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Review of modelling and additive manufacturing of auxetic materials for application in sport

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Abstract

The unconventional way that auxetic materials behave can result in advantageous mechanical properties, which could be made use of in applications such as protective equipment and clothing in sport. Much of the work to date demonstrates advantageous properties of auxetic materials well, but their application in sport is underdeveloped. This review paper demonstrates how modelling has helped develop auxetics research, highlighting how further work in this area could contribute to improved implementation of auxetics within sport. Additive manufacturing as a production technology for auxetic structures is also considered and discussed. Future work could look at creating a systematic finite element modelling process to design, optimise and apply auxetic structures for use in sports protective equipment.

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1. Introduction

Auxetics are innovative materials with a negative Poisson's ratio (NPR); they get thinner when compressed and thicker when stretched, the opposite of how a conventional material acts (Alderson, 1999). Such counter-intuitive behaviour is often due to the mechanical structure of the material and it can lead to beneficial mechanical properties including increased indentation resistance and greater energy absorption. Therefore, a potential auxetic application is within sport equipment designed for limiting harmful impact forces (e.g a shin-pad resisting a stud impact

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(Duncan et al., 2016) or implementation in helmet design (Sanami et al., 2014)). The potential of applying auxetic foam to sports protective equipment has been demonstrated by Allen et al. (2015), but current work mainly involves time-consuming development of material samples, accompanied with experimental testing (Allen et al., 2017). The potential is also reflected in the patents held by both Under Armour (2013) and Nike (2013) on auxetic technology.

Finite element modelling (FEM) is an established engineering technique that can be applied to predict the behaviour of materials and structures under pre-determined conditions. FEM has been applied to auxetic materials but it has not been thoroughly explored to support their implementation within sports protective equipment specifically. With FEM, the need for repeated prototype development and manufacture is often reduced, resulting in a more efficient design process. FE model outputs should, however, be compared to experimental data whilst they are being developed to ensure their validity, which requires a prototype for mechanical testing. An emerging technique for fabricating auxetic materials is additive manufacturing, which can be utilised to produce specifically designed, and often complex, structures (metamaterials) with relative ease. This review paper aims to critically report on the contribution that modelling has made on the field of auxetics and the potential FEM has to contribute to their application within sport. Additive manufacturing as a production technique to validate FE models of complicated auxetic structures is also assessed. While there exists other review papers on auxetics (Kolken and Zadpoor, 2017, Saxena et al., 2016, Prawato, 2012), this review paper considers the application to sport exclusively.

2. Modelling development of auxetic materials

A 'model' is used to explain complex systems and can have simplifications or assumptions to improve understanding of the system. Numerical, molecular and predictive computational models have been applied to auxetic materials. The models are used analyse the microstructure that contributes to the auxetic behaviour of the material. The microstructure of auxetics can be designated into three main types: re-entrant, chiral and rotating units, as shown by simple two-dimensional (2D) models in Figure 1.

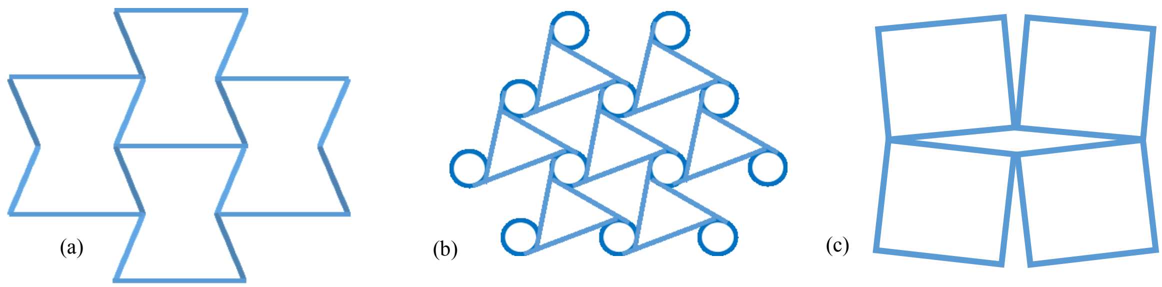

Figure 1. The three auxetic types; a) re-entrant, b) chiral and c) rotating units.

