



A review on the auxetic materials and their applications in biomedical engineering

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ABSTRACT

Over the past decade, auxetic materials have garnered significant attention due to their unconventional mechanical characteristics. Researchers have proposed multitudinous auxetic materials with improved mechanical properties by designing their core microcells. These advanced auxetic materials exhibit broad application prospects in fields such as transportation, civil engineering, aerospace, biomedical engineering, etc. This review focuses on the latest progress of auxetic materials in the biomedical field. The basic types, improvements, and mechanical properties of auxetic materials are introduced first. Then, the applications of auxetic materials in biomedical engineering are systematically reviewed, including stents, bone implants, tissue engineering, organ patches, and biomedical sensors. It can be summarized that auxetic materials have provided significant support for biomedical engineering from structural mechanics and biomechanics. Finally, several future outlooks for utilizing auxetic materials in biomedical engineering are discussed to promote the further development of auxetic biomedical devices.

1. Introduction

Metamaterials are artificially designed structures [1,2]. Unlike natural materials, metamaterials get their traits from core microcells. These microcells endow metamaterials with physical properties that natural materials cannot match [2–4]. Due to their subversive design mechanism, metamaterials have expanded beyond electromagnetics to diverse fields such as optics [5], acoustics [6], thermodynamics [7,8], and mechanics [9–12]. As one of the extensively studied mechanical metamaterials, auxetic materials are characterized by their unique negative Poisson's ratio (NPR) deformation properties, i.e., transverse expansion under uniaxial tension [13–16], as shown in Fig. 1. Since the first fabrication of NPR foam in 1987 [17], various studies on auxetic materials have been carried out successively [18–24].

Common artificial auxetic materials include Re-entrant structures [25–30], chiral structures [31–34] and rotating polygon structures [35–37] et al. Due to their unique deformation characteristics, auxetic materials are proven to have a higher shear modulus [38], increased

indentation resistance [39], and enhanced energy absorption capacity [40], when compared with traditional positive Poisson's ratio (PPR) materials. Accordingly, auxetic materials have been widely used in various engineering application scenarios, including transportation [41], civil engineering [42], aerospace [43], and biomedical engineering [16,44–46]. Especially, recent attention to the application of auxetic materials in biomedical engineering has significantly increased. Compared with other engineering fields, the application of auxetic materials in the biomedical field has unique requirements and challenges. In transportation and civil engineering, Re-entrant honeycomb structures are widely used in protective equipment and seismic design due to their excellent energy absorption and impact resistance [41,42]; the aerospace sector tends to prefer chiral or rotating polygon structures to achieve lightweight and curvature adaptability [43]. In contrast, biomedical applications (such as scaffolds and organ patches) demand higher flexibility, biocompatibility, and dynamic deformation adaptability of materials, and therefore tend to favor modified Re-entrant, chiral-hybrid, or hierarchical structures. These structures can maintain

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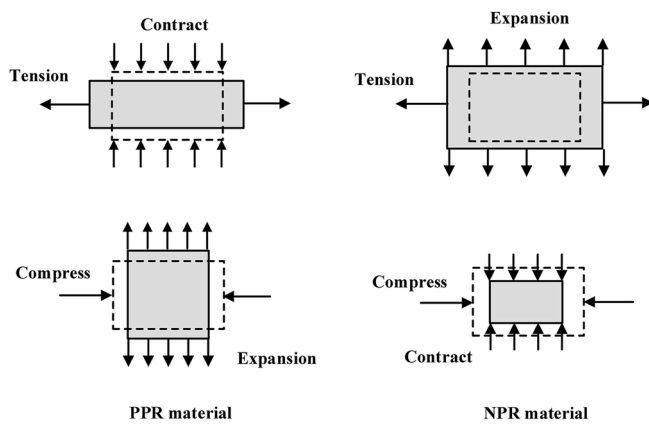


Fig. 1. Deformations of the PPR material and the NPR material.

a negative Poisson's ratio effect at low modulus while reducing stress concentration on surrounding biological tissues [16,44–46]. Most biomedical studies remain at the conceptual or in vitro stage. Clinical translation needs to be accelerated. For instance, stents designed based on the auxetic structure can exhibit a compact form during transportation. They expand radially and axially upon reaching the lesion site, effectively preventing incomplete tissue coverage [21,47]. When employed in tissue engineering scaffolds, auxetic materials not only demonstrate exceptional mechanical properties but also enhance cell proliferation under external loads [48–51]. Besides, the special deformation of auxetic materials makes them particularly adaptable to the dynamic deformation of organs, promoting them to be well applied in organ patches [52–54]. Therefore, considering the wide focus on auxetic materials and their broad prospects in biomedical engineering, it is necessary to review the relevant research progress.

Several researchers have endeavored to review the auxetic materials and their applications in the field of biomedical engineering. For instance, Balan et al. [14] comprehensively examined the futuristic auxetic structures, manufacturing techniques, fabrication materials, and potential future applications of the auxetic materials. Li et al. [15] comprehensively reviewed and categorized the mechanical design methodologies for the auxetic materials exhibiting both soft and stiff mechanical properties. Lvov et al. [55] conducted a comprehensive review of biomedical applications of auxetic materials, encompassing prosthetics, orthotics, ergonomic appliances et al. Shirzad et al. [48] reviewed the applications of the auxetic materials in bone medical devices. Sun et al. [56] carried out a comprehensive review on auxetic biomedical metamaterials in orthopedic surgery. Their work systematically summarizes typical structural configurations and highlights their applications in joint, spinal, trauma, and sports medicine. It emphasizes the great potential of auxetic materials in orthopedic clinical solutions. Shukla et al. [44] reviewed the applications of auxetic materials and auxetic textiles in medical engineering. Jiang et al. [57] reviewed the applications of additive manufacturing auxetic structures in orthopaedic implants, scaffolds, tissue engineering, and other fields. However, the existing literature lacks coverage of advanced biomedical engineering fields, especially the popular organ patches and biomedical sensors. This article provides a unique incremental contribution in the systematic coverage of emerging organ-on-a-chip and sensor subfields. A more comprehensive review of the application of auxetic materials in biomedical engineering needs to be further developed.

To sum up, this review first introduces the latest research progress on auxetic materials, encompassing their types, improved structural configurations, and corresponding mechanical properties. This review also highlights commercially promising applications. These include self-expanding vascular stents, patient-specific bone implants, smart cardiac patches, and wearable biosensors. These examples underscore the significant potential of auxetic materials to transition from laboratory

innovation to tangible medical products, addressing critical clinical needs. Compared with existing reviews (Lvov et al. [55]; Shukla et al. [44]), this work focuses on the integration of structural design-mechanical performance-clinical demand. Especially, on the basis of mechanical properties, the work maps these mechanical traits directly to unmet clinical needs: radial support and anti-shortening for vascular stents, stress-shielding reduction for bone implants, conformal dynamic fit for organ patches, and high sensitivity for biomedical sensors. By quantifying structure–performance–demand relationships, this review provides clear design guidance. It thus bridges fundamental research and translational medicine and offers a practical reference for developing clinically oriented auxetic biomedical devices.

2. Auxetic materials

Two key concerns for auxetic materials are mechanical property enhancement and microcell–macroscopic mechanics relationships. The former mainly relies on innovative structural design, and the latter usually requires research about the mechanical properties by analytical, numerical, and experimental methods. Given this, this section mainly focuses on the types, improvements, and mechanical properties of the auxetic materials.

2.1. Types of the auxetic materials

As seen in Fig. 2(a), the Re-entrant hexagonal structure is a typical artificial auxetic material. This structure undergoes a change when subjected to tension. By adjusting the wall angle of a regular hexagonal honeycomb, the walls rotate outwards, causing the entire structure to expand. Gibson et al. [58] first investigated the in-plane elastic mechanical properties of Re-entrant hexagonal honeycombs, subsequently inspiring numerous scholars to explore innovative variations of this structural design [59–65]. In addition to the Re-entrant hexagonal structure, other Re-entrant auxetic structures such as double-arrow structure [66–68] and star-shaped structure [69–71] have also been developed and studied by leveraging the Re-entrant mechanism.

Chiral structures are also a common type of auxetic materials, as shown in Fig. 2(b). The term "chiral" was originally used to describe an object that cannot coincide with its mirror image. Lakes [72] first proposed that chiral hexagonal microstructures exhibit an auxetic effect. The basic cell element of chiral structures is obtained by connecting a flexible straight beam to a central rigid node along the tangent direction. The mechanism of their NPR effect is that when the structure receives lateral load, the rigid nodes rotate under load, which drives the longitudinal beam to contract. By adjusting the number and tangential direction of tangential beams, tri-chiral structure, tetra-chiral structure, and anti-chiral structure, etc. are also developed [73].

In addition, rotating polygon structures are a widely studied class of auxetic materials, as shown in Fig. 2(c). These structures originate from the explanation of NPR deformation in natural crystal materials, where square lattices are interconnected through hinges. Under lateral compression, the hinges at the connections rotate to close internal gaps, resulting in longitudinal contraction. Building upon this concept, Grima et al. [37] designed a rotating quadrilateral auxetic structure by equalizing its side lengths, thereby achieving an isotropic negative Poisson's ratio with a constant value of -1 . By varying the internal polygons used, one can obtain rotating triangle structures, rotating double square structures, and so on [74]. Apart from these aforementioned designs, the auxetic materials also include origami structures [75,76] and perforated board structures [77,78]. As shown in Table 1, the Poisson's ratios and relative Young's moduli of the unit cells of traditional auxetic materials exhibit distinct differences. This can directly reflect the core mechanical properties of different structures. All quantitative parameters in the table are derived from the experimental or numerical simulation results of the corresponding studies, providing a quantitative reference for the selection and performance comparison of auxetic structures.

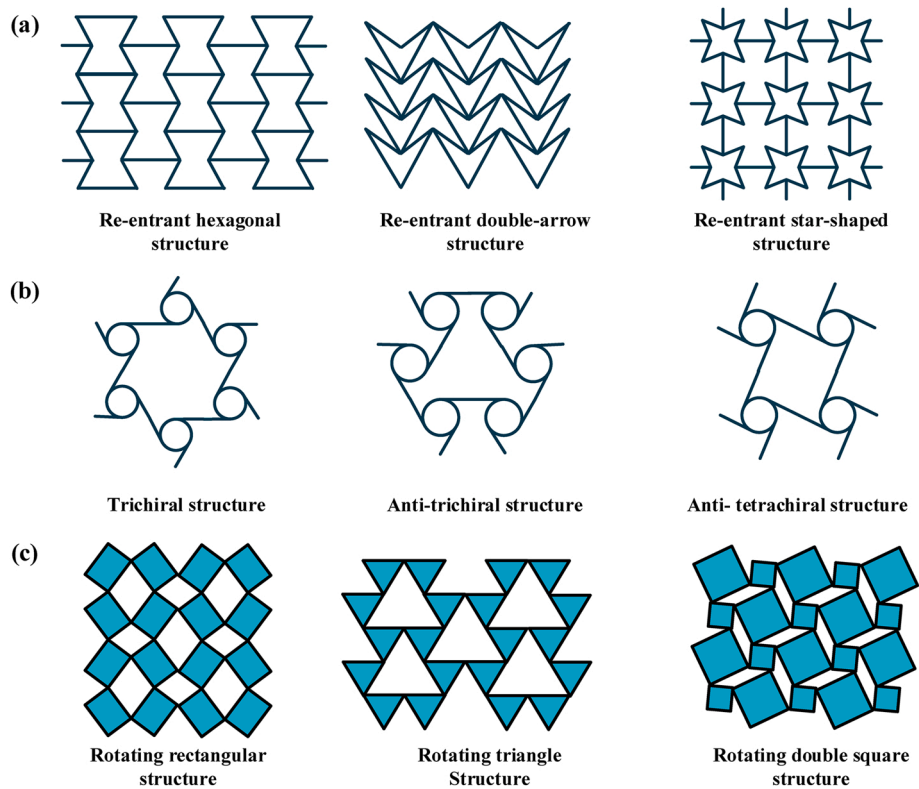


Fig. 2. Geometric configurations of the Re-entrant structures, chiral structures, and rotating polygon structures.

Table 1

Comparison of typical unit cells and quantitative parameters for traditional auxetic materials.

No.	Unit Cell Geometry	Statistical data		Ref.
		ν	E/E_s	
1	Re-entrant hexagonal structure	$[-2.0, -0.5]$	6.93×10^{-3}	[58]
2	Re-entrant double-arrow structure	-1.25	$[0.1, 1] \times 10^{-2}$	[68]
3	Re-entrant star-shaped structure	-0.37	$[0.1, 1] \times 10^{-2}$	[71]
4	Trichiral structure	$[-0.8, -0.3]$	0.44×10^{-2}	[79]
5	Anti-trichiral structure	$[-0.1, 0.08]$	$[3.8, 4.1] \times 10^{-4}$	[73]
6	Anti-tetrachiral structure	$[-1.6, -0.55]$	$[0.1, 1] \times 10^{-2}$	[73]
7	Rotating rectangular structure	-1.0	$[0.1, 5] \times 10^{-1}$	[36]
8	Rotating triangle structure	-1.0	$[0.1, 3] \times 10^{-1}$	[36]
9	Rotating double square structure	$[-1.78, 0.43]$	$[0.1, 10] \times 10^{-3}$	[74]

Note: "E/Es" is the relative Young's modulus, and " ν " is the Poisson's ratio. All quantitative parameters are derived from experimental or numerical results in the cited original publications.

2.2. Improved auxetic materials

The significant advantage of mechanical metamaterials lies in the ability to obtain enhanced mechanical properties by constructing novel basic cells. By innovating the design of internal structural cells, a large number of improved auxetic materials have been proposed in recent years [19]. For instance, by the design of the cell walls, the stiffness and strength of the traditional auxetic materials can be well improved [18, 20, 59–65, 80–99]. As shown in Fig. 3(a), Qi et al. [62] designed a new type of Re-entrant arc structure by replacing the inclined cell wall with a double arc cell wall, and studied its quasi-static compressive strength and deformation mode through numerical, experimental, and theoretical methods. The results indicate that the new design has a higher

compressive strength. Harkati et al. [100] conducted a parameterized study on the in-plane elastic mechanical properties of a multi-fold Re-entrant auxetic structure, as shown in Fig. 3(b). Further, they proposed a multi-fold Re-entrant honeycomb structure with circular cell walls by improving the structure and found that the new structure has a high in-plane shear compliance and customized anisotropy, as shown in Fig. 3(c) [101]. Zhang et al. [102] designed a new vertical strut combined Re-entrant structure, as shown in Fig. 3(d), which is confirmed to have a higher NPR effect and anisotropic performance. Liu et al. [103] proposed a novel zero Poisson's ratio honeycomb structure based on the star-shaped structure, as shown in Fig. 3(e), and studied the in-plane elastic mechanical properties of the structure. Ren et al. [104] proposed a multiple Re-entrant star-shaped honeycomb as shown in Fig. 3(f) and studied its dynamic performance.

In addition to improving the microcell structure, hierarchical design, and gradient design are also commonly used design strategies. As shown in Fig. 3(g), Tan et al. [105] proposed a novel hierarchical structure by using triangles to fill the Re-entrant cell walls, and the results showed that the proposed hierarchical structure has superior dynamic compressive stress. Sun and Pugno [106] designed a novel layered honeycomb structure by replacing the cell walls with Re-entrant cells, as shown in Fig. 3(h). As shown in Fig. (i), Wu et al. [107] designed a novel gradient Re-entrant honeycomb structure by adjusting the Re-entrant angle, and found that this new structure may be beneficial for the energy absorption performance.

