

Review

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Review

Research Progress on Helmet Liner Materials and Structural Applications

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Abstract: As a crucial part of head protection equipment, research on the material and structural application of helmet liners has always been a hot topic in the field of helmet manufacturing. This paper aims to introduce the most common helmet liner materials, including traditional polystyrene, polyethylene, polypropylene, and others, as well as emerging materials such as anisotropic materials, and polymer nanocomposites. In addition, the design principles of helmet liner structure are discussed, including the evolution of multi-layer structure, integration of geometric irregular bubbles, etc., to enhance energy absorption capacity. Advanced manufacturing processes such as additive manufacturing technology are introduced to fabricate complex structures. Finally, the application of biomimetic structures in helmet liner design is explored. For example, the structure of biological tissue can be used to design a helmet liner structure with superior energy absorption performance. On this basis, the idea of bionic structures is extended to the combination of plant stalks and animal skeletal structures, and additive manufacturing technology is used to significantly reduce energy loss during elastic yield energy absorption, thus designing a reusable helmet. This provides a promising research direction for future helmet liner materials and structural applications.

Keywords: helmet liner; polystyrene; composite materials; additive manufacturing; biomimetic structure

1. Introduction

In contemporary Chinese cities, rapid population growth and urbanization, the continuous expansion of commercial and industrial centers, has led to a sharp increase in car ownership, and the problem of traffic congestion has spread from big cities to smaller and medium-sized ones, making urban transportation a hot topic of widespread concern at all levels of society. Therefore, cycling, as an environmentally friendly, economical and healthy way to relieve traffic congestion, has gradually become the first choice for people to travel. In Kunming, for example, between 2006 and 2012, electric bicycles effectively replaced many urban car trips [1]. According to statistics, the proportion of cycling trips has increased from about 5% a few years ago to more than 10%, and continues to grow, and it is expected to continue to grow in the future [2]. According to the annual data of domestic road traffic accidents from 2019 to 2022 released by the National Bureau of Statistics (Table 1) [3], the total number of bicycle and motorcycle traffic accidents increased from 19.3% in 2019 to 20.2% in 2022. This increasing trend has aroused people's concerns about bicycle and motorcycle safety, and the traffic safety of cyclists has become an important issue of social concern. Every year, tens of thousands of vehicle collisions worldwide result in the death of a large number of two-wheeler cyclists, while causing huge economic losses [4]. In automobile-two-wheeler crashes, head injuries are the most common type of injury that causes fatalities and serious injuries among cyclists [5–7]. Studies have shown that wearing a helmet can effectively reduce head injuries suffered by cyclists in traffic accidents [8–10]. An analysis of the clinical features of 15,345 patients with traumatic brain injury (TBI) across 35 hospitals in Henan Province [11], the proportion of injuries caused by riding electric bicycles was 25.5% (2481/9731), which has become one of the main causes of traffic accidents. In addition, it has been reported that about 55% of cycling deaths are due to head injuries [12]. For

cyclists, helmets are their only protection against injuries such as TBI [13–16]. Jiangsu Province was the first to formally implement the "Regulations on the Administration of Electric Bicycles in Jiangsu Province" [17]. In the following years, similar laws were also implemented in various provinces and cities [18–21]. Studies have shown that mandatory helmet-wearing legislation has been associated with a substantial decrease in the number of e-bike roadway fatalities, with a year-on-year reduction in fatalities of 2.21% [22].

Table 1. Domestic traffic accident statistics per year from 2019 to 2022. Adapted from [3].

Type	Total amounts of traffic accidents in 2019 (n=247646)	Total amounts of traffic accidents in 2020 (n=244674)	Total amounts of traffic accidents in 2021 (n=273098)	Total amounts of traffic accidents in 2022 (n=256409)
The total number of bicycle and motorcycle traffic accidents	47918 (19.3%)	48400 (19.8%)	54584 (20.0%)	51833 (20.2%)
Number of car traffic accidents	159335 (64.3%)	156901 (64.1%)	171941 (63.0%)	157407 (61.4%)
Number of tractor traffic accidents	1865 (0.8%)	1591 (0.7%)	1502 (0.5%)	1136 (0.4%)
Number of pedestrian and passenger traffic accidents	3432 (1.4%)	3480 (1.4%)	4086 (1.5%)	3907 (1.5%)
Number of other traffic accidents	156 (0.06%)	151 (0.06%)	142 (0.05%)	174 (0.07%)

