3D Fabrics with Negative Poisson's Ratio: A Review

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Abstract: Three-dimensional (3D) fabrics with negative Poisson's ratio (NPR) are known as 3D auxetic fabrics. They expand (or contract) in the direction perpendicular to stretch (or compression) under uniaxial tensile (or compressing) conditions. Many enhanced properties come with this unusual auxetic behaviour, such as shear modulus, indentation resistance, fracture toughness, energy absorption, synclastic curvature, etc. Therefore, these 3D auxetic metamaterials have a broad prospect in applications like personal protective equipment as a replacement of polyurethane foams, fabric-reinforced composites with improved ballistic and impact resistance, and women's brassiere paddings with perfect shape-ability. This paper presents a review on 3D fabrics with NPR produced with different fabric technologies, including weaving, knitting, nonwoven, and other techniques.

Key words: auxetic; 3D fabrics; negative Poisson's ratio; fabric technology

1 Introduction

The value of Poisson's ratio v is defined as the negative of the ratio of transverse strain ε_t to axial strain ε_a, expressed as $v = -\frac{\varepsilon_t}{\varepsilon_a}$. It measures the deformation of a material in the direction perpendicular to the applied force [1]. Most materials possess a positive Poisson's ratio (PPR), ranging from 0 to 0.5. For example, rubber has a Poisson's ratio of almost 0.5, common steels have a Poisson's ratio of 0.27, and for cork it's nearly zero [2]. As shown in Fig. 1(a), when a two-dimensional (2D) material with PPR is compressed in the y direction, it will expand x-directionally, or when it is stretched y-directionally, it will contract along the x direction. In the case of 3D material with PPR, as shown in Fig. 1(c), it may expand in both x and z directions under y-directional compression, or show necking down when it is stretched in the y direction. But materials with NPR, also referred as auxetic materials, exhibit an opposite deformation under the same conditions. As shown in Fig. 1(b), a 2D material with NPR shrinks transversely under axial compressing forces, or enlarges transversely under axial tensile forces. For a 3D material with NPR, as shown in Fig. 1(d), when it is compressed in the y direction, the contracting behavior might appear in either x or z direction, or in both directions. And when it is stretched in the y direction, the fattening effect might show in either x or z direction, or in both directions. The NPR behavior can thus be classified into perfect auxetic effect and partial auxetic effect. If the NPR behavior only exists in one or some directions of the material, it is partial auxetic effect; if the NPR behavior appears in any direction of the material, it is a perfect auxetic effect. It is reported by many researchers that NPR would enhance properties including indentation resistance, fracture toughness, volumetric strain energy dissipation and shear modulus of the material [3]. Auxetic materials also show a superior sound absorption behaviour [4] and an unusual synclastic curvature [5] compared with conventional materials. They will deform into a dome shape instead of a saddle shape under out-of-plane bending, thus giving them a better shape fitting ability on curvy surfaces (e.g., human body parts like ankle or elbow). Plenty of natural auxetic materials have been found since 1944, such as iron pyrites [6], crystalline silica [7], and biomaterials like cancellous bone [8] and cow teat skin [9]. The enhanced mechanical properties and unique deformation behaviour that come with NPR also become a significant intrigue to push the development of synthetic auxetic materials at different scales, from cellular foams and polymers to textiles and composites.

