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Auxetics in Biomedical Applications: A Review

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Abstract

Materials exhibiting auxetic properties have a negative Poisson's ratio, which intrigued researchers to understand the behavior of auxetic structure. Several researchers focused on the different auxetic cell designs, while others focused on the auxetic applications. With the advance of additive manufacturing methods, computer-aided design and finite element analysis in recent decades, auxetics have been explored. One of the interesting applications is in the field of biomedical devices or implants, especially for certain natural biomedical organs such as tissues, certain ligaments that have auxetic properties. This paper is an overview of auxetic design approaches and biomedical applications.

Keywords

Auxetics, Negative Poisson's Ratio, Biomaterials, Biomedical Engineering

1. Introduction

1.1. Poisson's Ratio and Auxetic Properties

Poisson's ratio plays an important role in providing a unique strain performance in the transverse direction relative to axial direction. It measures the relative deformation of the material in the perpendicular direction, relative to the deformation at the applied load direction. If the force load is applied in tension, the material will increase in length in the direction of the loading, (axial), while the perpendicular direction (transverse) will decrease in length to conserve the volume change of the material. If the material is exposed to compression, the phenomena will hold, but the deformation direction will reverse. The mathematical equation for Poisson ratio has a negative sign to account for the decrease in the dimension of the strain, as shown in Equation (1).

$$v = -\frac{\epsilon_{\text{Transverse}}}{\epsilon_{\text{Axial}}} \quad (1)$$

If the material dimension increases in all directions in tensile loading or decreases in dimension in all directions in compressive loading, the result of the Poisson ratio equation will be negative. Materials with a negative Poisson's ratio are classified as auxetics.

Auxetic materials exhibit synclastic behavior, where the material displays a dome shape when subjected to bending, in contrast to the typical saddle shape for materials with a positive Poisson's ratio [1]. Auxetic materials also present higher amounts of indentation resistance when compressive loads are applied, in addition to higher fracture propagation [1]. Another observed property of auxetic materials is vibration damping of various patterns of auxetic structure, which can dampen up to 10 times more if the same material did not have an auxetic structure design [1] [2]. This leads to the use of auxetic structure for acoustic absorption, and various sound-related applications [2]. Another important feature of auxetic materials is their unique anisotropy, which can achieve different properties in distinct directions that are impossible by a material that has a positive Poisson's ratio [2].

Due to the anisotropic nature of the auxetic material, loading in the axial direction will yield different stresses, strains, and deformation patterns compared with loading along the transverse direction [3]. Additionally, auxetic properties are lost after yield stress is observed within the material due to deformation beyond the elastic region [4]. However, materials that have a low negative Poisson's ratio often have fewer other favorable mechanical properties, creating a fine line between mechanical and auxetic properties for most applications [4]. Thus, it is important to consider the direction, magnitude, and type of loading when analyzing auxetic materials to maximize the utilization of the auxetic function of the material.

1.2. Design and Analysis of Auxetics

1.2.1. Geometric Designs

Auxetic materials have a common feature as all designs can be broken down into specific unit cell designs that provide the structure with the unique aforementioned properties. These unit cell designs range from common material structures to ones that exist on the molecular level, as seen in some inorganic microstructure crystals [5]. There are different geometries that provide negative Poisson's ratio property, such as the S-shaped unit cell, which was explored by Meena, K. and Singamneni, S., 2019 [4] and the re-entrant unit cell, which was explored by Y. Zhu *et al*., 2022 [6]. A major challenge of unit cell design is the complexity of the detailed design relative to the load capacity that the structure can handle [3]. One of the parameters that should be considered as a constraint to each design is the direction of loading and maximum allowable load capacity due to the high stress zones of the structure [3]. Unit cell designs are affected by the network of cells attached to it and the direction of loading. One of the most common designs considered for research and products is the re-entrant unit cell. This design has been studied in numerous applications, such as cardiac patches by Kapnisi M. *et al*., 2018 [7], oesophageal stents by M. N. Ali *et al*., 2014 [8], and heel pads by M.S.-H. Leung *et al*., 2022 [9]. The S-shaped unit cell (right) and re-entrant unit cell are displayed in **Figure 1**.