Common life protective helmets are mainly composed of four parts: shell parts, adjusting devices, hard lining parts, and soft lining parts [23], where the hard lining parts and soft lining parts are collectively referred to as pads. In these components, the pad absorbs energy through viscoelastic compression to relieve acceleration to the head [24], thereby reducing the risk of head injury to the rider [25]. The majority of cushions are typically composed of synthetic cellular materials like expanded polypropylene (EPP) and expanded polystyrene (EPS), and the density of the cushion material is often adjusted to achieve the best energy absorption effect [26]. In recent years, scholars at home and abroad have devoted themselves to studying the head protection, heat dissipation and shock absorption performance of various advanced materials and innovative structures implanted in helmets, starting with the application of helmet padding materials and structures. This article reviews the most current designs of existing helmet liner materials, structures, and biomimetic structures and their protective properties, with a particular focus on the application of bio-inspired structures and materials for energy absorption in protective helmets. The paper will look at the innovativeness, practicability, and feasibility of the various design options, and based on this, it will provide an outlook on the possible challenges, limitations, and future directions for the field in the present time.

2. The Development of Helmet Liners

Helmets have long been employed as a main type of protection, covering the head from weapons and any kind of penetration [27]. Simultaneously, helmet liner is a kind of soft padding located inside

the helmet, and in ancient times, warriors usually added some soft materials such as leather, fabric, and grass as helmet liners inside the helmet. Hard leather, brass, or iron were the most common materials used to make ancient war helmets. The ancient Greeks' bronze helmets are notable examples (Figure 1) [28]. Although these bronze helmets were able to defend against direct attacks such as swords and arrows, they had to be improved due to the poor energy absorption and weight of the bronze material. With the advent of the Middle Ages, warfare technology advanced, and the helmet design became more complex. The helmet liner has been improved accordingly, with thicker fabrics, padding or cotton, etc., to provide better protection and reduce pressure on the helmet, as well as to enhance the comfort of wearing the helmet. With the development of metallurgical technology, helmet materials have gradually evolved from metal products to more advanced materials, such as steel and alloys. With the development of metallurgical technology, helmet materials have gradually evolved from metal products to more advanced materials, such as steel and alloys. In the 1940s, military and civilian helmets were commonly built of a robust steel casing with a plastic and cotton fiber interior. During World War II, the US Armed Forces used the M1 steel helmet in both European and Pacific theaters (Figure 2) [28]. The gasket material was made of high-elastic rubber material, and the whole helmet was relatively lightweight, allowing the wearer to move more flexibly, reducing the burden on the head and neck, and improving the survivability and mobility of soldiers in combat. With changes in the form of warfare, the combat environment, and the development of new materials, the U.S. military has designed advanced combat helmets (ACH). The inner surface of the ACH is regularly arranged with a set of discrete foam pads [29], which helps to improve the energy absorption performance of the helmet and reduce the force from external shocks, thereby improving the overall level of helmet protection. The geometry of the ACH helmet is depicted in Figure 3 [29].



Figure 1. Ancient Greek bronze helmet. Adapted from [28].



Figure 2. M1 helmet. Adapted from [28].



Figure 3. Advanced Combat Helmets (ACH): (a) External Side View; (b) Suspension System Side View; (c) Suspension System Bottom View. Adapted from [29].

Helmet padding has evolved from ancient leather, fabric, and other soft materials to modern foam plastics, rubber, and other new materials. While continuously improving the helmet's energy absorption, comfort, and adaptability, it has also significantly improved the helmet's protective performance, greatly reducing the risk of fatal head injuries.

2. The Main Materials of Helmet Padding

2.1. Head Protection Performance

When a pedestrian is engaged in a traffic collision, a shock to the head can produce multiple forms of brain damage, which can be separated into focal and diffuse brain injuries based on their clinical symptoms [30]. Focal brain injury is due to linear acceleration of the head, while diffuse brain injury is mainly related to rotational acceleration. As a result, it is critical to lessen the linear and rotational acceleration that the head experiences.