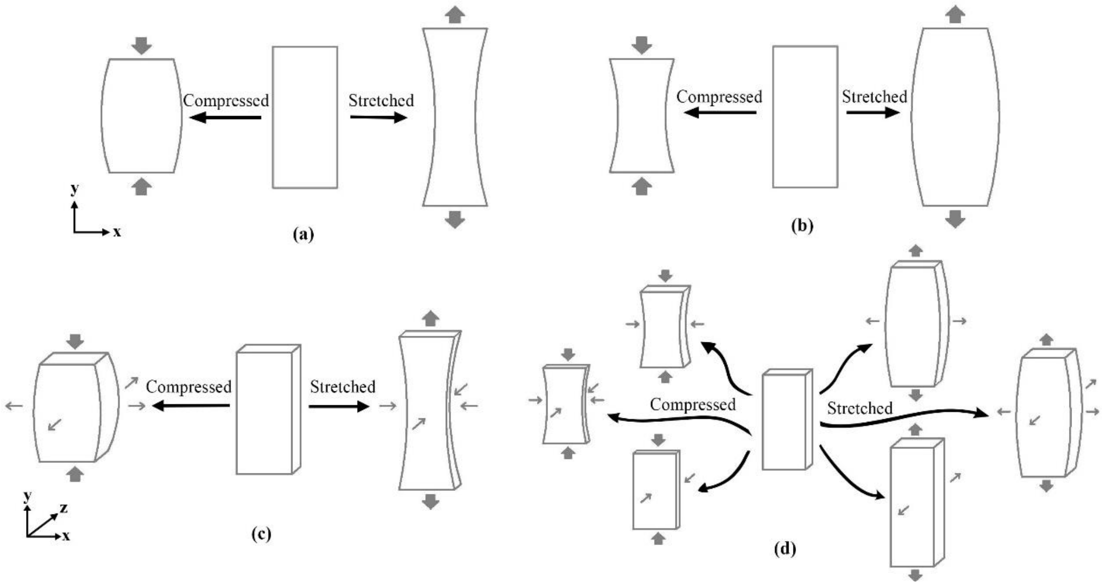

Fig. 1 a 2D material with PPR. **b** 2D material with NPR. **c** 3D material with PPR. **d** 3D material with NPR

The auxetic effect can be observed in many geometric structures, most typically re-entrant honeycomb [10], double arrowhead [11], rotating units [12-14], egg rack structure [15], etc. The investigation into auxetic textiles firstly started with microporous fibre materials like polytetrafluoroethylene (PTFE) [16, 17], polyethylene [18], and polypropylene [19]. Incorporating the helical auxetic yarns into woven fabric structures as warp, or as weft, or as both, fabrics with NPR were produced [20-22]. In the domain of 2D fabrics, woven fabrics with various auxetic geometries were produced either by making use of the differential shrinkage in different weaves [23], or by making use of the differential shrinkage of elastic and non-elastic yarns [24]. To improve the auxetic effect of the woven fabrics with re-entrant honeycomb structure, different weaves and yarns with various elasticity were combined together to design the fabrics, proving to be feasible to generate bi-directional auxetic behaviour in the fabrics [25]. Typical auxetic geometries like re-entrant hexagons, double arrowheads and rotating rectangles have also been induced into the warp-knitted fabric structures [26-29] and weft-knitted fabric structures [30, 31]. It is expected that the 2D woven and knitted fabric structures with an in-plane auxetic behaviour are suitable for apparels like children's wear and maternity dress, which may need to change their sizes to suit the changing body shape. They can also be used as underwear belts to reduce the contact pressure on the human body and thus improve its comfort. Other than these fabrics with in-plane NPR, there are 2D fabrics showing an out-of-plane auxetic behaviour, such as needle-punched nonwoven sheets, and sintered metal fibre sheets [32-34]. Other techniques have also been used to obtain fabrics with NPR, for example, laser-cutting a non-woven to form an auxetic rotating square geometry, or 3D printing re-entrant honeycombs on plain knitted fabrics [35, 36]. Despite the progress made in 2D auxetic fabrics, 3D fabrics with NPR have been studied due to their superb energy absorbing ability under impact and quasi-static forces. It is believed that they have broad application prospects in areas of protective equipment, composite reinforcement, as well as apparels like footwear.

In this paper, various 3D fabrics with NPR are reviewed, from woven and knitted ones to non-woven and orthogonal ones.

