42 g	1.5 – 2.8 krad/s^2	N/A
	B [96]	Same boundary conditions as Ref. D in MIPS Sample: Hövding 3.0	23 g	0.7 – 2 krad/s^2	0.2 – 0. 38

The range of the values refer to the results by various velocities and locations. Specific value can be achieved in the corresponding reference.

[*] AIS 2: Abbreviated Injury Score (AIS2) Brain injury probability

commercial helmets, as shown in Fig. 5. All the helmets were separated into five groups for tests under different scenarios. The results showed significant differences in effectiveness among these helmets. Some of them were able to reduce linear and rotational accelerations, whereas some showed little difference compared with EPS-based conventional one. The other researchers also claimed that novel helmets can work well, but at some specific impact location, the protection level has not been fully improved [96]. Another example is Hövding helmet. Despite

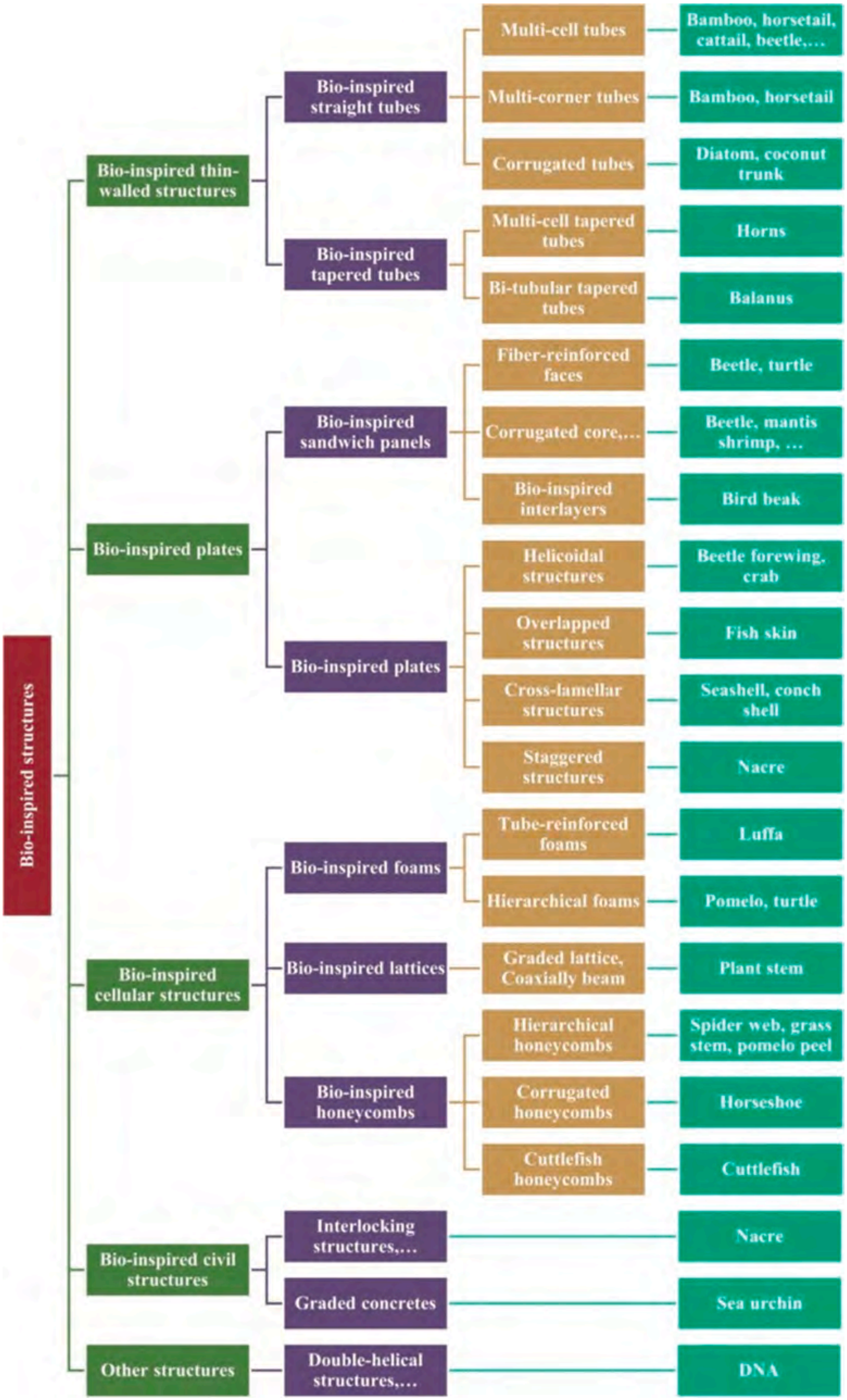

Fig. 8. Categories of bio-inspired structures (Reproduced from San Ha and Lu [105]).