2.3. Mechanical properties of auxetic materials

Studying the tensile mechanical properties of materials usually involves two objectives. First is to explore the basic elastic constants and deformation modes of materials. Second is to reveal how cell structure determines the performance. In the biomedical field, design goals usually include: (1) improving strength and energy absorption while maintaining a significant negative Poisson's ratio (NPR, ideally < -0.5); (2) achieving excellent bending adaptability (dome-shaped mode) to

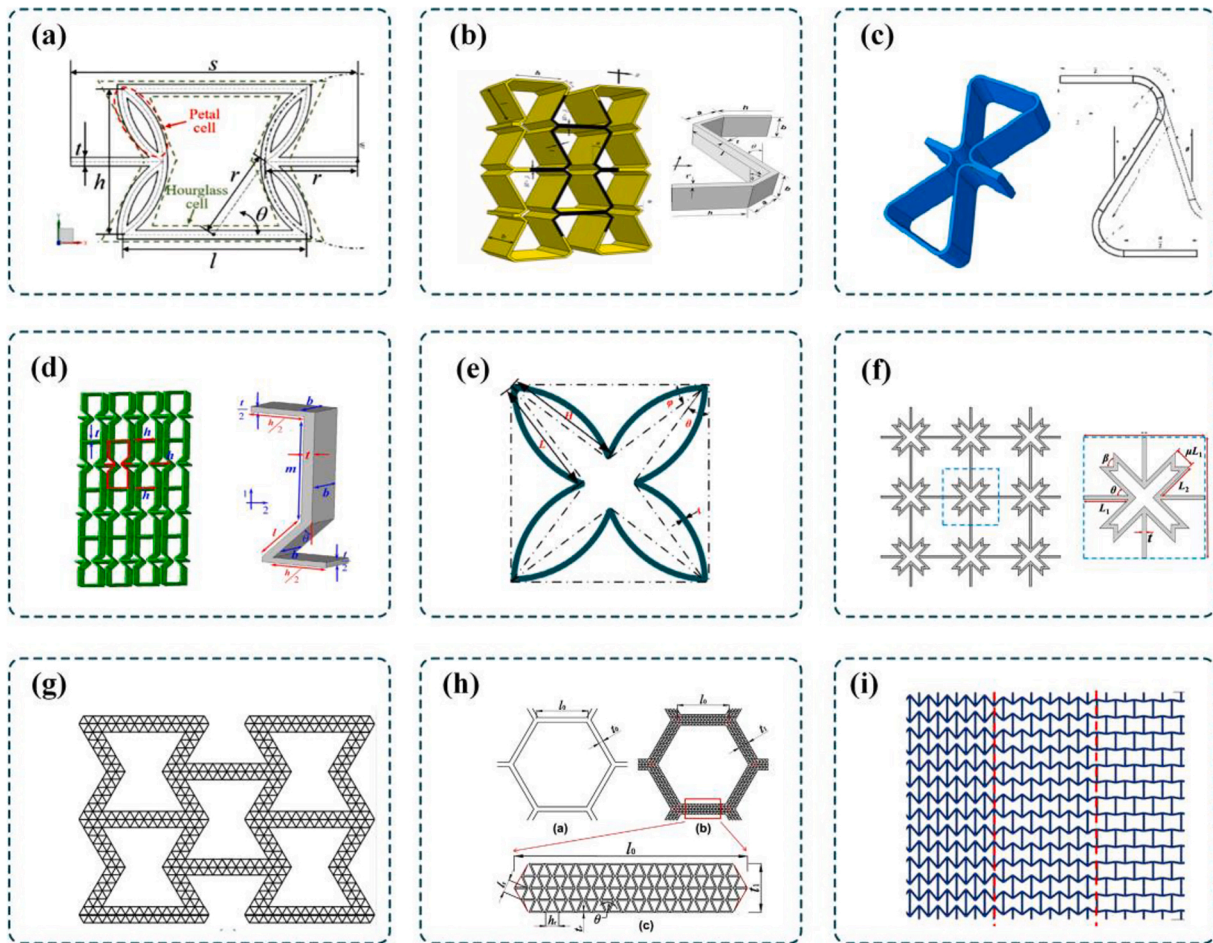


Fig. 3. Improved auxetic materials: (a) A Re-entrant arc structure proposed by Qi et al. [62]; (b) A multi-fold Re-entrant auxetic structure proposed by Harkati et al. [100]; (c) A multi-fold Re-entrant honeycomb structure with circular cell walls proposed by Harkati et al. [101]; (d) A vertical strut combined Re-entrant structure proposed by Zhang et al. [102]; (e) A novel star-shaped structure proposed by Liu et al. [103]; (f) A multiple Re-entrant star-shaped honeycomb proposed by Ren et al. [104]; (g) A hierarchical auxetic structure proposed by Tan et al. [105]; (h) A layered honeycomb structure proposed by Sun and Pugno et al. [106]; (i) A Re-entrant honeycomb structure proposed by Wu et al. [107].

match the curvature of dynamic organs; (3) balancing stiffness and flexibility to avoid stress shielding. The following will focus on the key trade-offs in tensile, compressive, and bending performance, as well as the impact of structural shape.

Linear elastic mechanical properties are the basic mechanical performance of the auxetic materials, which have been widely valued in past studies [58,90,108]. Usually, porous structures are regarded as continuous homogeneous materials, and the equivalent elastic constants can be calculated by analyzing the deformation of individual cells, such as Young's modulus, Poisson's ratio, and shear modulus of the structures.

The calculation typically follows a mechanics-of-materials approach, which involves three key steps: (1) isolating a representative unit cell (RUC) from the periodic lattice (2) applying simplified boundary conditions (e.g., periodic or symmetric boundary conditions); to simulate macroscopic loading (tension/compression or shear); (3) establishing force-displacement relationships for the cell walls (often treated as beams) under these loads, and then homogenizing the results to obtain the effective constitutive properties of the bulk material.

For instance, a fundamental analytical model for the in-plane elastic properties of a re-entrant honeycomb (Fig. 2(a)) was established by Gibson et al. [58]. By considering the flexural and axial deformations of the inclined (length l , angle θ) and vertical (height h) struts under uniaxial stress, the equivalent Young's moduli (E_x^* , E_y^*) and Poisson's ratios (ν_{xy}^* , ν_{yx}^*) can be derived. The Poisson's ratio ν_{xy}^* (for loading in the x -direction) is given by:

$$\nu_{xy}^* = - (h/l + \sin \theta) \sin \theta / (\cos^2 \theta) \quad (1)$$

This equation clearly shows that a negative Poisson's ratio ($\nu_{xy}^* < 0$) is achieved when the geometry satisfies $h/l > |\sin \theta|$, which is characteristic of the re-entrant shape. The corresponding Young's modulus in the x -direction is approximated by:

$$E_x \approx E_s (t/l)^3 [\cos \theta / (h/l + \sin \theta) \sin^2 \theta] \quad (2)$$

where E_s is the Young's modulus of the solid base material, and t is the thickness of the cell wall. These equations provide a practical tool for preliminary design, illustrating how the NPR and stiffness are directly controlled by the RUC's geometric parameters (h , l , θ , t).

Prall and Lakes [79] conducted theoretical modeling and experimental research on the in-plane Young's modulus and Poisson's ratio of chiral structures. They found that the Poisson's ratio of the structure remains -1 over a large strain range. Gao et al. [109] studied the elastic mechanical properties of the three-dimensional double arrow structure by considering the interaction between adjacent cells. Alderson et al. [110] studied the bending deformation modes of hexagonal honeycomb structures, Re-entrant honeycomb structures, and chiral honeycomb structures using the finite element model. The results showed that the bending modes of honeycomb materials are directly related to their in-plane Poisson's ratio. When subjected to an out-of-plane bending load, the material will produce transverse curvature. For the PPR

materials, the transverse curvature is opposite to the direction of the bending principal curvature, exhibiting a saddle-shaped deformation mode, as shown in Fig. 4(a). For the NPR materials, the transverse curvature is the same as the bending principal curvature direction, exhibiting a dome-shaped deformation pattern, as shown in Fig. 4(b). Zhou et al. [23] also obtained similar results when studying a novel Re-entrant structure with improved flexibility by the analytical, numerical, and experimental methods.

The nonlinear mechanical properties of the auxetic materials under large deformation loads have also been widely studied [111]. Zhou et al. [22] proposed a novel Re-entrant combined-wall honeycomb and studied its quasi-static compression properties by numerical and experimental methods, as shown in Fig. 5(a). Alomarah et al. [112] conducted numerical simulation and experimental research on the nonlinear tensile mechanical properties of Re-entrant hexagonal structure, as shown in Fig. 5(b). Jiang et al. [28] conducted numerical analysis on the quasi-static in-plane compression behaviors of the Re-entrant structure and conducted corresponding experimental studies based on 3D printed samples. Their results showed that the deformation process of the structure was clearly divided into two stages, and the corresponding stress-strain curves also showed two plateau regions. The existing studies on the mechanical properties of the auxetic materials promote a further understanding of how microcell structures determine the macroscopic mechanical properties, and provide some theoretical guidance for their further engineering applications and optimized designs. For clarity and comparison, Table 2 provides a summary of some advanced auxetic materials and their respective characteristics.

Many of the auxetic designs in this review rely on additive manufacturing technologies, which provide high-precision control of complex unit cells, something that is difficult to achieve with traditional methods. Emerging 4D printing, by incorporating time-responsive materials (such as shape memory materials), adds a dynamic dimension, allowing printed structures to undergo post-processing deformation in response to environmental stimuli (such as temperature or pH). This is particularly relevant to biomedical applications that require deployable or adaptive devices and will be further discussed in the future outlook.

3. Application of auxetic materials in biomedical engineering

The abnormal deformation characteristics and excellent mechanical properties of auxetic materials have aroused widespread interest in the field of biomedical engineering. Over the past few years, these materials have demonstrated positive outcomes in various advanced applications, such as flexible electronics, wearable sensors, etc. This section systematically reviews these applications, following a logical progression from internal implants to external devices, highlighting how auxetic properties address specific biomedical challenges in each area. The applications are discussed in the order of stents (vascular and tracheal), bone implants, tissue engineering scaffolds, organ patches, and finally, biomedical sensors. Besides, Figs. 3–7 show detailed summaries of the corresponding application research for clarity.

3.1. Stents

This subsection reviews auxetic stent designs by first addressing their

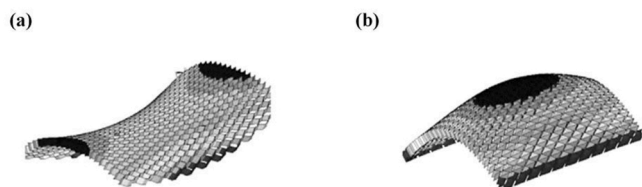


Fig. 4. (a) Bending deformation of the PPR structure; (b) Bending deformation of the NPR structure [110].

mechanical performance improvements, then their biomechanical interactions with vessels, and finally their extension to tracheal applications. Vascular stents are a type of common interventional medical device, which are widely used to treat cardiovascular diseases related to atherosclerosis [124,125]. Compared with other treatment methods, stent implantation has advantages such as minimally invasive, stable support, and low restenosis rate. However, there are still complications such as in-stent restenosis (ISR) and stent thrombosis (ST) with stents [113,126,127]. In recent decades, scientists have conducted extensive research to improve the safety of stent intervention and reduce the incidence of complications [128–130]. Among them, the mechanical properties of the stent are given special attention. Stents with weak mechanical properties may cause insufficient expansion, malapposition, fatigue fracture, and vascular injury, threatening long term safety [131–133].

Considering the mechanical issues mentioned above, the use of auxetic materials could be a viable solution [21,47,120,122,123,134–137]. The NPR deformation behavior of the auxetic stent overcomes the axial shortening issue of traditional stents, significantly reduces the transportation volume of stents, and improves the positioning accuracy during stent expansion [47]. Moreover, due to the unique out-of-plane bending curvature of the auxetic structure, it helps to alleviate the "dog bone" effect in the traditional stent expansion process [138]. Wang et al. [138] designed two forms of stents using different connection structures in 2006 and conducted numerical simulations on the expansion behavior of the stents under balloon expansion. They found that adjusting the connection structure of the stents can improve their dog bone effect and axial shortening effect. Han and Lu [139] also designed a group of PPR/NPR stents by adjusting the stent connection structure, and developed a gradient Poisson's ratio stent. Numerical and experimental results showed that the structure can fit well with curved arterial vessels after expansion. Alomarah et al. [134] proposed two types of Re-entrant chiral auxetic stents and systematically studied their mechanical characteristics. Asadi et al. [119] proposed and studied a type of chiral auxetic stents, which have been considered to have excellent NPR mechanical properties, as shown in Fig. 6(a). Xiao et al. [120] proposed the design and manufacturing strategy of thin-walled composite cardiovascular stent based on high-resolution projection micro-stereolithography (PμSL) 3D printing and metal thin film deposition, as shown in Fig. 6(b). They found that the proposed composite stent can significantly enhance the radial compression of the stent. Gupta and Meena [121] analyzed a novel double-arrowhead auxetic stent, which is expected to improve the mechanical properties of traditional stents, as shown in Fig. 6(c). Results showed that the proposed stent possesses reduced radial recoil property and completely avoids the foreshortening problem.

In addition to mechanical properties, scholars also pay attention to the biomechanical properties of the stent [140–142]. Stents implanted as foreign objects can generate high mechanical stress on the intima and media of blood vessels and trigger inflammatory reactions, thereby promoting reendothelialization of blood vessels. However, severe vascular injury may lead to continuous thickening of the intimal layer, resulting in restenosis within the stent [133,143]. Therefore, it is of great significance to study the biomechanical properties of stents and arteries. Wu et al. [122] proposed a type of anti-chiral stent and its hierarchical structures, as shown in Fig. 7(a). They first analyzed the in-plane mechanical properties of the stents by experimental and analytical methods. Further, they established the stent-artery coupling model to clarify the deformation of the proposed stent during the stenting process. Ruan et al. [123] proposed a novel chiral stent with zero/negative Poisson's ratio by combining the tetra-chiral element and the oscillating wave element, as shown in Fig. 7(b). The mechanical and biomechanical properties of the stent are systematically studied. Zhou et al. [21] proposed an improved hybrid auxetic structure by adding arrow-shaped and snake-shaped structures to the Re-entrant structure, and accordingly developed a novel self-expanding stent. They first

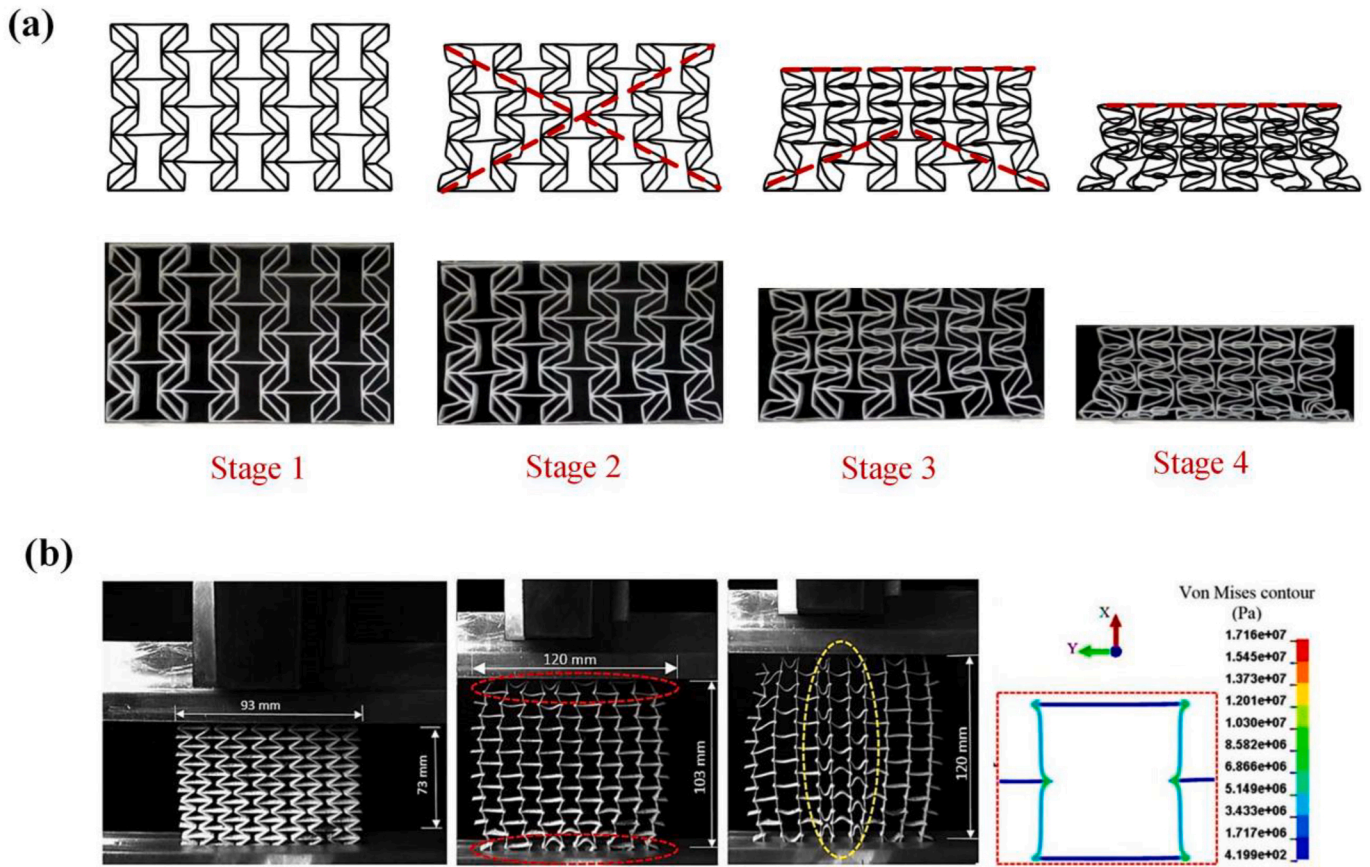


Fig. 5. (a) Quasi-static compression deformation of an improved Re-entrant combined wall structure proposed by Zhou et al. [22]; (b) Tensile deformation of the Re-entrant hexagonal structure [112].

analyzed the in-plane elastic properties of the auxetic structure and the stent. Further, they discussed the biomechanical properties of the Re-entrant stent and the proposed novel hybrid auxetic stent, including the displacement and stress damage of different arterial layers.

In addition to vascular stents, auxetic materials have also achieved positive application in tracheal stents. As a primary therapeutic approach, tracheal stent therapy is believed to be a substitute for surgical treatment of tracheal tumors. However, the mechanical properties of existing structures and materials make it difficult to meet the actual needs of the trachea, including high radial support and little migration motion [144,145]. Therefore, some groups proposed to use the auxetic material to improve the mechanical properties of the traditional tracheal stents. Liu et al. [146] proposed a novel flexible porous chiral auxetic tracheal stent based on the tetrachiral and anti-tetrachiral hybrid unit structure, as shown in Fig. 8. The simulation and the experiment results demonstrate that the auxetic tracheal stent shows NPR characteristic over a large strain range and flexibility similar to the native trachea. Besides, the porous structure of the stent can well promote cell adhesion. Table 3 shows the summary of the application of auxetic materials on stents.

