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Full Length Article

A comprehensive review on hybrid lattice meta-structures for biomedical engineering applications

Masoud Shirzad [a], Ali Zolfagharian [b], Seung Yun Nam [a,c,*], Mahdi Bodaghi [d,**]

[a] Industry 4.0 Convergence Bionics Engineering, Pukyong National University, Busan, 48513, South Korea
[b] School of Engineering, Deakin University, Geelong, VIC, 3216, Australia
[c] Major of Biomedical Engineering, Division of Smart Healthcare, Pukyong National University, Busan, 48513, South Korea
[d] Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham, NG11 8NS, UK

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ABSTRACT

Fabricating lattice structures with optimal physical, mechanical, and biological properties remains one of the key challenges in biomedical engineering. **Meta-structures** are geometry-driven systems that use structural architecture, often through periodic, hierarchical or graded designs, to achieve mechanical or functional properties not typically found in conventional bulk materials. Lattice meta-structures have emerged as a promising approach to meet the demanding requirements of biomedical devices, particularly due to their ability to mimic the structural and functional characteristics of host tissues. However, conventional meta-structures —composed of repeating single unit cells— often fall short in addressing all critical performance criteria. To overcome these limitations, hybrid meta-structures —combining two or more repeating architectures—have been developed, combining different structural architectures to enhance adaptability and functionality. The present review aims to provide a comprehensive overview of the design strategies and biomedical applications of hybrid meta-structures. Additionally, it offers insights into current challenges and outlines potential directions for future research in this rapidly evolving field.

1. Introduction

Meta-structures are artificially engineered architectures characterized by specific internal geometries that confer unique physical or mechanical properties—without altering the chemical composition of the base material. Typically designed as lattice systems, these structures enable unconventional behaviors not observed in conventional materials. Such attributes have broadened their applications across diverse domains, including public safety, aerospace engineering, sensing technologies, and biomedical engineering (Ma et al., 2025; Wang et al., 2023a; Suhas et al., 2025; Dogan et al., 2020).

Amid the rising demand for advanced health technologies, there is an urgent need for innovative design approaches capable of fulfilling complex functional requirements. However, fabricating biomedical devices that achieve both superior mechanical performance and biological compatibility remains a substantial challenge (Wang et al., 2022a; Foroughi and Razavi, 2022a; Lu et al., 2020). These requirements often conflict. For example, in bone tissue engineering, three-dimensional (3D) scaffolds must provide sufficient mechanical strength to withstand physiological loads while also maintaining high porosity to facilitate nutrient transport and cell infiltration—creating an inherent trade-off between structural strength and permeability. In such scenarios, the design strategy becomes a pivotal factor in achieving an optimal balance (Xu et al., 2024; Zhang et al., 2019).

One promising approach to overcoming these challenges lies in the use of meta-structures. While conventional meta-structures—such as re-entrant lattices—offer remarkable mechanical properties, they may still fall short of meeting the full spectrum of biomedical performance requirements (Yarali et al., 2024; Shirzad et al., 2024a). In response, hybrid meta-structures have emerged as a novel and adaptable solution. These architectures combine two or more distinct structural systems—either by integrating different meta-structures or by incorporating a meta-structure with a conventional design (Fig. 3). This hybridization preserves the advantages of traditional lattice configurations while introducing greater tunability and functional versatility, making them particularly well-suited to the multifaceted demands of biomedical

* Corresponding author.
** Corresponding author.
E-mail addresses: synam@pknu.ac.kr (S.Y. Nam), mahdi.bodaghi@ntu.ac.uk (M. Bodaghi).

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device design (Jin et al., 2020; Wang et al., 2023b; Li et al., 2024a; Shirzad et al., 2024b).

The study aims to provide a comprehensive overview of hybrid meta-structures, focusing on their design strategies and their applications across various subfields of biomedical engineering (Fig. 1). Specifically, this paper highlights recent advancements in the implementation of hybrid meta-structures and offers a critical perspective on potential future research directions.

This review discusses the innovative concept of using hybrid meta-structures for biomedical applications and highlights their advantages over conventional meta-structure designs. The covered topics include.

- Application of hybrid meta-structures for bone scaffolds and implants
- Application of hybrid meta-structures for mouth, dental, and jaw implants
- Application of hybrid meta-structures for interface area
- Application of hybrid meta-structures for stent
- Application of hybrid meta-structures for soft robotics and wearable devices
- Other emerging biomedical applications

2. Various designs for fabrication of hybrid meta-structures

Lattice-based meta-structures are widely employed across multiple engineering disciplines. Notable application areas include biomedical engineering (Shirzad et al., 2023), mechanical engineering (Miao et al., 2024), aerospace engineering (Khan and Riccio, 2024), and electrical engineering (Ma et al., 2025). Due to the varying functional requirements in these fields, each application necessitates a tailored design strategy to achieve optimal performance. In this review, lattice meta-structures are categorized into two primary design methodologies, followed by the introduction of a hybrid design approach.

2.1. Surface- and plate-based designs

One of the most common design strategies in meta-structure fabrication involves surface- and plate-based architectures. These systems are composed of repeating unit cells interconnected by walls or plates, forming continuous networks. Plate-based designs can incorporate either isotropic or anisotropic architectures, depending on the intended application (Fig. 2a) (Tancogne-Dejean et al., 2018). Surface-based designs, by contrast, tend to be more geometrically complex. Two notable subcategories are kirigami/origami-inspired structures and triply periodic minimal surfaces (TPMS) (Fig. 2b and c) (Viet et al., 2022; Qiu et al., 2024; Sabahi et al., 2024). These architectures are widely recognized for their combination of high strength and lightweight properties, making them suitable for applications that require deployability, flexibility, or enhanced surface area (Zhang and Paik, 2022; Feng et al., 2022).

2.2. Rod-based designs

Rod- or truss-based lattice structures constitute another major category of meta-structures, extensively used across various domains. These designs are valued for their high porosity and low density, combined

Fig. 1. Schematic illustration of the design of hybrid meta-structures and their applications in bone (Liu et al., 2024), dental (Alemayehu et al., 2025), disk (Barri et al., 2022), skin (Park et al., 2023), stent (Ghofrani et al., 2024), soft robotics (Pu et al., 2024), wearable devices (Oh et al., 2023), multifunctional applications such as interface and drug delivery (Jiang and Li, 2018a).

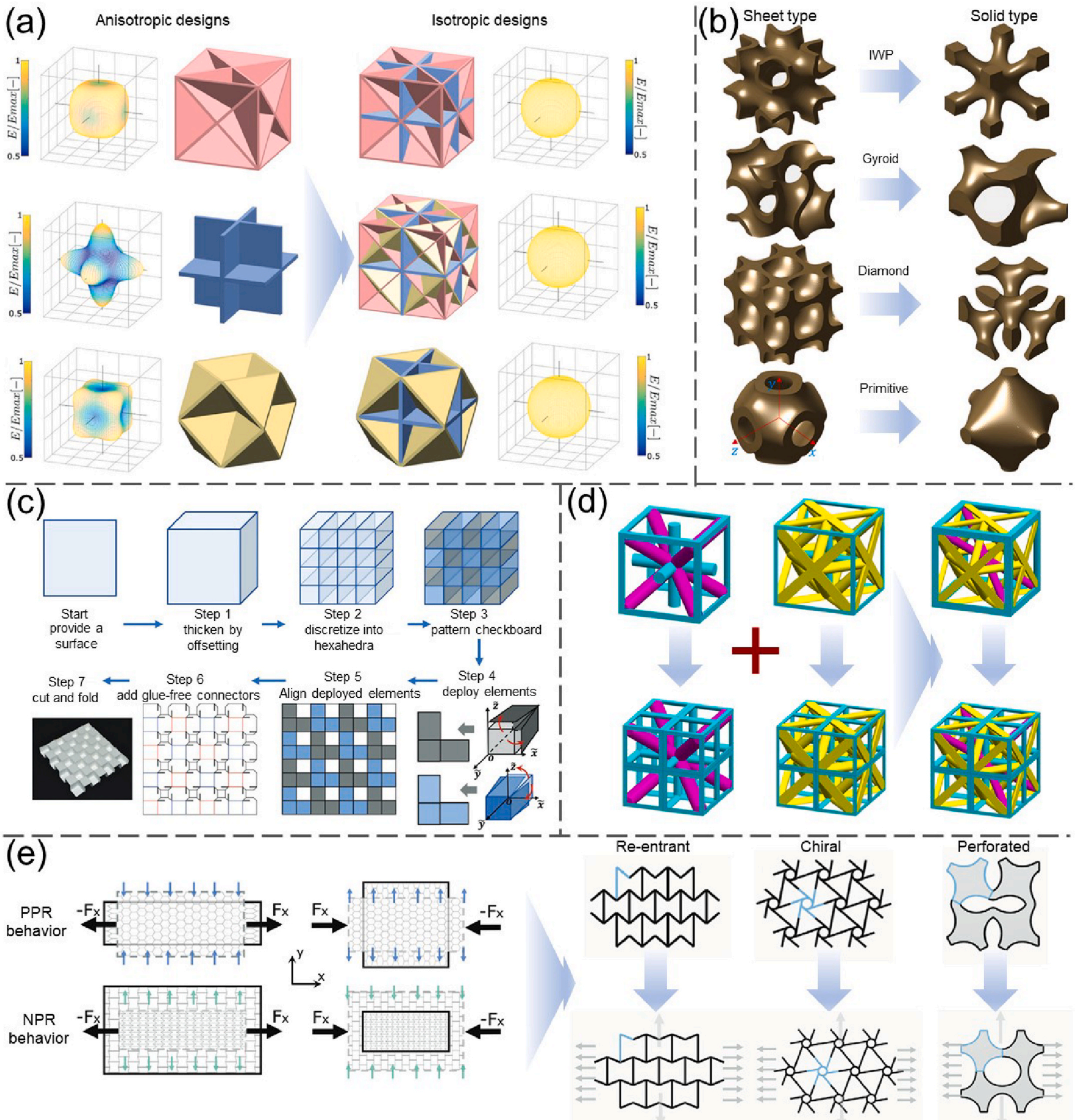

Fig. 2. Various meta-structure designs (Tancogne-Dejean et al., 2018). (a) Isotropic and anisotropic plate-based design and (b) TPMS design (Viet et al., 2022). (c) Step-by-step design of a kirigami structure (Zhang and Paik, 2022). (d) 3D truss or rod-based lattice structures (Tancogne-Dejean and Mohr, 2018). (e) Concept of auxetic designs with three conventional auxetic structures (Zhang et al., 2025a).

with excellent mechanical performance under compressive or tensile loads (Fig. 2d). The internal architecture of rod-based lattices can be precisely engineered by adjusting parameters such as strut thickness, unit cell topology, and rod cross-sectional geometry to achieve targeted physical and mechanical properties (Shirzad et al., 2020; Wang et al., 2021a).