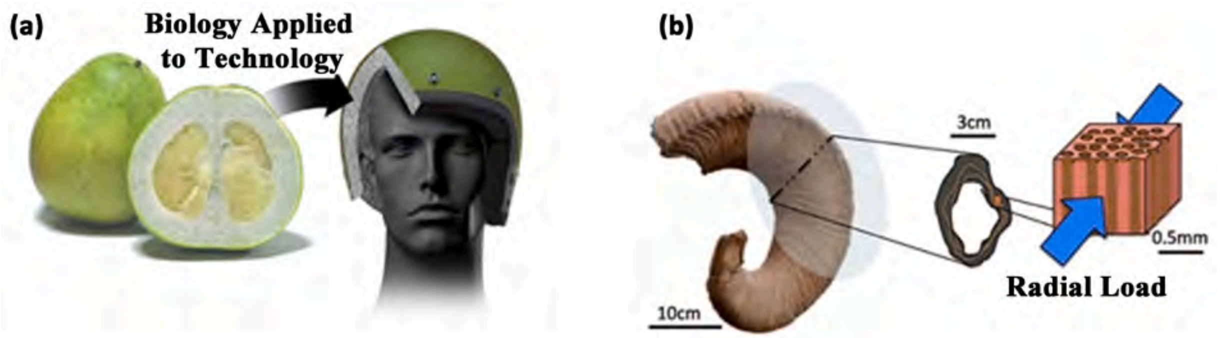

Fig. 9. (a) Pomelo-inspired helmets by BMW Group (reproduced from Frey [110]); (b) Sheep horn-inspired structure (reproduced from McKittrick et al. [32, 111]).

the excellent results in several tests, there are also some claims that the helmet might not pass EN1078 standard, and it has not been sold to US by CPSC standard [104]. To sum up, it was observed that many aforementioned designs can contribute to reduction of linear and rotational acceleration, compared to the conventional EPS helmet. However, it was also noted that the performance depends on various scenarios, even different manufacturers, or brands.

In common, all the mechanisms of anti-rotational designs seek to reduce rotational acceleration, while helmets can still absorb impact by linear acceleration at the same time. As researchers understand more in terms of the cause of TBI, concussion and other sever brain injuries, further studies are expected to focus on extension of latest research and commercial application.

4. Bio-inspired structures

4.1. General overview

As a new technology, bio-inspired structures were not widely used as energy absorbers around year 2000. The difficulty of manufacturing of these structures further impeded the promotion of this technology [105]. However, with the inspiration of biological models and advancement of manufacturing technology, many bio-inspired structures have been proposed and proved to be efficient in terms of energy absorption [105]. Therefore, in recent years, there has been an increasingly rapid development of biomimetic structures. San Ha and Lu [105] summarized a wide range of the latest bio-inspired structures for energy absorption and grouped them into many categories according to the shape, application, as shown in Fig. 8. Overall, biomimetic approaches have shown a promising prospect regarding energy absorption in various engineering areas.

4.2. Bio-inspired structure in protective helmet application

4.2.1. Application to helmets

It is claimed that for head impact prevention, related materials and structures can be learned from a wide range of creatures (e.g. woodpeckers, bighorn sheep, etc.) [34, 106–109]. One example is pomelo fruit, whose unique light-weight structure can withstand a force by a 10-meter fall and still remain its integrity [107, 110–112]. BMW group realized the effectiveness of this structure and developed helmet prototypes, as shown in Fig. 9 (a) [112]. Cellular and auxetic structures were also employed in the helmet made of fiber composites and foam [112]. The results showed that the bio-inspired helmet not only displayed an excellent performance, but also were 20% lighter and more stable than the conventional ones [112].