Although NPR stents perform well in radial expansion, reduced axial shortening, and mitigation of the dog-bone effect, most studies are still limited to simulations, in vitro tests, and short-term experiments. Long-term in vivo fatigue, anti-thrombosis, and endothelialization data are lacking. Key assumptions include idealized balloon expansion and uniform arterial walls, whereas real clinical scenarios involve patient-specific plaques, curvature, and pulsatile loads. Clinical benchmarks for commercial nitinol stents (such as radial strength >0.2 N/mm, fatigue life $>10^7$ cycles under physiological pulsation, $<10\%$ restenosis rate within 1 year, and $<1\%$ thrombosis incidence) have seldom been

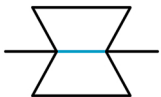
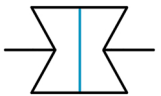
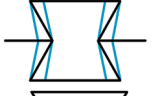
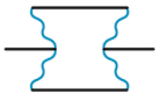
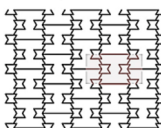
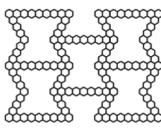
directly compared. Moreover, the potential inflammatory risks of degradation products from degradable variants have not been adequately assessed. Clinical translation requires multicenter randomized controlled trials, combined with patient-specific imaging (e.g., CTA) to optimize design, and compliance with FDA/ISO 10993 biocompatibility standards.

3.2. Bone implants

This section presents auxetic bone implants following a progression from large-scale joint replacements to smaller fixation devices. Bone implantation is a routine surgical procedure employed for the repair or replacement of damaged or missing bone tissue [48,148–150]. Typically, bone-implanted devices are fabricated from titanium alloy and stainless steel. However, implants made from these high-strength alloys may exhibit poor compatibility with native tissues, considering that the implants usually have a limited deformation capacity and bear the majority of applied loads [151,152]. This phenomenon of stress shielding can give rise to significant complications, including interface instability, adverse bone resorption, and chronic pain. The use of porous materials can effectively avoid this stress shielding, while it can make the implant have poor strength. The contradiction between biocompatibility and structural strength may be well adjusted by the introduction of the auxetic material [153]. It is considered that the auxetic material has good indentation resistance and energy absorption, which can effectively improve the load-bearing capacity of porous bone implants.

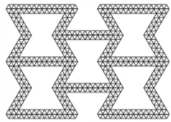
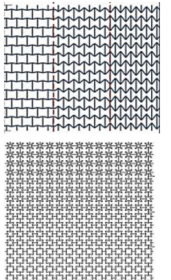
Total hip arthroplasty (THA) is one of the most popular bone implant surgeries. During the surgery, surgeons will perform surgical excision of damaged hip joint tissues and bones, followed by implantation of

Table 2
Novel auxetic materials and their characteristics.

Types	No.	Geometries	Unit Cell Geometry	Improvement Ratio		Ref.
				<i>E</i>	σ	
Adding or changing cell walls	1		Re-entrant with narrow rib	+150%	-	Lu et al. [95].
	2		Re-entrant with vertical rib	+340%	-	Li et al. [91].
	3		Re-entrant with rhombic embedding	+ [50,113]%	-	Fu et al. [93].
	4		Re-entrant with inclined walls	[30,50] times	-	Baran et al. [92].
	5		Re-entrant with circular wall	4.4 times	4 times	Tatlier et al. [87].
	6		Re-entrant with hexagonal substructures	-	2 times	Zhou et al. [22].
	7		Re-entrant with double arcs	-	2 times	Qi et al. [56,58].
	8		Re-entrant with arrow-snake structures	E(y): +36%; E(x): -57%	-	Zhou et al. [21].
	9		Diabolo shaped honeycomb	2.4 times	1.8 times	Liu et al. [114].
	10		Multi-arc re-entrant auxetic honeycomb	1.25 times	-	Xu et al. [115].
	11		Star-shaped with triangular walls	-	+109%	Wei et al. [85,86].
	12		Star-shaped with double-inclined walls	-	+180%	Lu et al. [80].
	13		tar-shaped with strengthening walls	+ [20,113]%	-	Xu et al. [88].
Hierarchical design	1		Vertex-based hierarchical Re-entrant	+ [80,116]%	-	Shen et al. [117].
	2		Hexagonal-substructure Re-entrant	-	+108%	Tan et al. [105].
	3		Triangle-substructure Re-entrant	-	+298%	Tan et al. [105].

(continued on next page)

Table 2 (continued)

Types	No.	Geometries	Unit Cell Geometry	Improvement Ratio		Ref.
				E	σ	
Functional gradient	1		Angle-graded Re-entrant	-	+ [10,20]%	Wu et al. [104].
	2		Gradient multi-arc Re-entrant	-	-	Xiao et al. [118].

Note: E is the Young's modulus, and σ is the crushing stress. The improvement is calculated based on the comparison of the material properties before and after optimization in the original publications. The compressive stress here is calculated under quasi-static or low-speed conditions, and the results under high-speed condition are not considered.

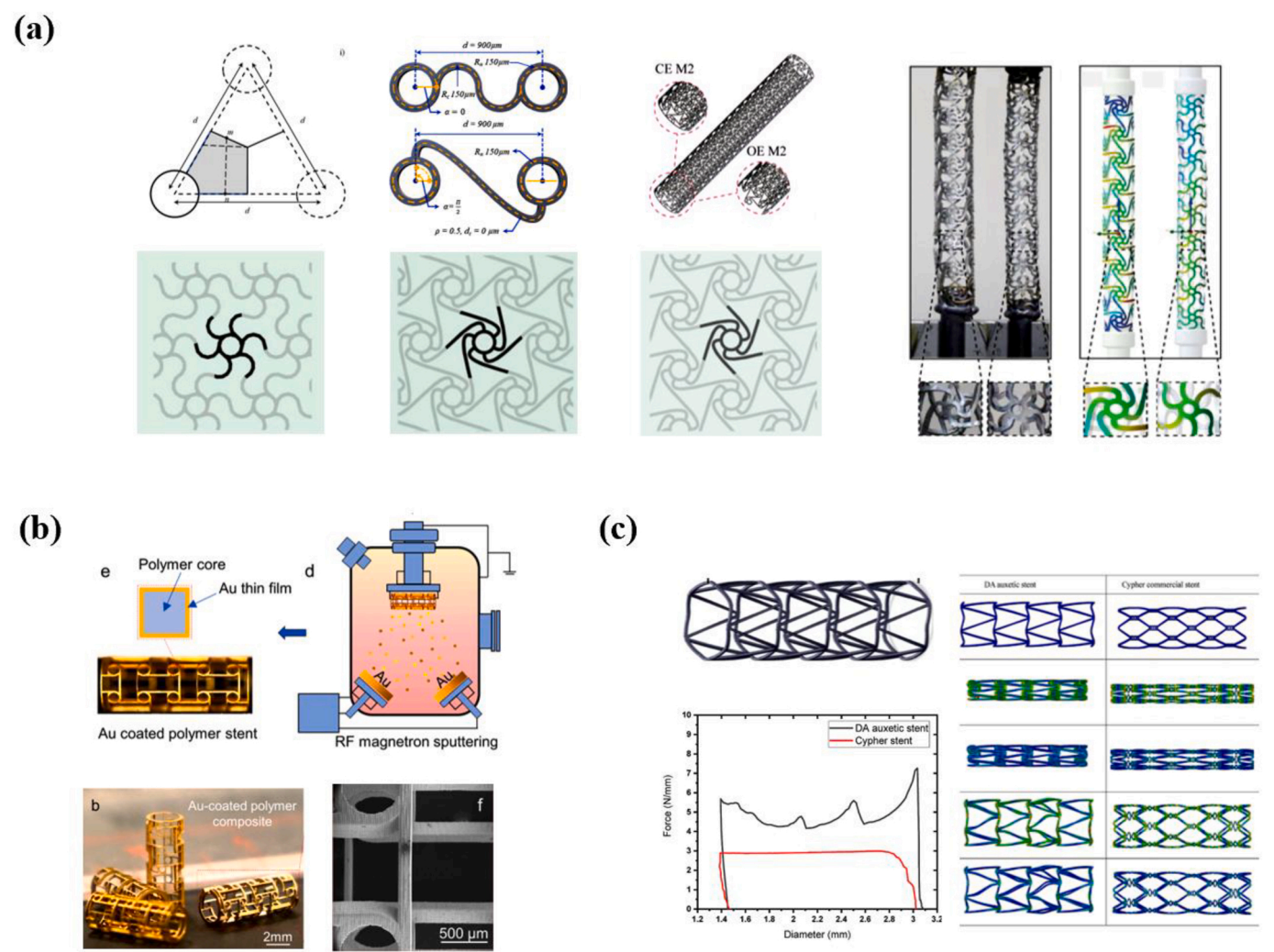


Fig. 6. Applications of the auxetic materials in vascular stents. (a) Geometric configuration of the hexachiral structure proposed by Asadi et al. [119] and the tensile test of the corresponding stent; (b) Manufacturing process and the geometric configuration of a thin-walled 3D-printed composite cardiovascular stent proposed by Xiao et al. and its partially enlarged SEM image [120]; (c) Geometric configuration of a double-arrowhead auxetic stent proposed by Gupta and Meena [121], and the analysis of radio force and crimping deformation.

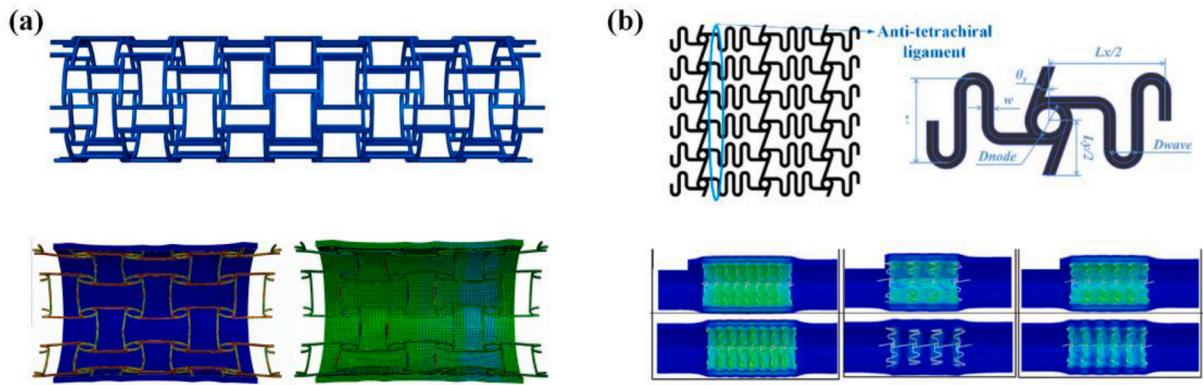


Fig. 7. Vascular stent-artery coupling modeling. (a) Geometric configuration of the anti-tetrachiral auxetic stent proposed by Wu et al. [122] and the stress and deformation of the corresponding stent-artery coupling model; (b) Geometric configuration of the chiral constrained structure proposed by Ruan et al. [123] and the tissue stress in the stent-artery coupling model.

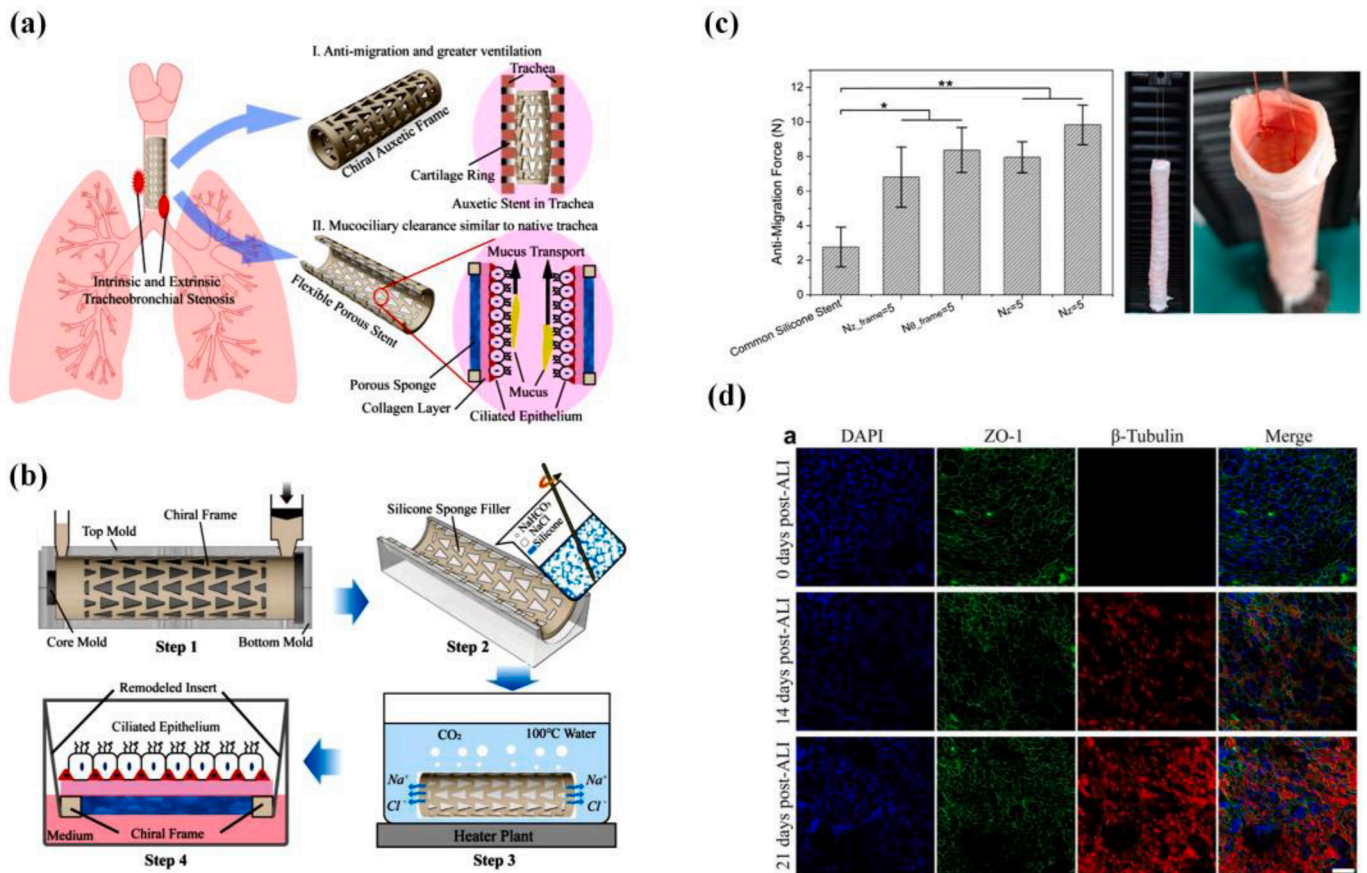
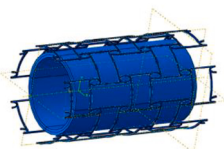
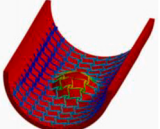
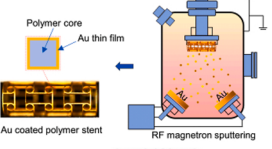
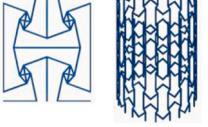
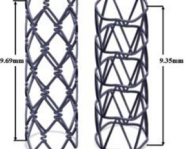
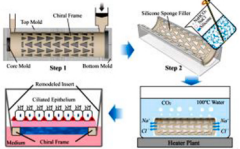


Fig. 8. Auxetic tracheal stent proposed by Liu et al. [146]. (a) Application scenario; (b) Processing technique of the auxetic tracheal stent; (c) Anti-migration force of the auxetic tracheal stent; (d) Immunofluorescent staining for differentiated NHBE cells.

artificial hip joint components composed of materials such as metallic alloys or biocompatible polymers [154]. Ghavidelnia et al. [155] proposed a graded Poisson's ratio hip implant. They compared it with three other structures, as shown in Fig. 9(a). The results revealed that all the implants exhibited appropriate micromotion ranges, while those with NPR effect and graded Poisson's ratios demonstrated a more compatible and uniformly distributed micromotion at critical regions. Their research further proves that NPR materials can adjust the stress shielding of bone implants. Garner et al. [156] proposed a computational method to develop patient-specific bone implants, as shown in Fig. 9(b). In their research, the involved micro-architecture has a wide range of

mechanical properties. By optimizing the micro-architecture parameters within the entire space, the interface incompatibility issue has been significantly improved. Kolken et al. [157] also proposed a novel concept of hybrid meta-biomaterials to improve the interface between the implant and the bone tissue, as shown in Fig. 9(c). Their research further demonstrates the prospect of innovative construction of micro-cells in improving the stress distribution of bone implants. Besides, auxetic materials also show promising prospects in custom hemipelvic prostheses. Tan et al. [158] developed 3D-printed custom hemipelvic prostheses with Re-entrant chiral auxetic structures. The prostheses achieve 75% porosity while ensuring mechanical stability, significantly

Table 3
Summary of the application of auxetic materials on stents.