A particularly noteworthy subgroup within this category is the auxetic meta-structure, which exhibits a negative Poisson's ratio (NPR)—a characteristic that leads to lateral expansion under tensile loading (Fig. 2e). This counterintuitive mechanical behavior results in enhanced energy absorption, indentation resistance, and deformation tunability, making auxetic lattices especially appealing for biomedical and protective applications (Shirzad et al., 2022, 2024a; Hedayati et al., 2023; Montgomery-Liljeroth et al., 2023). For instance, auxetic lattices can be utilized in stent designs requiring circumferential expansion—an essential feature for proper deployment. Additionally, their tunable auxetic behavior allows them to mimic the high auxeticity observed in tendon tissues or the lower auxetic response characteristic of cancellous

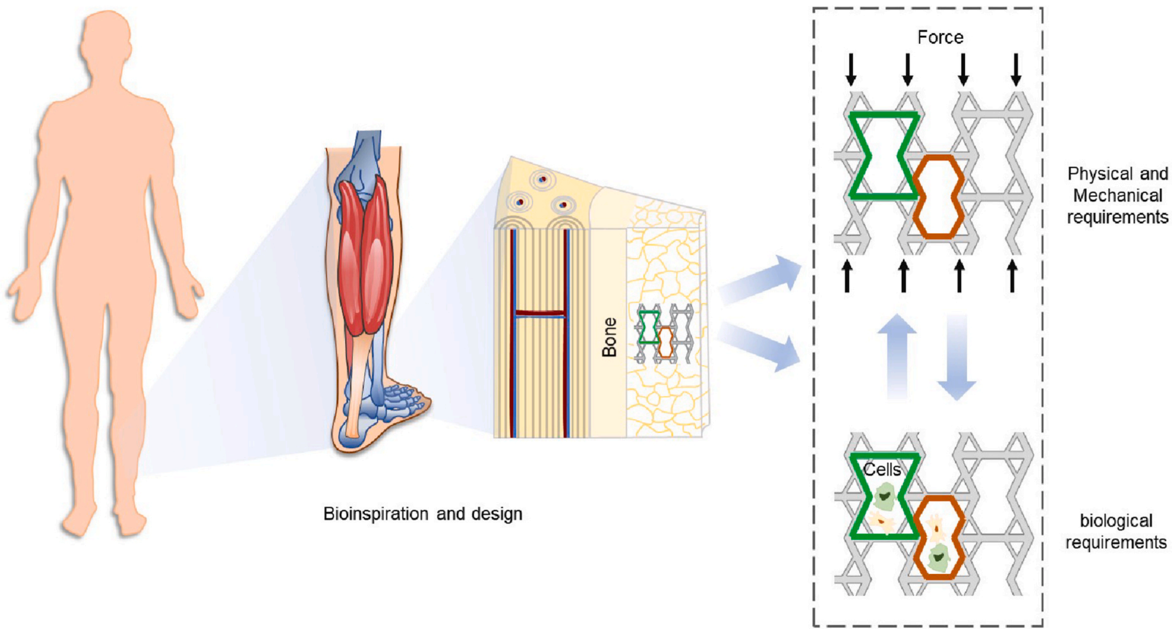

Fig. 3. Fabrication of hybrid meta-structures to meet the requirements of an appropriate bone tissue scaffolds (Shirzad et al., 2024a).

bone (Shirzad et al., 2023; Gatt et al., 2015; Hasanzadeh et al., 2025).

2.3. Hybrid meta-structures

Hybrid meta-structures refer to architectures that combine at least two distinct structural types—either two different meta-structures or a meta-structure integrated with a conventional design, such as a grid-based framework. The hybrid design strategy allows for enhanced mechanical or functional performance by leveraging the unique advantages of each component.

The integration can take two primary forms: (1) interpenetrated hybrid structures, in which two architectures are combined within the same spatial domain, and (2) side-by-side hybrid structures, where distinct components are placed adjacent to one another within the overall design. These approaches offer flexibility in tuning local and global properties, enabling tailored responses under specific loading or functional requirements.

It is important to note that in the present study, gradual changes in porosity or density using similar base unit cells—commonly referred to as gradient structures—are not classified as hybrid meta-structures, as they do not involve the combination of structurally distinct architectures.

3. Application of hybrid meta-structures for bone scaffolds and implants

Developing new biomaterials has long been one of the most critical challenges in biomedical engineering, especially in the design of implants that can meet complex clinical demands. The emergence of lattice structures—particularly lattice-based meta-structures—has significantly advanced the fabrication of biocompatible implants with tailored physical and mechanical properties (Liu et al., 2024; Shirzad et al., 2023; Zadpoor, 2020; Giorgio et al., 2021; Saldívar et al., 2025). With recent progress in advanced manufacturing techniques, it is now feasible to construct increasingly complex architectures, further enhancing the performance of biomedical implants (Fig. 3) by better matching the mechanical properties of host tissue and promoting cell adhesion and proliferation at the implantation site. In this context, hybrid meta-structures have been introduced to improve mechanical, physical, and biological characteristics (Ma et al., 2025).

One of the foremost benefits of hybrid meta-structures is the enhancement of mechanical performance. This improvement can be achieved by combining various structural designs. For example, Kang et al. (2025) proposed a hybrid scaffold that incorporated and modified both auxetic and conventional honeycomb structures, using biocompatible materials to enhance mechanical behavior. The hybrid approach allowed for improved control over Poisson's ratio and transverse deformation, which in turn optimized auxeticity and strengthened mechanical resilience. Moreover, hybridization offers a wider range of mechanical tunability than single-architecture designs (Fig. 4a) (Ding et al., 2021; Zhang et al., 2025b; Wang et al., 2017; Bobbert et al., 2020; Xiong et al., 2020a; Shirzad et al., 2021; Distefano et al., 2023; Ozdemir et al., 2023). Complex hybrid configurations can also significantly boost energy absorption capacity. For instance, dynamic loading conditions can be better managed through hierarchical hybrid structures such as TPMS-Voronoi tessellations (Fig. 4b), whose multi-level design inherently enhances load-bearing capability from multiple perspectives (Mu et al., 2023).

In addition to improving mechanical behavior, hybrid meta-structures can help mitigate stress shielding, thereby extending implant longevity (Wojnicz et al., 2021). Stress shielding arises when an implant bears a disproportionate share of mechanical load, leading to decreased stress in the surrounding bone tissue. This imbalance reduces bone cell activity and may result in bone resorption over time (Kök et al., 2025; Jafari Chashmi et al., 2020). Although conventional meta-structures can help alleviate stress shielding, they sometimes do so at the expense of yield strength. Hybrid designs can help balance these competing requirements by offering programmable mechanical responses tailored to specific anatomical or clinical scenarios (Chen et al., 2022; Zeng et al., 2023). This approach enables the fabrication of patient-specific implants by employing auxetic designs in regions requiring lower mechanical properties and conventional structures where higher strength is needed. As a result, stress shielding can be effectively controlled, and the implant–bone contact is improved, potentially reducing the risk of implant loosening and promoting an osseointegration-friendly environment (Fig. 4c) (Rana et al., 2023; Kolken et al., 2018). Osseointegration, the process by which bone tissue integrates with the implant surface, is a key determinant of the device's long-term success. Its efficiency can be influenced by structural design parameters (Jain and Ghosh, 2024; Zhang et al., 2025c).

