

Additively Manufactured Auxetic Materials for Healthcare Innovations

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Abstract: This review explores the mechanical properties, manufacturing techniques, and biomedical applications of auxetic metamaterials. Auxetic materials, characterized by a negative Poisson's ratio, exhibit unique deformation behaviours that make them highly suitable for medical applications such as orthopedic implants, vascular stents, and protective equipment. The study systematically examines recent advancements in the design and additive manufacturing of auxetic structures, focusing on their mechanical performance, durability, and potential for biomedical innovations. Key research findings from experimental and computational studies are summarized to provide insights into the advantages and challenges of implementing these materials in healthcare. The review highlights current trends, limitations, and future research directions in the field of auxetic metamaterials for biomedical applications.

Keywords: metamaterials, 3D printing, biomedical engineering, polymers, additive technology, auxetic, healthcare

1. Introduction

A metamaterial is a material that has been designed to exhibit properties that do not occur in nature. The term metamaterial was introduced already in 1999 by Rodger W. Walters from the University of Texas at Austin. It was originally defined as an artificial macroscopic composite material, characterized by a three-dimensional periodic cellular structure. In today's well, however, the cell structure does not have to be strictly periodic. Its periodicity is only related to the homogeneity of the given material [1,2].

Metamaterials can currently be divided into 4 categories based on their properties, namely electromagnetic metamaterials (EMM), acoustic metamaterials (AMM), thermal metamaterials (TMM) and mechanical metamaterials (MMM). In this article, we will only discuss mechanical materials, because they are used for application in the biomedical industry [3].

Mechanical metamaterials are distinguished by their ability to exhibit unconventional mechanical responses, such as converting mechanical energy from one direction to another, transforming compressive forces into torque, or absorbing energy. These materials are engineered to provide tunable properties, which make them ideal for biomedical applications like implants, prosthetics, and medical devices. For example, auxetic structures, a type of mechanical metamaterial, expand laterally when stretched, enabling enhanced energy absorption, flexibility, and comfort in medical applications. This adaptability has made them a subject of intense research in advancing healthcare technologies.

2. Innovative Auxetic Structures

Auxetic structures are huge part of mechanical metamaterials that exhibit a

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negative Poisson's ratio, hence their counterintuitive behaviour. Poisson's ratio is defined as the negative ratio of transverse strain (lengthening/shortening) to longitudinal strain [4]:

$$\nu = -\frac{\varepsilon_y}{\varepsilon_x}. \quad (1)$$

The main feature of auxetics is their behaviour during deformation, especially under uniaxial loading. Conventional materials expand (contract) under compression (tension) loading, while auxetics contract (expand) under compression (tension) loading as seen in Figure 1 [4].

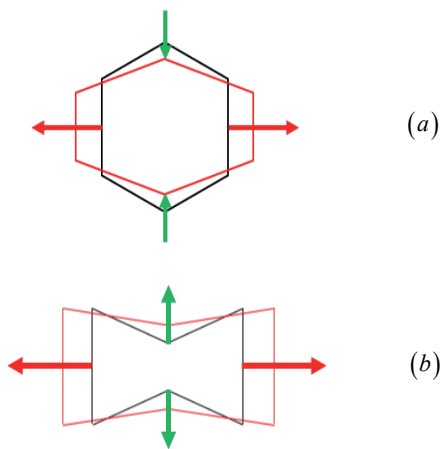


Figure 1: The difference between standard and auxetic material: (a) Standard material under tensile stress contracts perpendicular to stress; (b) Auxetic material under tensile stress stretches perpendicular to stress.

Additive manufacturing processes, which are based on the gradual controlled addition of the given material, are mostly used to produce auxetic structures. These are projection micro-stereolithography (PmSL) as seen in Figure 1 (c), liquid polymerization (SLA), direct laser writing (DLW), powder melting techniques (SLM, SLS, EBM) or selective electron beam melting (SEBM) [4]. With the help of optimization in the metamaterial design process, we can achieve the ideal distribution of the material for the given application.

3. Medical Applications

Metamaterials have a wide range of applications due to their unusual properties. Thanks to these properties, they are suitable candidates for use in the field of biomedical engineering. Of all types of metamaterials, mechanical metamaterials are

mainly used in biomedical engineering for the purpose of manufacturing bone implants, vascular stents, healthcare applications etc. [5].