To overcome the barriers of manufacturing difficulty, numerous attempts have been taken in using additive manufacturing technology (i.e. 3D printing) for production. Mimicking the trabecular bone in any bone tissues, Mehta et al. [107] proposed a highly porous structure by using topology optimization and fabricated by 3D printing, for their helmet layer. Mehta et al. [107] claimed that the innovative design provided a lighter-weight prototype with better performance. However, the design is only in its early stage as there was no simulation or experiment involved to evaluate its performance. On the other hand, Kassar et al. [35] not only proposed the idea inspired by the animal horn microstructure and tubule arrangement (Fig. 9 (b)), but also carried out both the numerical simulation and experimental tests on the fabricated samples to verify their conceptual design. Topology optimization was also conducted to modify the structure specifically for protective helmets.

Gokhale et al. [113] introduced a lattice array of multi-material compliant mechanism (LCM), enabling the structure to redirect radial forces into tangential forces. The numerical simulation results showed that with a similar total mass, 300% and 500% more energy were absorbed under linear and oblique impacts, respectively. Another

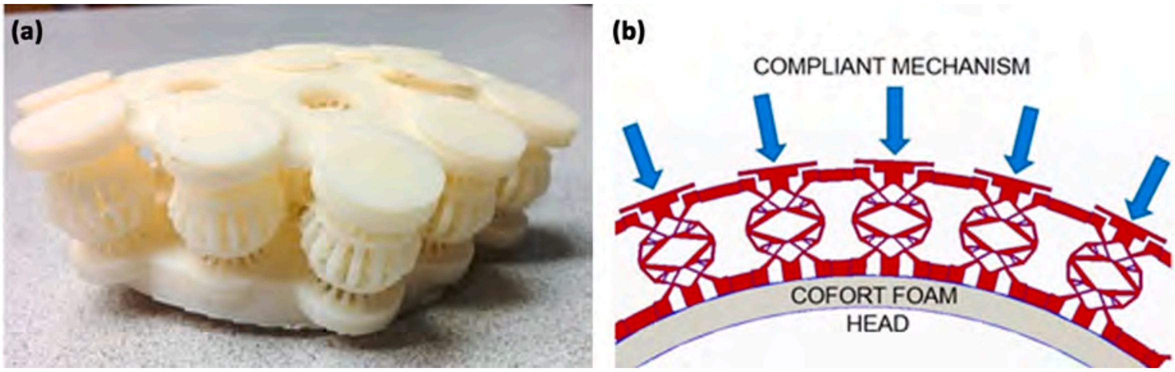

Fig. 10. (a) 3D-printed ALC design; (b) Mechanism of ALC (Reproduced from Gokhale et al. [114]).