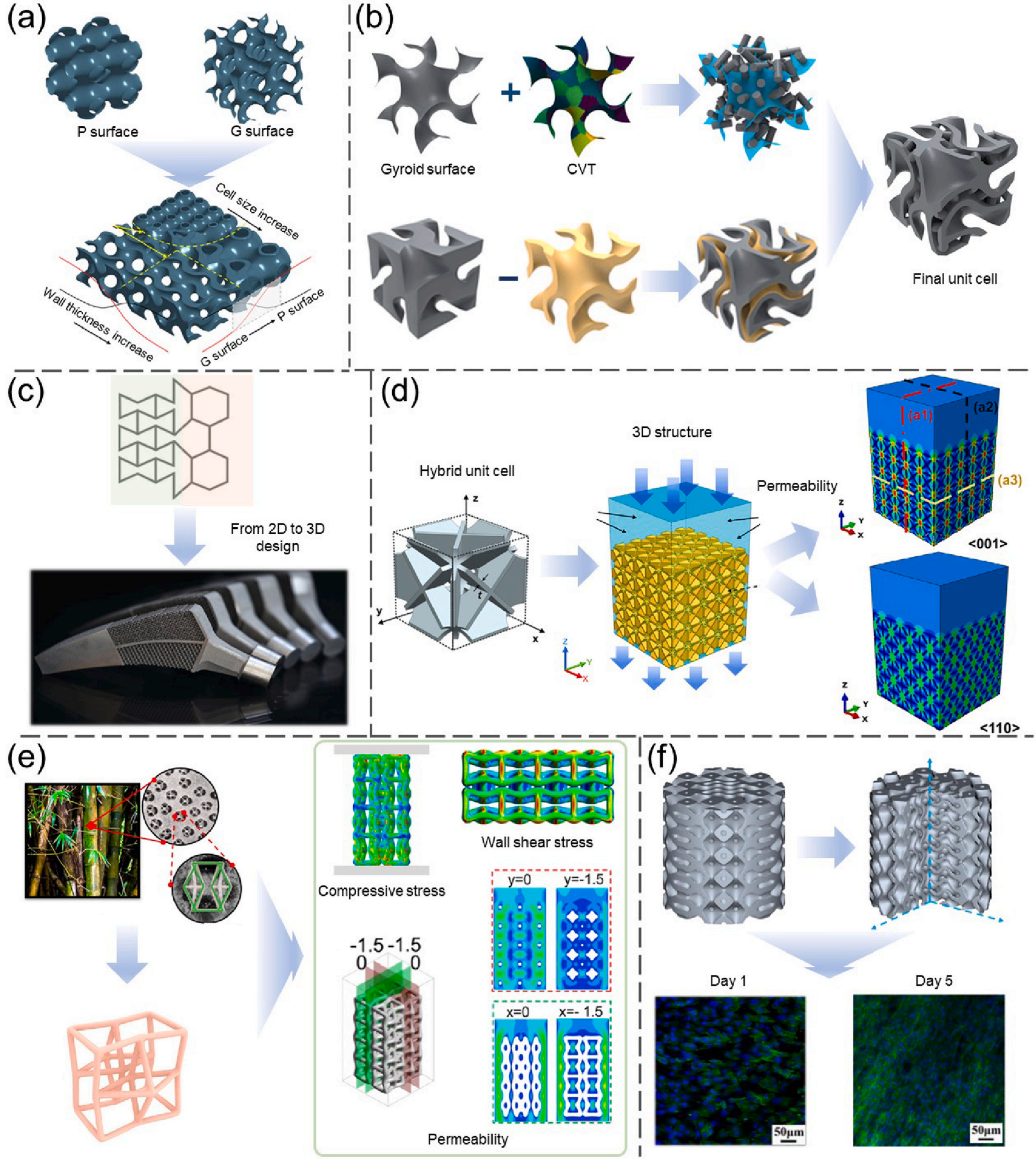

Fig. 4. Designing various hybrid meta-structures for bone-implanted medical devices and different applications. (a–b) Hybrid TPMS structures for enhancing mechanical properties (Ding et al., 2021; Mu et al., 2023). (c) Implementing hybridization to improve osseointegration in the surrounding bone (Kolken et al., 2018). (d–e) hybridization and bio-inspiration strategy for fabrication of multi-objective scaffolds with superior permeability and wall shear stress (Wang et al., 2022b; Chen et al., 2024). (f) Role of hybrid meta-structures in cell viability in scaffolds (Yu et al., 2023).

While mechanical properties are crucial, mass transport characteristics are equally important in bone tissue engineering. Scaffolds must function as three-dimensional frameworks that not only support mechanical loads but also promote fluid and nutrient transport to facilitate bone regeneration (Fig. 4d) (Li et al., 2024a; Peng et al., 2023; Foroughi and Razavi, 2022b). Hybrid meta-structures offer a promising solution to the inherent conflict between structural strength and permeability. Their geometrical versatility enables them to minimize stress concentrations and manage deformation effectively, ensuring robust mechanical behavior while maintaining sufficient porosity for biological function (Shirzad et al., 2024a; Li et al., 2021a, 2024a; Wang et al., 2022b; Garner et al., 2019).

Another key parameter is wall shear stress, which is influenced by the fluid flow through the porous scaffold. Optimizing this shear stress—ideally below 30 mPa—can promote cell attachment, growth, and differentiation. However, permeability, mechanical properties, and shear stress are interdependent and must be optimized together (Chen et al., 2024; Xiong et al., 2024). Chen et al. (2024) introduced a bamboo-inspired hybrid meta-structure—combining auxetic designs with 3D truss-based architectures—to achieve a balance between mechanical performance and fluid characteristics in titanium implants. Their design demonstrated mechanical properties comparable to those of natural cortical bone (elastic modulus: 17–22 GPa; yield stress: 120–160 MPa), while maintaining high fluid permeability. This synergy

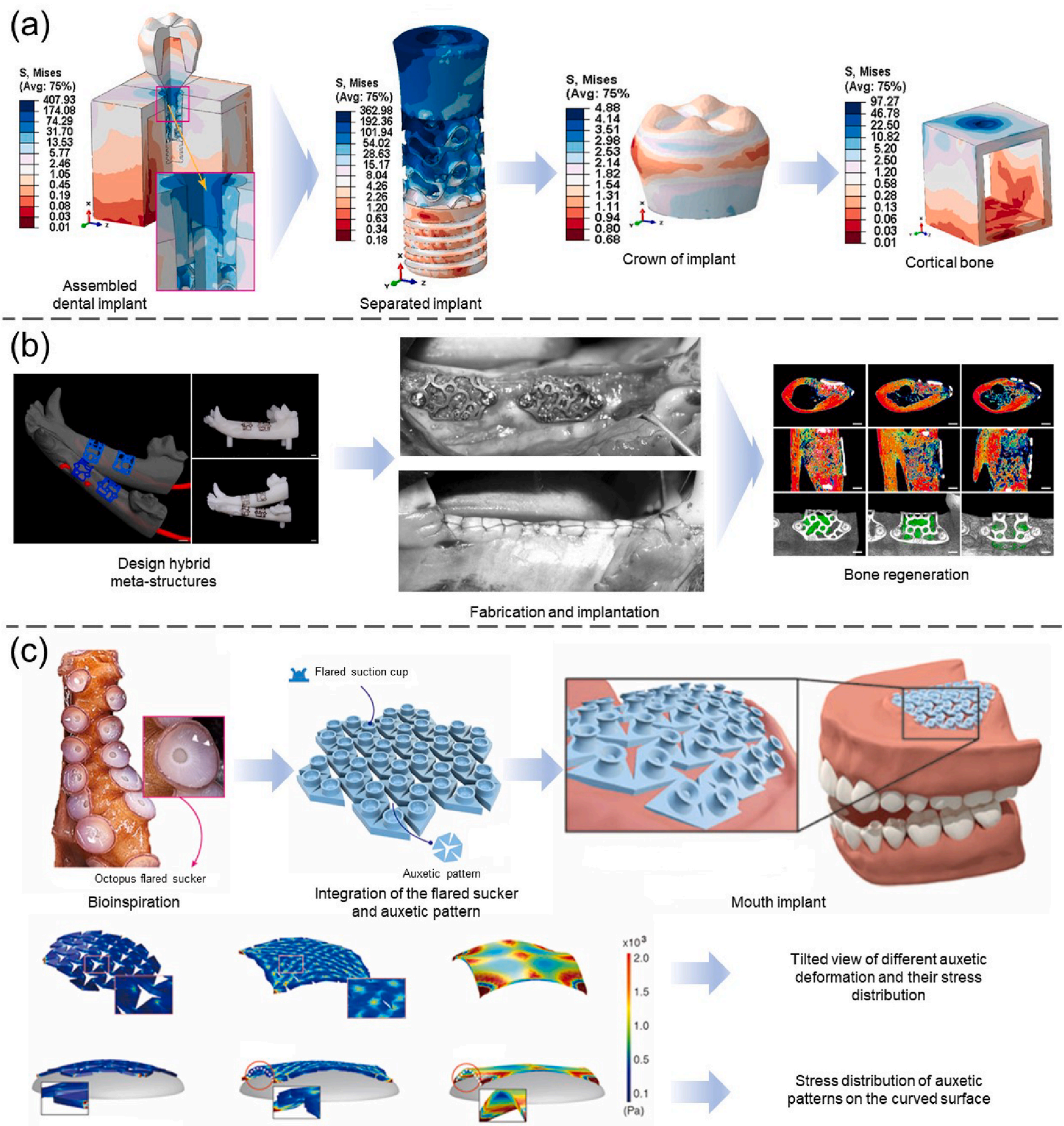

Fig. 5. (a) Using hybrid TPMS structures for dental implants to control stress shielding and improve load-bearing behavior (Alemayehu et al., 2025). (b) Bone regeneration and in-vivo study of using hybrid meta-structures for mandibular application (Ma et al., 2023a). (c) Bioinspired meta-structure with shape-matching behavior for mouth implants (Lee et al., 2024).

of mechanical and fluid properties can help reduce stress shielding and facilitate deep cell migration within the scaffold (Fig. 4e). It is worth noting that while conventional auxetic structures are inherently highly permeable, hybridization with truss elements offers enhanced control over mechanical performance.

Ultimately, the goal of any scaffold is to create an environment conducive to bone cell adhesion, proliferation, and regeneration. While single-unit cell architectures can achieve either mechanical or biological targets, multi-objective designs require hybrid architectures. Researchers have successfully combined rod- and surface-based structures to simultaneously improve mechanical performance and cell viability (Özeren and Altan, 2020; Yu et al., 2023; Choi et al., 2025). Fig. 4f illustrates how the integration of various meta-structures enables the design of multifunctional scaffolds. By employing hierarchical architectures—such as primitive, diamond, gyroid, and I-graph-wrapped structures—it is possible to achieve mechanical properties within the range of natural bone, with a 73.7 % increase in yield strength compared to mono-structure scaffolds. Additionally, the hierarchical porosity in these hybrid designs allows for tunable permeability, which can enhance cell growth rates compared to simple designs (Yu et al., 2023). Additional studies have explored heterogeneous architectures (Garner et al., 2022), isotropic structures (Zhang et al., 2024a), and strategies to maximize surface area for enhanced biological interaction, further demonstrating the broad potential of hybrid meta-structures in bone tissue engineering (Zhang et al., 2021a).

4. Application of hybrid meta-structures for mouth, dental, and jaw implants

In modern society, where facial aesthetics and oral health are closely linked to self-confidence and overall well-being, the demand for dental and jaw implants has significantly increased. This growing demand has driven continuous advancements in biomaterials and fabrication technologies (Jiang et al., 2020; Saghiri et al., 2021). However, the development of long-lasting, biocompatible implants for such delicate and mechanically active regions remains a significant challenge (Oladapo et al., 2022).

One of the key concerns in this area is the stress shielding effect, particularly in dental and jaw implants. This phenomenon arises from the mechanical mismatch between the implant material and the surrounding host tissue. Tough, high-stiffness materials—primarily metals—are commonly used to withstand continuous static and dynamic loads in the oral environment (Xiong et al., 2020b; Xu et al., 2022). However, these materials often cause uneven load distribution, leading to bone resorption over time. To address this issue, researchers have explored topology optimization and novel structural designs (Xu et al., 2022; Ouldyerou et al., 2022).