The inspiration for the usage and production of metamaterials in biomedicine was the fact that even some naturally occurring materials exhibit properties such as negative Poisson's number, such as cancellous bone, embryonic epithelial tissues [5,6], the nuclei of embryonic stem cells arteries [7], tendons [8], and the annulus fibrosis of the intervertebral disc [9], which are all natural tissues.

3.1. Orthopedic scaffolds

Mechanical metamaterials have properties such as low weight, adjustable stiffness, auxeticity, which makes them a great candidate of Mechanical metamaterials possess unique properties such as low weight, adjustable stiffness, and auxeticity, making them an excellent choice for use in orthopedic scaffolds and bone-replacement structures. These materials are not only lightweight but also exhibit remarkable mechanical versatility, allowing for fine-tuning of their properties to closely mimic the behaviour of natural bone. Thanks to their architected structure, they are highly suitable for the transmission of tensile and compressive loads, ensuring effective load-bearing capabilities in critical applications. Furthermore, mechanical metamaterials excel in energy dissipation, which is particularly beneficial in mitigating the effects of impact forces, thereby enhancing durability and reducing the risk of material failure. Their auxetic nature, characterized by a negative Poisson's ratio, provides exceptional resistance to shear forces, making them highly resilient under complex loading conditions. This combination of properties makes them an ideal solution for designing advanced orthopedic implants that promote load sharing and integration with surrounding tissues. In addition to their mechanical advantages, the porous and interconnected architecture of these materials can also support biological processes, such as cell adhesion and tissue regeneration, which are essential for successful bone healing and integration. This adaptability highlights their potential to revolutionize the design of next-generation medical implants, offering improved performance and longer lifespans compared to conventional materials [9-10].

3.1.1. Auxetic screw

One of the most used bone implants is auxetic

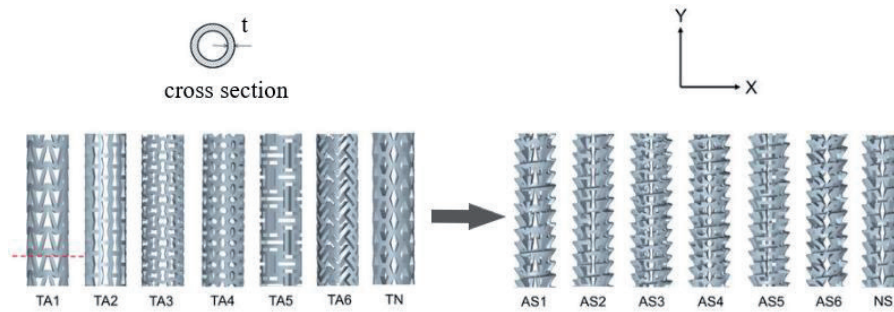


Figure 2: Schematic diagram of designed auxetic screws: (a) Tubular structures; (b) Screw bodies [10].

bone screw. The principle of auxetic bone screw is simple. When the bone screw is loosened there is a noticeable pullout force, at which the radial expansion of the auxetic bone screw expand the mechanical interaction between the screw and the bone, hence improving the anti-pullout effect. When pulled, the bone screw will expand transversal making a screw body of itself, so the fixation is enforced like in Figure 2. In the research [10], the research team designed auxetic bone screws with different unit cells (chiral, re-entrant and rotating). Computationally and experimentally, the re-entrant structure performed the best results and was considered to have the greatest strength and stiffness out of all designs.

3.1.2. Femur implants

The implementation of auxetic metamaterials for femur implants are relatively early. The lightweight properties of metamaterials have drawn the attention of the researchers all around the world. For example, the triply periodic minimal surface (TPMS) structures are widely applied in bone scaffolds [11]. The applications of TPMS structures guarantee that the bone scaffolds are both lightweight and meet the required biomechanical proper-ties. This is also like the properties of natural human bone.

Authors [12] designed acetabular cup-shaped socket based on six different auxetic unit cells and showed after series of bionic compression tests that metamaterial implants with functional gradient had the best space-filling behaviour as seen in Figure 3.

However, stress shielding and micro motions are two of the most serious problems in the stem of artificial joints [13]. To solve these problems, auxetic mechanical metamaterials are used to design femur implants. Therefore, different types of meta-biomaterials are also designed and additively manufactured with a rational distribution of positive

and negative Poisson's ratios, thereby improving the contact between implant and bone, increasing the implant longevity [14]. In addition, heterogeneous structural hip implant stems with the positive and negative Poisson's ratio are effective in preventing bone implant failure [15]. Furthermore, fatigue performance and fatigue crack initiation and propagation are investigated in auxetic implants [15].