Mosleh et al. [31] suggested an anisotropic EPS composite foam concept to reduce head rotational acceleration, hence minimizing the risk of brain injury. Experimental studies have shown that the concept of polystyrene composite foam has great application potential in applications such as protective helmets. Vanden Bosche et al. [32] investigated the usage of anisotropic polyethersulfone foam (Figure 4) [32] in bicycle helmet liners. The results show that the peak rotational acceleration of polyethersulfone (PES) foam helmets is about 40% lower than that of EPS foam helmets, and PES foam has the potential to replace EPS liners. Ramirez et al. [33] fabricated spray polyuria elastomer (SPUA) foams with densities of 98kg/m³, 170kg/m³, and 230kg/m³ and integrated them into helmet liners for FMVSS motorcycle helmet testing. The results showed that the use of additional SPUA foam liners on top of existing EPS foam liners successfully reduced peak acceleration by 17%. In the field of equestrian helmets, Cui et al. [34,35] found that the decrease in peak acceleration depends on the contact area, the stress distribution along the cushion thickness, and dissipative plastic energy density (DPED). To lower peak linear acceleration, functional gradient foam (FGF) cushions should be utilized instead of discrete foam layers. To achieve the results of reducing both rotational and linear accelerations, Maheswaran et al. [36] investigated quasi-static compressive shear response of freestanding vertically oriented carbon nanotubes (VAVNT) foams under different initial precompression conditions. The results demonstrate that VAVNT can tolerate substantial shear strain at a low shear stress level under an enormous compressive shear load. This indicates that VAVNT foam can minimize linear acceleration and rotational acceleration by absorbing normal impact. In motorcycle helmet liner materials, Shuaeib et al. [37] confirmed that EPP foam is widely used due to its multi-impact protection properties and the potential to improve ventilation systems. However, EPP foam is still deficient in head protection due to its material characteristics. In quasi-static compression and shear testing on three VN foams, Bailly et al. [38] discovered that vinyl nitrile foam helmet liners were thought to minimize head rotation acceleration more than EPP foam helmet liners.

Chang et al. [39] investigated the influence of filler materials (type and density) on the protective performance of the head and found that ethylene vinyl acetate copolymer (EVA) foam outperformed EPP foam.

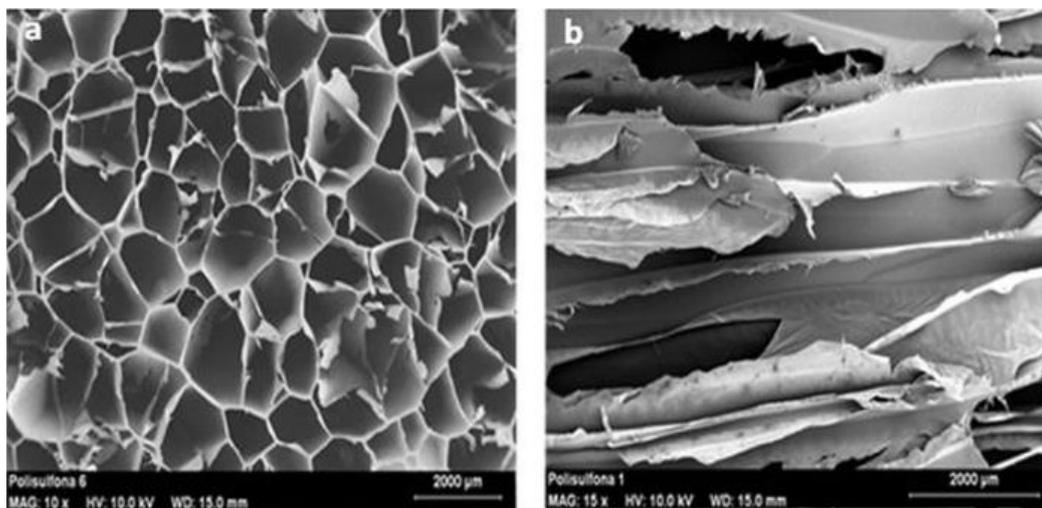


Figure 4. Anisotropic polyethersulfone foam: (a) SEM micrographs of a cross section of a PES foam, perpendicular to the rising direction of the foam (side A); (b) view parallel to the rising direction of the foam. Adapted from [32].