In this context, hybrid meta-structures (Fig. 5a) have been proposed as a promising solution. These architectures are designed to simultaneously withstand external loading, reduce stress shielding, and promote osseointegration—all of which are critical for successful implant function (Alemayehu et al., 2025; Yang et al., 2022; Zhai et al., 2023). Hybrid structures can facilitate bone regeneration at the implant site, enhancing osseointegration and ensuring a durable connection between the jawbone and the implant (Kalia et al., 2024; Mehboob et al., 2022; Zhang et al., 2024b). One of most important characteristics of these structures is the balancing between bending and buckling in porous designs, along with optimized stress distribution, making them an appropriate choice for jaw implants (Zhang et al., 2024b).

Beyond their mechanical advantages, hybrid meta-structures also enhance the biological performance of dental implants (Kök et al., 2025; Obaton et al., 2017). For example, Obaton et al. demonstrated that dental implants with varying lattice cell sizes could increase bone penetration by approximately 30 %, underlining the value of structural heterogeneity in optimizing bone–implant interactions (Obaton et al., 2017). Importantly, this effect is not limited to traditional dental implants. The versatility of hybrid designs enables their use in broader applications—such as jaw and oral implants—to achieve multi-functional performance.

All the aforementioned challenges—mechanical performance, stress shielding, and osseointegration—are also critical in the context of jaw and mouth implants. Due to the frequent use of metallic or high-stiffness materials in these regions, achieving a balance between mechanical and biological performance is essential. To address this, hybrid meta-structures have been explored as a promising design strategy to reconcile these competing requirements.

Such hybridization strategies may involve, for example, integrating conventional hexagonal architectures with 3D rod-based elements (Peng et al., 2021) or combining different lattice configurations within a spherical geometry to match complex anatomical features (Kilina et al., 2024). These studies aim to develop optimized pore architectures that simultaneously deliver high mechanical stability and enhanced biological compatibility (Peng et al., 2021; Zhang et al., 2024c; Senhora et al., 2022; Van Kootwijk et al., 2022). Importantly, bone regeneration plays an even more prominent role in jaw and mouth implants due to its direct impact on aesthetic outcomes (Ma et al., 2023a) (Fig. 5b) As a result, the structural design must not only ensure mechanical integration but also support effective biological remodeling.

Additionally, the fabrication of multiscale, adaptable three-dimensional structures is crucial for mouth and jaw implants. These anatomical regions are characterized by complex geometries and heterogeneous physical and mechanical properties, making implant design particularly challenging. Therefore, the development of multi-functional implants with tunable properties that can closely mimic the native tissue environment is highly desirable (Senhora et al., 2022; Lee et al., 2024). For instance, Lee et al. (2024) designed a bioinspired structure that combines octopus-like suction features with an auxetic lattice design. This hybrid architecture serves two primary purposes. First, the flare-shaped suction cap, inspired by octopus tentacles, enhances adhesion in the moist oral environment. Second, the auxetic component, with its negative Poisson's ratio, enables better conformity to the complex, deformable structure of the mouth (Fig. 5c). This hybrid structure can be applied as an oral prosthetic device on the irregular and moist surface of palatal tissues. The design exemplifies how bioinspiration combined with hybrid meta-structures can be leveraged to address the unique functional requirements of oral and maxillofacial implants.

5. Application of hybrid meta-structures for interface area

The human body contains numerous biological interface regions that exhibit complex transitional structures. These interfaces have evolved over thousands of years to facilitate gradual transitions from soft to hard tissues, providing mechanical continuity and biological function. Some of the most critical interface areas include.

- tendo-to-bone (Zhu et al., 2021),
- ligament-to-bone (Zhu et al., 2025),
- muscle-to-tendon (Narayanan and Calve, 2021),
- cartilage-to-bone (Khajehmohammadi et al., 2023),
- enamel-to-dentin (Sui et al., 2016),
- cancellous-to-cortical bone transition (Li et al., 2021a).

Due to their intricate hierarchical architectures and mechanical gradients, these interface zones are highly vulnerable to injury. A deep understanding of their biomechanics, combined with precise implant design, can significantly reduce patient recovery time and support earlier return to normal function (Apostolakos et al., 2014; Baldino et al., 2016).

One of the most studied interface areas is the enthesis, or the tendon-to-bone junction, which must withstand high loads while minimizing stress concentrations. Designing implants that can replicate this functionality is challenging. A promising strategy involves modifying TPMS-based structures by integrating them with randomly distributed particles designs. For example, combining gyroid structures with randomly distributed particles in the transition zone between soft and hard regions can help control strain concentrations and enable smoother changes in the modulus profile compared to single porous structures (Fig. 6a) (Saldívar et al., 2023). This approach can also be extended to ligament-to-bone interfaces, where similar soft-to-hard tissue transitions exist (Laurent et al., 2018).

Another critical interface is the cartilage-to-bone region, which is frequently damaged and exhibits low intrinsic healing capacity. Native cartilage exhibits a multi-zonal structure, and effective biomimicry requires scaffolds that replicate this organization (Han et al., 2021). A viable strategy is to design zonal hybrid architectures that mimic the biochemical and mechanical gradients of this interface (Fig. 6b) (Vijayavenkataraman et al., 2018). These scaffolds can be further enhanced by spatially controlled cell placement within mechanically supportive matrices, thereby achieving both biological fidelity and mechanical robustness (Golebiowska and Nukavarapu, 2022).

A particularly promising application of hybrid meta-structures is in cancellous-to-cortical bone interfaces, where multi-level energy absorption and anisotropic mechanical behavior are essential. Studies have demonstrated that hybrid architectures significantly enhance the energy absorption capacity of scaffolds in these regions due to their multi-morphology and hierarchical design (Li et al., 2021a; Xi et al., 2023; Lin et al., 2025; Zhang et al., 2023a; Surmeneva et al., 2017; Ma et al., 2020). As shown in Fig. 6c, during compressive loading, such scaffolds exhibit increasing strain-dependent energy absorption, which can help dissipate forces and protect surrounding tissues. Another critical feature of bone is anisotropy, which can be effectively mimicked through hybrid meta-structures. Reproducing this directional mechanical behavior facilitates the development of patient-specific implants, improves load distribution, and reduces complications such as stress shielding (Ma et al., 2020; Khaleghi et al., 2021; Sh Sufiiarov et al., 2021; Gao et al., 2024).

Looking toward advanced strategies, four-dimensional (4D) printing—which enables time-dependent shape transformation—can be

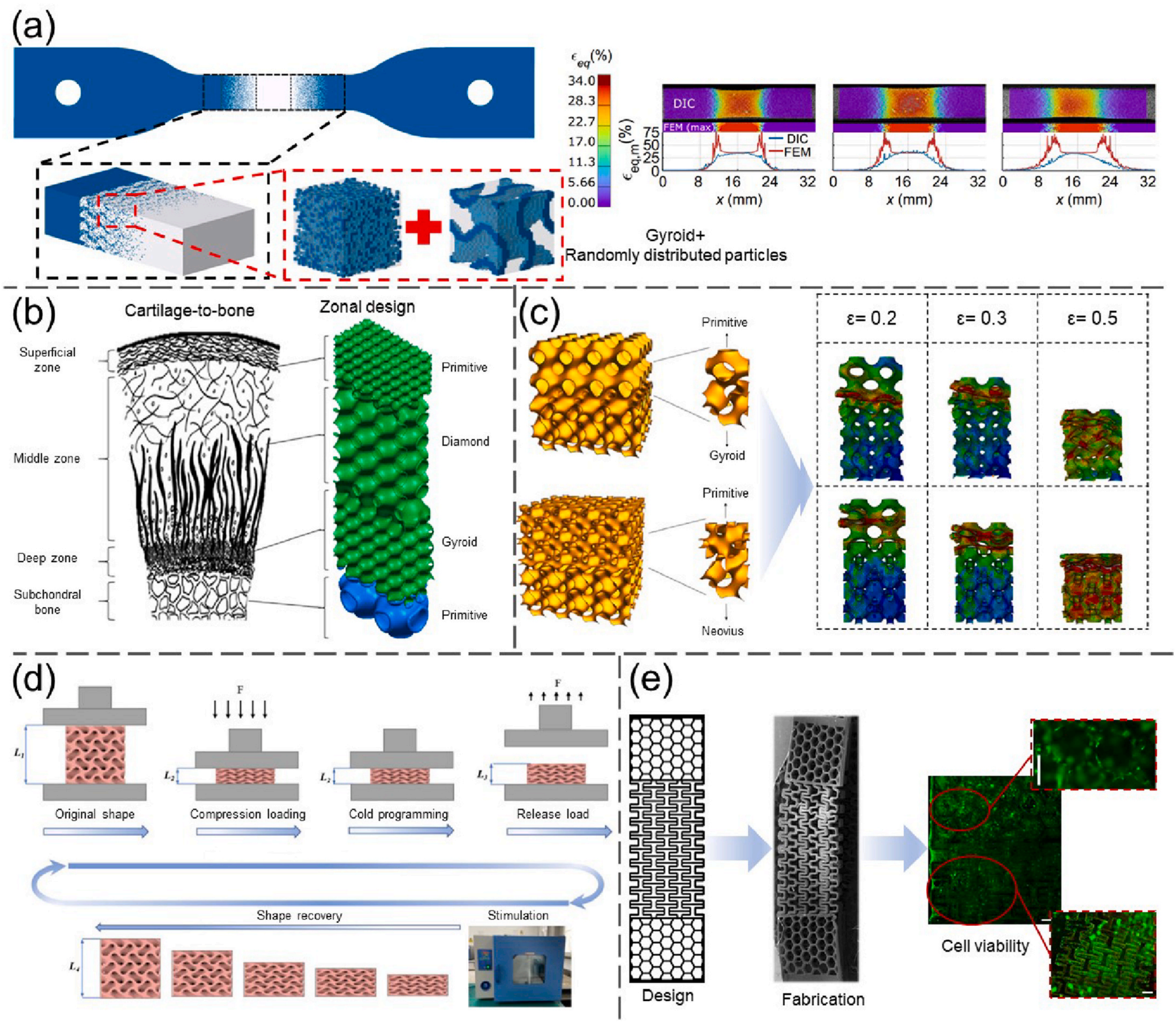

Fig. 6. (a) Fabrication of various structures for (a) tendon-to-bone (Saldívar et al., 2023), (b) cartilage-to-bone (Vijayavenkataraman et al., 2018), (c) cancellous-to-cortical bone area (Xi et al., 2023). (d) Using the 4D printing method to recover the original shape of a porous structure for an interface problem (Sang et al., 2023). (e) Application of interface design for soft-to-soft tissue interaction (Warner et al., 2017).

integrated with hybrid meta-structures to develop dynamic, multi-functional interface implants. For example, structures deformed during insertion can recover their original shape post-implantation, enhancing adaptability and functionality (Fig. 6d) (Sang et al., 2023, 2024).