The re-entrant structure was the first to be modelled analytically and was developed in early work on auxetic foams. Auxetic foam can be thermo-mechanically converted from conventional foam, as originally demonstrated by Lakes (1987). Gibson and Ashby (1988) used 2D hexagonal honeycombs to model the behaviour of foams numerically. Replacing the hexagon with a re-entrant structure resulted in an NPR. The model assumed that the deformation of the cell wall was by flexure alone, excluding stretching (rib length increase) and rotation or hinging (of the angle between ribs) mechanisms. It was also assumed that the cell ribs behaved as beams of uniform thickness. The model was used to accurately predict mechanical properties of honeycombs, such as the Young's modulus and Poisson's ratio, a technique used throughout auxetic modelling development.

An auxetic molecular model was proposed by Nkansah et al. (1994), consisting of a network of repeating unit cells of acetylene bonds and benzene rings, which considered deformation due to both hinging and stretching of cell walls. A finite element method was used to simplify the intricate molecular arrangement. The predicted Poisson's ratio did not compare well to those calculated via the molecular model nor the analytical model of Gibson and Ashby. However, Nkansah and colleagues demonstrated that auxetic structures had the potential to be modelled more simply, without the need for complex molecular models. Evans et al. (1995) also designed molecular models of auxetic honeycombs, which they compared with analytical models, but not experimental work. The models included deformation mechanisms of flexure, hinging and stretching (independently or simultaneously), while showing good agreement with one another. As an extension of this work, Masters and Evans (1996) modelled the deformation of a honeycomb structure due to flexure, stretching and rotation combined. In this 2D model, each mechanism was defined numerically in terms of properties of the cell material and geometry. Smith et al. (2000) proposed a 2D missing rib model (Fig. 2b), which considered cell ribs broken during the fabrication of foams. This novel model more accurately predicted the strain-dependent Poisson's ratio compared to the existing 2D models.

Choi and Lakes (1995) modelled the unit cell of conventional and re-entrant foam as a quasi-three-dimensional (3D) 14-sided polyhedron. The deformation mechanism of the re-entrant cell in linear elasticity was due to cell rib bending, and an NPR was achieved by 'unfolding' these cell ribs in axial deformation. Lu et al. (2011) developed the work of Choi and Lakes by creating a 3D re-entrant model that incorporated all three modes of deformation. An FE model was also created, in order to make predictions of Poisson's ratio, which was found to support the newly adapted model well. Auxetic research in 3D progressed with the creation of a 3D auxetic structure; created by modelling the 2D re-entrant unit cell and repeating and cross-layering it orthogonally (Shokri Rad et al., 2014).

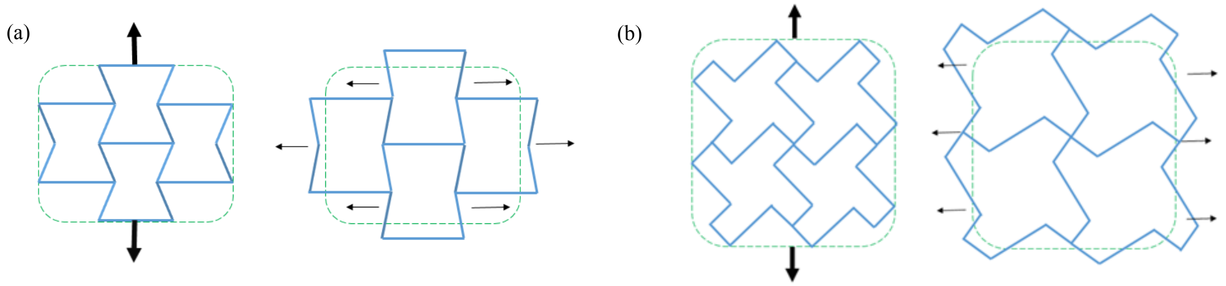

Figure 2 – (a) Re-entrant structure gets thicker in tension and (b) Smith's missing rib model and its auxetic effect.