1.2.2. Finite Element Analysis

The fields of mechanics and materials clearly illustrate the difference between theoretical values obtained from technological analysis and actual values obtained through mechanical testing. Oftentimes, auxetics are tested through physical loading of specimens to measure the observed stress and strain values. It is also common for the use of Finite Element Analysis (FEA) models to simulate the auxetic performance, using various software packages, such as Ansys, ABAQUS and Solid Works.

Finite Element Analysis software allows for a simulation of the deformations and critical stress values that will occur in different materials, shapes and interactions utilizing computer-aided design (CAD) models. The software allows for visualization of common concepts that cannot be physically seen, such as Von-mises stresses, displaying the varying magnitudes of stress distribution on the CAD model of the auxetic structure. It also shows the deformation and strain on the structure at different loading levels and directions. FEA software is used to run multiple iterations that would cost time and money if they were all designed and fabricated for testing. It assists in limiting the number of prototypes for testing. Finite element analyses are also utilized to identify the performance of different materials on the same auxetic design and loading limits.

There are no standards or specifications that can be followed when designing auxetic structures that would lead to pre-defined negative Poisson ratio values. Designing negative Poisson ratio material follows an empirical approach. One of the observations is that the geometry of the auxetic structure has a direct impact on the overall performance. Unit cells that have sharper angles lead to stress

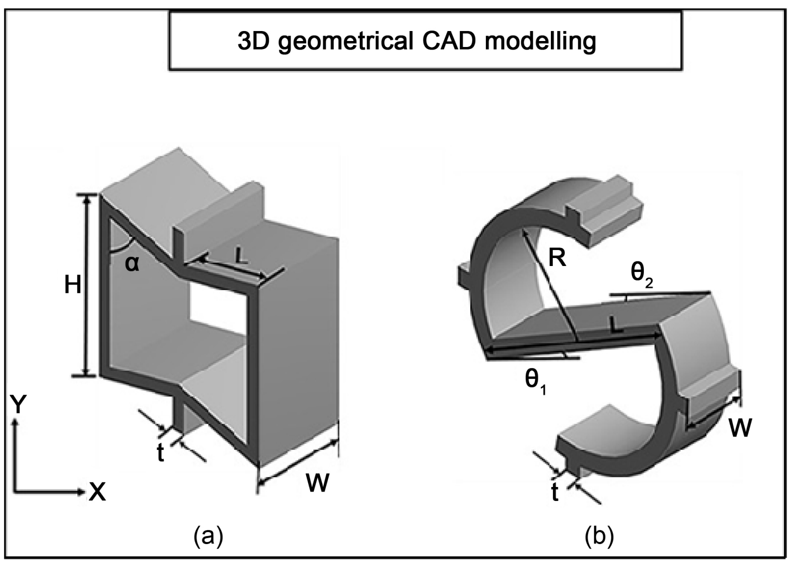

Figure 1. (a) Re-entrant unit cell and (b) S-shaped unit cell [4].

points of larger magnitudes (stress concentration), ultimately leading to prematurefailure [4]. Meena, K. and Singamneni, S., 2019 [4] performed FEA models of both the S-shaped and re-entrant unit cells and concluded that the sharp internal corners ultimately led to the earlier failure of the re-entrant cell compared to the smoother internal edges of the S-shaped cell. It was also determined that re-entrant unit cells with an internal angle of 75˚ exhibited the optimal auxetic response when loaded. Other interesting observations were made, such as unique deformations along areas that are rotationally symmetrical, with identical deformation patterns [4].

Further studies on auxetic design and performance are needed in order to adapt them for specific applications. Other researchers adopted the design for an application approach. Due to their unique performance, auxetic materials can be used in a vast variety of applications, including the biomedical field.

The use of auxetics in the biomedical field has become popular due to the use of auxetic biomaterials [10] [11]. An auxetic biomaterial is simply an auxetic structure manufactured from a material derived from a biocompatible material such as protein-based hydrogel [12]. It is most common for these structures to be produced with 3D printing methods [10] [12]. This paper focuses on specific examples of biomedical applications of auxetic structures that have been used in various studies.

1.3. Biomedical Application of Auxetics

Physiological aspects of various fields can be improved through the implementation of auxetic properties into already-existing devices. One common example includes the synclastic behavior of helmets, which increases the protection provided to the user's head upon impact [1]. These properties can also be expanded to a wide range of other protective equipment to allow for lighter weight and increased comfort [2].