2.2. Cushioning Performance

The helmet liner is an important component of shock absorption and comfort in the overall helmet design. Wu et al. [40,41] added polyethylene (PE) foam padding to industrial and construction helmets, and the results showed that helmets with PE foam padding can greatly improve the shock absorption performance against large impacts. On the one hand, cushioning materials have an impact on shock absorption and cushioning. Mosleh et al. [31], Kroeker et al. [42], Huang et al. [43] and Drane et al. [44] all confirmed that selecting the right material density or material thickness can significantly improve energy absorption performance. On the other hand, cork is a naturally porous, non-renewable material that is highly resistant to crashes, and due to its viscoelastic behavior, it has good resilience after compression, which is an ideal property in multi-impact applications [45]. Buil et al. [46] used cork and its derivatives instead of traditional EPS liners. However, to solve the non-renewable problem of cork materials, Fernandes et al. [45] further investigated whether there were materials that could be synthesized into cork, and finally found that agglomerated cork liners were excellent materials for synthesizing cork liners. Black cork has excellent thermal stability, while agglomerated cork can absorb high energy. Kaczyński et al. [47] discovered that merging two cork materials (agglomerated and black) into a cork composite sandwich structure combines their advantages, but also has good cushioning properties. It has also been used in electric helmets (Figure 5) [47].

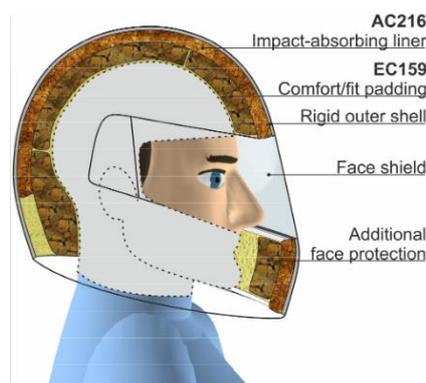


Figure 5. A cross-section of a motor helmet with cork sandwiches applied. Adapted from [47].

2.3. Heat Dissipation Performance

In recent years, studies have found that the effectiveness of heat dissipation directly affects the comfort of wearing a helmet. In an inventive move to regulate the interior temperature of a motorcycle helmet, Sinnappoo et al. [48] introduced a paraffin phase change material (PCM) cloth to the interlayer between the scalp and the helmet liner. Textile materials have a positive impact on helmet heat dissipation, as studies have demonstrated that employing PCM materials as textile liners may lower the temperature within the helmet by 3.8 degrees Celsius. Bhinder et al. [49] The carbon nanotube (CNT) nano-filler was incorporated into polyurethane (PU) foam. After experimental comparison, the combination of CNT-reinforced polyurethane foam has better heat dissipation performance than the EPS foam currently used. This combination is expected to become a more suitable replacement for helmet liners. Kim et al. [50] designed a combination of foam and flocking energy-absorbing material (FEAM) layer elements (Figure 6) [50], which has been shown to combine the advantages of foam materials (light weight) with FEAM's excellent impact absorption characteristics, breathability, comfort, perspiration, and heat management. Many studies have started with the heat dissipation properties of materials, but few scholars have studied active cooling methods. Consequently, Jain et al. [51] presented a passive cooling technique based on a multifunctional liner made of eicosane and evenly dispersed graphene oxide nanosheets, as well as a composite thermal liner. Studies have shown that the pad has good thermal management properties and can be used to develop lightweight heat-dissipating helmets.

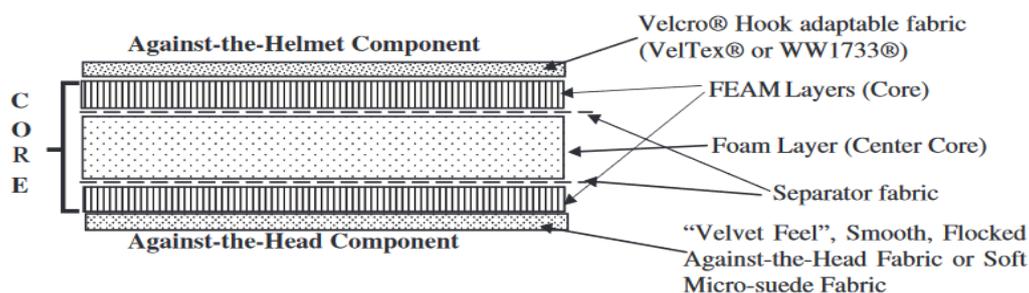


Figure 6. Layered cellular structure. Adapted from [50].

