Study on the Mechanical Properties and Energy-Absorption Characteristics of a Pennate Muscle-Inspired Honeycomb Structure

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Abstract

To meet the requirements of protective equipment for energy absorption and mechanical performance, a bionic pennate-muscle-inspired honeycomb structure (pennate muscle-inspired honeycomb structure, PM-HS) was designed based on the principle of structural bionics and inspired by the morphology of human pennate muscle. Structural specimens were fabricated using 3D printing technology, and the proposed PM-HS model was validated and analyzed through quasi-static compression tests combined with finite element simulation. By designing PM-HS models with 7 structural parameters, the effects of geometric parameter variations on their equivalent mechanical properties and energy absorption characteristics were systematically investigated. The results show that, among the 7 designed structures, PM-HS-D exhibits the best overall performance, with lower equivalent stress (241.01MPa) and strain (0.19) and a more uniform stress distribution. In terms of energy absorption performance, the energy absorbed (E) by PM-HS-D reaches 3611.64mJ, while the specific energy absorption per unit mass (Sm) and per unit volume (Sv) are 206.34mJ/g and 231.10mJ/cm3, respectively, both significantly superior to those of the other structures. These results indicate that PM-HS-D demonstrates clear advantages in load-bearing capacity and energy absorption performance and, after further optimization, can serve as a potentially preferred material for specific protective scenarios.

Full Text

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Abstract: To meet the demand for energy absorption and mechanical performance in protective equipment, and inspired by the morphology of human pennate muscle structures, a bio-inspired pennate muscle-inspired honeycomb structure (PM-HS) was designed based on the principles of structural biomimicry. Structural specimens were fabricated using 3D printing technology, and quasi-static compression tests together with finite element simulations were used to validate and analyze the proposed PM-HS model. By designing seven PM-HS models with different structural parameters, the effects of changes in geometric parameters on their equivalent mechanical properties and energy-absorption characteristics were systematically investigated. The results show that, among the seven designed structures, PM-HS-D exhibits the best overall performance, with relatively low equivalent stress (241.01 MPa) and strain (0.19), and a more uniform stress distribution. In terms of energy-absorption performance, the energy absorbed by PM-HS-D (E) reaches 3 611.64 mJ, while the specific energy absorption per unit mass (S_m) and per unit volume (S_v) are 206.34 mJ/g and 231.10 mJ/cm^3, respectively, both significantly superior to those of the other structures. These results indicate that PM-HS-D shows clear advantages in load-bearing capacity and energy absorption, and after further optimization, it may serve as a potentially preferred material for specific protective scenarios.

Keywords: bio-inspired pennate muscle structure; honeycomb structure; finite element simulation; mechanical properties; energy-absorption performance

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Abstract: In response to the need for energy absorption and mechanical performance in protective equipment, this study presents a bio-inspired pennate muscle-inspired honeycomb structure (PM-HS), designed based on the principles of structural biomimicry. The structure was fabricated using 3D printing technology, and both quasi-static compression experiments and finite element simulations were conducted to validate and analyze the performance of the proposed PM-HS model. Seven PM-HS models with varying structural parameters were designed to systematically investigate the effects of geometric variations on their equivalent mechanical properties and energy absorption characteristics. The results indicated that among the seven structures, PM-HS-D exhibited the best overall performance, with lower equivalent stress

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(241.01 MPa) and strain (0.19), as well as a more uniform stress distribution. In terms of energy absorption, PM-HS-D absorbed 3,611.64 mJ; its specific energy absorption per unit mass (S_m) and specific energy absorption per unit volume (S_v) were 206.34 mJ/g and 231.10 mJ/cm^3, respectively, both significantly outperforming the other models. These findings suggest that PM-HS-D shows clear advantages in both load-bearing capacity and energy-absorption performance. With further optimization, it could serve as a potential material for specific protective applications.