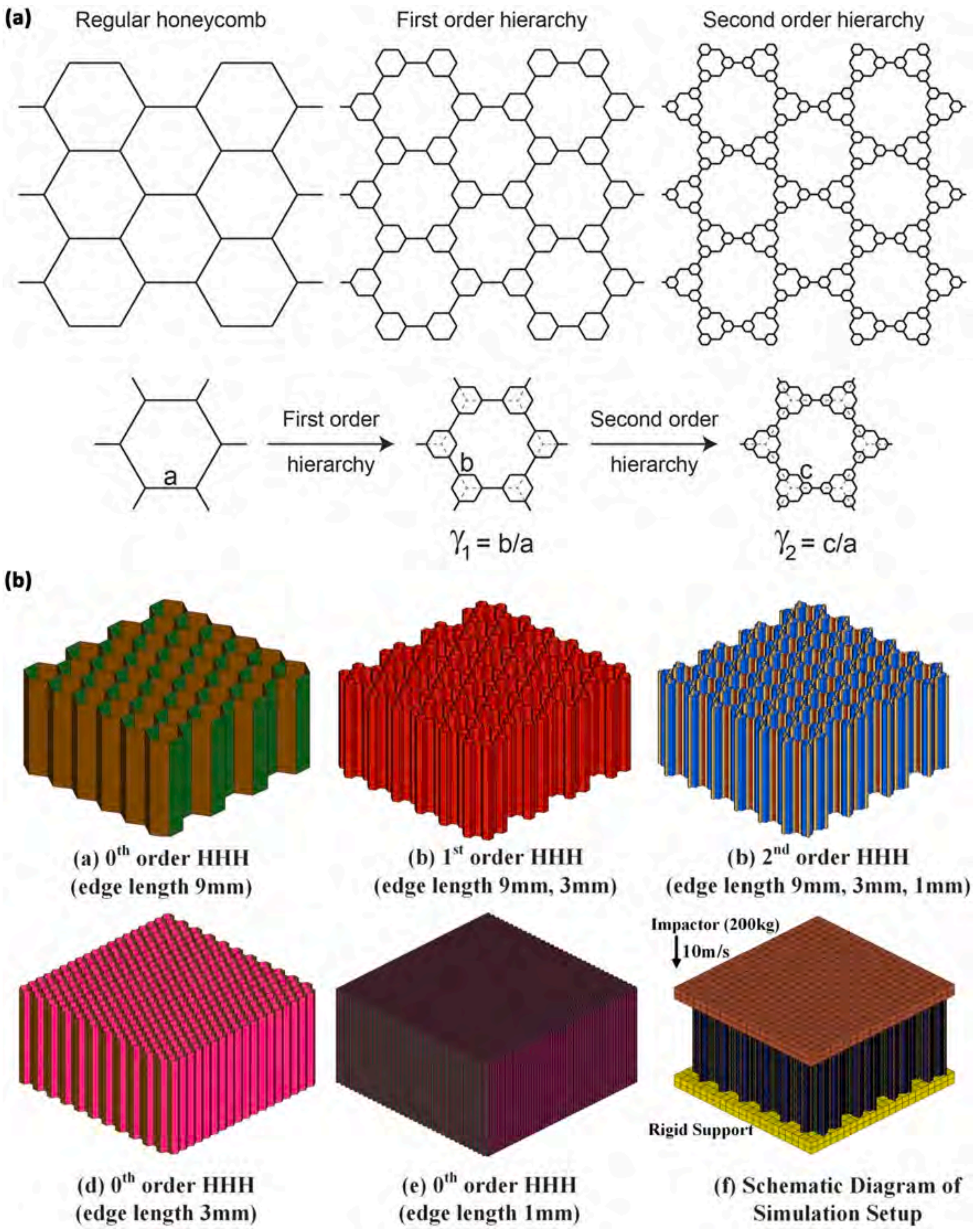

Fig. 11. (a) First and second-order honeycomb structures (Reproduced from Mousanezhad et al. [115]); (b) honeycomb structures with hexagon on edges (Reproduced from Zhang et al. [116]).

design, namely Advanced Layered Composite (ALC) design, also followed the same mechanism, and 3D printing using thermoplastic polyurethane (TPU) was introduced to facilitate the fabrication, as depicted in Fig. 10 [114]. The group extended LCM and ALC to a Compliant Mechanism Lattice (CML) based design combined with bio-inspired structures. Moreover, Najmon et al. [34] mimicked the organic and skeletal structures of pomelo peels, nautilus, and woodpeckers' skulls. They put emphasis on the natural structures which have similar anti-concussion functions to helmet liners. Furthermore, since it was claimed that some cellular structures failed to redirect impact forces, a CML based design was developed based on LCM [34, 113]. Gokhale et al. [113]proposed six types of cellular liners. A drop test simulation was carried out to assess the performance of these novel liners. Results revealed that peel liner showed best energy absorption capacity when using 40 A hardness rubber. In addition, future work on a series of physical experiements with a full-sized helmet was recommended.

4.2.2. *Other structures with potential applications in helmets*

Besides the aforementioned designs that have been investigated to be energy absorbers in helmets, there are still enormous types of biological structures that have potential to be applied. Among them, honeycomb structure is one of the most popular structures with excellent properties