Finally, hybrid meta-structures are also promising in non-bony interfaces, such as tendon-to-muscle junctions and more anatomically complex regions like the pelvis. These areas involve the interaction of two soft tissues or heterogeneous organs, and benefit greatly from the tunable, multi-material capabilities of hybrid meta-structure designs (Fig. 6e) (Warner et al., 2017; Li et al., 2024b). Designing hybrid structures for the interface area can not only mimic the mechanical properties of various tissues but also offer the ability to tailor physical properties such as porosity and Poisson's ratio (Warner et al., 2017).

6. Application of hybrid meta-structures for stent

In today's increasingly sedentary lifestyle, coronary artery disease remains one of the leading causes of mortality. This condition results from the buildup of plaques—composed of fats and cholesterol—along the inner walls of arteries, leading to narrowed vascular pathways and impaired blood flow (Gupta and Meena, 2023; Messeder et al., 2024). In response, biomedical engineering has advanced significantly in developing artificial vascular implants, including stents, to treat these occlusive conditions.

Stents are cylindrical devices, often designed to be expandable, that restore and maintain blood flow through narrowed or blocked vessels. To perform effectively, stents must possess a unique combination of mechanical strength, flexibility, and radial support to maintain vessel patency while avoiding damage to the surrounding tissue (Ahadi et al., 2023; Feng et al., 2024).

One major challenge in stent design is restenosis—the re-narrowing

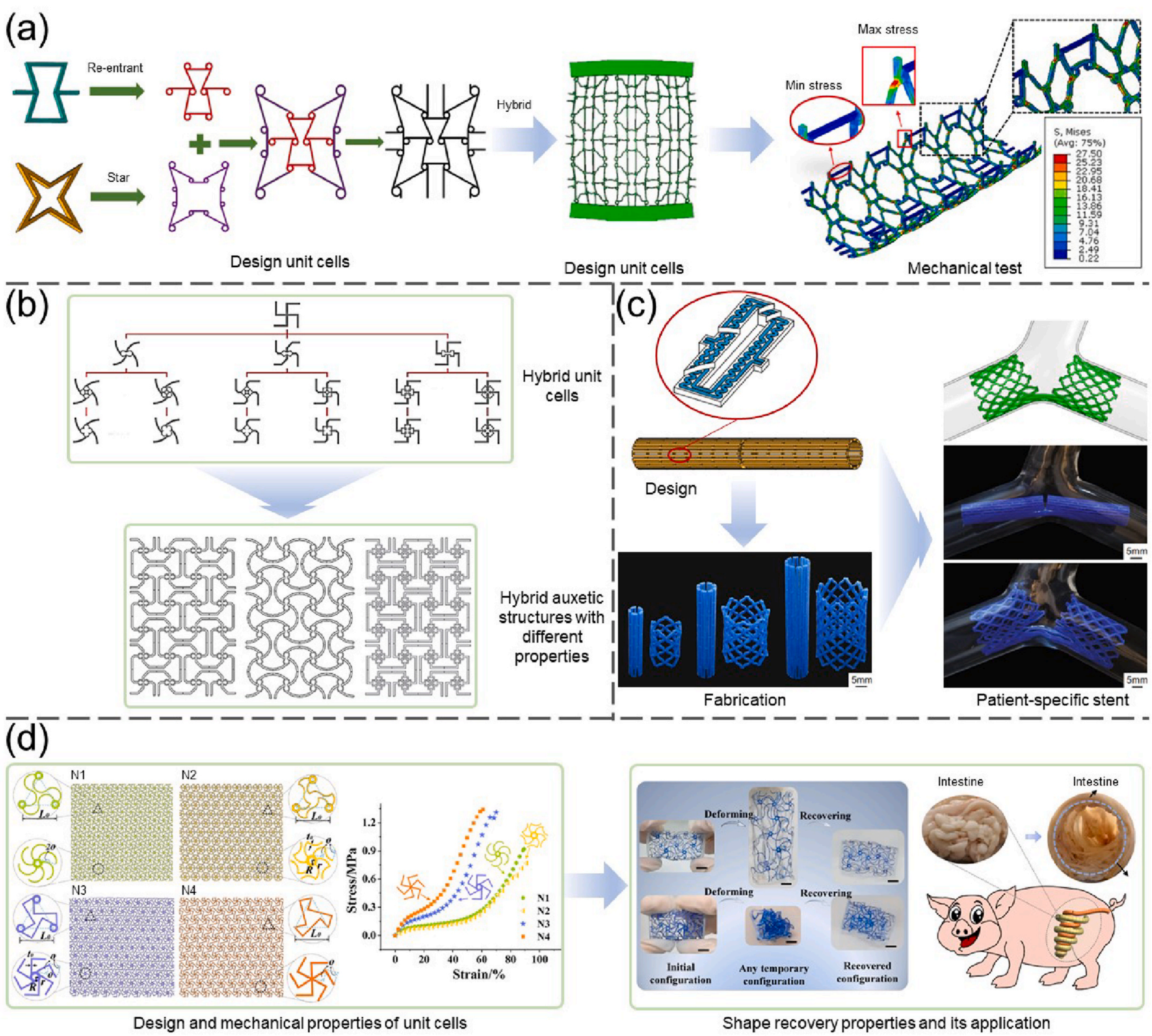

Fig. 7. (a) Integrating different structures to make appropriate physical and mechanical properties (Zamani et al., 2023). (b) Application of hybrid meta-structures for covering a wide range of properties (Ebrahimi et al., 2023). (c) Fabrication of patient-specific stent with hybrid meta-structures (van Manen et al., 2021). (d) Using the 4D printing method to apply shape recovery properties to hybrid meta-structures (Lin et al., 2023).

of the treated vessel—which may result from non-uniform expansion or mechanical recoil under physiological loading (Kumar and Bhatnagar, 2021). To address this, researchers have employed auxetic meta-structures—which exhibit a negative Poisson's ratio (NPR)—to ensure radial expansion under tensile loads. However, while auxetic behavior enhances circumferential expansion, it often compromises overall mechanical integrity. In this regard, hybrid meta-structures have emerged as a solution that balances transverse flexibility with mechanical robustness (Fig. 7a) (Ghofrani et al., 2024; Yasmin et al., 2025).

Hybrid meta-structures also help mitigate common stent deployment issues such as dogboning (bulging at the ends) and foreshortening (reduction in length upon expansion) by integrating unit cell designs with differing mechanical responses (Zamani et al., 2023; Abbaslou et al., 2023). These structures can outperform conventional auxetic-only designs, which often fail to meet the full set of mechanical and functional demands required for successful vascular intervention.

Beyond managing dogboning, stents must withstand multi-axial mechanical loads, including tension, compression, torsion, and bending—all of which occur simultaneously in the dynamic vascular environment (Feng et al., 2024; Xiao et al., 2023; Zhang et al., 2021b; Wu et al., 2018; Zhou et al., 2024; Asadi et al., 2023). These properties must also be coupled with high energy absorption to withstand pulsatile blood flow without failure (Hamzehei et al., 2020). Notably, increasing auxeticity often leads to reduced structural strength. Hybrid meta-structures, however, allow designers to overcome this trade-off by selectively tuning architecture to optimize both properties simultaneously. Nevertheless, excessive mechanical stiffness may lead to adverse effects, such as vessel wall damage or imprinting on arterial tissue (Erdogus and Yunus, 2024). Meta-hybrid designs (Fig. 7b) provide fine control over both structural stiffness and deformation behavior, allowing for tailored performance depending on clinical need (Erdogus and Yunus, 2024; Ebrahimi et al., 2023).

Beyond mechanical performance, hybrid meta-structures enable the customization of patient-specific stents. The human vascular system comprises arteries, veins, and capillaries with a wide range of diameters, geometries, and compliance profiles. Therefore, stents must be tailored to individual vascular characteristics to optimize treatment efficacy (Fig. 7c). By leveraging hybrid architectures, clinicians and engineers can pre-program physical and mechanical properties prior to implantation, resulting in personalized vascular implants with enhanced therapeutic outcomes (Capelli et al., 2012; van Manen et al., 2021).

Looking to the future, 4D printing—which combines shape transformation with additive manufacturing—offers a powerful complement to hybrid meta-structure design. For instance, biocompatible and biodegradable shape-memory materials can be used to fabricate self-expanding stents triggered by body temperature. Such designs eliminate the need for secondary procedures to retrieve temporary implants (e.g., intestinal stents), thereby reducing procedural risks and improving patient comfort (Fig. 7d) (Lin et al., 2023).

7. Application of hybrid meta-structures for soft robotics and wearable devices

Over the past decades, robotics has become increasingly important in biomedical engineering. More recently, the integration of soft materials into robotic systems has given rise to soft robotics, enabling direct interaction with the human body in applications such as rehabilitation, assistance devices, and even artificial limbs or organs (Cianchetti et al., 2018; Hann et al., 2020; Wang et al., 2020). To effectively mimic human tissue, soft robotic devices must exhibit biocompatibility, mechanical adaptability, and programmable deformation behavior (Cianchetti et al., 2018).