Despite most of the early modelling work focusing on the re-entrant structure, some simple models were proposed for other auxetic structure types. Chiral auxetics – asymmetric structures that are non-superimposable on their mirror image – were proposed by Prall and Lakes (1997). Another mechanism to describe auxeticity was suggested by Grima and Evans (2000), whereby the NPR was caused due to rotation of connected squares. As extension of this work, a similar mechanism that used rotating rectangles was suggested (Grima et al., 2005). Overall, these early models and the associated analytics helped improve our understanding of auxetics and their behavior, leading to a plethora of additional research.

3. Finite element modelling

Computer based modelling was able to advance auxetic research and FEM software has been used in various studies. Evans et al. (1994) established an FE model for 3D open-cell foams, after simple 2D models were shown to predict properties of a 3D network poorly. The first example of the homogenisation FE method was by Lee et al. (1996), who analysed 'spatially periodic materials' in the linear elastic region. Huang et al. (2002) expanded upon this by considering Eringen's micropolar elastic theory and using a linear triangular FE formulation. The latter two papers showed that the Poisson's ratio was dependent on the angle of the cell ribs and this was further consolidated by Yang et al. (2003). The ability to tailor mechanical properties (such as Poisson's ratio) of a structure by varying geometric parameters is of great interest when considering possible applications in sport. Parameter changes within FE models can be made easily and the simulation can provide updated results to analyse, which could be useful in product design. Another example of exploring design parameter changes within FEM was demonstrated by Shokri Rad and Ahmad (2015). Three different cross-sectional geometries (per structure) were used to scrutinise the effect cellular parameters had on mechanical properties. The study showed that the tailoring of mechanical properties was possible by careful cell parameter manipulation and this was all done using computer software.

Whitty et al. (2002) used FE models to investigate the effect of density variation of the honeycomb structure on material properties. The models were validated against results from both analytical and experimental methods. Rib flexure was shown to be the dominant deformation mechanism and reducing the thickness of the vertical ribs (and consequently the structure's mass) was investigated and considered for potential structural applications. Specific FE models for protective equipment would allow us to investigate the effect of mass (and more lightweight designs) on mechanical properties and impact protection performance. Doyoyo and Wan Hu (2006) used FEM to validate analytical results and consequently make early recommendations of auxetic strut designs that could be implemented within miniaturised sandwich structures. Similar techniques were used by Qiao and Chen (2015), in order to assess the impact resistance of auxetic double arrowhead honeycombs (drawn in Figure 3a) and their deformation mechanisms for potential use in blast protection devices.

FEM can also lead to innovative design processes. Bezazi et al. (2005) proposed a new centre-symmetrical honeycomb design (Figure 3b) and explored the effect that the internal cell angle had on the value of Poisson's ratio, using FEM. The new design curved the sharp corners of the unit cell to remove stress singularities that could arise, considering future manufacturing techniques.

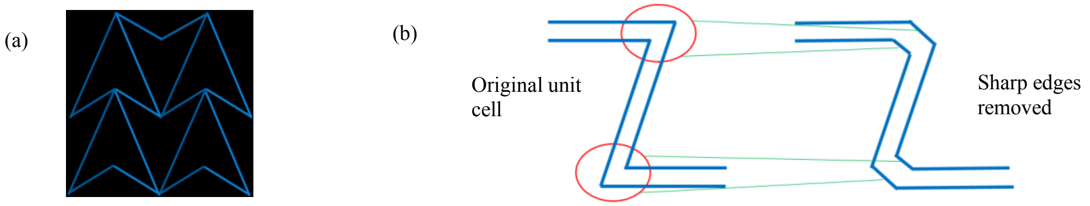

Figure 3 – (a) Auxetic double arrowhead and b) removal of unit cell stress singularities (Bezazi et al., 2005) to improve simulation performance.

Ge et al. (2013) used FEM to develop an innovative 3D textile structure designed to be auxetic under compression. The finite model was used to assess the effect of changing the structural parameters on the performance of the textile. Yang et al. (2016) analysed auxetic polymeric structures and highlighted their potential for body protection applications in sport (e.g. helmets, gloves and shoulder pads) and defence. The work combined two different auxetic structures into one design, but the effect of changing cell parameters was not explored. Their research provides further evidence of how FEM can improve and simplify the design and application process.