2 3D knitted fabrics with NPR

2.1 3D weft knitted fabrics

The design of 3D weft knitted fabric with NPR mainly arises from the auxetic foldable geometries, also known as origami structures. The term "origami" originates from a Japanese word meaning paper folding. Although there are numerous kinds of origami structures, the first one that has been adopted in weft knitted fabric designs was the foldable parallelograms [30]. When the parallelograms are unfolded, the thickness of the structure will decrease, and, at the same time, a bi-directional expansion in the sheet plane will be observed. To realize the folded effect, the combination of face loops and back loops in weft knitting can be considered. One of the simplest examples is the rib structure, such as 1×1 rib or 2×2 rib. The rib structure will fold naturally in the course direction after knitting. The other basic example is the purl structure, which is formed of alternative courses of face loops and back loops in the wale direction through loop transferring. As shown in Fig. 2(a), faces loops and back loops will be arranged in groups of the parallelogram shape. In one repeating unit, four face loops and four back loops are alternatively arranged in the first course, and in the second course, the repeating unit moves to left with one needle distance by selectively transferring loops in the front to the back and transferring loops in the back to the front. When all of the face loops have moved to the positions where back loops originally are, the move direction changes. In this case, there are 8 courses in each unit cell and the simulation of loop pattern is shown in Fig. 2(c). The disequilibrium between face loops and back loops leads the fabric to curling and folding, thus forming a 3D structure. When a tensile force is applied along the course direction, the folded loops will unfold, showing a distinct auxetic effect in the fabric plane.

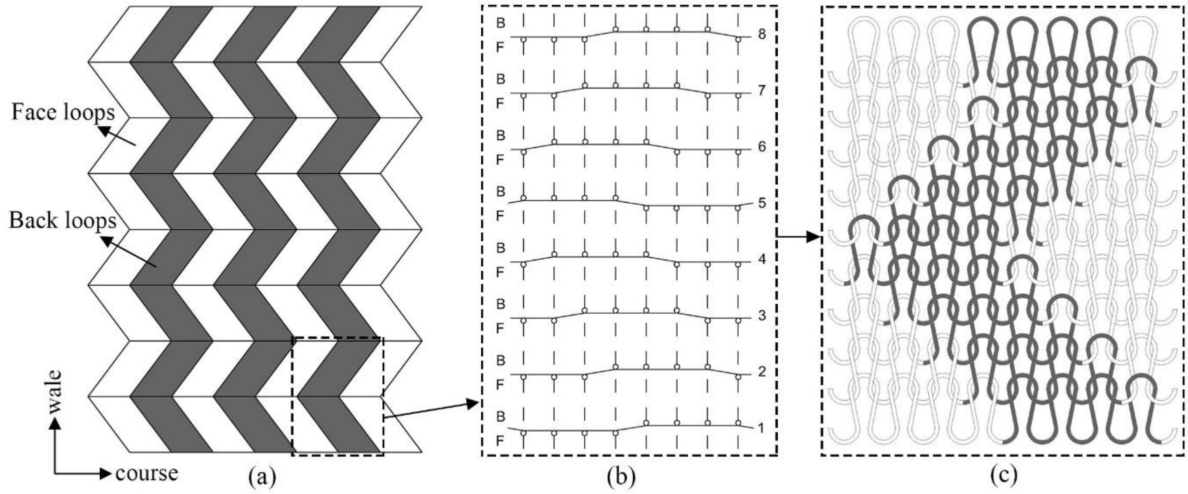

Fig. 2 A 3D weft knitted fabric with folded parallelograms. **a** pattern of folded parallelograms. **b** knit pattern of a repeating unit. **c** loop pattern simulation of a repeating unit

Based on the former design principle, 3D weft knitted fabrics with different unit cell sizes were produced and tested to investigate the effects of varying structural parameters [30]. Results showed that the initial opening angle is a critical structural parameter which to some extent represents how closely folded the fabrics are. This study proved the possibility to produce 3D fabrics with NPR directly using weft knitting techniques for the first time, and paved a way for the following research. A tubular fabric was developed based on the similar zigzag-shaped folded structure using flat knitting techniques [37]. Different yarn materials were used to fabricate the tubular fabrics on a commercially available flat knitting machine. The changes in the length and the diameter of the tubular fabric were measured and its ratio was calculated to characterize its auxetic behaviour. But the auxetic behaviour of the tubular fabric with the foldable parallelograms is smaller than the former ones, mainly because the tubular fabric can only be knitted using alternate needles on normal flat machines. It was the first attempt to fabricate auxetic tubular fabrics directly using non-auxetic yarn materials and flat weft knitting machinery.