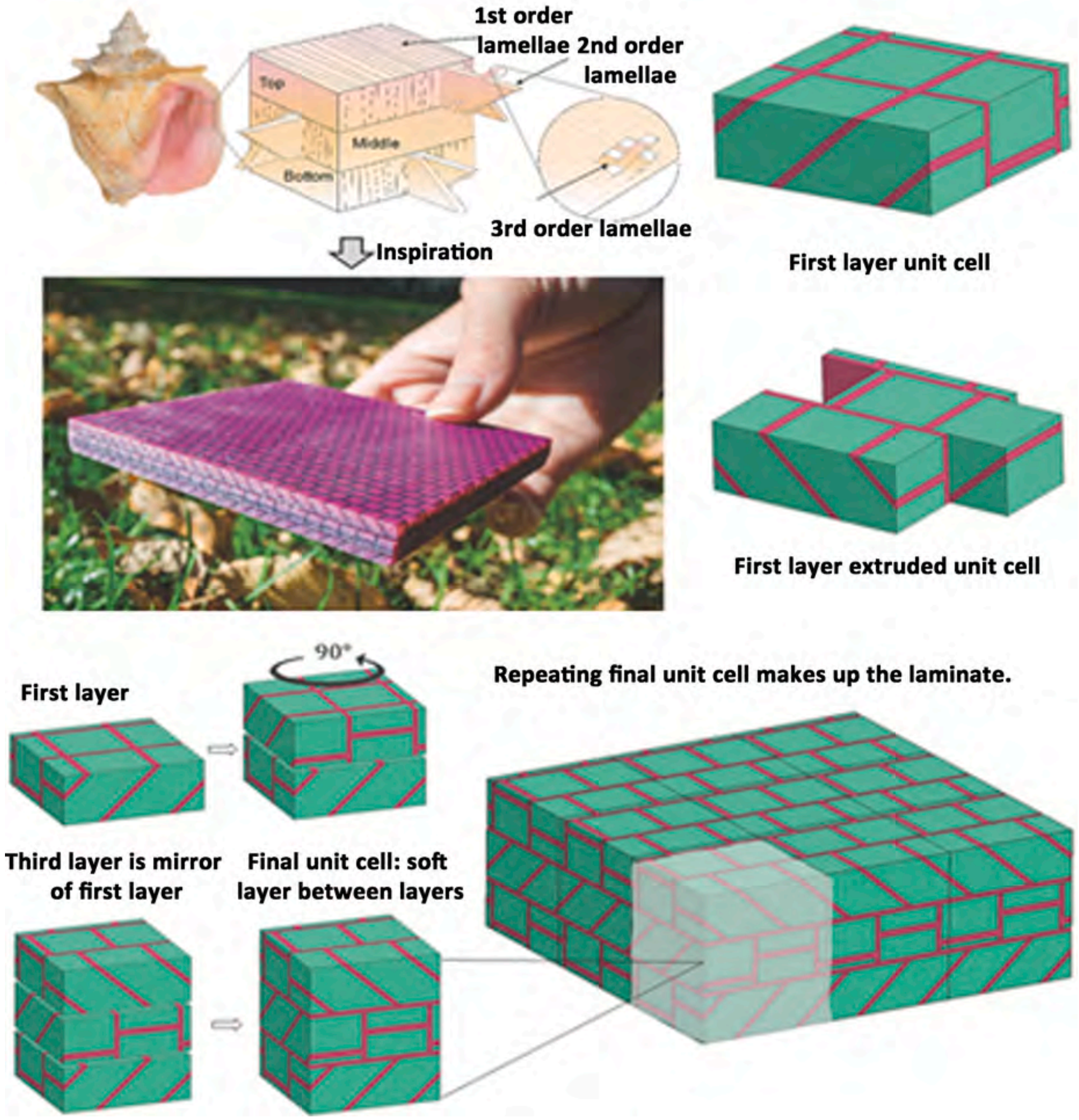

Fig. 12. Hierarchical structures inspired by conch shell (Reproduced from Gu et al. [126]).

and has been recently used in helmets (e.g. HEXR helmet). Mousanezhad et al. [115] optimized the honeycomb structure by employing first and second order hierarchical arrangement, as shown in Fig. 11 (a). The proposed hierarchical architecture exhibits characteristics by showing two different deformation modes with different geometrical parameters subjected to the same-direction compression. The specimen was manufactured by a 3D-printed rubber-like material. The structure behaviors were examined numerically and experimentally, providing insights into the role of hierarchical structure in energy absorption application. Zhang et al. [116] also explored the honeycomb structure with hierarchy. They replaced each three-edge vertex of a hexagonal structure with a smaller regular hexagon and obtained a first-order and second-order structures, as shown in Fig. 11 (b). Through simulation and out-of-plane compression tests, they concluded that the energy absorption capacity could be enhanced with hierarchical organization of various cells. Yin et al. [117] considered alternative shapes to revise the traditional structure. The bio-inspired honeycomb structure was optimized based on hexagonal, Kagome, and triangular tessellations. Parametric study was undertaken numerically, showing that triangular shape absorbed two times more energy than others. There are other researchers [118–123] focusing on honeycomb structures as well, based on cell, material, etc.