3. The Main Structure of the Helmet Liner

3.1. Honeycomb Structure

In recent years, research has focused on exploring new helmet liner structures, and honeycomb structures have become a hot research topic due to their stress structures consisting of many hexagonal or hexagonal-like small units. In [52], Kholoosi et al. presented a hierarchical honeycomb structure design (Figure 7a) [52]. The honeycomb structure was designed as an EPP foam with a thickness of 5.9 mm and covered with ABS (a terpolymer of acrylonitrile, butadiene, and styrene monomers) plastic layer as an energy absorber for the helmet. In contrast to EPS foam, the honeycomb structure exhibits a longer energy absorption period and reduced acceleration of impact force transmission to the user, according to the data. What result would the combination of the two produce? In order to further increase the energy dissipation characteristics and hence raise the safety of head injuries, Bhudolia et al. [53] suggest a novel way for creating hybrid EPS/honeycomb structural foams utilizing an integrated manufacturing process. As a consequence of the accompanying foam densification and the honeycomb's elastic buckling properties, the integrated EPS honeycomb hybrid lining's energy absorption capacity has been demonstrated to improve by 20%, according to the findings of the Roadstone impact test. As a result, integrated manufacturing methods have gradually become the main design principle for researchers. The research of Li et al. [54] is to optimize the configuration of honeycomb packing geometry and foam density of helmet linings to increase helmets' protective performance. In addition to the honeycomb structure, there are

also conical structures studied by Teng et al. [55] (Figure 7b), Ingrole [56], which discovered new tensile and inflated pillar structures, and spherical structures studied by Toboła et al. [57], all of which have good research prospects.

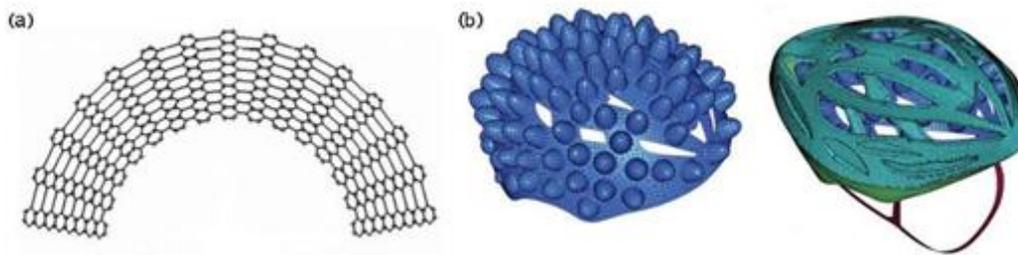


Figure 7. Schematic diagram of two helmet padding structures: (a) Layered cellular structure; (b) Cone shaped pads in helmet models. Adapted from [52,55].

3.2. Lattice Structure

A lattice structure is a common design in helmet liners, which is formed by a series of cross-interwoven lines or grids, similar to the arranged structure of a crystal. The lattice structure can provide better stability and support, and it can effectively maintain the shape and structure of the helmet, preventing excessive deformation or damage when exposed to external pressure, thus protecting the wearer's head. Previously, to verify whether the lattice structure is suitable for helmet liners, Khosroshahi et al. [58] evaluated the performance of the lattice liner topology (Figure 8) [58] as a helmet liner structure. The results showed that the prismatic lattice outperformed the tetrahedral lattice and EPS foam commonly used in helmets in preventing traumatic brain injury (TBI). On this basis, Khosroshahi et al. [59] also studied the feasibility of using layered lattice pads for helmets. Studies have shown that helmets with layered lattice structure pads can be considered as a new generation of helmet energy-absorbing pads. On the other hand, as additive manufacturing becomes more efficient, traditionally fabricated structures can be replaced by 3D printing technologies with specific application characteristics. For example, Clough et al. [60] used additive manufacturing technology to fabricate a honeycomb structure of a lattice-based impact attenuator. After several impact experiments, it was found that this structure can effectively reduce head acceleration.