One key requirement for soft robotics is the ability to self-deploy, transitioning from a compact to a functional configuration to emulate biological movement. However, conventional soft structures often lack adequate control over deformation and recovery. To address this, hybrid meta-structures have been introduced as a promising design strategy to tune mechanical and functional properties (An et al., 2020a; Li et al., 2021b; Dudek et al., 2022). While enabling deformation is essential, it can also compromise mechanical integrity. Thus, achieving the right balance between deformability and mechanical performance is crucial (Ma et al., 2023b; Wang et al., 2021b; Dong et al., 2022). For instance, Tang and Yin combined kirigami and auxetic structures to develop soft deployable systems with enhanced tensile and compressive properties (Tang and Yin, 2017). Their work underscores the importance of integrating multiple structural motifs to achieve multifunctional behavior.

All the aforementioned strategies aim to facilitate the biomimicry of complex human motions by providing structures with suitable physical and mechanical properties. Due to the inherent complexity of human movement, especially in joints and soft tissues, this topic has attracted widespread research interest. However, conventional structural designs are limited in their ability to dynamically adapt to the multidirectional and variable-load conditions associated with natural motion (Hu et al., 2023; Zhang et al., 2023b). For example, a human finger must simultaneously withstand compressive and tensile forces during bending while also maintaining flexibility across multiple degrees of freedom. As shown in Fig. 8a and b, the strategic arrangement of two distinct meta-structures can enable programmable bending, closely mimicking this kind of complex motion (Jin et al., 2020; Pu et al., 2024).

Moreover, controlling and replicating such motions has led to the development of grippers with highly stable grasping behavior, which can respond to diverse tasks and loading scenarios. In many real-world applications, motion is not limited to a single deformation mode but involves combinations of twisting, bending, and extension/contraction. Designing separate structures to handle each mode independently is not practical for soft robotics. In this context, hybrid meta-structures offer a compelling solution by enabling multi-mode deformation within a single, unified architecture (Fig. 8c) (Jin et al., 2020; An et al., 2020b; Huang et al., 2022; Hussain et al., 2020; Pan et al., 2020).

Furthermore, researchers have explored additional applications of hybrid meta-structures in the field of biomedical soft robotics. One key goal in the development of artificial muscles is the reduction of operating voltage, which minimizes the risk of tissue damage during actuation. Safaei et al. demonstrated that interpenetrating TPMS-based hybrid structures can significantly enhance the performance of dielectric elastomer actuators by improving their deformation efficiency and mechanical response. Their bioinspired structures allow control over permittivity, stiffness, and volume fraction, which are crucial for actuation (Safaei et al., 2025).

Moreover, hybrid meta-structures (Fig. 8d) enable the integration of diverse actuation mechanisms, such as piezoelectric, conductive, and structural elements, within a single framework—offering multiple degrees of freedom. This multifunctionality is particularly beneficial for microrobots, which require compact, lightweight designs capable of active sensing, autonomous movement, and cargo delivery within the body (Cui et al., 2022).

Another promising application lies in the localized control of deformation in 3D architectures. In such designs, each unit cell can be independently actuated, allowing for programmable shape changes and fine-tuned mechanical responses across the structure (Novelino et al., 2020). Finally, hybrid meta-structures can replicate the J-shaped stress–strain behavior observed in natural soft tissues, making them excellent candidates for bio-integrated devices that require nonlinear elastic properties to match biological environments (Fig. 8e) (Yan et al., 2020).

Typically, it is difficult to clearly separate the fields of soft robotics, bio-integrated devices, and wearable devices, as they often share similar design goals and functional requirements. The use of hybrid structures is driven by comparable motivations across these fields. However, the present study aims to identify the most critical aspects of employing hybrid meta-structures specifically within these application domains.

In wearable devices, the primary motivation for using hybrid meta-

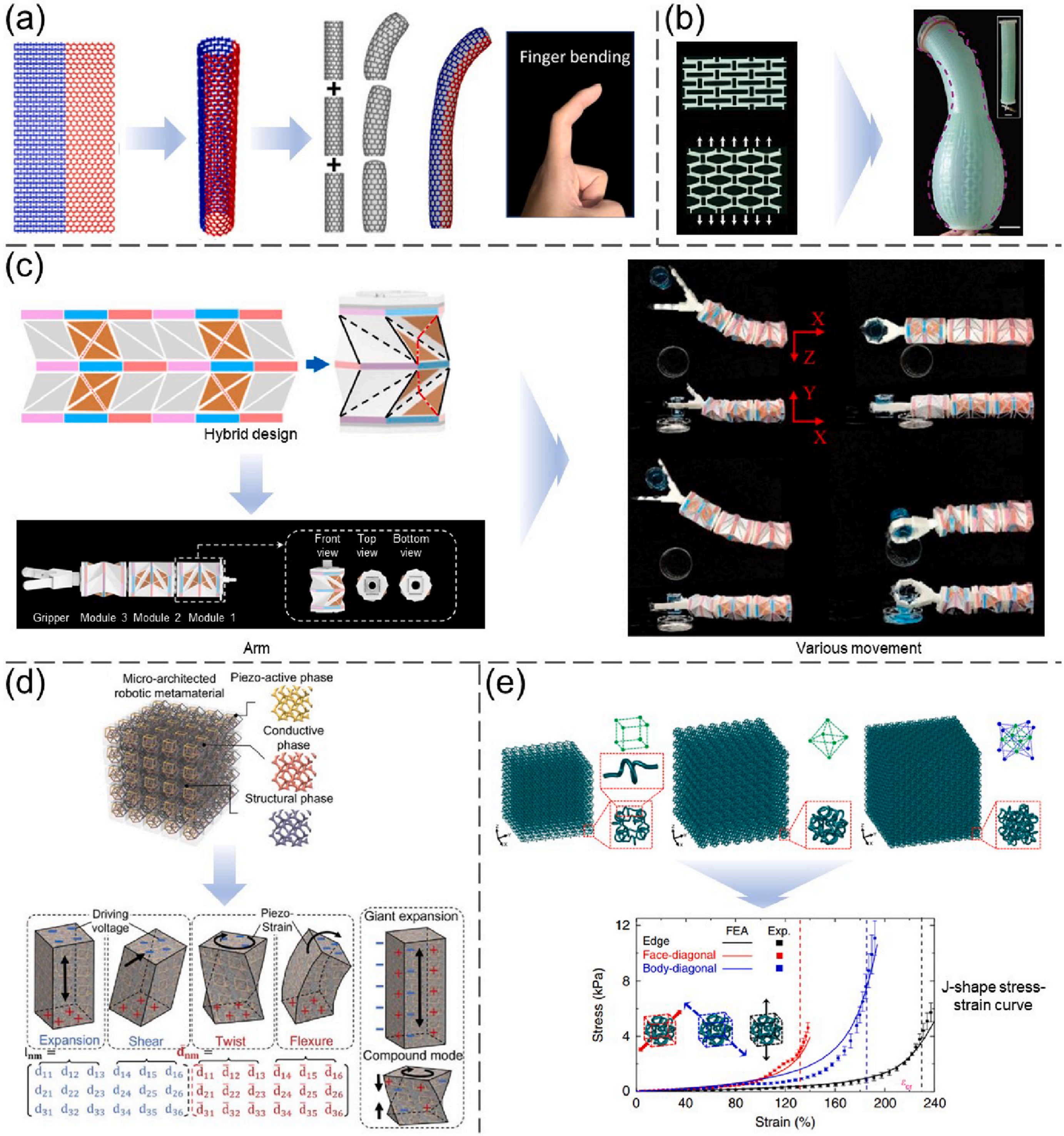

Fig. 8. (a–b) Programmable and deployable bending with hybrid meta-structure (Jin et al., 2020; Pu et al., 2024). (c) Using different unit cells to possess different deformation for a successful grasping (Zhang et al., 2023b). (d) Role of integrated design for enabling various actuation capabilities and multiple degrees of freedom (Cui et al., 2022). (e) Application of hybrid meta-structures in bio-integrated devices with mimicking natural tissues (Yan et al., 2020).

structures is to mimic the physical and mechanical properties of biological tissues and to create systems that are self-adaptive for ease of use (Fig. 9a) (Yuan et al., 2024). Skin grafting is a particularly relevant topic in this context due to the skin's protective function and its status as the largest organ in the human body (Özsoylu et al., 2023; Kim et al., 2023; Singh et al., 2022). Because skin is frequently subject to external injury, it demands materials and structures that can effectively replicate its biomechanical behavior (Özsoylu et al., 2023). Although conventional auxetic designs can accommodate expansion under tensile loads—mimicking one key property of natural skin—they have limitations in addressing the full complexity of skin mechanics.