Configurations	Characteristics	Quantitative indicators	Ref.
	●Proposing a novel anti-tetrachiral stent and its hierarchical structure based on the chiral structure; ●Studying the in-plane mechanical properties and the stent-artery mechanical properties of the proposed stents; ●Illustrating the stable NPR deformation and the significant application prospects of the auxetic stents.	ν : [-5, -1]	Wu et al. [122]
	●Developing a concurrent topological optimization method; ●Proposing a novel auxetic stent based on the obtained; ●Performing a numerical validation on the self-expanding stent.	ν : -0.8	Xue et al. [47]
	●Proposing a design and fabrication method of the composite stent; ●Performing experimental studies on the radial compression and biocompatibility; ●Verifying the sufficient compressional capacity of the stent.	Radial stiffness: improvement: 70%; Radial compression resistance: 35%.	Xiao et al. [120]
	●Proposing a novel Re-entrant chiral hybrid honeycomb with enhanced anisotropy in the orthogonal direction; ●Deriving and verifying the analytical models of the elastic constants of the hybrid honeycomb; ●Studying the compressional properties of the stent designed based on the honeycomb.	ν : [-10, 0]	Chen et al. [147]
	●Studying the mechanical properties of a novel double-arrow auxetic stent, including its radial strength and radial recoil; ●Verifying the improved strength, reduced radial recoil and eliminated the foreshortening issue of the stent.	ν : -16.9; RS: 7.26 N/mm; CR: 3.78%.	Gupta and Meena [121]
	●Designing a novel chiral porous tracheal stent; ●Studying the tensile and radial compressional properties, and cell differentiation; ●Verifying the sufficient service performance, including ideal anti-migration, bending flexibility, and cell differentiation.	ν : close to 0	Liu et al. [146]

Note that the ν is Poisson's ratio; RS is the radial strength; and CR is the crimping recoil.

improving bone ingrowth and MSTS-93 scores. Meanwhile, 3D-printed hemipelvic prostheses with auxetic porous structures have also been clinically verified, as shown in Fig. 9(d). Their work provides a new solution for complex pelvic tumor resection and reconstruction [159].

Apart from the hip arthroplasty, auxetic materials have been used in bone screws. Bone screws, usually made of metal, are used to stabilize and fix the fractured bone [160]. A well-designed bone screw should be stable under various loads, while in clinical practice, screw loosening remains a common poor prognosis [161]. Accordingly, some researchers proposed using auxetic materials to enhance the screw-bone fixation. Yao et al. [162] proposed a group of novel auxetic bone screws based on the Re-entrant structures, chiral structures, and rotating structures, as shown in Fig. 10(a). Through the numerical simulation and experiment, the tensile properties of the bone screws were studied, and the results showed that the bone screw based on the Re-entrant hexagonal structure has the largest stiffness and strength. Further, Yao et al. [163] carried out a parameter optimization to adjust the structure of the microcell for a better pulling stiffness, as shown in Fig. 10(b). Their research shows that auxetic materials have a positive effect on bone screws; and the adjustment of micro-cell structures is of great significance for improving the mechanical properties of bone screws. Table 4 shows the summary of the application of auxetic materials on bone implants.

Negative Poisson's ratio bone implants effectively alleviate stress shielding and improve interface micromotion, but most studies are numerical optimizations or in vitro tensile tests, lacking long-term bone

integration and load-bearing data in large animal models [155,156]. The main assumption is uniform bone density, whereas clinical osteoporosis or defects exhibit significant variability. Although the benchmark modulus (0.1–4.5 GPa) and Poisson's ratio (0.2–0.3) of human cancellous bone partially match, the risk of stress shielding with bone resorption rates >20% after implantation still needs to be quantified compared to commercial titanium alloy implants (bone integration rate >90%, 10-year survival rate >95%). Fatigue fracture, loosening, and infection risk assessments are insufficient. Future work should conduct prospective clinical trials, combine patient bone density scans for personalized designs, and meet ISO 10993 long-term implantation standards.

3.3. Tissue engineering

Tissue engineering is usually defined as an interdisciplinary field that combines cell biology, materials science, and engineering technology. Its aim is to construct tissues or organs in vitro or in vivo and to restore the normal function of damaged organs [45]. The scaffolds used in tissue engineering should have good biocompatibility and mechanical properties to promote cell proliferation. As a promising emerging material, auxetic material can support tissue engineering in two aspects. First, it is considered that the structure of materials with the NPR effect may provide a more suitable surface and mechanical environment for cell attachment, which may be beneficial for cell proliferation [49–51].

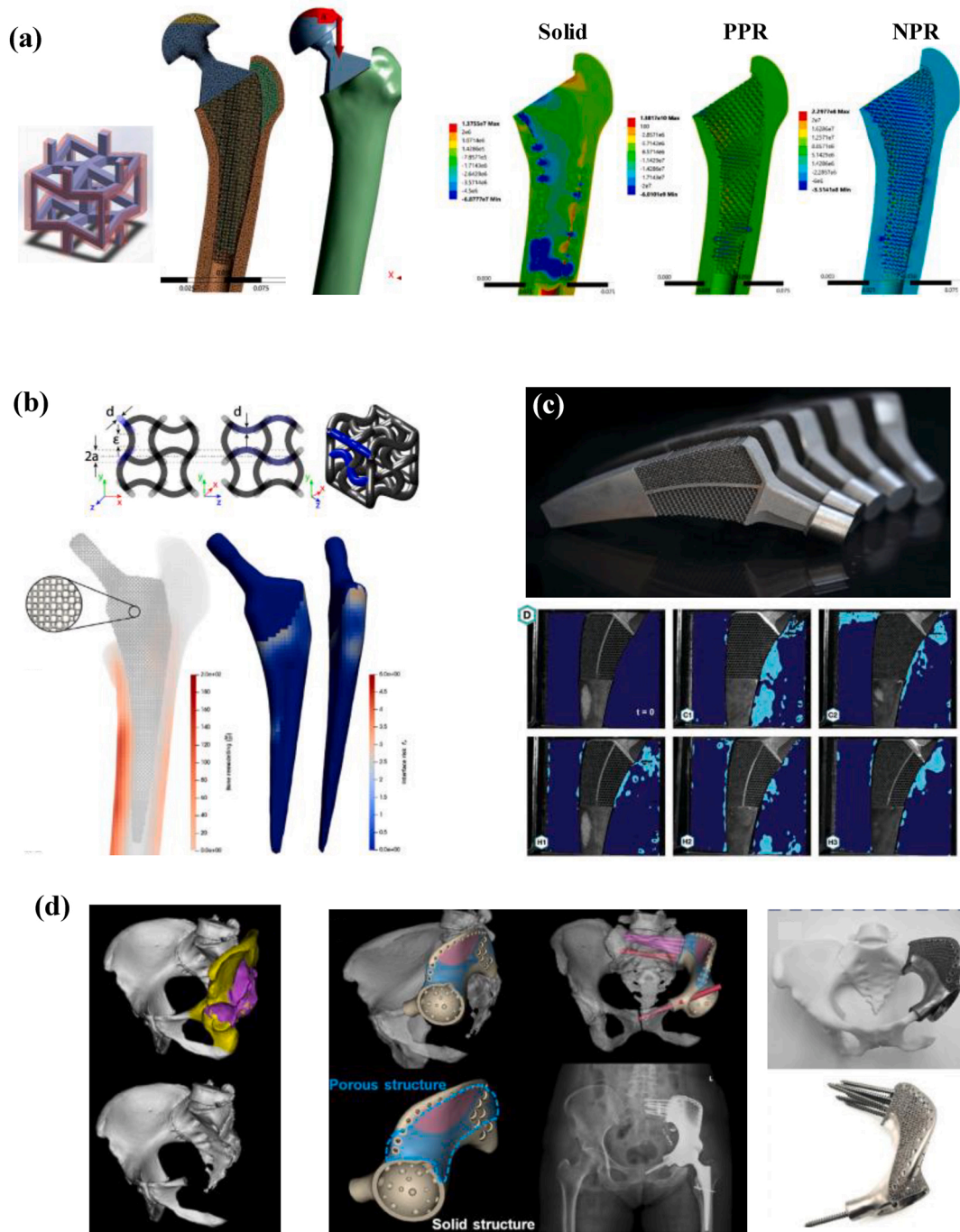


Fig. 9. Applications of auxetic materials in bone implants of hip arthroplasty. (a) A hip meta-implant with graded Poisson's ratio proposed by Ghavidelnia et al. [155]; (b) A parametric micro-architecture and the corresponding 3D titanium hip implant proposed by Garner et al. [156]; (c) A novel bone implant based on the hybrid meta-biomaterial proposed by Kolken et al. [157]; (d) Workflow for designing a 3D-printed auxetic custom hemipelvic prosthesis [159].

Second, the excellent mechanical properties of auxetic materials enable them to better simulate the host during *in vivo* service [164–167]. The following discussion first focuses on how auxetic scaffolds modulate cellular behavior at the microscale, and then examines their role in constructing functional tissues such as vasculature and skin.

The elastic modulus and Poisson's ratio of the scaffolds may significantly affect the biophysical properties of the 3-D microenvironment and accordingly improve cell adhesion and differentiation. Yan et al. [51] studied the influence of the mechanical properties of the scaffolds on the modulation of cellular differentiation, in which the auxetic scaffolds were used for the expansion and neural differentiation of mouse ESCs and hiPSCs. They fabricated a group of auxetic

polyurethane scaffolds with Poisson's ratios from 0 to -0.45 . Besides, additional polyurethane scaffolds with a PPR effect were included in the comparison. By comparison, the auxetic scaffolds were confirmed to support smaller aggregate formation and higher neuronal marker expression. Their study demonstrated that adjusting the microstructure to tune the elastic modulus and Poisson's ratio has the potential to improve the biophysical properties of the scaffold for tissue engineering. Tang et al. [50] fabricated and studied aerogels with different Poisson's ratios, as shown in Fig. 11. The mentioned CNF/PEGDA aerogels were fabricated by the stereolithography process with the mixture of cellulose nanofibers (CNFs) and polyethylene glycol diacrylate (PEGDA). By adjusting the scaffold structure, its Poisson's ratio can be well-tuned

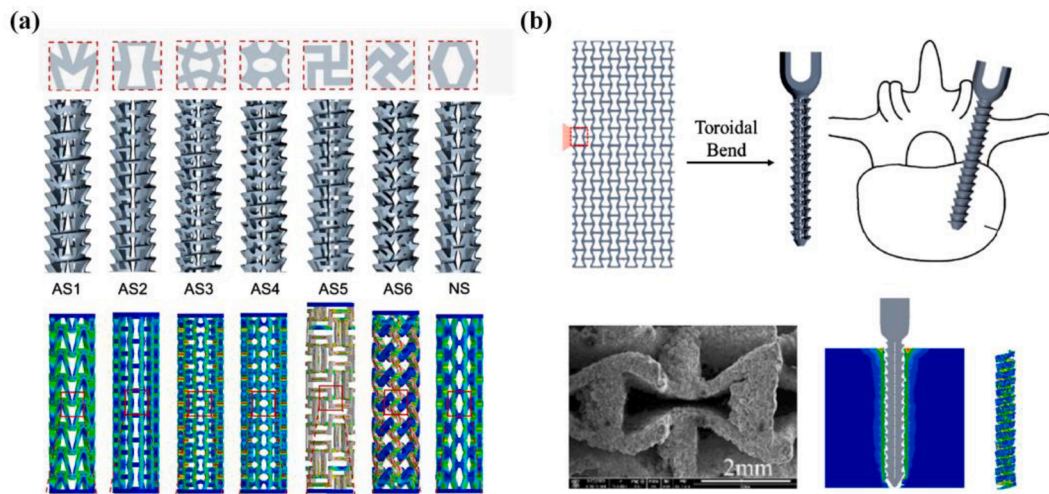


Fig. 10. Applications of the auxetic materials in bone screws. (a) Geometric configurations and the tensile simulation of the bone screws designed by Yao et al. [162]; Geometric configurations of the bone screw designed by Yao et al. [163], and its SEM image and tensile simulation.

from positive to negative. Different scaffolds with different Poisson's ratios were compared to analyze their chondrogenic induction characteristics. Their results found that the auxetic scaffolds can well provide a suitable cell growth condition and affect the proliferation and chondrogenic induction of mouse bone marrow mesenchymal stem cells. Chen et al. [49] developed six NPR polyurethane (PU) foams with different mechanical properties including Young's modulus and Poisson's ratio, and their surfaces were decorated with chitosan or heparin to obtain an improved cell adhesion. The neural differentiation of human induced pluripotent stem cells (hiPSCs) on the NPR foams was analyzed. Their results verified that the mechanical properties related to the form of pore structures can significantly affect cell differentiation.

The auxetic material can also improve the mechanical properties of the scaffolds in tissue engineering. Vascular grafts are a type of medical device used to replace human blood vessels and to maintain normal blood circulation. Ahn et al. [164] designed a novel additive manufacturing system and then fabricated an auxetic three-layer vascular scaffold, as shown in Fig. 12. The intima layer and the adventitia layer of the scaffold are made of nanoscale/microsized electrospun fibers, and the tunica media of the scaffold with auxetic effect is fabricated by the designed printing system. They found that the scaffold with auxetic effect shows superior flexibility when compared with the PPR scaffold. Besides, with the auxetic scaffolds, the endothelial cell and the smooth muscle cell showed better proliferation. Except for vascular grafts, auxetic materials also have the potential to improve the mechanical properties of scaffolds in bone tissue engineering [168,169]. The porous structure of the auxetic material can provide good lightweight performance, and its NPR effect can also provide an enhanced energy absorption ability. By adjusting or optimizing the geometric parameters and the relative density of the auxetic material, the impact resistance or energy absorption performance of the bone scaffold can be well improved.

Besides, auxetic materials are also widely used in the treatment of skin injuries, i.e., used for skin tissue engineering. Traditional skin transplantation has significant limitations in terms of expansion and is difficult to apply to large-scale skin injuries. By cutting the skin into a mesh pattern, the area of the skin graft can be well expanded. Some research groups have introduced auxetic materials into the skin tissue engineering to improve the expansion rate of skin grafts [166,167,170,171]. Gupta et al. [167] proposed eight different incision patterns with auxetic effect, including RE structures, chiral structures and perforated panel structures. Uniaxial and biaxial tensile tests were performed to analyze the deformation and stress of the eight skin grafts. The results found that the RE structure and rotating triangle structure show

significantly high expansions. Besides, they also studied a series of perforated plate structures used for skin grafts [166]. Table 5 shows the summary of the application of auxetic materials on tissue engineering.

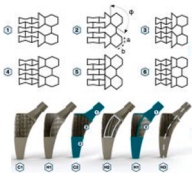
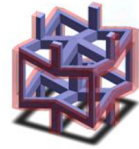
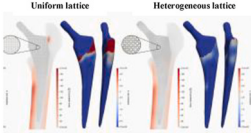
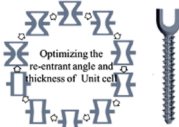
Negative Poisson's ratio scaffolds [49–51] promote cell adhesion, differentiation, and proliferation, but experiments are mostly limited to in vitro 2D/3D cultures or small-scale induction, lacking long-term validation in complex physiological environments. Assumptions are made about uniform external loads, whereas dynamic stresses and bodily fluids in vivo have significant effects. Clinical benchmarks include matching the modulus of natural tissues (cartilage 10–100 MPa, blood vessels 0.1–1 MPa) and a cell viability rate >90%, yet few current studies quantify neural/cartilage induction efficiency compared to commercial collagen scaffolds. Applications for skin expansion (such as the incision pattern in Gupta et al. [166]) have improved expansion rates, but risks of healing scars and infections have not been fully assessed. Translational challenges include large-scale manufacturing and GMP standards, and future studies require validation of functional recovery in large animal ectopic/in situ transplantation trials.

3.4. Organ patches

Organ patches typically refer to hydrogel or fabric patches, a type of biocompatible structure used to repair diseased organs. In a broad sense, the organ patches belong to the range of tissue engineering. Considering that organ patches usually refer to a type of special repair tool that fits closely to the surface of organs, different from vascular or bone scaffolds, we will discuss them separately in this section. In the past two decades, there has been a notable rise in the advancement and utilization of organ patches for enhancing the repair and regeneration of human organs. These patches have been applied to various medical purposes, including addressing myocardial infarction, cancer, and chronic wound healing [173–175]. Especially, the organ patches of the heart and lung have received widespread attention.

Auxetic patches show a dome shaped bending mode, unlike the saddle shape of conventional materials, enabling better adaptation to dynamic organs. Cardiac patches are a type of promising medical device for myocardial infarction [176–178]. The normal PPR material usually shows a saddle-shaped bending mode, which is difficult to adapt to the cardiac surface. Considering this point, the auxetic material may have significant superiority due to its dome-shaped bending mode. Olvera et al. [53] fabricated a novel cardiac patch that meets the mechanical characteristics of the human myocardium. The auxetic patches possess the capacity to accommodate the strains and stresses experienced by the human myocardium throughout both diastole and systole. Besides, the

Table 4
Summary of the application of auxetic materials on bone implants.