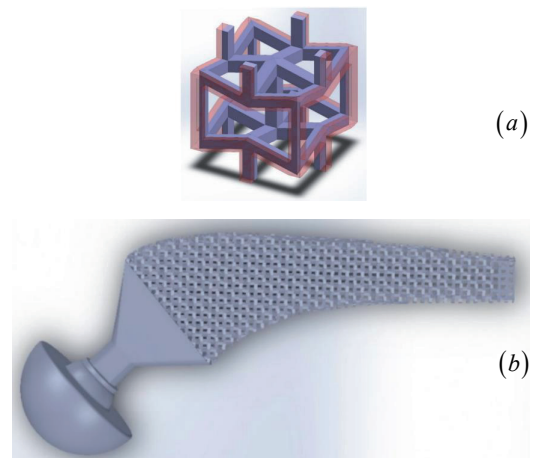


Figure 3: Femur bone implant: (a) 3D re-entrant unit cell; (b) CAD model of auxetic femur implant [12].

3.2. Self-aware metamaterial implants

3D printed mechanical metamaterials can not only have been used in auxetic screws and femur implants but also on self-aware metamaterial implants capable of responding to their environment. The lumbar spine with its intervertebral discs is very important part of the body to carry loads. That's why lumbar disc herniation is a restriction on mobility for all group of ages. There is research that shows that polymeric auxetic intervertebral disc implant can be used as a replacement for natural disc [16]. The negative Poisson's ratio of this structure can provide

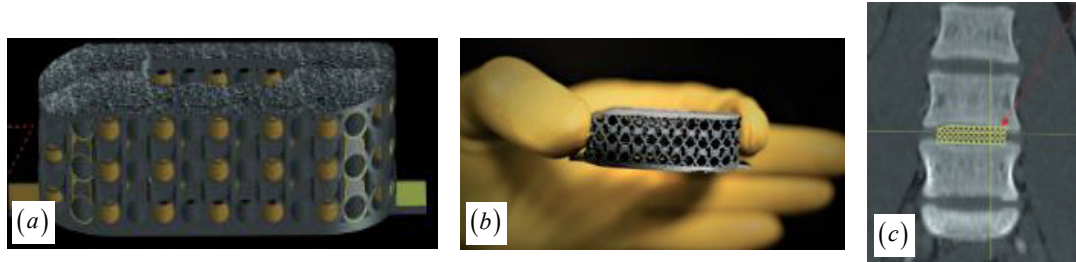


Figure 4: Self-aware implant: (a) CAD model; (b) 3D printed implant; (c) CT scan [18].

great compression stability and energy absorption. When compressed, the metamaterial disc will decrease in the transverse plane, and so the nerves will not be compressed [16].

Metamaterial intervertebral discs can be made of re-entrant cellular structures in the form of auxetic foam [17]. Finite element analysis has shown that the use of artificial auxetic disc with negative Poisson's ratio is a solution to the problem due to eradication of damage to the spinal nerves [18]. In Figure 4, authors created novel auxetic self-aware intervertebral implant and the results showed that it can achieve better surgical outcomes than the regular intervertebral implant [18].

3.3. Auxetic venous stent

Venous stents are small tubular scaffolds widely used in the treatment of arterial stenosis (narrowing of the vessel) to prevent acute vessel closure and late restenosis in a variety of vessels such as coronary arteries [19]. In the clinic, the shape-shifting or reconfigurable behaviour of venous stents is essential for the successful implantation. The inner radius of blood vessel is so small and varies from location to location, requiring vascular stent to be miniature and can be moved to the target location

and fixed at that location. The reconfigurable behaviour of auxetic mechanical metamaterials exactly matches this possibility [19].

The vascular stent is shrunk and placed into the target location through minimally protruding surgery and then opened out in the target location to secure that region. The shape-shifting metamaterial will change their structure and dimension upon activation via external stimuli (e.g. light, heat, magnetism, electricity, etc.), as shown in Figure 5 [20]. For the example, the auxetic 3D polymers are temporarily frozen and deformed, and are transferred to the target location. When the temperature increases, they expand and fill the inside of the vessel. [21]. The shape-shifting auxetic polymers have characteristics such as elasticity and deformability, excellent biocompatibility, and controlled degradation properties, making them one of the most optimal vascular stent materials.