Key words: pennate muscle structure; honeycomb structure; finite element simulation; mechanical properties; energy absorption properties

Energy-absorbing structures are widely used in fields such as automotive safety, sports protection, and building engineering. Their primary function is to reduce the harm caused by impact loads to target objects or the human body, thereby significantly improving safety performance[1]. Through plastic deformation of materials and structures or energy-dissipation mechanisms, energy-absorbing structures can effectively absorb and dissipate energy during impact, protecting internal objects from damage. In practical applications, the design of protective structures must comprehensively consider multiple factors, including performance indicators such as mass, volume, peak stress, and specific energy absorption[2]. In competitive sports, such as ice hockey and skiing, which are high-risk events, the protective role of sports equipment can effectively reduce the risk of injury to athletes. Therefore, in recent years, increasing attention has been paid to research on the materials and structural design of sports protective equipment.

Head injury is a common and severe type of injury in ice hockey, and an effective helmet-liner design is crucial for protecting head safety. Statistics show that the incidence of concussion in ice hockey is as high as 22%, while the use of protective equipment such as helmets has been proven to effectively reduce athletes' injury risk[3]. As the main component for energy absorption during collision, the helmet liner is currently a key research focus in terms of its material properties, density, and structural design[4-5]. Traditional helmet-liner materials include expandable polystyrene (EPS), polyethylene, and polypropylene[6]. These materials exhibit certain limitations under high-energy impacts: if the material is too soft, collision with the head may occur even under low-speed impact, whereas if the material is too hard, the head may be directly injured[7]. Linear acceleration and rotational acceleration are considered important factors leading to head injury. Previous studies have indicated that, compared with traditional materials, novel liner materials with a negative Poisson' s ratio can significantly reduce peak linear acceleration in both frontal and lateral impacts, thereby helping reduce injury risk[8]. The density of helmet-liner materials directly affects helmet weight and impact performance. MUSTAFA et al.[9] found that EPS foams of different densities all influence peak linear acceleration at side, front, top, and rear impact locations of helmets. At present, optimizing the mechanical properties of materials through artificially designed structures is one of the hotspots in the development of new materials. CHEN et al.[10] designed a helmet liner with a negative-Poisson' s-ratio lattice structure; while reducing the risk of traumatic brain injury, this structure also achieved lightweighting. KHOSROSHAHI et al.[11] adopted a layered lattice structure for helmet liners, which, compared with traditional liner materials, reduced linear and oblique accelerations by 38%–55% and effectively decreased the risk of brain injury. NASIM et al.[12] investigated the energy-absorption performance of a PA12 lattice structure as a helmet pad through 3D printing and finite element simulation, finding that it exhibited higher energy-absorption efficiency than traditional EPS materials in multiple impact tests. These studies show that the development of helmet-liner materials is moving toward improving energy-absorption performance and impact-protection capability through structural design.

Biomimetic honeycomb structures (HS) can, through geometric design, reduce weight while still maintaining relatively high structural strength, stiffness, or energy-absorption capability[13-17]. HS can be divided into two types: periodic and nonperiodic structures. Periodic HS are structures formed by repeating a single unit cell and arranging it in a regular manner, whereas nonperiodic HS are composed of unit cells with different shapes and sizes arranged randomly. Although traditional manufacturing methods are widely applied to these two types of structures, they suffer from problems such as material waste, low manufacturing accuracy, and difficulty in producing complex structures within a short time. The emergence of additive manufacturing technology has made HS research more convenient and precise[13]. Many biomimetic HS designs are derived from nature. Inspired by the impact resistance of pomelo peel in protecting the pulp, ZHANG et al.[18] designed uniform and gradient-varying structures and investigated the effects of structural arrangement and material hardness/softness on energy absorption. ZHANG et al.[19] constructed a face-centered cubic lattice structure based on the hollow structure and ductility of bamboo, and optimized a lightweight structure with a high compression ratio by adjusting diameter parameters. Inspired by the dactyl club structure of the mantis shrimp, QI Yingchun et al.[20] established four spiral layered structures with different shapes; through comparative analysis combined with 3D-printed specimens, they found that interlayer spiral distribution was more conducive to improving the energy-absorption performance of the structure. In addition, inspired by the porous structure of human bone, LIU et al.[21] designed two anisotropic porous scaffolds and, by controlling the cell shape and arrangement, verified that they possessed mechanical properties similar to those of human bone, making them potential materials for bone-transplant surgery. XIANG et al.[22] mimicked the microstructure of cortical bone in the human skeleton and designed a biomimetic multilayer gradient foam-filled structure. They studied the energy-absorption performance of this structure and the influence of geometric parameters on its energy-absorption capacity, ultimately establishing a theoretical model for predicting the mean crushing force. It can thus be seen that,