In addition to honeycomb structure, many other types of biological structures also exhibit excellent performance in terms of energy absorption. Xiang and Du [124] learned from the elytra structure of septempunctata ladybeetle and dichotoma beetle, and optimized traditional honeycomb structures by mimicking the internal structures from these creatures. Parametric study was undertaken to compare the crushing performance of these structures. Further study of the bio-inspired structures were conducted as well [125].A honeycomb column thin-wall structure (BHTS) was developed based on the biological model of beetles. Simulations were carried out under axial loading, and Hao and Du [125] concluded that BHTS outperformed conventional honeycomb structures. Gu et al. [126] employed simulation and drop tower tests on biomimetic conch shell (Fig. 12) and concluded that the performance could be improved greatly with hierarchical structures.

5. Discussion and conclusion

With the growing belief in shear-induced tissue damage caused by rotational acceleration being the predominant mechanism of severe traumatic brain injuries [36], numerous novel designs of bicycle helmet, as presented in Section 3.1.2 and Section 3.2.3, have been proposed recently. Many of these bicycle helmets adopted innovative designs with the use of advanced materials and/or structures in their liner and/or helmet shell. Nevertheless, their actual performance is still being questioned. This can be attributed to the lack of requirements in the current bicycle helmet testing standards for evaluating the head rotational responses, leading to non-standardized bicycle helmet tests being set up specifically for certain purposes. For instance, Abayazid et al. [96] conducted oblique impact tests for five types of helmets at three different locations, and found that the helmet performance varies at different impact locations. Furthermore, it remains challenging to consider other factors besides energy absorption capacity. For example, total mass of a helmet is a representative parameter that decides comfort level of the wearers. However, due to the excellent light-weight property of EPS foam, it is challenging to develop a novel liner with new material but keep the same mass. Instead, mass increasing has been reported by using another type of material [83]. Some of the latest helmets mentioned in the previous sections were found to show no benefits over the conventional ESP helmet [87].Furthermore, despite the implementation of advanced manufacturing technologies, manufacturing issues of proposed bicycle helmet liners have not been fully resolved. For the helmet liners using novel structures, we have found that some research only presented the promising CAD designs without a fabricated prototype. The main challenge is to conform the head-form shape of bicycle helmets [127].

Possible directions for future helmet designs are:

- More comprehensive tests can be conducted, including different impact locations and angles. This would be helpful to decide what type of anti-rotational design works the best. Furthermore, it would be much valuable if a widely accepted rotational acceleration threshold can be determined, which also helps the amendment of the existing standards.
- Designs can be proposed by using specific structures such as thin-wall structures, cellular structures and auxetic structures, which can potentially decrease the total mass.
- Biomimicry can be combined with the cellular structures, thin-wall structures, etc.
- 3D printing is recommended to be employed for production. The aforementioned HEXR helmet has been available and showed outstanding performance.

This review has provided a comprehensive overview of the development of bicycle helmets and recent exploration for improvement. Specifically, we introduced the history of bicycle helmets and discussed the widely used test standards, followed by the design of existing helmets such as bicycle helmets with the typical EPS liner. Energy absorption improvement of the liner was subsequently reviewed. The improvement methods include but not limited to material replacement, graded layers application with different densities, and novel structures. We also discussed the latest anti-rotational design, including MIPS helmets, WaveCel helmets, etc. The development of bio-inspired structures was reviewed, with the current investigation of their application in bicycle helmets. This comprehensive review summarizes the current state-of-the-art bicycle helmet designs, highlights the current potential issues and challenges, providing insights on future research directions for bicycle helmet design.

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CRediT authorship contribution statement

Bing Leng: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Dong Ruan:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Kwong Ming Tse:** Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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