3.4. Other application

Mechanical polymeric metamaterials can be used in impact protector devices, like pads, gloves, helmets, and mats, to utilize greater conformability for comfort, support, and protection. A cylinder-ligament honeycomb structured metamaterial with

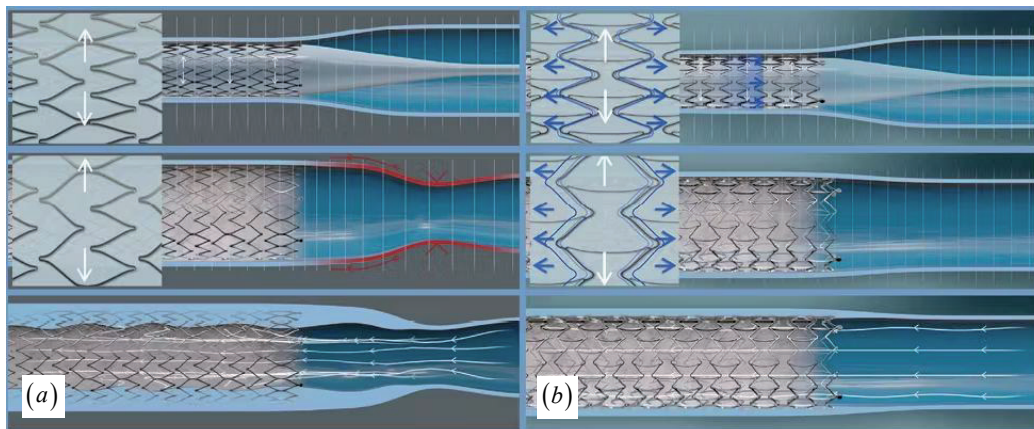


Figure 5: Behavior of venous stents: (a) Regular stent; (b) Auxetic stent [20].

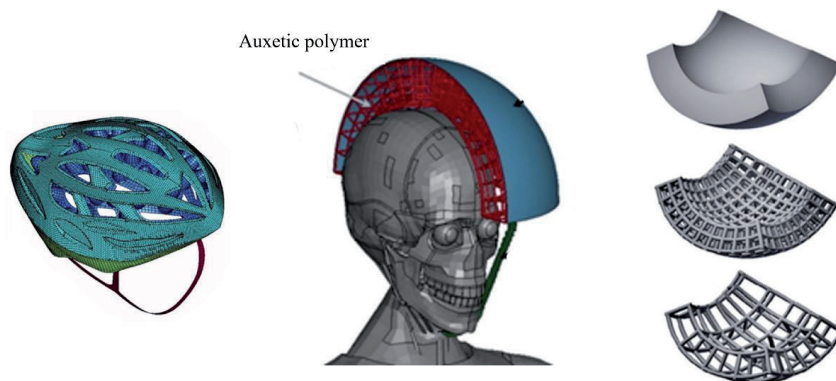


Figure 6: Auxetic helmet model [22].

synclastic curvature was reported, which made this system a candidate core material in sports helmet applications, as shown in Figure 6. [22].

Polymeric metamaterials have compelling potential for textile applications [23]. In the biomedical engineering fields, the fibre or yarn form of metamaterial textiles can be developed in different ways. The bandage was made of auxetic fibres with wound-healing agents. When swelling appeared in the wound, the bandage would open and release the agents. When the wound healed, the bandage closed and stopped releasing the agents.

4. Results and Future Trends

This review highlights the growing significance of auxetic metamaterials in biomedical engineering, particularly in the development of orthopedic implants, vascular stents, and protective medical devices. Auxetic structures, characterized by their negative Poisson's ratio, offer unique mechanical advantages such as improved energy absorption, enhanced flexibility, and superior load distribution, making them highly promising for healthcare applications.

A comprehensive analysis of recent studies reveals that additive manufacturing techniques have played a crucial role in enabling the fabrication of complex auxetic structures. However, despite these advancements, challenges remain in optimizing material properties, ensuring mechanical reliability, and addressing manufacturing limitations such as defects and variability in large-scale production.

Future research should focus on:

– *Optimization of auxetic structures through computational modeling and experimental validation to enhance their mechanical performance and adaptability in biomedical applications.*

- *Improved fabrication techniques to minimize defects and achieve higher precision in manufacturing processes.*
- *Comprehensive testing and validation using numerical simulations, mechanical testing, and musculoskeletal modeling to ensure the reliability and effectiveness of auxetic-based medical devices.*

By addressing these challenges, auxetic metamaterials have the potential to revolutionize modern biomedical engineering, offering innovative solutions for implants, prosthetics, and protective medical equipment.

Acknowledgments

The work was supported by the grant project VEGA No. 1/0152/24.

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