First of all, multi-degree-of-freedom behavior and the ability to switch Poisson's ratio—which are crucial for restoring the skin's original shape—cannot be achieved through simple designs alone (Fig. 9b). Two distinct structural components are typically required to absorb and release energy by alternating their deformation phases (Wang et al.,

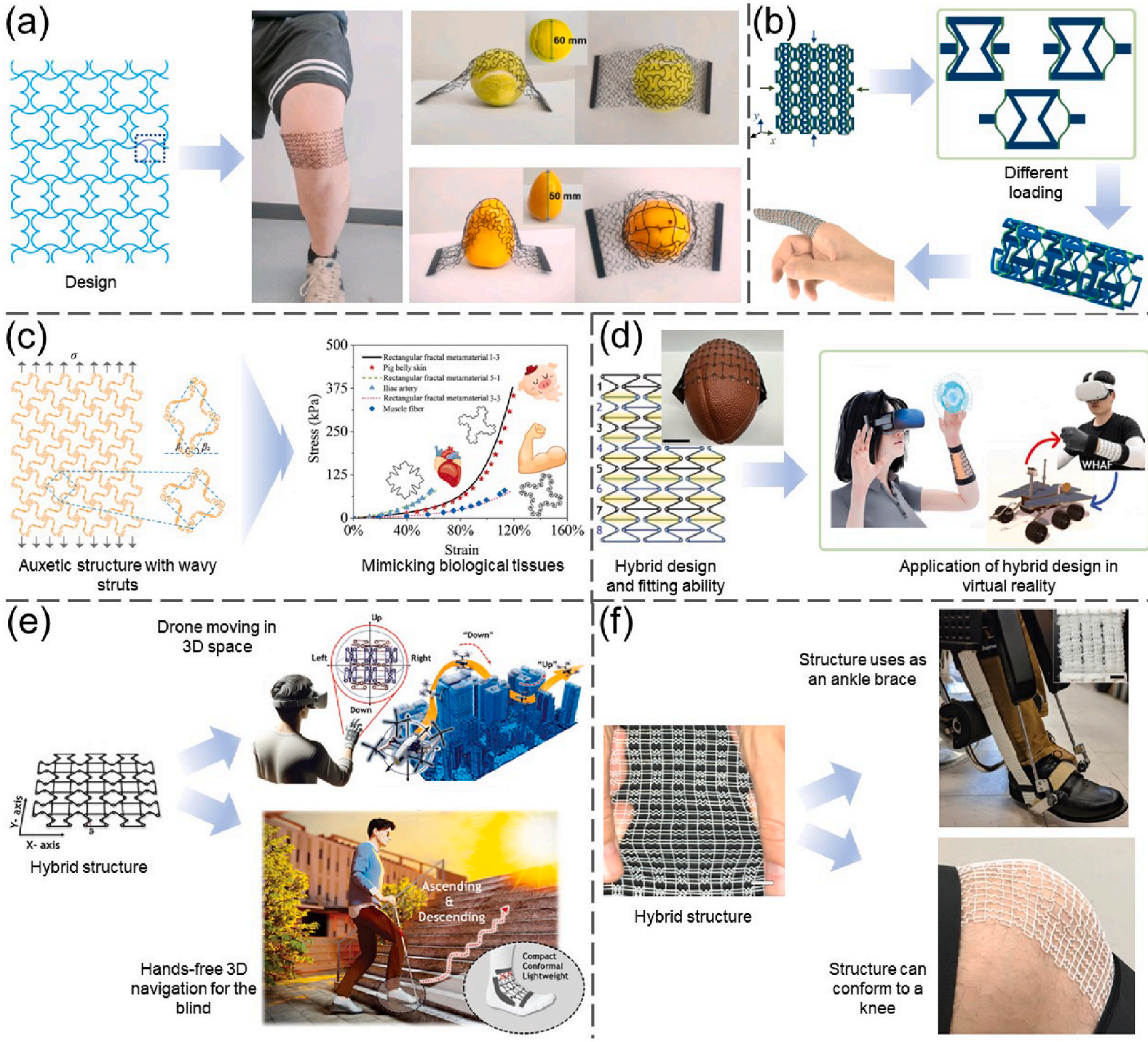

Fig. 9. (a) Self-adaptable hybrid meta-structure (Yuan et al., 2024). (b) facilitating the recovery process of the original shape of the wearable device with hybrid meta-structures (Wang et al., 2022c). (c) Improving stretchability and mimicking the stress-strain curve of biological tissues with hybrid design (Wang et al., 2023b). (d–e) Fitting ability and application of the hybrid meta-structures for virtual reality applications (Oh et al., 2023; Khan et al., 2025). (f) Convenient fitting of hybrid structures to a knee and its application in ankle brace (Pattinson et al., 2019).

2022c). As mentioned earlier, the J-shaped mechanical response is one of the outcomes of utilizing hybrid structures. This hybrid design concept can also be implemented using wavy architectures to achieve high stretchability, enabling the fabrication of soft structures that mimic the mechanical properties of biological tissues (Fig. 9c) (Wang et al., 2023b).

In addition to these fundamental aspects, Hwang et al. investigated the long-term application of such sensors and evaluated their comfort during various activities. They also demonstrated how hybrid designs can improve signal monitoring during motion by optimizing energy consumption in hybrid meta-structures. Their novel structure created an isotropic region with uniform mechanical properties in all directions, in contrast to conventional auxetic designs, which exhibited directional variations in both mechanical properties and comfort index (Hwang et al., 2023).

The excellent shape-conforming capability of hybrid meta-structures extends their applicability beyond basic skin sensors. Their ability to conform to complex geometries allows for the transmission of diverse spatiotemporal information to users. Notably, these structures can convey directional and timing cues during hands-free activities, such as navigation or object manipulation in virtual reality environments (Fig. 9d and e) (Oh et al., 2023; Khan et al., 2025). It is also worth noting that the integration of hybrid meta-structures into virtual reality systems may be applied in advanced fields such as remote surgery (Desselle et al., 2020).

Beyond skin-related applications, the nonlinear mechanical behavior of natural muscle can be emulated using hybrid meta-structures. For example, they have been employed in ankle braces to facilitate natural knee movement (Fig. 9f) (Pattinson et al., 2019). Lastly, hybrid meta-structures have been highlighted in applications such as hand-wrist orthoses, which can help prevent muscular atrophy (Badini et al., 2023).

8. Other emerging biomedical applications

8.1. Application of hybrid meta-structures for disk implants

The intervertebral disk is a load-bearing tissue located between adjacent vertebrae. Its primary function is to absorb shock while enabling flexibility in the human spine. Due to the anatomical structure of the human body, constant axial compression is the most dominant load experienced by the spine. As a result, lumbar disk bulging is a common condition that can lead to severe back pain. A novel approach to treating such disk disorders is the fabrication of intervertebral disk implants with tailored physical and mechanical properties (Barri et al., 2022; Kanno et al., 2019; Jiang et al., 2023).

As discussed, the physical, mechanical, and biological properties of disk implants are critical to their success (Lvov et al., 2023). Jiang et al. investigated various mechanical loads that affect disk performance and demonstrated that hybrid meta-structures could enhance bending, torsion, extension, and flexion properties (Fig. 10a). Moreover, the dynamic mechanical behavior of the implant was significantly improved through hybrid architectures compared to conventional designs (Jiang et al., 2023). Hybrid designs also offer advantages such as reduced stress shielding (Huo et al., 2024), improved permeability (Han et al., 2024), and enhanced cell proliferation (Jiang et al., 2023). These outcomes are attributed to precise control over unit cell geometry in hybrid structures, allowing for fine-tuning of both physical and mechanical characteristics.

8.2. Application of hybrid meta-structures for drug delivery

Drug delivery scaffolds and implants represent a smart alternative to traditional drug formulations by enabling precise spatiotemporal

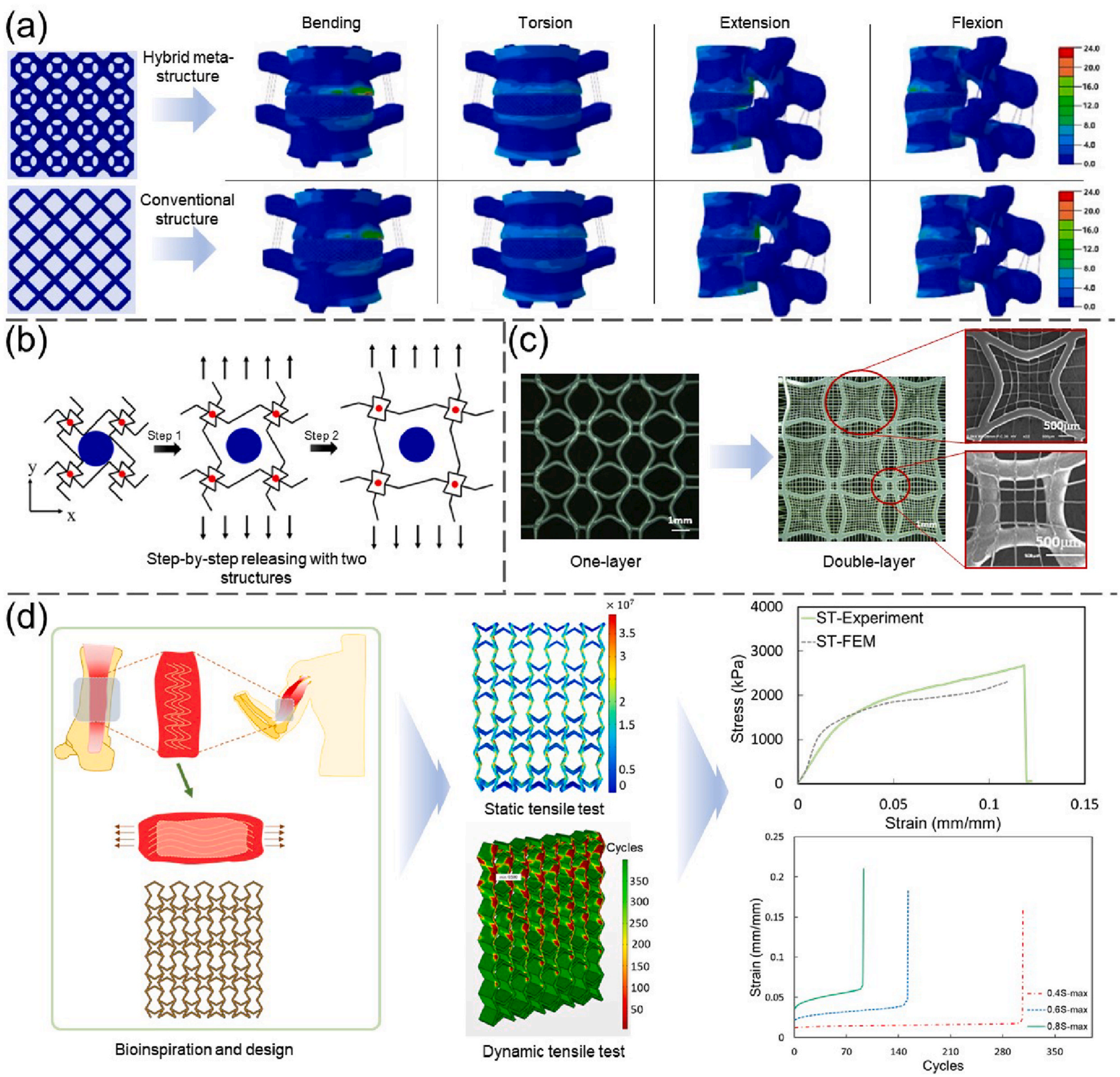

Fig. 10. Further applications of the hybrid meta-structures for: (a) intervertebral disk implant (Jiang et al., 2023), (b) drug delivery (Jiang and Li, 2018b), (c) skin scaffolds (Jin et al., 2021), and (d) tendon scaffolds (Shirzad et al., 2024b).

control over the release of therapeutic agents (Calori et al., 2020). However, controlling the opening ratio of unit cells under external forces presents a major design challenge. Hybrid meta-structures address this issue by enabling sequential drug release through the integration of two distinct architectures within the same structure (Fig. 10b). These architectures can be engineered with different mechanical and physical properties, allowing independent control over drug release profiles (Jiang and Li, 2018b).