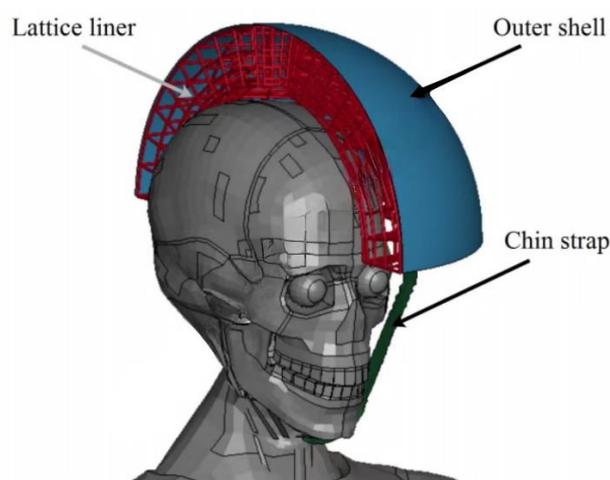


Figure 8. Helmet model with lattice padding. Adapted from [58].

3.3. Fillable Structure

When it comes to helmet liner structures, honeycomb structures, lattice structures, and cone structures are often mentioned, but Goel [61] suggested a novel approach to helmet liner construction, namely the addition of materials that fill the passages inside the liner with either solid

or liquid substances. Digital models and experiments have shown that the use of viscous fluids in the sandwich structure for drop testing can improve the impact attenuation effect of the helmet. On this basis, La Fauci et al [62] proposed a shear thickening fluid based on boronated organosilicon to fill the chambers of the the liner's impact energy dissipating pads to form a new type of helmet liner (Figure 9) [62], and the study's findings demonstrated that, in terms of impact energy attenuation, this method was the most efficient.

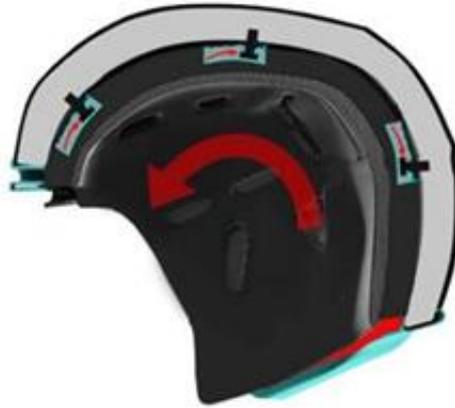


Figure 9. Cross-sectional view of helmet design with impact attenuation module. Adapted from [62].

4. Bionic Structure

As a novel technology, biomimetic structures were not widely employed as energy-absorbing materials until about 2000, and the complexity of producing these structures hampered their promotion. Many bionic structures, inspired by biological models and advancements in fabrication processes, have been developed and demonstrated to be successful in energy absorption. Thus, throughout the past several years, bionic structures have been developed more and more rapidly. As seen in Figure 10, San Ha and Lu [63] compile a wide range of current bioenergy absorption structures and categorize them into several groups according to their form and use. In general, energy absorption in a variety of engineering domains has demonstrated the promise of biomimetic approaches.