Novel honeycomb structures designed under inspiration from structures in nature have certain potential application value in improving energy-absorption efficiency and achieving lightweighting.

This study proposes a pennate muscle-inspired honeycomb structure (PM-HS). The design inspiration for this structure comes from the lateral arrangement of fibers in human pennate muscle. Polylactic acid (PLA) was selected as the base material, specimens were prepared using 3D-printing technology, and the structure was validated through quasi-static compression tests and finite element analysis (FEA). On this basis, a parametric study of the PM-HS structure was further carried out to investigate the effects of geometric parameters on its mechanical characteristics and energy-absorption performance, with the aim of seeking a structural design scheme that combines high energy absorption with lightweighting and of enhancing its potential for application in protective equipment and other high-performance materials.

1 Materials and Methods

1.1 Design of structural parameters

The name "pennate muscle" derives from the structural feature of the arrangement of muscle fibers. In pennate muscle, the muscle fibers are arranged obliquely along the central tendon or line of pull, forming unipennate, bipennate, or multipennate structures; in a multipennate structure, muscle fascicles attach to the central tendon from different directions. Because the muscle fibers are arranged obliquely, the physiological cross-sectional area of pennate muscle is greater than its anatomical cross-sectional area. This allows more muscle fibers to be accommodated within the same volume, thereby generating greater force. Consequently, pennate muscles are widely distributed in parts of the human body such as the lower limbs, which need to bear gravity and provide strong propulsive force.

Based on the unique muscle-fiber arrangement of human pennate muscle, and drawing on its structural characteristic of optimizing the normal force by reducing lateral force during tension and compression, a pennate muscle-inspired honeycomb structure (PM-HS) was designed. In the PM-HS, each unit cell is composed of four main parts: an inner frame, an outer frame, a cross-shaped frame, and the pennate structure. The inner and outer frames are connected by a cross-shaped frame centered on a circular node, and the cross-shaped frame protrudes outward to connect with neighboring unit cells. The pennate structure starts from the four connection points between the cross-shaped frame and the inner frame and ends at the midpoint of the central strut (Fig. 1). The structure contains seven specific parameters: the inner side length of the outer frame l_1, the outer side length of the outer frame l_2, the inner diameter of the inner frame d_1, the outer diameter of the inner frame d_2, the length of the cross-shaped frame l_3, the structural height h, and the strut thickness t. In this study, the basic structure was named PM-HS-D, and the other six structures were defined according to the parameter sequence as PM-HS-A, PM-HS-B, PM-HS-C, PM-HS-E, PM-HS-F, and PM-HS-G. The height and strut thickness of all structures are fixed, and the other geometric parameters and overall structural dimensions are summarized in Table 1.