Configurations	Characteristics	Quantitative indicators	Ref.
	●Designing and comparing six different hybrid meta-biomaterials and corresponding bone implants; ●Conducting simulations and experiments in a biomechanical environment; ●Improving the contact between implants and bones.	E [30,50]: MPa	Kolken et al. [157]
	●Driving the elastic constants of a classic RE auxetic material; ●Comparing three implants by PPR, NPR and graded material; ●Numerical results illustrate that the introduction of auxetic material can alleviate the stress shielding problem; ●The proposed graded lattice material shows the best local stress performance.	Stress: PPR: [-11.6, 3.3]10 ⁸ Pa; NPR: [-6.0, 14]10 ⁹ Pa; Graded: [-3.5, 2.3]10 ⁸ Pa.	Ghavidelnia et al. [155]
	●Designed a novel parametric micro-architected material with highly adjustable mechanical properties; ●Proposed a parameter optimization method for alleviating load-induced interface fracture post-operative bone remodeling ●Performing a parameter optimization in a specific hip implant.	Interface risk: Solid: 5.85; Optimized lattice: 5.08.	Garner et al. [156]
	●Proposed a novel bone screw based on RE structure; ●Studied the pullout mechanical properties by the finite element model; ●Auxetic effect can effectively improve the fixation performance of screws.	Pullout forces: [1000, 1200]N.	Yao et al. [163]
	●Studied and compared several auxetic bone screws by experimental and numerical methods; ●Auxetic cell shows a great effect on the functional properties of bone screws.	Pullout forces: Low-density bone: about 350 N; Mid-density bone: about 400 N; High-density bone: about 1000 N.	Yao et al. [162]

mechanical properties of the cardiac patch can be fine-tuned to reflect anisotropy for better adaptability. How to enhance the dynamic mechanical properties of the patch structures is also one challenge of organ patches. Chansoria et al. [52] designed a double-layered, hydrogel-based patch platform that is expected to meet the auxetic and anisotropic features of the human dynamic organs, as shown in Fig. 13 (a). Combining the computational and experimental methods, they obtained a design law for improving the organ patch to suit the dynamics of the human organs. The in vitro and in vivo experiments proved that the auxetic patches have superior dynamic performance. Kapnisi et al. [54] designed a novel cardiac patch using the Re-entrant structure, as shown in Fig. 13(b). They used the process of excimer laser microablation to characterize the honeycomb geometry. The results confirmed that compared with the patches without auxetic structure, the auxetic patches showed superior mechanical adaptability. Table 6 shows the summary of the application of auxetic materials on organ patches.

Negative Poisson's ratio organ patches (such as bilayer cardiac hydrogels or Re-entrant structured patches, Chansoria et al. [52], Kapnisi et al. [54], and Olvera et al. [53]) exhibit excellent dome-shaped bending and anisotropy, adapting to dynamic myocardial strain. However, studies are mainly based on ex vivo mechanical tests or small animal myocardial infarction models, lacking electrophysiological integration and long-term anti-fibrotic data. They assume ideal adhesion, while clinical cardiac surface curvature and contractile forces vary widely (diastolic/systolic modulus 10–500 kPa, strain >40%). Benchmarks for commercial cardiac patches (such as >20% survival improvement and no significant foreign body reaction) have not been directly compared, with notable risks of immune rejection and patch detachment. Manufacturing scalability and FDA-approved materials (such as degradable hydrogels) remain bottlenecks. Future work requires validation in chronic myocardial infarction models in pigs/sheep and integration of conductive elements to achieve synchronized

contraction.

3.5. Biomedical sensors

Biomedical sensors are a special type of sensor that can perceive specific information within an organism, such as physiological parameters, biomarkers, etc. [179,180]. Among them, wearable sensors have become one of the most widely concerned biomedical sensors over the last decade, which can be affixed onto the skin surface to perceive various signals [181–183]. Numerous types of these wearable sensors have been documented in scientific literature during recent years encompassing electromyograms for muscle activity monitoring, electroencephalograms for brainwave analysis, tactile sensors for touch perception, chemical sensors capable of detecting specific substances and temperature sensing capabilities [116,181,184,185]. This type of sensor is required to have good adhesion to the skin to maintain good stability in different states of the human body [184]. Auxetic designs contribute to wearable sensors in two distinct aspects: improving skin-device interface stability and enhancing sensing performance. Deng et al. [186] proposed an innovative dual-phase metamaterial that exhibits a broad range of adaptable mechanical characteristics. They affixed the sensors onto the surface of human skin and effectively tracked human signals. Kim et al. [187] designed a novel hygroscopic sensor by introducing the auxetic chiral structure to improve the adaptability of the traditional sensors. Based on the proposed design, they produced a haptic device and an electrocardiogram sensor. Benefiting from the outstanding mechanical properties of the auxetic material, the designed sensors exhibited consistent detection capabilities in diverse settings, including physical activities, immersion in water, exposure to highly concentrated salt water, and prolonged periods of continuous usage.

In the field of biomedical engineering, improving the sensitivity and

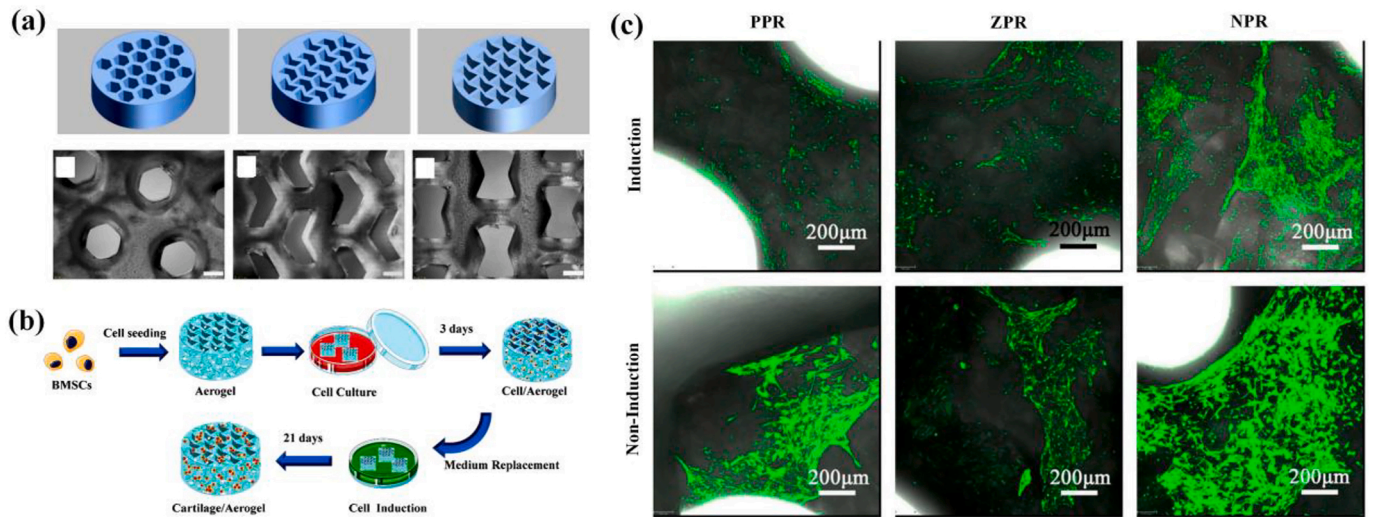


Fig. 11. Tissue engineering scaffolds with tunable Poisson's ratios proposed by Tang et al. [50]. (a) Geometric configurations of the scaffolds with different Poisson's ratios; (b) Culture and induction of cells; (c) Confocal laser scanning microscopy.

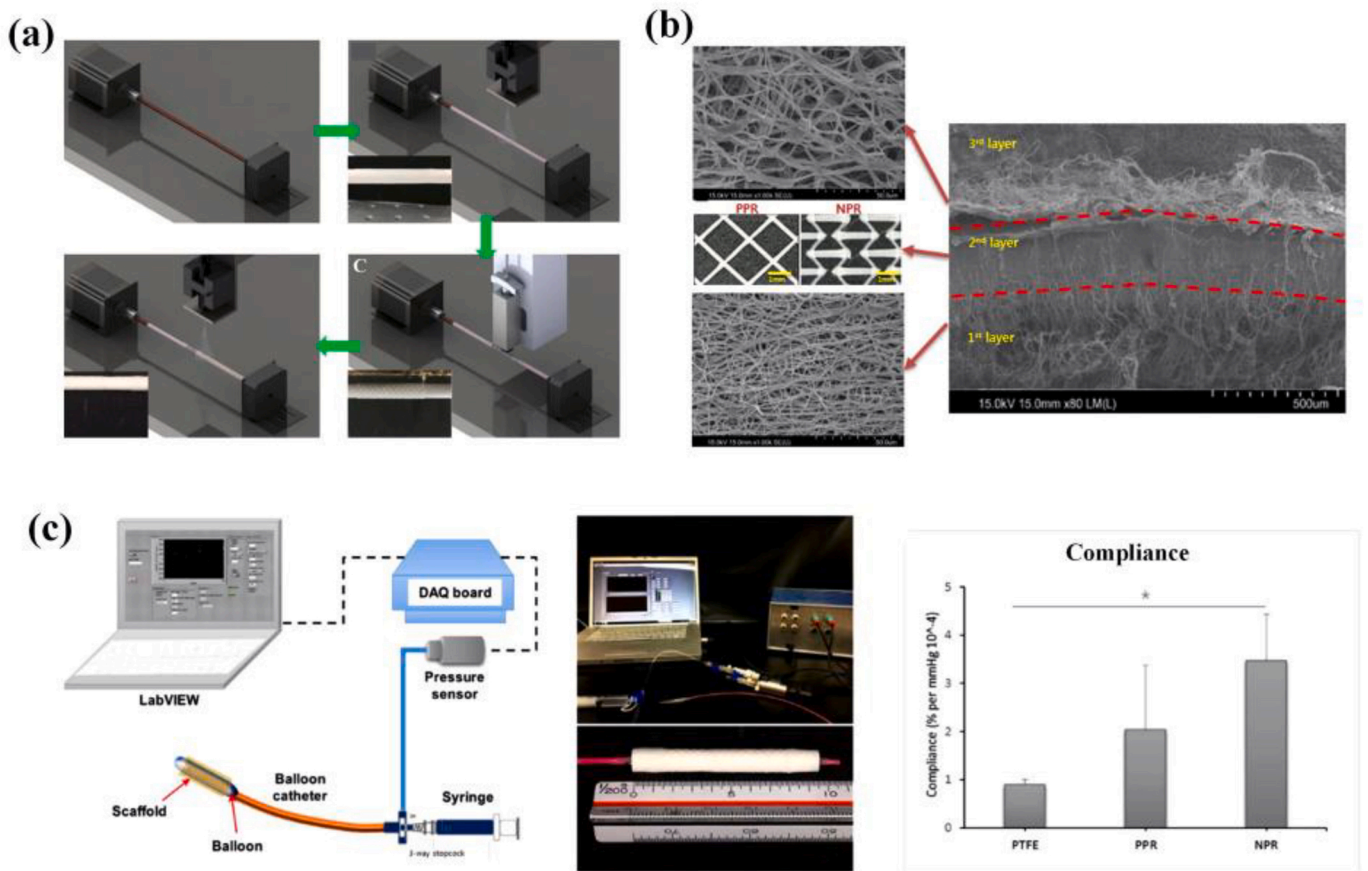
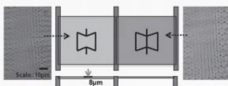
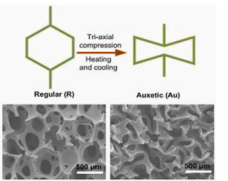
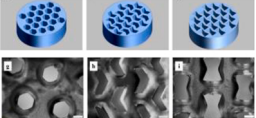
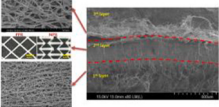


Fig. 12. Research of an auxetic three-layer vascular scaffold designed by Ahn et al. [164]. (a) Fabrication process of the tubular vascular scaffold; (b) SEM images of the fabricated scaffold; (c) Compliance measurement and the results of the scaffold.

detection range of sensors is one of the main challenges. Due to the constraints posed by flexible sensors including limited sensing range and inadequate linearity, it remains challenging to employ a monolayer sensor for extensive monitoring and collection of motion data. Gao et al. [188] proposed a new composite sensor with circumferential auxetic material. They found that the composite auxetic sensor showed enhanced capabilities in terms of sensor range, linear range, and

sensitivity. Besides, they also obtained the analytical relationship between the geometric parameters and the structural deformation, which can be used to guide structural optimization. Jiang et al. [189] proposed to introduce the auxetic material to the stretchable strain sensors to improve their sensor sensitivity. They attributed the increase in sensitivity of the sensor to a decrease in Poisson's ratio and strain concentration. Table 7 shows the summary of the application of auxetic

Table 5
Summary of the application of auxetic materials on tissue engineering.

Configurations	Characteristics	Quantitative indicators	Ref.
	●Suspended web structures with PPR and NPR effects are fabricated; ●Unusual cell division is found on the structure with the NPR effect.	Cell movements: NPR: up to 15 μm ; PPR: about 2 μm .	Zhang et al. [172]
	●Study the effect of Poisson's ratio on the neural cell differentiation; ●Analyze the influence of pore structure, Poisson's ratio, and elastic modulus of the auxetic scaffolds; ●Combining pore structure, Poisson's ratio, and elastic modulus can obtain more diversified ranges of biophysical 3-D microenvironments.	Cell numbers: NPR: about 7.0×10^5 ; PPR: about 5.5×10^5 .	Yan et al. [51]
	●Fabricated a group of nano cellulose aerogels with PPR, ZPR and NPR Poisson's ratios; ●Obtained aerogel scaffold by the freeze-drying method; ●The NPR scaffold shows a good favorable biomechanical environment.	Absorbance value: NPR: about 1.5; ZPR: about 0.7; PPR: about 0.2.	Tang et al. [50]
	●Designed and fabricated an auxetic three-layer scaffold; ●Showing a higher compliance property than the PPR scaffold; ●The cells inside the scaffold survived well within 10 days.	Compliance: NPR: about 3.4; PPR: about 2.0. Cell survival rate: Larger than 90%.	Ahn et al. [164]

materials on biomedical sensors.

Auxetic sensors significantly enhance sensitivity, detection range, and skin adhesion, but most tests are conducted in vitro under stretching/bending conditions, lacking long-term stability data during continuous human movement [186,188,190]. Assuming a clean skin environment, sweat, friction, and biological contamination can easily cause signal drift. Although some commercial wearable sensor benchmarks (e.g., strain gauge factor $GF > 10$, linear range $>50\%$, continuous wear >7 days with accuracy $>95\%$) are partially surpassed, evaluations of biocompatibility (skin irritation, allergies) and waterproof/durability are insufficient. Clinical applications need to comply with IEC 60601 medical device standards and HIPAA data privacy. Future research should conduct human trials to verify the reliability of multimodal signals (such as ECG/EMG) in motion/wet scenarios and explore self-powered integration.

Table 8 summarizes the key information of the five major application fields, facilitating quick retrieval and comparative analysis. It integrates typical configurations, core characteristics, key quantitative indicators, and representative references of stents, bone implants, tissue engineering, organ patches, and biomedical sensors, providing a holistic perspective to grasp the application landscape of auxetic materials in biomedicine. **Table 8** shows the consolidated summary of auxetic material applications in biomedicine.

4. Future outlook for auxetics in biomedical engineering

1. Mechanical metamaterials utilize cell design to achieve target mechanical behaviors. The enhanced Re-entrant or chiral structures with superior performance have been extensively reported. However, current research predominantly focuses on enhancing mechanical

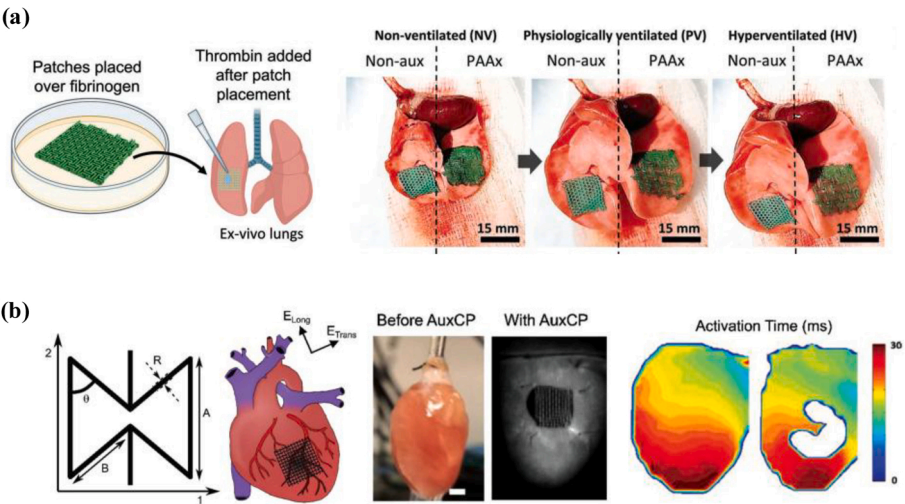


Fig. 13. Auxetic/non-auxetic patches designed and fabricated by Chansoria et al. [52]; Cardiac patches based on the Re-entrant hexagonal structure designed by Kapnisi et al. [54].