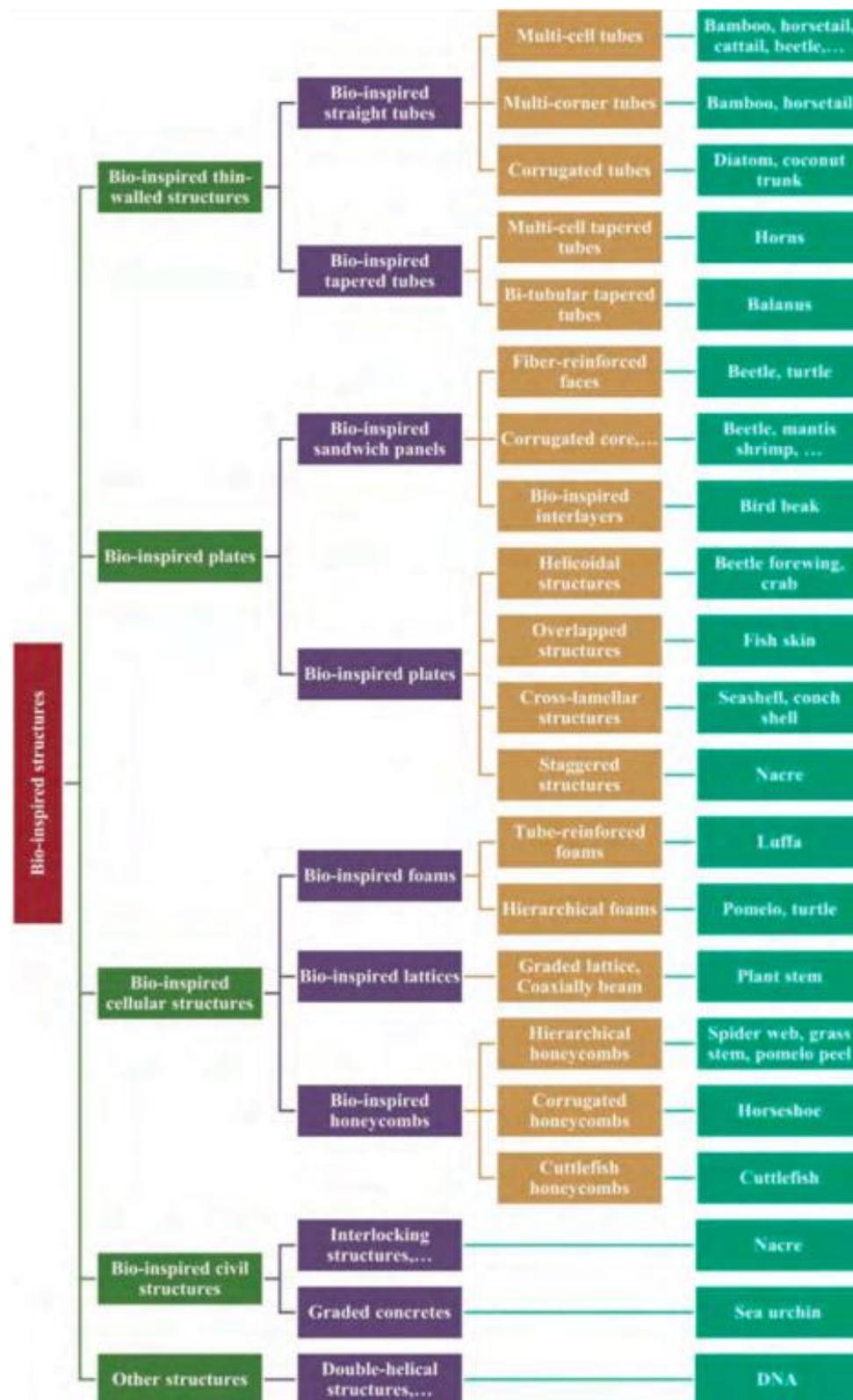


Figure 10. Categories of bio-inspired structures. Adapted from [63].

Studies have shown that improving the protective performance of helmets, relevant cushion materials, and structures can be inspired by a wide range of organisms (such as macadamia nuts, grapefruit, and horseshoes) [64–67]. Wang et al. [68] were inspired by this and discovered that the bovine hoof wall has a multilayer structure that can efficiently absorb the energy generated by crack propagation. They believe the novel bionic structure may be used in motorcycle helmets and sports' protective equipment. Leng et al. [69] designed a helmet with a structure inspired by the

characteristics of the ponytail and human spine. The research findings indicate that the ideal bionic ponytail structure (Figure 11a) [69] can lessen the kinetic energy brought on by rotational and linear accelerations, indicating the structure's possible use as a helmet liner. This finding also provides a means of exploring new bionic structures created by fusing animal bones and plant stalks. Chen et al. [70] designed a hedgehog bionic helmet (Figure 11b) [70] with a hemispherical stretch mesh liner. According to the findings, stretch mesh-padded helmets performed better than unpadded or other padded designs, offering better protection. The findings of this study broaden the use of tensile materials and direct the creation of helmet liners that provide improved TBI relief.