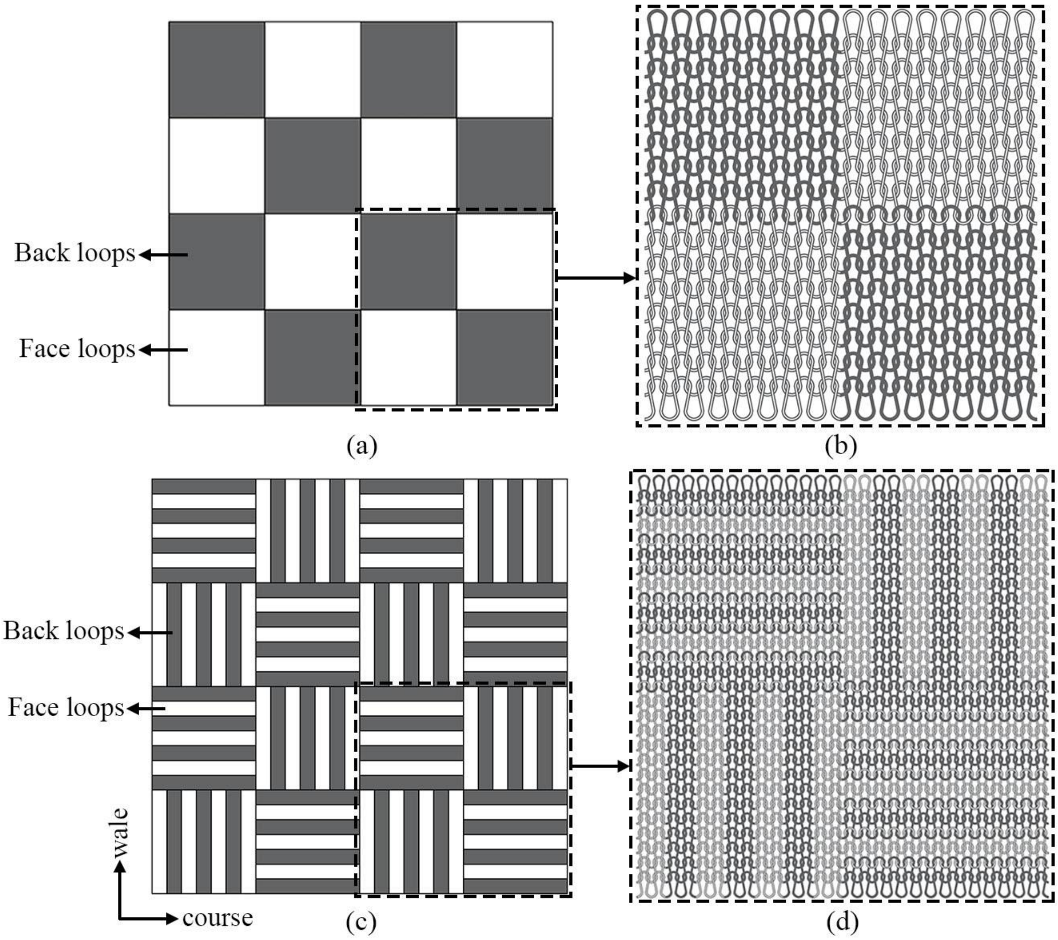

Fig. 3 3D weft knitted fabrics with folded structures. **a** pattern of folded rectangles. **b** pattern simulation of a repeating unit. **c** pattern of folded strips. **d** pattern simulation of a repeating unit