Fig. 1 Schematic of the PM-HS

Table 1 Specific geometric parameters of the PM-HS
(Unit: mm)

Structure	l_1	l_2	l_3	d_1	d_2	h	t
PM-HS-A	16	20	22	4	8	40	2
PM-HS-B	16	20	22	5	9	40	2
PM-HS-C	16	20	22	6	10	40	2
PM-HS-D	16	20	22	7	11	40	2
PM-HS-E	16	20	22	8	12	40	2
PM-HS-F	16	20	22	9	13	40	2
PM-HS-G	16	20	22	10	14	40	2

One of the key factors affecting the mechanical behavior of porous materials is the volume fraction, which directly influences the deformation morphology, compressive strength, and energy absorption of the structure [23]. The volume fraction is defined as

$$\phi_i = \frac{v_i}{v_{\text{total}}} \times 100\%$$

where ϕ_i denotes the volume fraction of i; v_i denotes the volume of structure i; and v_{total} denotes the total spatial volume. Therefore, the volume fractions of PM-HS-A to PM-HS-G are 8.18%, 8.36%, 8.63%, 8.97%, 9.31%, 9.57%, and 9.75%, respectively.

1.2 Specimen parameters

The specimen models were designed using the computer-aided design (CAD) software SOLIDWORKS and saved in STL file format. The specimens were fabricated using fused deposition modeling (FDM) 3D-printing technology (Liantai 800 printer), with C-UV 9400E polylactic acid as the material. To ensure structural consistency and uniformity, all specimens were printed in the same layer direction and post-processed after printing to ensure specimen accuracy. In this study, three basic specimens ($3 \times 3 \times 1$ structure) were printed to verify the validity of the model.

1.3 Uniaxial compression test

A universal testing machine was used to conduct quasi-static compression tests on these specimens

test (Fig. 2). During the test, the specimen was placed between the compression platens of the testing machine, and a vertical compressive load was applied. The compression rate was kept constant at 1 mm/min, and the sampling frequency was 10 Hz. The initial alignment error of the specimen was controlled within 1 mm, and stable loading conditions were maintained throughout compression. During the entire test, the testing equipment recorded the load and displacement data in real time. These data were used to calculate and plot the load-displacement curves and to validate the finite element model.

Fig. 2 Static compression of PM-HS-D

1.4 Finite Element Modeling and Analysis

To simulate the material behavior of the 3D-printed structure, an elastoplastic constitutive law was adopted to describe the behavior of the PLA material. A quasi-static compression test simulation of the specimen was carried out in ANSYS to verify the validity of the model. According to the ASTM D638 test method, the material properties of PLA were obtained: the elastic modulus was 1,300 MPa, the Poisson' s ratio was 0.4, and the density was 1.12 g/cm^3. These parameters were applied in the finite element model. The boundary conditions of the model were set as follows: compression steel plates were placed at the upper and lower ends of the specimen; the lower steel plate was in bonded contact with the specimen structure, while the upper steel plate was in frictional contact with the specimen structure, with a friction coefficient of 0.3. The lower steel plate was fixed, and a vertically downward displacement was applied to the upper steel plate. The displacement value was 2 mm, and the loading rate was the same as that used in the compression test. To ensure the accuracy of the simulation results, both automatic and manually controlled methods were used to mesh the specimen and the steel plates [24-26]. A mesh sensitivity study was conducted for models with different mesh sizes [27] (Fig. 3). The results showed that when the mesh size was 2 mm, the force value was 3,095.3 N, with an error of 0.15% relative to the average value of the three experimental results (3,100 N), indicating that mesh independence was ensured. The final model contained 42,485 elements and 89,959 nodes.

Fig. 3 Mesh sensitivity analysis

After the finite element model was validated, a parametric study was conducted on seven structures, and compression simulation tests were performed for each model. According to the compression test results from the universal testing machine, the structural force began to decrease when the displacement reached 2 mm; therefore, the loading displacement condition was set to 2 mm. The cushioning performance was analyzed through von Mises stress, strain, energy absorption, and specific energy absorption [28].

The energy absorption E is the energy absorbed by a material under compression or impact, namely,

$$E = \int_0^x F(x)\,dx$$

where $F(x)$ is the load corresponding to the displacement, and dx is the displacement [27].