Table 6
Summary of the application of auxetic materials on organ patches.

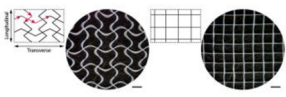
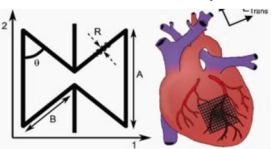
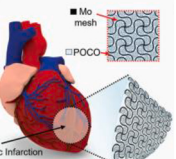
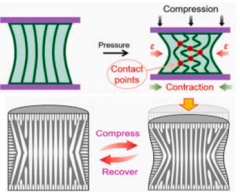
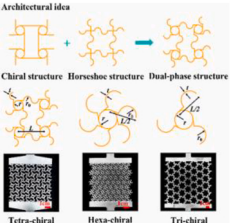
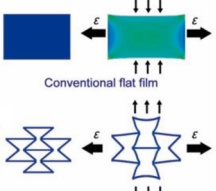
Configurations	Characteristics	Quantitative indicators	Ref.
	●Fabricated a novel electroconductive cardiac patch with auxetic effect; ●The patch is capable of accommodating the strains and stresses manifested by the human myocardium during both diastole and systole.	Conductivity: Square: about 2.8 S/m; Auxetic: [2, 2.5] S/m.	Olvera et al. [53]
	●Introduced an auxetic cardiac patch for the treatment of myocardial infarction; ●The patch exhibits a wide range of mechanical strength and anisotropy; ●Compliant native cardiac movements.	Conductivity: Unpatterned: about $13.5 \times 10^{-2} \text{ S} \cdot \text{cm}^{-1}$; Auxetic: about $9.2 \times 10^{-2} \text{ S} \cdot \text{cm}^{-1}$ (x) and about $3.2 \times 10^{-2} \text{ S} \cdot \text{cm}^{-1}$ (y).	Kapnisi et al. [54]
	●Proposed a composite cardiac patch combining bioresorbable metals and polymers; ●Showing high conductive and elastic mechanical properties.	Resistance: Proposed design: 1.1 Ω ; Previous works: [30, 5000] Ω .	Ryu et al. [178]

Table 7
Summary of the application of auxetic materials on biomedical sensors.

Configurations	Characteristics	Quantitative indicators	Ref.
	●Introducing an applicable methodology for fabricating anisotropic porous foams with an NPR effect; ●Auxetic metastructures enhance the sensitivity and sensing reliability of sensors due to the improvement of wall contact; ●Improving the elasticity and compression properties;	S: [-0.0054, -5.4]kPa ⁻¹ .	Liu et al. [190]
	●Designing and fabricating a dual-phase metamaterial with wide and programmable mechanical properties; ●With stable monitoring ability; ●Application on monitoring the physiological signals under various actions;	GF: [2,16].	Deng et al. [186]
	●Improving the sensitivity of the Stretchable strain sensors by introducing the auxetic materials, with a 24-fold improvement.	GF: Auxetic: 830; pillar, square, and flat: less than 100.	Jiang et al. [189]

Note that the S is the piezoresistive sensitivity and GF is the gauge factor used to describe the sensitivity.

properties including stiffness and strength [20,80]. Innovative designs pertaining to auxetic materials within the biomedical field hold tremendous promise. For instance, by incorporating additional structures with the traditional cell, it is possible to maintain the NPR effect and rigidity of the auxetic structure along one direction while simultaneously augmenting the flexibility along another direction [21,23], which may be beneficial for implantable medical devices.

2. Additive manufacturing plays a pivotal role in the investigation of auxetic materials, owing to its exceptional performance in intricate structural formation [13]. Extending this to 4D printing using shape-memory or stimulus-responsive material could enable auxetic devices to actively change shape or performance after implantation (such as scaffolds that self-expand at body temperature or pH-responsive scaffolds). This approach can reduce the need for auxetic deployment tools, improve minimally invasive surgery outcomes, and open up new possibilities for adaptive implants [191–193]. These materials typically exhibit significant deformability and mechanical responsiveness to environmental stimuli, greatly promoting the implantation of medical stents that require deployment after reaching the desired position. This inherent capacity for automatic response deformation also significantly obviates the need for superfluous auxetic mechanical equipment.
3. Advanced numerical calculation methods are extensively employed for assessing the nonlinear and intricate mechanical properties of medical equipment [140,194]. This high-resolution simulation facilitates designers in conducting preliminary evaluations of medical equipment before costly experiments, providing detailed distributions of mechanical responses encompassing stress and strain parameters. Furthermore, advanced optimization algorithms can be integrated to iteratively optimize structural parameters. However, the investigation into comprehensive numerical models incorporating auxetic materials with biological tissue structural mechanics, fluid dynamics, and other domains remains relatively limited. In addition, through advanced medical imaging technology and 3D tissue reconstruction [195,196], patient-personalized biomechanical numerical simulations can be conducted [197–201]. Combined with additive manufacturing technology, the auxetic materials are expected to be well used for personalized treatment.
4. The in vivo operation of biomedical devices usually necessitates the integration of multiple functionalities, including repair, sensing, and self-power supply [202,203]. Biomedical devices that can seamlessly incorporate these diverse functions hold immense potential. In this context, auxetic materials with unique deformation modes and exceptional mechanical properties offer a robust mechanical support

Table 8
Consolidated summary of auxetic material applications in biomedicine.

Application Field	Performance requirements	Typical Configurations	Ref.
Stents	1Radial strength > 0.2 N/mm, fatigue life > 10 ⁷ cycles (under physiological pulsatile loads), restenosis rate < 10% within 1 year, thrombosis incidence < 1%. 2Must match arterial mechanical properties and adapt to patient-specific plaques, vessel curvature, and pulsatile loads. Clinical translation requires compliance with FDA/ISO 10993 biocompatibility standards.	Anti-tetrachiral, Re-entrant chiral, Double-arrowhead, Hybrid auxetic structures	[21,47,120,122,123,134–137]
Bone Implants	1Elastic modulus matching human cancellous bone (0.1–4.5 GPa), Poisson's ratio matching (0.2–0.3), to reduce stress shielding (bone resorption rate > 20% after implantation needs quantitative control). 2Bone integration rate > 90%, 10-year survival rate > 95%, with assessment of fatigue fracture, loosening, and infection risks. Must meet ISO 10993 long-term implantation standards	Graded Poisson's ratio lattices, Hybrid meta-biomaterials, Re-entrant, Chiral structures	[154–157]
Tissue Engineering	1Elastic modulus matching natural tissues, cell viability rate > 90%, and quantification of neural/cartilage induction efficiency. 2Provide a favorable 3D microenvironment for cell adhesion, proliferation, and differentiation, with long-term stability in complex physiological environments. Large-scale manufacturing must comply with GMP standards.	PU foams, CNF/PEGDA aerogels, 3D printed porous structures with tunable ν	[49–51,168,169].
Organ Patches	1Adapt to dynamic myocardial strain (diastolic/systolic modulus 10–500 kPa, strain > 40%), improve survival rate > 20%, with no significant foreign body reaction or immune rejection. 2Require dome-shaped bending and anisotropy to match organ surface curvature, with scalable manufacturing and use of FDA-approved materials.	Re-entrant honeycomb, Anisotropic/bilayer hydrogel patches	[52,53,176–178]
Biomedical Sensors	1High sensitivity (Gauge Factor GF > 10), linear detection range > 50%, continuous wear > 7 days with accuracy > 95%. 2Possess biocompatibility (no skin irritation or allergies), waterproofness, and durability, with stable signals under motion/wet conditions. Clinical applications must comply with IEC 60601 medical device standards and HIPAA data privacy.	Chiral structures, Dual-phase metamaterials, Circumferential NPR designs	[186,188,189]

platform for embedding complex sensors. By leveraging the advanced triboelectric nanogenerator (TENG) [204–206], these devices can achieve a self-sustained power supply during operation without any external power supply required. However, further advancements in this domain still warrant extensive exploration.

5. Conclusion

This review focuses on the latest advancements in auxetic materials within the biomedical field. These examples demonstrate that auxetic materials can enhance the utilization of biomedical equipment through improvements in mechanical properties and biocompatibility. Through the analysis of the current research status, several highly promising avenues for development are listed, including biomedicine-driven structural innovations, 4D printing techniques, structure-tissue coupling and patient-personalized numerical modeling, and integrated biomedical equipment with multi-functionality. It is anticipated that the auxetic material will open a new era in the biomedical field.

CRediT authorship contribution statement

Qiang Gao: Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yang Zhou:** Writing – original draft, Software, Resources, Funding acquisition, Formal analysis, Conceptualization. **Zhou Li:** Writing – review & editing, Project administration, Formal analysis, Conceptualization.

Declaration of competing interest

The author Zhou Li is an associate editor for Smart Materials in Medicine and was not involved in the editorial review or the decision to publish this article.

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References

[1] D. Smith, J. Pendry, M. Wiltshire, Metamaterials and negative refractive index, *Science* 305 (5685) (2004) 788–792.
[2] Y. Liu, X. Zhang, Metamaterials: a new frontier of science and technology, *Chem. Soc. Rev.* 40 (5) (2011) 2494–2507.
[3] B. Wu, W. Jiang, J. Jiang, et al., Wave manipulation in intelligent metamaterials: recent progress and prospects, *Adv. Funct. Mater.* 34 (29) (2024) 2316745.
[4] J. Fan, L. Zhang, S. Wei, et al., A review of additive manufacturing of metamaterials and developing trends, *Mater. Today* 50 (2021) 303–328.
[5] W. Ji, J. Chang, H.X. Xu, et al., Recent advances in metasurface design and quantum optics applications with machine learning, physics-informed neural networks, and topology optimization methods, *Light Sci. Appl.* 12 (1) (2023) 169.
[6] E. Dong, P. Cao, J. Zhang, et al., Underwater acoustic metamaterials, *Natl. Sci. Rev.* 10 (6) (2023) nwac246.
[7] R. Kovács, Heat equations beyond Fourier: from heat waves to thermal metamaterials, *Phys. Rep.* 1048 (2024) 1–75.
[8] C. Zhu, E.A. Bamidele, X. Shen, et al., Machine learning aided design and optimization of thermal metamaterials, *Chem. Rev.* 124 (7) (2024) 4258–4331.
[9] P. Sinha, T. Mukhopadhyay, Programmable multi-physical mechanics of mechanical metamaterials, *Mater. Sci. Eng. R Rep.* (2023) 155.
[10] P. Jiao, J. Mueller, J.R. Raney, et al., Mechanical metamaterials and beyond, *Nat. Commun.* 14 (1) (2023) 6004.
[11] R. Xu, C. Chen, J. Sun, et al., The design, manufacture and application of multistable mechanical metamaterials—a state-of-the-art review, *Int. J. Extrem. Manuf.* 5 (4) (2023) 42013.
[12] X. Zheng, X. Zhang, T.T. Chen, et al., Deep learning in mechanical metamaterials: from prediction and generation to inverse design, *Adv. Mater.* 35 (45) (2023).
[13] W.T. Nugroho, Y. Dong, A. Pramanik, et al., Additive manufacturing of re-entrant structures: well-tailored structures, unique properties, modelling approaches and real applications, *Addit. Manuf.* 78 (2023) 103829.
[14] P.M. Balan, A.J. Mertens, M.V.A.R. Bahubalendruni, Auxetic mechanical metamaterials and their futuristic developments: a state-of-art review, *Mater. Today Commun.* 34 (2023) 105285.
[15] X. Li, W. Peng, W. Wu, et al., Auxetic mechanical metamaterials: from soft to stiff, *Int. J. Extrem. Manuf.* 5 (4) (2023) 42003.
[16] U. Veerabagu, H. Palza, F. Quero, Review: auxetic polymer-based mechanical metamaterials for biomedical applications, *ACS Biomater. Sci. Eng.* 8 (7) (2022) 2798–2824.
[17] R. Lakes, Foam structures with a negative poisson's ratio, *Science* 235 (4792) (1987) 1038–1040.