Inspired from the structure of folded parallelograms, more weft-knitted fabrics were designed to achieve other folded geometries like folded rectangles and folded stripes [31]. Squares of face loops and back loops are arranged alternatively to form weft knitted fabrics with folded rectangles. A typical pattern of such geometry is shown in Fig. 3(a), a repeating unit of which is shown in Fig. 3(b). Similarly, alternatively arrayed strips of face and back loops form a square unit cell. An example of such a geometry is given in Fig. 3(c), a repeating unit of which is in Fig. 3(d). In both cases, the folded structures will unfold under course-directional tensile forces, and show an auxetic behaviour along the wale direction in the fabric plane. To get the folded effect, the use of yarns with suitable elasticity is very important. Tensile test results revealed that in the fabrics with folded rectangles, the auxetic effect was only found when stretched along the course direction, while in the fabrics with folded strips, the auxetic effect was obtained in both course and wale directions [31].

2.2 3D spacer warp knitted fabrics

The 3D spacer auxetic warp knitted fabric structure (Fig. 4(a)) was designed based on a plane geometry in parallelograms arranged in a V form [38], which could be also seen as a network of rotated hexagons with six rotational ribs, including two long ribs and four short ribs, as shown in Fig. 4(b). The ribs can rotate when the geometry is under course- or wale-directional tensile forces, leading to a bi-directional expansion in the fabric plane, and thus achieving an auxetic behaviour, as shown in Fig. 4(c). A two-step approach was adopted to manufacture this type of 3D fabrics [38]. Firstly, base warp knitted spacer fabrics with hexagonal meshes were produced on a commercially available double needle bar warp knitting machine equipped with 6 guide bars by using non-auxetic polyester multi-filaments in the two outer layers and mono-filaments in the spacer layer. Then, the base spacer fabrics were compressed along their wale direction to transform the hexagonal meshes into the desired parallelogram meshes, after which the compressed fabrics underwent a heat setting process to ensure a good retainment of the geometry. Tensile tests were conducted on the fabric samples along course, wale, and diagonal directions respectively to evaluate the auxetic behaviour in these three directions. Results proved that the fabric structure was auxetic when stretched along all three directions, with a highest auxetic effect under the course-directional tension, and a lowest auxetic effect under the wale-directional tension. An excellent shape fitting ability of the 3D auxetic fabric was also verified by placing both non-auxetic and auxetic warp-knitted spacer fabrics on a spherical surface of 100mm diameter. The non-auxetic fabric forms into a saddle shape on the curved surface, while the auxetic fabric forms into a dome shape, perfectly covering the hemisphere.

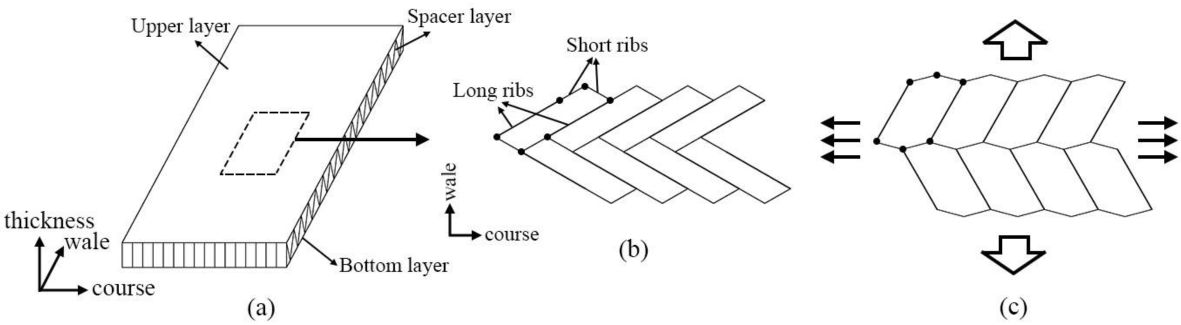

Fig. 4 3D spacer auxetic warp-knitted fabric structure. **a** 3D structure. **b** geometric structure with rotating ribs in face layers at the initial state. **c** geometric structure expanded in course and wale directions under tensile forces