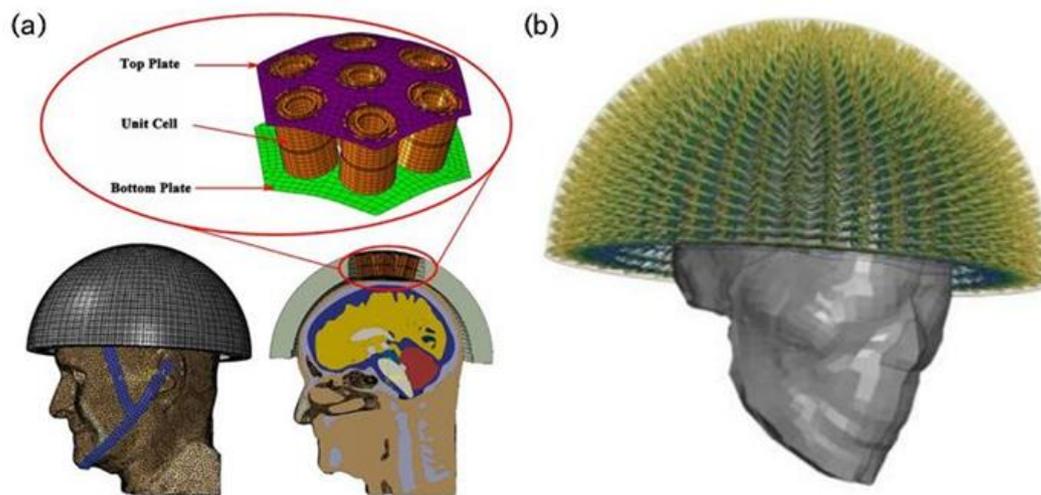


Figure 11. Two bionic helmets: (a) Helmet liner with multi-layer ponytail biomimetic structure; (b) A hedgehog biomimetic helmet. Adapted from [69,70].

In reference to the pyramid-shaped thorns on durian shells, Teng et al. [55,71] devised and created a hemispherical, pyramid-shaped helmet liner out of ABS resin. When the top of the helmet is impacted by a free-falling body on a flat plate, its energy absorption is 13% higher than that of a helmet filled with EPS foam. Yang et al. [72] created and prepared a two-way ripple sandwich structure based on the two-way ripple characteristics of the mantis shrimp jaw foot. This structure can reduce stress concentration in the uniaxial out-of-plane compression test and has an energy absorption that is 118% higher than that of the conventional triangular ripple sandwich structure. Liu and Xu [73] devised a two-way staggered rectangular truncated cone pad by incorporating the two-way corrugated configuration of the mantis shrimp jaw foot and the pyramid-shaped spine arrangement of the durian shell into the helmet pad. In this paper, the dynamic behavior of gaskets with various pyramidal element structures during impact compression is studied. The findings demonstrate that the bidirectional cell's design and the reduction of the outer wall's inclination angle both enhance the helmet's ability to absorb energy. Of the helmets tested, the bidirectional staggered rectangular optic cone helmet has the highest specific energy absorption, measuring 1.3 times greater than that of the honeycomb helmet and 2.7 times higher than that of the gradient lattice. This also gives us new ideas for the application of helmet liner structures for animal and fruit internal structure combinations.

4. Conclusion

This article provides an exhaustive overview of the evolution of helmet liners and recent structural advances. The liner's progression is succinctly delineated, with material R&D moving away from traditional EPS foam towards composite foam and polymer composites. Structure research, meanwhile, is evolving from the initial honeycomb geometry to additive manufacturing techniques. Adopting lattice, inflatable, or bionic structures, Jiang et al. [74] have endorsed the substantial benefits of 3D printing in industrial design, advocating the implementation of intricate structures via this technology. One-time molding, minimizing processing time, ensures accurate transmission of design

parameters. Bionic structures, a nascent technology in helmet liners, show promising research potential due to their superior energy absorption capabilities. This article encapsulates the current design status of helmet liners, highlights existing potential issues and challenges, and proposes novel perspectives on future research directions for helmet liner materials and structural applications.

Based on current domestic and international research, future helmet liner material and structure research can focus on the following three areas.

(1) Integrate the novel helmet liner with the existing helmet model and fabricate a prototype to further evaluate its performance enhancement, rather than simply simulate it in finite element simulation software.

(2) Biomimetic design concepts can be extended to the examination of composite plant stem and animal bone structures.

(3) Additive manufacturing enables the use of cellular structures with enhancement and adjustment properties, facilitating lossless energy absorption in pads, potentially paving the way for reusable helmets.

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