K. Saxeen *et al*., 2016 [2] have illustrated numerous biomedical applications for auxetic structures. The uses can be divided into various categories such as implant devices, medical or surgical devices. Some of the most noteworthy implant applications include auxetic stents that reduce inflammation inside the body, and artificial blood vessels. Some procedures include dental floss, surgical sutures, and even smart bandages.

2. Biomedical Applications

2.1. Tissue Engineering

Tissue engineering aims to restore damaged tissue functions using biomaterials. Tissues engineered with an auxetic internal structure can potentially better mimic the mechanical properties of the original tissues than the ordinary engineered tissues. Tendons, vasculature, cancellous bone, embryonic epithelial tissues, arteries, and the annulus fibrosus of the intervertebral disc all have auxetic properties [10] [13].

It is a common practice for researchers to use computer-aided design software and finite element method to evaluate mechanical properties and compare them with experimental data. Warner *et al.*, 2017 [10] found that modified unit-cell architecture with stabilized rounded hinges is effective at transmitting displacement throughout the structure and can minimize out-of-plane deflections using FEA. Combined with further research, these findings can potentially be used in tendon-muscle tissue regeneration. Kapnisi M. *et al.*, 2018 [7] compared the theoretical resultant effective stiffness and anisotropic ratio of effective stiffness using an analytical model established by I. G. Masters and K. E. Evans, 1996 [14] with the experimental data collected, and an agreement was discovered between the two researchers.

R. Ajdary *et al.*, 2022 [15] fabricated bacterial nanocellulose (BNC) with triangular, circular and star unit cell shapes using molds designed in SolidWorks. The Poisson's ratios of −0.19, −0.36, and −0.13 are found for the triangular, circular, and star unit cells, respectively. The auxetic BNC meshes obtained after cell culturing can have a tensile strength up to 456 MPa depending on the cell culturing time. The reversible structural expansion under tension minimizes the tissue damage that commonly occurs by shrinkage of plastic-based mesh implants, and is expected to maximize comfort, minimize material fatigue, and thus improve the overall success of future long-term mesh implants.

M. N. Ali *et al.*, 2014 [8] simulated the auxetic esophageal stent using a single square FEA model and an auxetic-ring FEA model in ABAQUS. The auxetic polyurethane film is compared with the auxetic film model derived from a single square FEA model extracted from the auxetic film for simplicity and accuracy, shown in Figure 2. The rigid auxetic polyurethane stent is comparable with the auxetic-ring FEA model. The two FEA models are concluded to be in good agreement with the experiment.

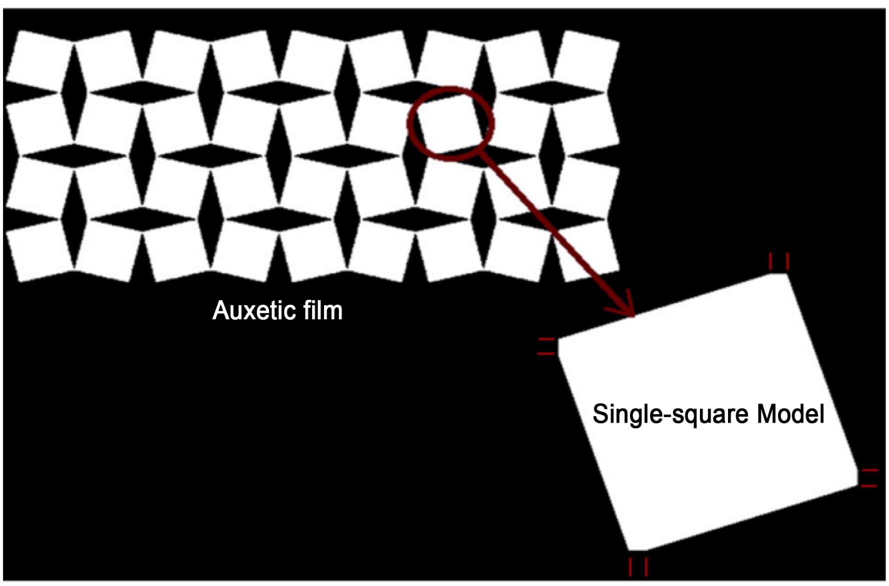

Figure 2. Single square FEA model [8].