8.3. Application of hybrid meta-structures for skin scaffolds

Burn injuries are among the most common injuries experienced by individuals. Among the various complications associated with burns, damage to the skin is particularly prevalent. Biomimetic scaffolds offer a promising strategy to address skin injuries by replicating the mechanical behavior of native skin tissue (Gupta et al., 2022). However, these scaffolds must exhibit a high degree of stretchability and tunable auxeticity (Mardling et al., 2020). The auxetic behavior should be adaptable to the host tissue environment and must also support cell proliferation. One pioneering approach involves a two-layer hybrid scaffold design that combines a conventional grid layer with an auxetic layer. In this configuration, auxeticity can be modulated by one layer, while the smaller grid structure promotes cell attachment and growth (Fig. 10c) (Jin et al., 2021). While this multi-layer design may present fabrication challenges due to the interdependency of the layers, it holds great potential for creating patient-specific skin scaffolds (Jin et al., 2021; Tsegay et al., 2022; Gupta and Chanda, 2023).

8.4. Application of hybrid meta-structures for tendon scaffolds

Tendons and ligaments are responsible for transferring loads between muscle and bone or between bones. Their hierarchical structure enables them to effectively manage loads and dissipate stress across soft-to-hard tissue interfaces. Tendon ruptures are particularly common in adults, necessitating the development of engineered substitutes that mimic the physical and mechanical properties of native tissue to promote healing (Warner et al., 2017; Karathanasopoulos and Al-Ketan, 2022).

Recent studies have focused on developing bioinspired tendon scaffolds that replicate the auxetic and mechanical behavior of natural tendons. Notably, tendon tissue can exhibit a highly negative Poisson's ratio, reaching values as low as -3.81 (Gatt et al., 2015). This unique property, combined with its load-bearing function, has motivated researchers to explore various strategies for tuning mechanical performance. Hybrid auxetic structures have proven effective in achieving negative Poisson's ratios along with superior static and dynamic tensile properties (Fig. 10d). These designs also enhance stress distribution and help control bending moments induced by external loads (Shirzad et al., 2024b).

9. Future directions

This review has explored various biomedical applications of hybrid meta-structures, including their integration into implants, scaffolds, soft robotics, and wearable devices (Table 1). In this section, potential future directions are proposed to guide the continued development of this field. As discussed, hybrid meta-structures can enhance the mechanical performance of biomedical constructs, with further improvements possible through structural modifications aimed at achieving high mechanical strength alongside tunable auxeticity (Gao et al., 2021; Etemadi et al., 2023; Peng and Bargmann, 2021). A promising future strategy involves the integration of machine learning (ML) techniques for the predictive design and optimization of hybrid meta-structures. ML models can accelerate development by reducing both fabrication time and experimental costs. While ML approaches require large datasets, this limitation can be addressed by leveraging numerical simulations or analytical models to generate sufficient training data (Dutta et al., 2024; Sun et al., 2024; Li et al., 2020; Pahlavani et al., 2024).

In addition to mechanical enhancement, hybrid meta-structures offer the potential to mimic the anisotropic, orthogonal, and heterogeneous properties of native biological tissues. For instance, tendons exhibit

Table 1
Summary of the hybrid meta-structures, applications, and their objectives in biomedical engineering.

Structures	Applications	Research objectives	References
TPMS, Voroni, plate, and auxetic	Bone	Enhancement of the mechanical performance, Mechanical tunability, mitigating stress shielding, promoting fluid transport and tissue regeneration	(Kang et al., 2025; Ding et al., 2021; Mu et al., 2023; Kolken et al., 2018; Wang et al., 2022b; Chen et al., 2024; Yu et al., 2023)
TPMS, auxetic, round, and spindle	Mouth, dental, and jaw	Enhancement of the mechanical properties, promoting osseointegration, effective biological remodeling, and self-aligning capability	(Alemayehu et al., 2025; Ma et al., 2023a; Lee et al., 2024; Álvarez-Trejo et al., 2023)
TPMS, auxetic, and hexagonal	Interface area	Preventing crack propagation, mimicking gradient structures, biological fidelity, increasing strain-dependent energy absorption	(Saldívar et al., 2023; Vijayavenkataraman et al., 2018; Xi et al., 2023; Sang et al., 2023; Warner et al., 2017)
Auxetic, rectangular	Stent	Enabling circumferential expansion, mechanical robustness, preventing dogboning and foreshortening, and improving patient comfort	(Zamani et al., 2023; Ebrahimi et al., 2023; van Manen et al., 2021; Lin et al., 2023)
Auxetic, hexagonal, origami and kirigami, and diamond	Soft robotics	Mimicking complex motion, enabling multi-mode deformation, integration of diverse actuation mechanism, replicating complex mechanical behavior	(Jin et al., 2020; Pu et al., 2024; Zhang et al., 2023b; Cui et al., 2022; Yan et al., 2020)
Auxetic, rectangular, and spindle	Wearable devices	Self-adaptive structures, switching Poisson's ratio, achieving high stretchability, transmission of diverse spatiotemporal information, and rehabilitation	(Wang et al., 2022c, 2023b; Oh et al., 2023; Yuan et al., 2024; Khan et al., 2025; Pattinson et al., 2019)
Auxetic, diamond, and rectangular	Disk, drug delivery, skin, and tendon	Enhancement of the mechanical properties, enabling sequential drug release, promoting cells attachment and cells growth, improving dynamic mechanical properties	(Shirzad et al., 2024b; Jiang et al., 2023; Jiang and Li, 2018b; Jin et al., 2021)

direction-dependent mechanical behavior, a feature that hybrid architectures can emulate (Gatt et al., 2015; Li et al., 2020; Teng et al., 2023; Lyu et al., 2024). Moreover, the hierarchical organization found in many soft, hard, and interface tissues (e.g., tendon-to-bone junctions) may be replicated through programmable, multi-scale hybrid designs. Achieving such hierarchical control remains a significant challenge in tissue engineering, but it holds the key to more biomimetic and functional implants (Liu et al., 2022; Wang et al., 2023c; Wei et al., 2024; Li et al., 2024c; Chen et al., 2025).

Looking toward specific applications, bone screws represent a compelling target for hybrid meta-structure integration. Although auxetic structures have been explored to improve fixation, they often compromise mechanical strength. Hybrid architectures could overcome this limitation by balancing auxeticity with enhanced load-bearing capability, resulting in more durable bone screws (Yao et al., 2020). Another emerging application is in nerve regeneration, where scaffolds with negative Poisson's ratio have shown promise. However, challenges related to low mechanical strength and personalization can potentially be addressed through advanced hybrid meta-structure designs (Chen et al., 2020; Yan et al., 2017).

One of the most intriguing topics, which has received limited attention in the literature, is the application of meta-structures for breast implants (Zhang et al., 2025d; Wang et al., 2024). Breast implants require several essential features, including good thermal conductivity, appropriate mechanical properties, and the ability to support personalized shape reconstruction as fat tissue grows. This multi-objective challenge presents a promising direction for the development of hybrid meta-structures (Zhang et al., 2025d; Wang et al., 2024; Lee et al., 2023).

Additional areas of opportunity include cardiovascular patches (Kapnisi et al., 2018; Brazhkina et al., 2021), synclastic-effect skin wound dressings (Chow et al., 2022; Tsegay et al., 2023), and esophageal scaffolds (Ali et al., 2014), where hybrid structures can provide both mechanical compliance and biological functionality.

Finally, hybrid meta-structures also offer new avenues for fluid regulation within scaffolds by precisely tuning permeability and wall shear stress. Such control can positively influence biological outcomes, including cell proliferation and tissue integration (Ali et al., 2020). Dual micro-/macro-porosity designs, for example, have been shown to enhance cell differentiation and vascularization (Garcia Cruz et al., 2010; Song et al., 2019). Beyond static implants, these structures may also revolutionize wearable devices by enabling efficient energy harvesting from ambient sources, reducing the need for external charging (Song et al., 2019).

10. Conclusion

This review examined the current state of research on hybrid design principles and hybrid meta-structures, with a focus on their applications in biomedical engineering. It began with an overview of different types of meta-structures, followed by a clear definition and classification of hybrid meta-structures. Their applications were then discussed across a range of biomedical domains, including bone scaffolds, implants, and interface regions such as tendon-to-bone attachments. Additionally, it discussed how hybridization could enhance the mechanical and biological properties of the implants and scaffolds.

The review also covered applications in oral and maxillofacial implants—including mouth, dental, and jaw implants—as well as stents. Additionally, the use of hybrid meta-structures in soft robotics and wearable biomedical devices was explored. Emerging applications in intervertebral disk implants, drug delivery systems, skin scaffolds, and tendon scaffolds were also highlighted. Hybrid meta-structures showed significant improvements, ranging from preventing crack propagation in interfacial tissues to enabling highly negative Poisson's ratio stents.

Finally, a dedicated section presented future research directions to further develop hybrid meta-structures in terms of mechanical performance, biomimicry, fabrication strategies, and smart functionalities. This review aims to support the development of next-generation biomedical devices by summarizing current achievements and identifying key opportunities for innovation.

CRediT authorship contribution statement

Masoud Shirzad: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Ali Zolfagharian:** Writing – review & editing, Methodology, Investigation. **Seung Yun Nam:** Writing – review & editing, Supervision, Methodology, Investigation. **Mahdi Bodaghi:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Data availability statement

Data sharing is not applicable to this review article as no new data were created or analyzed in this study.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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