- [18] E. Etemadi, A.M.M. Zamani, F. Scarpa, et al., Modified re-entrant auxetic metamaterials with energy absorption enhancement, *Mater. Today Commun.* 38 (2024) 108079.
- [19] C. Qi, F. Jiang, S. Yang, Advanced honeycomb designs for improving mechanical properties: a review, *Compos. B Eng.* 227 (2021) 109393.
- [20] Y. Chen, M. Fu, H. Hu, et al., Curved inserts in auxetic honeycomb for property enhancement and design flexibility, *Compos. Struct.* 280 (2022) 114892.
- [21] Y. Zhou, Y. Pan, B. Sun, et al., Mechanical properties of an improved flexible auxetic metamaterial and its application in self-expanding vascular stents, *Eur. J. Mech. Solid.* 106 (2024) 105345.
- [22] Y. Zhou, Y. Pan, Q. Gao, et al., In-Plane quasi-static crushing behaviors of a novel reentrant combined-wall honeycomb, *Journal of Applied Mechanics-Transactions of the ASME* 90 (5) (2023) 51002.
- [23] Y. Zhou, Y. Pan, L. Chen, et al., Study on the bending behaviors of a novel flexible Re-Entrant honeycomb, *Journal of Engineering Materials and Technology-Transactions of the ASME* 145 (4) (2023) 41006.
- [24] Y. Zhou, Y. Pan, L. Chen, et al., Mechanical behaviors of a novel auxetic honeycomb characterized by re-entrant combined-wall hierarchical substructures, *Mater. Res. Express* 9 (11) (2022) 115802.
- [25] Q. Hu, G. Lu, K.M. Tse, Compressive and tensile behaviours of 3D hybrid auxetic-honeycomb lattice structures, *Int. J. Mech. Sci.* 263 (2024) 108767.
- [26] X. Zhang, X. Zheng, L. Song, et al., Compressive properties and failure mechanisms of 3D-printed continuous carbon fiber-reinforced auxetic structures, *Compos. Commun.* 43 (2023) 101744.
- [27] Y. Yao, J.H. Park, L. Wang, et al., Design, fabrication and mechanical properties of a 3D re-entrant metastructure, *Compos. Struct.* 314 (2023) 116963.
- [28] F. Jiang, S. Yang, C. Qi, et al., Two plateau characteristics of re-entrant auxetic honeycomb along concave direction, *Thin-Walled Struct.* 179 (2022) 109665.
- [29] Y. Zhou, H. Wu, X. Zhong, et al., A novel honeycomb tube-combined metamaterial by a sequential arrangement strategy with designable dual-stage mechanical properties, *Thin-Walled Struct.* 219 (2026) 114262.
- [30] Y. Zhou, Y. Ding, Y. Pan, et al., Multi-pattern crushing properties of coupling-designed honeycombs based on a non-contact interweaving combination strategy, *Thin-Walled Struct.* 210 (2025) 113034.
- [31] S. Qin, X. Deng, F. Yang, et al., Energy absorption characteristics and negative Poisson's ratio effect of axisymmetric tetrachiral honeycombs under in-plane impact, *Compos. Struct.* 323 (2023) 117493.
- [32] D. Gao, C. Zhang, J. Zhang, Compressive behavior of a novel hexagonal nodes-based 3D chiral auxetic structure, *Appl. Sci.* 13 (14) (2023) 8480.
- [33] C. Qi, F. Jiang, C. Yu, et al., In-plane crushing response of tetra-chiral honeycombs, *Int. J. Impact Eng.* 130 (2019) 247–265.
- [34] D. Gao, C. Zhang, Theoretical and numerical investigation on in-plane impact performance of chiral honeycomb core structure, *J. Struct. Integrity Maint.* 3 (2) (2018) 95–105.
- [35] J. Plewa, M. Plonska, G. Junak, Studies of auxetic structures assembled from rotating rectangles, *Materials* 17 (3) (2024).
- [36] J. Plewa, M. Plonska, P. Lis, Investigation of modified auxetic structures from rigid rotating squares, *Materials* 15 (8) (2022) 2848.
- [37] J.N. Grima, K.E. Evans, Auxetic behavior from rotating squares, *J. Mater. Sci. Lett.* 19 (17) (2000).
- [38] F. Scarpa, P.J. Tomlin, On the transverse shear modulus of negative Poisson's ratio honeycomb structures, *Fatig. Fract. Eng. Mater. Struct.* 23 (8) (2000) 717–720.
- [39] I.I. Argatov, R. Guinovart-Díaz, F.J. Sabina, On local indentation and impact compliance of isotropic auxetic materials from the continuum mechanics viewpoint, *Int. J. Eng. Sci.* 54 (2012) 42–57.
- [40] M.B. Francisco, J.L.J. Pereira, G.A. Oliver, et al., A review on the energy absorption response and structural applications of auxetic structures, *Mech. Adv. Mater. Struct.* 29 (27) (2021) 5823–5842.
- [41] Y. Zhang, L. Yan, C. Zhang, et al., Low-velocity impact response of tube-reinforced honeycomb sandwich structure, *Thin-Walled Struct.* 158 (2021) 107188.
- [42] Z. Gan, Y. Zhuge, D.P. Thambiratnam, et al., Recent advances in auxetics: applications in cementitious composites, *Int. J. Prot. Struct.* 13 (2) (2022) 295–316.
- [43] H. Heo, J. Ju, D. Kim, Compliant cellular structures: application to a passive morphing airfoil, *Compos. Struct.* 106 (2013) 560–569.
- [44] S. Shukla, B.K. Behera, Auxetic fibrous materials and structures in medical engineering - a review, *J. Text. Inst.* 114 (7) (2023) 1078–1089.
- [45] Y. Kim, K.H. Son, J.W. Lee, Auxetic structures for tissue engineering scaffolds and biomedical devices, *Materials* 14 (22) (2021) 6821.
- [46] P. Mardling, A. Alderson, N. Jordan-Mahy, et al., The use of auxetic materials in tissue engineering, *Biomater. Sci.* 8 (8) (2020) 274–283.
- [47] H. Xue, Z. Luo, T. Brown, et al., Design of self-expanding auxetic stents using topology optimization, *Front. Bioeng. Biotechnol.* 8 (2020) 736.
- [48] M. Shirzad, A. Zolfagharian, M. Bodaghi, et al., Auxetic metamaterials for bone-implanted medical devices: recent advances and new perspectives, *Eur. J. Mech. Solid.* 98 (2023) 104905.
- [49] X. Chen, C. Liu, M. Wadsworth, et al., Surface engineering of auxetic scaffolds for neural and vascular differentiation from human pluripotent stem cells, *Adv. Healthcare Mater.* 12 (6) (2023).
- [50] A. Tang, J. Ji, J. Li, et al., Nanocellulose/PEGDA aerogels with tunable poisson's ratio fabricated by stereolithography for mouse bone marrow mesenchymal stem cell culture, *Nanomaterials* 11 (3) (2021) 603.
- [51] Y. Yan, Y. Li, L. Song, et al., Pluripotent stem cell expansion and neural differentiation in 3-D scaffolds of tunable Poisson's ratio, *Acta Biomater.* 49 (2017) 192–203.
- [52] P. Chansoria, J. Blackwell, E.L. Etter, et al., Rationally designed anisotropic and auxetic hydrogel patches for adaptation to dynamic organs, *Adv. Funct. Mater.* 32 (43) (2022).
- [53] D. Olvera, M. Sohrabi Molina, G. Hendy, et al., Electroconductive melt electrowritten patches matching the mechanical anisotropy of human myocardium, *Adv. Funct. Mater.* 30 (44) (2020).
- [54] M. Kapnsi, C. Mansfield, C. Marijon, et al., Auxetic Cardiac patches with tunable mechanical and conductive properties toward treating myocardial infarction, *Adv. Funct. Mater.* 28 (21) (2018).
- [55] V.A. Lvov, F.S. Senatov, A.A. Veveris, et al., Auxetic metamaterials for biomedical devices: current situation, main challenges, and research trends, *Materials* 15 (4) (2022) 1439.
- [56] M. Sun, X. Hu, L. Tian, et al., Auxetic biomedical metamaterials for orthopedic surgery applications: a comprehensive review, *Orthop. Surg.* 16 (8) (2024) 1801–1815.
- [57] D. Jiang, H. Thissen, T.C. Hughes, et al., Advances in additive manufacturing of auxetic structures for biomedical applications, *Mater. Today Commun.* 40 (2024) 110045.
- [58] L.J. Gibson, M.F. Ashby, G.S. Schajer, et al., The mechanics of two-dimensional cellular materials, *Proceedings Of The Royal Society Of London Series A-Mathematical Physical And Engineering Sciences* 382 (1782) (1982) 25–42.
- [59] X. Zhang, H. Hao, R. Tian, et al., Quasi-static compression and dynamic crushing behaviors of novel hybrid re-entrant auxetic metamaterials with enhanced energy-absorption, *Compos. Struct.* 288 (2022) 115399.
- [60] C. Qi, F. Jiang, S. Yang, et al., Multi-scale characterization of novel re-entrant circular auxetic honeycombs under quasi-static crushing, *Thin-Walled Struct.* 169 (2021) 108314.
- [61] M. Xu, D. Liu, P. Wang, et al., In-plane compression behavior of hybrid honeycomb metastructures: theoretical and experimental studies, *Aero. Sci. Technol.* 106 (2020) 106081.
- [62] C. Qi, F. Jiang, A. Remennikov, et al., Quasi-static crushing behavior of novel re-entrant circular auxetic honeycombs, *Compos. B Eng.* 197 (2020) 108117.
- [63] M. Xu, Z. Xu, Z. Zhang, et al., Mechanical properties and energy absorption capability of AuxHex structure under in-plane compression: theoretical and experimental studies, *Int. J. Mech. Sci.* 159 (2019) 43–57.
- [64] D. Li, J. Yin, L. Dong, et al., Strong re-entrant cellular structures with negative Poisson's ratio, *J. Mater. Sci.* 53 (5) (2018) 3493–3499.
- [65] A. Ingrole, A. Hao, R. Liang, Design and modeling of auxetic and hybrid honeycomb structures for in-plane property enhancement, *Mater. Des.* 117 (2017) 72–83.
- [66] G. Chen, Y. Cheng, P. Zhang, et al., Blast resistance of metallic double arrowhead honeycomb sandwich panels with different core configurations under the paper tube-guided air blast loading, *Int. J. Mech. Sci.* 201 (2021) 106457.
- [67] X. Lan, L. Meng, J. Zhao, et al., Mechanical properties and damage characterizations of 3D double-arrowhead auxetic structure with high-relative-density realized via selective laser melting, *Eur. J. Mech. Solid.* 90 (2021) 104386.
- [68] U.D. Larsen, O. Sigmund, S. Bouwstra, Design and fabrication of compliant micromechanisms and structures with negative Poisson's ratio, *J. Microelectromech. Syst.* 6 (2) (1997) 99–106.
- [69] J.P. Lang, D. Han, X.G. Zhang, et al., A star-shaped tubular structure with multiple-directional auxetic effect, *Thin-Walled Struct.* 193 (2023) 111247.
- [70] V. Sindelić, A. Nikolić, G. Minak, et al., An improved 2D arc-star-shaped structure with negative Poisson's ratio: in-plane analysis, *Mater. Today Commun.* 37 (2023) 107593.
- [71] J.N. Grima, R. Gatt, A. Alderson, et al., On the potential of connected stars as auxetic systems, *Mol. Simul.* 31 (13) (2005) 925–935.
- [72] R. Lakes, Deformation mechanisms in negative Poisson's ratio materials - structural aspects, *J. Mater. Sci.* 26 (9) (1991) 2287–2292.
- [73] A. Alderson, K.L. Alderson, D. Attard, et al., Elastic constants of 3-, 4- and 6-connected chiral and anti-chiral honeycombs subject to uniaxial in-plane loading, *Compos. Sci. Technol.* 70 (7) (2010) 1042–1048.
- [74] J.N. Grima, R. Gatt, A. Alderson, et al., On the auxetic properties of 'rotating rectangles' with different connectivity, *J. Phys. Soc. Jpn.* 74 (10) (2005) 2866–2867.
- [75] F. Meng, S. Chen, W. Zhang, et al., Negative Poisson's ratio in graphene Miura origami, *Mech. Mater.* 155 (2021) 103774.
- [76] M. Schenk, S.D. Guest, Geometry of Miura-folded metamaterials, *Proc. Natl. Acad. Sci.* 110 (9) (2013) 3276–3281.
- [77] K. Billon, I. Zampetakis, F. Scarpa, et al., Mechanics and band gaps in hierarchical auxetic rectangular perforated composite metamaterials, *Compos. Struct.* 160 (2017) 1042–1050.
- [78] X. Tian, W. Chen, R. Gao, et al., Design of pore layout for perforated auxetic metamaterials with low-frequency band gaps, *APEX* 13 (4) (2020) 45503.
- [79] D. Prall, R.S. Lakes, Properties of a chiral honeycomb with a Poisson's ratio of -1, *Int. J. Mech. Sci.* 39 (3) (1997) 305–313.
- [80] J. Pan, Q. Zhang, M. Li, et al., A novel misplaced reinforced honeycomb with in-plane bidirectional enhancement, *Int. J. Mech. Sci.* 270 (2024) 109088.
- [81] Z. Chen, J. Li, B. Wu, et al., Enhanced mechanical properties of re-entrant auxetic honeycomb with self-similar inclusion, *Compos. Struct.* 331 (2024) 117921.
- [82] K. Meena, S. Singamneni, Novel hybrid auxetic structures for improved in-plane mechanical properties via additive manufacturing, *Mech. Mater.* 158 (2021) 103890.

- [83] H. Lu, X. Wang, T. Chen, In-plane dynamics crushing of a combined auxetic honeycomb with negative Poisson's ratio and enhanced energy absorption, *Thin-Walled Struct.* 160 (2021) 107366.
- [84] M. Hazrat Ali, S. Batai, D. Karim, Material minimization in 3D printing with novel hybrid cellular structures, *Mater. Today Proc.* 42 (2021) 1800–1809.
- [85] L. Wei, X. Zhao, Q. Yu, et al., Quasi-static axial compressive properties and energy absorption of star-triangular auxetic honeycomb, *Compos. Struct.* 267 (2021) 113850.
- [86] L. Wei, X. Zhao, Q. Yu, et al., A novel star auxetic honeycomb with enhanced in-plane crushing strength, *Thin-Walled Struct.* 149 (2020) 106623.
- [87] K.P. Logakannan, V. Ramachandran, J. Rengaswamy, et al., Quasi-static and dynamic compression behaviors of a novel auxetic structure, *Compos. Struct.* 254 (2020) 112853.
- [88] H. Wang, Z. Lu, Z. Yang, et al., In-plane dynamic crushing behaviors of a novel auxetic honeycomb with two plateau stress regions, *Int. J. Mech. Sci.* 151 (2019) 746–759.
- [89] H. Wang, Z. Lu, Z. Yang, et al., A novel re-entrant auxetic honeycomb with enhanced in-plane impact resistance, *Compos. Struct.* 208 (2019) 758–770.
- [90] M.S. Tathier, M. öztürk, T. Baran, Linear and non-linear in-plane behaviour of a modified re-entrant core cell, *Eng. Struct.* 234 (2021) 111984.
- [91] N. Xu, H. Liu, M. An, et al., Novel 2D star-shaped honeycombs with enhanced effective Young's modulus and negative Poisson's ratio, *Extreme Mech. Lett.* 43 (2021) 101164.
- [92] T. Baran, M. öztürk, In-plane elasticity of a strengthened re-entrant honeycomb cell, *Eur. J. Mech. Solid.* 83 (2020) 104037.
- [93] Z. Chen, X. Wu, Y.M. Xie, et al., Re-entrant auxetic lattices with enhanced stiffness: a numerical study, *Int. J. Mech. Sci.* 178 (2020) 105619.
- [94] X. Li, Q. Wang, Z. Yang, et al., Novel auxetic structures with enhanced mechanical properties, *Extreme Mech. Lett.* 27 (2019) 59–65.
- [95] Y. Chen, M. Fu, Design and modeling of a combined embedded enhanced honeycomb with tunable mechanical properties, *Appl. Compos. Mater.* 25 (5) (2018) 1041–1055.
- [96] M. Fu, Y. Chen, L. Hu, A novel auxetic honeycomb with enhanced in-plane stiffness and buckling strength, *Compos. Struct.* 160 (2017) 574–585.
- [97] M. Fu, Y. Chen, L. Hu, Bilinear elastic characteristic of enhanced auxetic honeycombs, *Compos. Struct.* 175 (2017) 101–110.
- [98] Z. Lu, X. Li, Z. Yang, et al., Novel structure with negative Poisson's ratio and enhanced Young's modulus, *Compos. Struct.* 138 (2016) 243–252.
- [99] K. Zied, M. Osman, T. Elmahdy, Enhancement of the in-plane stiffness of the hexagonal re-entrant auxetic honeycomb cores, *Phys. Status Solidi* 252 (12) (2015) 2685–2692.
- [100] E. Harkati, N. Daoudi, A. Bezazi, et al., In-plane elasticity of a multi re-entrant auxetic honeycomb, *Compos. Struct.* 180 (2017) 130–139.
- [101] A. Harkati, D. Boutagoug, E. Harkati, et al., In-plane elastic constants of a new curved cell walls honeycomb concept, *Thin-Walled Struct.* 149 (2020) 106613.
- [102] X. Zhang, R. Tian, Z. Zhang, et al., In-plane elasticity of a novel vertical strut combined re-entrant honeycomb structure with negative Poisson's ratio, *Thin-Walled Struct.* 163 (2021) 107634.
- [103] W. Liu, H. Li, Z. Yang, et al., Mechanics of a novel cellular structure for morphing applications, *Aero. Sci. Technol.* 95 (2019) 105479.
- [104] F. Ren, H. Liu, Strain induced low frequency broad bandgap tuning of the multiple Re-entrant star-shaped honeycomb with negative poisson's ratio, *J. Vib. Eng. Technol.* 10 (8) (2022) 3157–3168.
- [105] H. Tan, Z. He, K. Li, et al., In-plane crashworthiness of re-entrant hierarchical honeycombs with negative Poisson's ratio, *Compos. Struct.* 229 (2019) 111415.
- [106] Y. Sun, Q. Chen, N. Pugno, Elastic and transport properties of the tailorable multifunctional hierarchical honeycombs, *Compos. Struct.* 107 (2014) 698–710.
- [107] X. Wu, Y. Su, J. Shi, In-plane impact resistance enhancement with a graded cell-wall angle design for auxetic metamaterials, *Compos. Struct.* 247 (2020) 112451.
- [108] Y. Sun, N. Pugno, Hierarchical fibers with a negative poisson's ratio for tougher composites, *J. Mater.* 6 (2) (2013) 699–712.
- [109] I. Masters, K. Evans, Models for the elastic deformation of honeycombs, *Compos. Struct.* 35 (4) (1996) 403–422.
- [110] Q. Gao, L. Wang, Z. Zhou, et al., Theoretical, numerical and experimental analysis of three-dimensional double-V honeycomb, *Mater. Des.* 139 (2018) 380–391.
- [111] A. Alomarah, D. Ruan, S. Masood, et al., An investigation of in-plane tensile properties of re-entrant chiral auxetic structure, *Int. J. Adv. Manuf. Technol.* 96 (5–8) (2018) 2013–2029.
- [112] A. Alderson, K.L. Alderson, G. Chirima, et al., The in-plane linear elastic constants and out-of-plane bending of 3-coordinated ligament and cylinder-ligament honeycombs, *Compos. Sci. Technol.* 70 (7) (2010) 1034–1041.
- [113] N. Kipshidze, G. Dangas, M. Tsapenko, et al., Role of the endothelium in modulating neointimal formation, *J. Am. Coll. Cardiol.* 44 (4) (2004) 733–739.
- [114] J. Zhang, G. Lu, Z. You, Large deformation and energy absorption of additively manufactured auxetic materials and structures: a review, *Compos. B Eng.* 201 (2020) 108340.
- [115] J. Liu, H. Liu, Energy absorption characteristics and stability of novel bionic negative Poisson's ratio honeycomb under oblique compression, *Eng. Struct.* 267 (2022) 114682.
- [116] A. Osman, J. Lu, 3D printing of polymer composites to fabricate wearable sensors: a comprehensive review, *Mater. Sci. Eng. R Rep.* 154 (2023) 100734.
- [117] H. Xu, H. Liu, G. Li, In-plane characteristics of a multi-arc re-entrant auxetic honeycomb with enhanced negative Poisson's ratio effect and energy absorption, *Eur. J. Mech. Solid.* 109 (2025) 105473.
- [118] L. Shen, Z. Wang, X. Wang, et al., Negative Poisson's ratio and effective Young's modulus of a vertex-based hierarchical re-entrant honeycomb structure, *Int. J. Mech. Sci.* 206 (2021) 106611.
- [119] Y. Han, W. Lu, Optimizing the deformation behavior of stent with nonuniform Poisson's ratio distribution for curved artery, *J. Mech. Behav. Biomed. Mater.* 88 (2018) 442–452.
- [120] S. Zhao, L. Gu, S.R. Froemming, Effects of arterial strain and stress in the prediction of restenosis risk: computer modeling of stent trials, *Biomed. Eng. Lett.* 2 (3) (2012) 158–163.
- [121] A. Asadi, D. Hedayat, S. Ghofrani, et al., Modification of hexachiral unit cell to enhance auxetic stent performance, *Mech. Adv. Mater. Struct.* (2022) 1–15, ahead-of-print(ahead-of-print).
- [122] X. Ruan, W. Yuan, Y. Hu, et al., Chiral constrained stent: effect of structural design on the mechanical and intravascular stent deployment performances, *Mech. Mater.* 148 (2020) 103509.
- [123] A. Alomarah, Z.A. Al-Ibraheemi, D. Ruan, 3D printed auxetic stents with re-entrant and chiral topologies, *Smart Mater. Struct.* 32 (11) (2023) 115028.
- [124] J. Xiao, Z. Guo, In-plane impact dynamics of angular gradient honeycomb structure with adjustable Poisson's ratio multi-arc concave cell, *Mech. Adv. Mater. Struct.* (2023) 1–14, ahead-of-print(ahead-of-print).
- [125] H. Holman, M.N. Kavarana, T.K. Rajab, Smart materials in cardiovascular implants: shape memory alloys and shape memory polymers, *Artif. Organs* 45 (5) (2021) 454–463.
- [126] C. Pan, Y. Han, J. Lu, Structural design of vascular stents: a review, *Micromachines* 12 (7) (2021) 770.
- [127] J. Wang, X. Jin, Y. Huang, et al., Endovascular stent-induced alterations in host artery mechanical environments and their roles in stent restenosis and late thrombosis, *Regen. Biomater.* 5 (3) (2018) 177–187.
- [128] D.R. Holmes, D.J. Kereiakes, S. Garg, et al., Stent thrombosis, *J. Am. Coll. Cardiol.* 56 (17) (2010) 1357–1365.
- [129] S. Steiner, B. Honton, R. Langhoff, et al., 2-Year results with a sirolimus-eluting self-expanding stent for femoropopliteal lesions, *JACC Cardiovasc. Interv.* 15 (6) (2022) 618–626.
- [130] J. Torrado, L. Buckley, A. Durán, et al., Restenosis, stent thrombosis, and bleeding complications, *J. Am. Coll. Cardiol.* 71 (15) (2018) 1676–1695.
- [131] T. Hu, C. Yang, S. Lin, et al., Biodegradable stents for coronary artery disease treatment: recent advances and future perspectives, *Mater. Sci. Eng. C* 91 (2018) 163–178.
- [132] D. Lim, S. Cho, W. Park, et al., Suggestion of potential stent design parameters to reduce restenosis risk driven by foreshortening or dogboning due to non-uniform balloon-stent expansion, *Ann. Biomed. Eng.* 36 (7) (2008) 1118–1129.
- [133] V.M. Shah, G.S. Mintz, S. Apple, et al., Background incidence of late malapposition after bare-metal stent implantation, *Circulation* 106 (14) (2002) 1753–1755.
- [134] R. Xiao, X. Feng, W. Liu, et al., Direct 3D printing of thin-walled cardiovascular stents with negative Poisson's ratio (NPR) structure and functional metallic coating, *Compos. Struct.* 306 (2023) 116572.
- [135] W. Wu, X. Song, J. Liang, et al., Mechanical properties of anti-tetrachiral auxetic stents, *Compos. Struct.* 185 (2018) 381–392.
- [136] R. Vellaparambil, W. Han, P. Di Giovanni, et al., Potential of auxetic designs in endovascular aortic repair: a computational study of their mechanical performance, *J. Mech. Behav. Biomed. Mater.* 138 (2023) 105644.
- [137] G.B. Rahinj, H.S. Chauhan, M.L. Sirivella, et al., Numerical analysis for non-uniformity of balloon-expandable stent deployment driven by dogboning and foreshortening, *Cardiovascular Engineering and Technology* 13 (2) (2022) 247–264.
- [138] T.W. Tan, G.R. Douglas, T. Bond, et al., Compliance and longitudinal strain of cardiovascular stents: influence of cell geometry, *Journal Of Medical Devices-Transactions Of The Asme* 5 (4) (2011).
- [139] W. Wang, D. Liang, D. Yang, et al., Analysis of the transient expansion behavior and design optimization of coronary stents by finite element method, *J. Biomech.* 39 (1) (2006) 21–32.
- [140] K. Gupta, K. Meena, A novel double arrowhead auxetic coronary stent, *Comput. Biol. Med.* 166 (2023) 107525.
- [141] L. Wiesent, A. Spear, A. Nonn, Computational analysis of the effects of geometric irregularities on the interaction of an additively manufactured 316L stainless steel stent and a coronary artery, *J. Mech. Behav. Biomed. Mater.* 125 (2022) 104878.
- [142] L. Wei, H.L. Leo, Q. Chen, et al., Structural and hemodynamic analyses of different stent structures in curved and stenotic coronary artery, *Front. Bioeng. Biotechnol.* 7 (2019).
- [143] L. Wei, J. Wang, Q. Chen, et al., Impact of stent malapposition on intracoronary flow dynamics: an optical coherence tomography-based patient-specific study, *Med. Eng. Phys.* 94 (2021) 26–32.
- [144] A. Farb, D.K. Weber, F.D. Kolodgie, et al., Morphological predictors of restenosis after coronary stenting in humans, *Circulation* 105 (25) (2002) 2974–2980.
- [145] J.H. Park, J.M. Hong, Y.M. Ju, et al., A novel tissue-engineered trachea with a mechanical behavior similar to native trachea, *Biomaterials* 62 (2015) 106–115.
- [146] M. Lin, N. Firoozi, C. Tsai, et al., 3D-printed flexible polymer stents for potential applications in inoperable esophageal malignancies, *Acta Biomater.* 83 (2019) 119–129.
- [147] J. Liu, X. Yao, Z. Wang, et al., A flexible porous chiral auxetic tracheal stent with ciliated epithelium, *Acta Biomater.* 124 (2021) 153–165.
- [148] M. Chen, R. Zhong, Y. Wang, et al., Mechanical properties of re-entrant chiral anisotropic honeycomb, *Eng. Struct.* 291 (2023) 116431.