The mass-specific energy absorption S_m is the energy absorbed per unit mass of the structure and is an important parameter for comparing the energy absorption of different structures. It is calculated as

$$S_\mathrm{m} = \frac{\int_0^x F(x)\,dx}{m}$$

where m is the mass of the structure [29].

The volume-specific energy absorption S_v is the ratio of the total energy absorption to the volume, expressed as

$$S_\mathrm{v} = \frac{\int_0^x F(x)\,dx}{V}$$

where V is the volume of the structure [27].

2 Experimental Results

2.1 Model Validation

According to the force–displacement curves obtained from structural testing and finite element analysis (FEA) results (Fig. 4), within the linear variation region, the FEA curve and the three experimental test curves showed strong consistency. Through the mod—

The simulated peak value was compared with the mean of the peak values measured in the three tests, and the error was 0.16%. A further linear correlation analysis was performed, with $R^2 = 0.9724$, indicating a strong correlation between the FEA results and the experimental results; thus, the model was validated.

Figure contents: In the upper plot, the vertical axis is force/N and the horizontal axis is displacement/mm; the legend entries are Test 1, Test 2, Test 3, test mean, and simulated value. In the lower plot, the vertical axis is simulated value/N and the horizontal axis is test mean/N; the legend entries are original data and regression fitted line. The regression annotation is

$$y = 0.8852x + 378.17, \qquad R^2 = 0.9724$$

Fig. 4 Finite element model validation

2.2 PM-HS Structural Mechanics Analysis

In this study, the load-bearing capacities of the seven structures were evaluated by analyzing and calculating the equivalent stress and equivalent strain of the structures through simulated compression tests. Figure 5 shows the equivalent-stress contour plots of the seven models. Overall, the stress distributions of the models exhibit a certain regularity, with stress-concentration regions mainly appearing in the middle of the structures. The stress peak of PM-HS-A is concentrated in the central region. For PM-HS-B and PM-HS-C, the stress distribution begins to diffuse from the center toward both sides of the struts. For PM-HS-D, PM-HS-E, PM-HS-F, and PM-HS-G, the stress distribution is more uniform, and the stress in the supporting regions is dispersed by a greater number of structural members.

According to the equivalent-stress and strain results from the simulated compression tests of the seven structures (Fig. 6), as the inner-frame diameter changes by 1 mm and the structural mass and volume fraction increase, both the equivalent stress and the strain first decrease and then increase. Structure PM-HS-A has the largest equivalent stress and strain values, 455.56 MPa and 0.36, respectively; structure PM-HS-E has the smallest equivalent stress and strain values, 206.21 MPa and 0.16, respectively.

There are many structures in nature with high energy-absorption capacity, which provides useful design ideas. In the study of biomimetic structures, parametric research is an important part of structural design. Changes in structural diameter, shape, and infill can all directly affect energy-absorption performance [22, 30–31].

Figure contents: Seven stress-contour panels are labeled PM-HS-A, PM-HS-B, PM-HS-C, PM-HS-D, PM-HS-E, PM-HS-F, and PM-HS-G. Unit: MPa.

Fig. 5 Stress contour of PM-HS

After proposing a structure designed on the basis of human pennate muscle, this study conducted a parametric investigation of the position of its inner frame and the size of the annular area, with the aim of proposing a structure with greater energy absorption. The results show that changes in the annulus position (inward or outward), that is, the size of the annular area, significantly affect the structure' s load-bearing capacity and energy-absorption capacity. In terms of load-bearing capacity, regions of high stress concentration are usually the structure