All of the FEM reviewed so far in this paper consider only static structural analysis (implicit). FEM software has also been used to evaluate rate-dependent (explicit) properties of auxetics, for example when considering impact forces, which occur in various sporting scenarios. These explicit simulations are therefore important to investigate when considering applications within sports protective equipment. Yang et al. (2012) simulated the crushing of a re-entrant honeycomb structure and examined its energy absorption capabilities. It was suggested that an analytical model could be developed to go alongside FEM work and increase validation. Qi et al. (2013) simulated ballistic impacts at speeds between 150 and 300m/s on honeycomb sandwich panels, demonstrating the benefit of utilising FEM to investigate auxetics with a specific application in mind.

Imbalzano et al. (2016, 2017) also constructed rate-dependent studies to examine the blast resistance performance of auxetics in military applications. The research explored a range of parametric studies but lacked experimental work to validate their range of FE models and accelerate the application process. A jounce bumper with NPR was designed and fabricated by Wang et al. (2016). The effect of changing load velocities and material densities on computational efficiency was explored using explicit FEM. FEM has been used to investigate dynamic effects in certain applications, which are crucial to also consider when investigating auxetic application in sports protective equipment.

4. Additive manufacturing of auxetic materials

Due to advances in additive manufacturing, auxetic structures with highly specific and repeatable geometries can be made and tested to validate the FE models. Wang et al. (2015) used additive manufacturing to create a composite auxetic that combined two materials within one re-entrant unit cell. The 'dual material auxetic metamaterial' (DMAM) was printed (Connex 350®, with the materials supplied by Stratasys) with a stiffer material (VeroWhitePlus®) for the beams and walls of the unit cell and a more elastic material (TangoBlackPlus®) with low stiffness at the hinges, as shown in Figure 4. The combination of materials allowed more parameters to be investigated, including the ratio of cell wall that constitutes the stiffer material and even the material choice for each region. FEM could facilitate these investigations very easily.

Shen et al., (2014) printed auxetic lattices with TangoBlack®. A new methodology for generating these 3D auxetic lattices was conceived, whereby a simple initial unit cell was taken and replicated in three directions to form a bulk material. Li et al. (2017) used 3D printing to validate an FE model of a new stiff square lattice. The cellular structure was made auxetic by indenting the vertical ribs with a rectangular shape and repeating the unit cell from this point to form a lattice. Critchley et al. (2013) additively manufactured auxetic foam but encountered issues with the support structure generated, a limitation to consider in future work. The research clearly demonstrates the ability to create and produce novel auxetic structures using additive manufacturing techniques and FEM, something that could work well within the design of auxetic sport protective equipment.

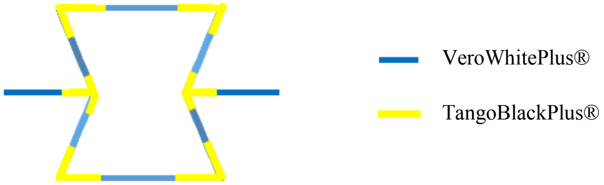

Figure 4 – DMAM unit cell, showing more elastic material at hinges and stiffer material for cell walls.

Discussion

Modelling studies have been conducted on various aspects of auxetic materials, from original molecular models (for improving auxetic understanding), to predicting mechanical properties from analytical models. More recently, parametric studies with FE models have been used when designing and tailoring auxetic structures for specific applications. The advantages of this technique are clear; with a validated model, design alterations can be made quickly and easily with the use of FE software. The effect of these changes can then be analysed. FE modelling has also been used to consider dynamic simulations, although this work is not quite as developed. The possibility of additive manufacturing auxetics also been considered. Benefits of this technology are also evident; metamaterials with complicated structures can be specifically designed and fabricated. Of course, limitations exist (available materials, costing) but the potential and feasibility of this technology should be noted.

Future work could look at using finite element modelling systematically as a method of demonstrating the application potential of auxetics to sport. This work could also investigate parameter changes to unit cells and conceive a method to optimise these parameters in terms of auxetic performance (i.e. more energy absorbed, less indentation from impact). 3D printing of samples has been shown to be viable and this should be considered as a process when validating the FE models. The potential of auxetic materials is known, but the application process needs developing and this review paper provides evidence that the application process can be developed through FE modelling and additive manufacturing.

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