The M. N. Ali *et al*., 2014 [8] expected the auxetic esophageal stent with anisotropic mechanical behavior to conform well to the multilayered esophageal wall with a non-linear anisotropic mechanical response. Additionally, the small auxetic stent graft can be delivered orally into the esophagus without the use of an expensive dedicated delivery device using a balloon catheter [16]. With further study, such auxetic esophageal stents can potentially replace the current esophageal stents.

2.2. Implants

The auxetic pedicle screw proposed by Y. Yao *et al*., 2020 [17] is reported to have an improved fixation strength, while the femur auxetic meta-implant proposed by N. Ghavidelnia *et al*., 2021 [18] is reported to reduce the stress shielding and micromotions.

Y. Yao *et al*., 2021 [19] conducted thorough mechanical tests experimentally and computationally using FEA on the designed auxetic pedicle screw. Predictions by the FEA simulations are consistent with experimental results, but there are discrepancies between FEA and experimental results, including higher tensile stiffness, tensile strength and Poisson's ratio [17]. The auxetic pedicle screw can improve bone-screw fixation by its radial expansion of the screw body under tensile force to resist pulling out. The pullout force was increased by 6.29% - 14.46% compared to that of the solid screw; however, a few auxetic screws have fewer pullout forces than the solid screw [19]. N. Ghavidelnia *et al*., 2021 [18] focused on developing an analytical solution with FEA and found the femur auxetic meta-implants to have enhanced stress and strain distributions and a more compatible and uniform distribution of micromotion.

2.3. Other Biomedical Applications

Biomaterials with auxetic properties usually have complex geometry, making it difficult for researchers to design and analyze. However, with the increasing computation power in recent decades, researchers can incorporate auxetics in some other biomedical applications.

A. Bonfanti and A. Bhaskar, 2019 [20] proposed a wrinkle-resistant auxetic film to tackle the wrinkling problem of synthetic skin. The auxetic films showed the ability to be stretched without forming wrinkles with experiments, analytical solutions, and FEA. The wrinkle-resistant auxetic film can be a promising candidate for future applications such as artificial skin, cardiac patches, and biomedical stretchable sensors.

A. Arjunan *et al*., 2021 [21] developed a one size fits all auxetic nasopharyngeal swab that can be easily 3D printed. The FE model overestimates the yield and peak forces by 4.30% and 3.87% respectively, but the force-displacement curve of the swab heads shows that the FE model agrees with experimental results. The swab head can reduce patient discomfort by shrinking inward while navigating the nasal cavity, thus exerting a reduced stress on surrounding tissue compared to a regular swab.

V. Gupta and A. Chanda, 2023 [22] developed skin graft computational models using I-shaped auxetic incision structures and tested them under uniaxial and biaxial loads to evaluate their expansion potentials. The finite element model and testing of the auxetic skin graft using an isotropic and elastic material to represent skin demonstrated a high expansion and skin cover.

F. Tsegay *et al*., 2023 [12] presented an auxetic hydrogel skin pH indicator wound dressing as a smart band-aid or dressing. Using a phenol red dye in the hydrogel matrix of the material could help monitor pH changes in the vicinity of the wound to better indicate what treatment is required for the patient.

As mentioned before, a large constraint to auxetic unit cell design is the high stress zones of the structure, which limits the use cases for these structures, especially when manufactured from biomaterials. It is possible that auxetic biomaterials can be further optimized, which would involve exploring composite materials such as nano-size particles. However, it is beyond the scope of this paper.

3. Conclusion

Several biomedical applications can implement the use of auxetics; however, challenges arise from unit cell design, manufacturing, FEA simulation and more. Variations in unit cell designs and manufacturing methods can result in different auxetic properties and even in different bulk mechanical properties. FEA computer simulation can also be challenging when working with auxetics, as several research papers have reported that the auxetic behavior agrees with the simulation but fails to theoretically predict the mechanical properties values. Numerous studies have found that auxetics can be more suitable in certain biomedical applications using FEA and analytical solutions, but further experimental and clinical research is needed before replacing the current non-auxetics biomaterials.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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