the main weak point. In PM-HS-A, the stress peak is mainly concentrated in the middle region of the structure, which makes this location more prone to fracture under impact; compared with the other six structures, its load-bearing capacity is weaker. As the structural parameters change—that is, as the area of the middle circular ring increases—the stress distribution in the supporting region gradually shifts toward both sides, and the stress-dispersion effect becomes more pronounced. In particular, the structures PM-HS-D, PM-HS-E, and PM-HS-F can effectively disperse the stress concentration caused by loading, exhibiting superior mechanical performance. Combined with the numerical analysis of equivalent stress and strain, the stress peak shows a decreasing trend as the ring area increases. However, PM-HS-E and PM-HS-F have relatively the smallest stress peaks, and their strain values are also the same, indicating that they have the lowest fracture risk and better load-transfer capacity. In addition, from the perspectives of mass and volume, these structures are at an intermediate level and have a relatively desirable balance between mass and performance. When material usage is limited and stress concentration must be reduced—for example, in the design of ice-hockey helmet liner materials, where lightweight design and efficient protection are required—PM-HS-D, PM-HS-E, and PM-HS-F can be included in the range of structures considered when seeking a balance between material consumption and performance.

Fig. 6 Comparison of equivalent stress and equivalent strain of PM-HS

2.3 Energy-Absorption Analysis of the PM-HS Structures

According to the load–displacement curves under the same loading condition (Fig. 7), the seven structures exhibit similar load variation during the initial stage of compression. After the displacement exceeds 0.3 mm, PM-HS-F, PM-HS-E, and PM-HS-G are the first to reach their load peaks, which are 3,740.6, 3,830, and 3,980 N, respectively, and then enter a plateau stage. After the displacement of PM-HS-D exceeds 0.5 mm, its load peak reaches 4,742.5 N, after which it enters a plateau stage. PM-HS-A, PM-HS-B, and PM-HS-C reach their load peaks only after the displacement exceeds 0.6 mm, with peak values of 4,702.5, 4,610.6, and 4,935.6 N, respectively, and then enter a plateau stage. Among them, PM-HS-C has the highest load peak, while PM-HS-F has the lowest load peak.

From the perspective of energy absorption (Fig. 8), among the seven structures, PM-HS-D absorbs the most energy, with an E value of $3,611.64$ mJ. At the same time, its S_m and S_v are also the largest, at 206.34 mJ/g and 231.10 mJ/cm^3, respectively. The values of E, S_m, and S_v for PM-HS-G are all the smallest, at $2,928.96$ mJ, 153.92 mJ/g, and 172.39 mJ/cm^3, respectively. In terms of the rates of change (Table 2), the maximum rates of change in E, S_m, and S_v all occur in the transition from PM-HS-D to PM-HS-E, and are -10.97%, -14.25%, and -14.24%, respectively. The minimum rate of change in E occurs in the transition from PM-HS-A to PM-HS-B, with a value of 0.51%. The minimum rates of change in S_m and S_v occur in the transitions from PM-HS-B to PM-HS-C and from PM-HS-C to PM-HS-D, both with values of approximately 1.29%.

Fig. 7 Load–displacement curve of PM-HS

Fig. 8 Comparison of energy absorption performance of PM-HS

In the design of protective structures, energy absorption is one of the key considerations [22,32–34]. This study shows that, as the parameters change—that is, as the area of the central circular ring increases—the energy absorption of the structures does not increase or decrease monotonically. On the contrary, the structures in the middle range, PM-HS-B, PM-HS-C, and PM-HS-D, absorb more energy, indicating that their protective effect is superior to that of the other four structures. In addition, lightweight design and space utilization are also important indicators for evaluating the protective performance of materials and structures [35]. A larger S_m value means that the material can absorb more energy per unit mass. In this study, the structures with relatively large S_m are PM-HS-A, PM-