- [149] H.M.A. Kolken, A.F. Garcia, A.D. Plessis, et al., Mechanisms of fatigue crack initiation and propagation in auxetic meta-biomaterials, *Acta Biomater.* 138 (2022) 398–409.
- [150] S. Vijayavenkataraman, A. Gopinath, W.F. Lu, A new design of 3D-printed orthopedic bone plates with auxetic structures to mitigate stress shielding and improve intra-operative bending, *BioDes. Manuf.* 3 (2) (2020) 98–108.
- [151] M.Z. Ibrahim, A.A.D. Sarhan, F. Yusuf, et al., Biomedical materials and techniques to improve the tribological, mechanical and biomedical properties of orthopedic implants – a review article, *J. Alloys Compd.* 714 (2017) 636–667.
- [152] A.A. Al-Tamimi, P.R.A. Fernandes, C. Peach, et al., Metallic bone fixation implants: a novel design approach for reducing the stress shielding phenomenon, *Virtual Phys. Prototyp.* 12 (2) (2017) 141–151.
- [153] D.R. Sumner, Long-term implant fixation and stress-shielding in total hip replacement, *J. Biomech.* 48 (5) (2015) 797–800.
- [154] X. Wang, S. Xu, S. Zhou, et al., Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: a review, *Biomaterials* 83 (2016) 127–141.
- [155] A. Buford, T. Goswami, Review of wear mechanisms in hip implants: paper I – general, *Mater. Des.* 25 (5) (2004) 385–393.
- [156] N. Ghavidelnia, M. Bodaghi, R. Hedayati, Femur auxetic meta-implants with tuned micromotion distribution, *Materials* 14 (1) (2021) 114.
- [157] E. Garner, J. Wu, A.A. Zadpoor, Multi-objective design optimization of 3D micro-architected implants, *Comput. Methods Appl. Mech. Eng.* 396 (2022) 115102.
- [158] H.M.A. Kolken, S. Janbaz, S.M.A. Leeflang, et al., Rationally designed meta-implants: a combination of auxetic and conventional meta-biomaterials, *Mater. Horiz.* 5 (1) (2018) 28–35.
- [159] L. Tan, Y. Li, X. Hu, et al., Clinical application of 3D-Printed custom Hemipelvic prostheses with re-entrant chiral structure in reconstruction after pelvic tumor resection, *Orthop. Surg.* 17 (11) (2025) 3067–3077.
- [160] Y. Yao, H. Yuan, H. Huang, et al., Biomechanical design and analysis of auxetic pedicle screw to resist loosening, *Comput. Biol. Med.* 133 (2021) 104386.
- [161] S.Y. Heo, N.S. Kim, Comparison of the bone response to xenogenic bone screws and metallic screws in canine femur, *Vet. Med.* 59 (12) (2014) 641–648.
- [162] X. Hu, C. Li, X. Tang, et al., Clinical application of 3D-printed custom Hemipelvic prostheses with negative poisson's ratio porous structures in reconstruction after resection of pelvic malignant tumors, *Orthop. Surg.* 17 (6) (2025) 1691–1701.
- [163] Y. Yao, L. Wang, J. Li, et al., A novel auxetic structure based bone screw design: tensile mechanical characterization and pullout fixation strength evaluation, *Mater. Des.* 188 (2020) 108424.
- [164] Y. Kim, W. Choi, K. Rhyu, Assessment of pedicle screw pullout strength based on various screw designs and bone densities—an ex vivo biomechanical study, *Spine J.* 12 (2) (2012) 164–168.
- [165] C.B. Ahn, J.H. Kim, J. Lee, et al., Development of multi-layer tubular vascular scaffold to enhance compliance by exhibiting a negative poisson's ratio, *International journal of precision engineering and manufacturing-green technology* 8 (3) (2021) 841–853.
- [166] L. Song, M.F. Ahmed, Y. Li, et al., Vascular differentiation from pluripotent stem cells in 3-D auxetic scaffolds, *J. Tissue Eng. Regen. Med.* 12 (7) (2018) 1679–1689.
- [167] V. Gupta, A. Chanda, Auxetic incisions with alternating slit shapes: a promising technique for enhancing synthetic skin grafts expansion, *Mater. Res. Express* 10 (7) (2023) 75802.
- [168] S. Gupta, V. Gupta, A. Chanda, Biomechanical modeling of novel high expansion auxetic skin grafts, *Int. J. Numer. Methods Biomed. Eng.* 38 (5) (2022).
- [169] E. Yarali, M. Klimopoulou, K. David, et al., Bone cell response to additively manufactured 3D micro-architectures with controlled Poisson's ratio: auxetic vs. non-auxetic meta-biomaterials, *Acta Biomater.* 177 (2024) 228–242.
- [170] H.M.A. Kolken, A.F. Garcia, A. Du Plessis, et al., Fatigue performance of auxetic meta-biomaterials, *Acta Biomater.* 126 (2021) 511–523.
- [171] Ó. Lecina-Tejedo, M.Á. Pérez, E. García-Gareta, et al., The rise of mechanical metamaterials: auxetic constructs for skin wound healing, *J. Tissue Eng.* 14 (2023).
- [172] V. Gupta, A. Chanda, Expansion potential of skin grafts with novel I-shaped auxetic incisions, *Biomed. Phys. Eng. Express* 8 (1) (2021).
- [173] W. Zhang, P. Soman, K. Meggs, et al., Tuning the poisson's ratio of biomaterials for investigating cellular response, *Adv. Funct. Mater.* 23 (25) (2013) 3226–3232.
- [174] C. Wang, Y. Ye, G.M. Hochu, et al., Enhanced cancer immunotherapy by microneedle patch-assisted delivery of Anti-PD1 antibody, *Nano Lett.* 16 (4) (2016) 2334–2340.
- [175] K. Kataria, A. Gupta, G. Rath, et al., In vivo wound healing performance of drug loaded electrospun composite nanofibers transdermal patch, *Int. J. Pharm.* 469 (1) (2014) 102–110.
- [176] X. Lin, Y. Liu, A. Bai, et al., A viscoelastic adhesive epicardial patch for treating myocardial infarction, *Nat. Biomed. Eng.* 3 (8) (2019) 632–643.
- [177] D. Bannerman, S. Pascual-Gil, S. Campbell, et al., Itaconate and citrate releasing polymer attenuates foreign body response in biofabricated cardiac patches, *Mater. Today Bio* 24 (2024) 100917.
- [178] T. Su, K. Huang, K.G. Mathews, et al., Cardiac stromal cell patch integrated with engineered microvessels improves recovery from myocardial infarction in rats and pigs, *ACS Biomater. Sci. Eng.* 6 (11) (2020) 6309–6320.
- [179] H. Ryu, X. Wang, Z. Xie, et al., Materials and design approaches for a fully bioresorbable, electrically conductive and mechanically compliant Cardiac patch technology, *Adv. Sci.* 10 (27) (2023).
- [180] T. Tat, A. Libanori, C. Au, et al., Advances in triboelectric nanogenerators for biomedical sensing, *Biosens. Bioelectron.* 171 (2021) 112714.
- [181] L. Li, J. Zheng, J. Chen, et al., Flexible pressure sensors for biomedical applications: from Ex vivo to in vivo, *Adv. Mater. Interfac.* 7 (17) (2020).
- [182] W.A.D.M. Jayatilaka, K. Qi, Y. Qin, et al., Significance of nanomaterials in wearables: a review on wearable actuators and sensors, *Adv. Mater.* 31 (7) (2019).
- [183] M. Rana, V. Mittal, Wearable sensors for real-time kinematics analysis in sports: a review, *IEEE Sens. J.* 21 (2) (2021) 1187–1207.
- [184] B. Kaur, S. Kumar, B.K. Kaushik, Novel wearable optical sensors for vital health monitoring Systems-A review, *Biosensors (Basel)* 13 (2) (2023).
- [185] J. Liu, Y. Zhang, Soft network materials with isotropic negative Poisson's ratios over large strains, *Soft Matter* 14 (5) (2018) 693–703.
- [186] X. Zhang, C. Wang, T. Zheng, et al., Wearable optical fiber sensors in medical monitoring applications: a review, *Sensors* 23 (15) (2023) 6671.
- [187] Y. Deng, X. Guo, Y. Lin, et al., Dual-phase inspired soft electronic sensors with programmable and tunable mechanical properties, *ACS Nano* 17 (7) (2023) 6423–6434.
- [188] H.W. Kim, T.Y. Kim, H.K. Park, et al., Hygroscopic auxetic On-Skin sensors for easy-to-handle repeated daily use, *ACS Appl. Mater. Interfaces* 10 (46) (2018) 40141–40148.
- [189] W. Gao, J. Yao, X. Yue, et al., A flexible sensor with circumferential negative poisson's ratio characteristics for human interaction, *IEEE Sens. J.* 23 (19) (2023) 22313–22322.
- [190] Y. Jiang, Z. Liu, N. Matsuhisa, et al., Auxetic mechanical metamaterials to enhance sensitivity of stretchable strain sensors, *Adv. Mater.* 30 (12) (2018).
- [191] H. Liu, Y. Li, M. Zhou, et al., Ambilateral convergent directional freeze casting meta-structured foams with a negative Poisson's ratio for high-performance piezoresistive sensors, *Chem. Eng. J.* 454 (2023) 140436.
- [192] M.H. Yousuf, W. Abuzaid, M. Alkhader, 4D printed auxetic structures with tunable mechanical properties, *Addit. Manuf.* 35 (2020) 101364.
- [193] C. Lin, L. Zhang, Y. Liu, et al., 4D printing of personalized shape memory polymer vascular stents with negative Poisson's ratio structure: a preliminary study, *Sci. China Technol. Sci.* 63 (4) (2020) 578–588.
- [194] P. Xu, X. Lan, C. Zeng, et al., Compression behavior of 4D printed metamaterials with various Poisson's ratios, *Int. J. Mech. Sci.* 264 (2024) 108819.
- [195] Y. Zhou, B. Sun, M. Chen, et al., Research of flow dynamics and occlusion condition in roller pump systems used for ventricular assist, *Artif. Organs* 45 (1) (2021) E1–E13.
- [196] B. Zheng, C. Huang, X. Chen, et al., Toward head computed tomography image reconstruction standardization with deep-learning-assisted automatic detection, *IEEE Trans. Instrum. Meas.* 73 (2024) 1–14.
- [197] R. Archibald, A. Gelb, A method to reduce the gibbs ringing artifact in MRI scans while keeping tissue boundary integrity, *IEEE Trans. Med. Imag.* 21 (4) (2002) 305–319.
- [198] K. Kardash, C. Koutras, M.A. Otaduy, Design of personalized scoliosis braces based on differentiable biomechanics—Synthetic study, *Front. Bioeng. Biotechnol.* 10 (2022).
- [199] I. Toniolo, P. Pirini, S. Perretta, et al., Endoscopic versus laparoscopic bariatric procedures: a computational biomechanical study through a patient-specific approach, *Comput. Methods Progr. Biomed.* 243 (2024) 107889.
- [200] M. Nikkhoo, W. Chen, M. Lu, et al., Anatomical parameters alter the biomechanical responses of adjacent segments following lumbar fusion surgery: personalized poroelastic finite element modelling investigations, *Front. Bioeng. Biotechnol.* 11 (2023).
- [201] A. Mazier, S.P.A. Bordas, Breast simulation pipeline: from medical imaging to patient-specific simulations, *Clin. BioMech.* 111 (2024) 106153.
- [202] J. Gutiérrez-Gil, E. Nadal, K. Bouza, et al., Bone remodelling-based numerical evaluation of personalized masticatory forces from CT-scans, *Comput. Methods Appl. Mech. Eng.* 401 (2022) 115635.
- [203] J. Rao, Z. Chen, D. Zhao, et al., Recent progress in self-powered skin sensors, *Sensors (Basel, Switzerland)* 19 (12) (2019) 2763.
- [204] S. Wu, P. Dong, X. Cui, et al., The strategy of circuit design for high performance nanogenerator based self-powered heart rate monitor system, *Nano Energy* 96 (2022) 107136.
- [205] P. Yang, L. Zhou, Y. Gao, et al., Achieving high-performance triboelectric nanogenerator by DC pump strategy, *Adv. Mater. Technol.* 8 (9) (2023).
- [206] Z. Zhao, L. Zhou, S. Li, et al., Selection rules of triboelectric materials for direct-current triboelectric nanogenerator, *Nat. Commun.* 12 (1) (2021) 4686.