HS-C and PM-HS-D, indicating that the lightweight design of these three structures is superior to that of the other structures. Meanwhile, a larger S_v value means that the structure can absorb more energy within a limited space. The three structures PM-HS-A, PM-HS-C, and PM-HS-D have relatively large S_v values, further supporting their advantages in space utilization. From the perspective of the rate of change, the maximum rates of change in E, S_m, and S_v all occur when PM-HS-D changes to PM-HS-E, and all values show a decreasing trend. This indicates that, in structural design, the structural parameters of PM-HS-D have almost reached the limit in terms of energy absorption. When the ring area of the structure continues to increase, the energy absorption capacity will decrease sharply. Therefore, PM-HS-C and PM-HS-D perform relatively well in terms of E, S_m, and S_v. Considering energy absorption capacity, lightweight design, and the load-bearing performance of the structure, PM-HS-D exhibits the optimal energy-absorption effect and can be further studied as a helmet protective structure.

The helmet liner is the main device for absorbing energy during head impact, and improving its energy-absorption characteristics can effectively reduce head injury[^36]. As a high-energy-absorption design, honeycomb structures have been widely used in various protective fields, such as cushioning human falls and preventing concussions. By adjusting parameters such as liner thickness and material properties, their adaptability to various impact conditions can be optimized, thereby improving energy absorption capacity[^37-^40]. In this study, finite element simulation was adopted to systematically analyze the mechanical properties and energy absorption characteristics of the parameterized PM-HS. The results show that PM-HS-D performs best in energy absorption and can be used as an optimized candidate for ice hockey helmet liner materials. Compared with other similar honeycomb structures, the PM-HS-D proposed in this study is relatively prominent in peak stress and has good mechanical properties, while its energy absorption is superior to that of some structures. This is also because this study considered only a single material property, resulting in certain limitations in the energy absorption effect[^1,^20,^31]. However, the energy-absorbing structure proposed in this study mainly provides a reference for sports protective equipment. In actual ice hockey, head collisions are not limited to a single impact type; the head may face various complex impact modes, including linear and nonlinear collisions, different impact angles, velocities, and impacts at different locations. Therefore, future optimization should conform to practical application scenarios, expand the range of material selection, and comprehensively consider factors such as impact angle, velocity, and location, so as to improve the energy absorption effect and more accurately evaluate the protective effect of helmet liners[^5,^41-^42].

Table 2 PM-HS Energy Absorption Data

Tab. 2 Energy absorption data of PM-HS

Parameter	PM-HS-A	PM-HS-B	PM-HS-C	PM-HS-D	PM-HS-E	PM-HS-F	PM-HS-G
E/mJ	3 266.02	3 282.67	3 429.07	3 611.64	3 215.28	3 073	2 928.96
Rate of change of E/%	–	0.51	4.46	5.32	−10.97	−4.43	−4.69
Rate of change of S_m/%	–	−1.66	−1.29	−1.29	−14.25	−7.05	−6.42
Rate of change of S_v/%	–	−1.66	−1.28	−1.29	−14.24	−7.05	−6.42

3 Conclusions

Based on the structural morphological characteristics of human pennate muscles, this study proposed a bioinspired pennate-muscle honeycomb structure using the principles of biomimetic structural design. Specimens were then prepared using 3D printing technology, and the validity of the structural model was verified by finite element numerical simulation and experimental testing. Finally, the mechanical characteristics and energy-absorption performance of the structure under seven parameter settings were compared through finite element numerical simulation analysis, leading to the following conclusions.

1) Among the seven designed structures, PM-HS-D has relatively low equivalent stress (241.01 MPa) and strain value (0.19), and its stress distribution is more uniform than those of the other structures.

2) In terms of energy-absorption performance, the absorbed energy (E) of PM-HS-D is 3 611.64 mJ, the specific energy absorption per unit mass S_m is 206.34 mJ/g, and the specific energy absorption per unit volume S_v is 231.10 mJ/cm^3, all of which are significantly better than those of the other structures.

For the structure proposed in this study, its parameter settings affect the stress distribution mode, mechanical properties, and energy characteristics. Among them, PM-HS-D exhibits the best overall performance and, after further optimization, can serve as a potential preferred material for protective equipment in specific scenarios.

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