Furthermore, the deformation behaviours of these 3D spacer auxetic warp knitted fabrics in two principal directions (course and wale) were investigated by geometrical analysis [39] and finite element method [40]. Based on the geometrical analysis, two semi-empirical equations were established to anticipate the Poisson's ratio of the fabric at different tensile strains in both course and wale directions. It was also proven feasible to use the finite element models to predict the deformation behaviours of the fabric when stretched along two principal plane directions. In terms of the tensile and forming properties, uniaxial tensile tests and hemispherical compression tests were conducted on both non-auxetic and auxetic warp knitted spacer fabrics [41]. It was found that 3D auxetic spacer fabrics have a prolonged low stress stage when stretched along the wale direction compared with the non-auxetic base fabrics. And the formability of the auxetic fabrics was also better than the non-auxetic ones because lower forming energy was required in the auxetic fabrics under hemispherical compression.

3 3D woven fabrics with NPR

3.1 Using auxetic yarns

The first try to produce an auxetic woven fabric is by way of using helical auxetic yarns [20]. A typical helical auxetic yarn structure is formed of a finer and stiffer yarn wrapping around a thicker and elastomeric core yarn. When it is under axial tensile strain, the wrap yarn and the core yarn will switch their positions. The stiffer wrap yarn will eventually turn straight, becoming the new core wound around by the elastomeric core yarn. In this process, its thickness will enlarge, thus showing an auxetic effect. When the helical auxetic yarns are arranged out of register in a woven fabric structure, the fabric will possess an auxetic behaviour under ideal situations. But experimental research showed that a plain weave fabric silicone rubber composite using helical auxetic yarn as weft and non-auxetic meta-aramid fibre as warp could not exhibit an in-plane NPR due to the overlapping of yarns. Instead, the thickness of the material increased when it was stretched, leading to an out-of-plane NPR. When two layers of the woven fabric were stacked together to form the composite, the lateral strain increased with the increase of longitudinal strain, indicating the obtainment of an in-plane auxetic effect. The results also indicated that there have to be at least two layers of the woven fabrics in this composite structure in order to show NPR in the fabric plane. The authors did not give an experimental research on the NPR effect of the fabric itself woven with helical auxetic yarns, but still provided a simple approach to produce a 3D woven fabric composite with NPR.

3.2 Using non-auxetic yarns

In addition to the multi-layer stacking of 2D woven fabrics, 3D woven fabrics with NPR can also be produced directly using non-auxetic yarn materials and 3D weaving techniques. 3D weaving is the interlacing of multiple layers of warp sheet with two sets of weft yarns, one of which is ground yarn, and the other is binding yarn [42]. 3D woven fabric reinforcements show better resistance to delamination failure than stacked 2D woven fabrics, thus are preferable in composites [43]. The auxetic behaviour could further enhance the fracture toughness, crack resistance, and energy absorption of composites [44]. Therefore, 3D woven fabric with NPR is a promising candidate as high-performance composite reinforcement. In a recent research, 3D orthogonal woven structures showing NPR in the thickness direction when stretched along the warp direction were developed [45]. Cotton was used as the warp and weft yarn to fabricate the ground weave, while jute, which has higher Yong's modulus than cotton, was used as binding yarn. The binding yarns tend to straighten when axial load is applied on the structure, thus pushing the adjacent weaves outwards, leading to the thickening of the structure, or, to put it in another way, showing an auxetic behaviour along the thickness direction. Based on this deforming principle, various fabric samples were produced to investigate the effect of float length of ground weave and binding yarn on the NPR effect. And epoxy resin composites reinforced with these 3D woven fabrics were fabricated to investigate their energy absorption under impact loading. It was found that specimen with higher float length enabled greater room for the structure to expand, as a result better auxetic effect. At the same time, the difference between the float lengths of ground and binding yarns should be equal or near to zero, otherwise the NPR effect is almost negligible. It was also concluded that the composites reinforced with the 3D auxetic woven fabrics had better impact resistance and energy absorption compared to composites with non-auxetic ones.

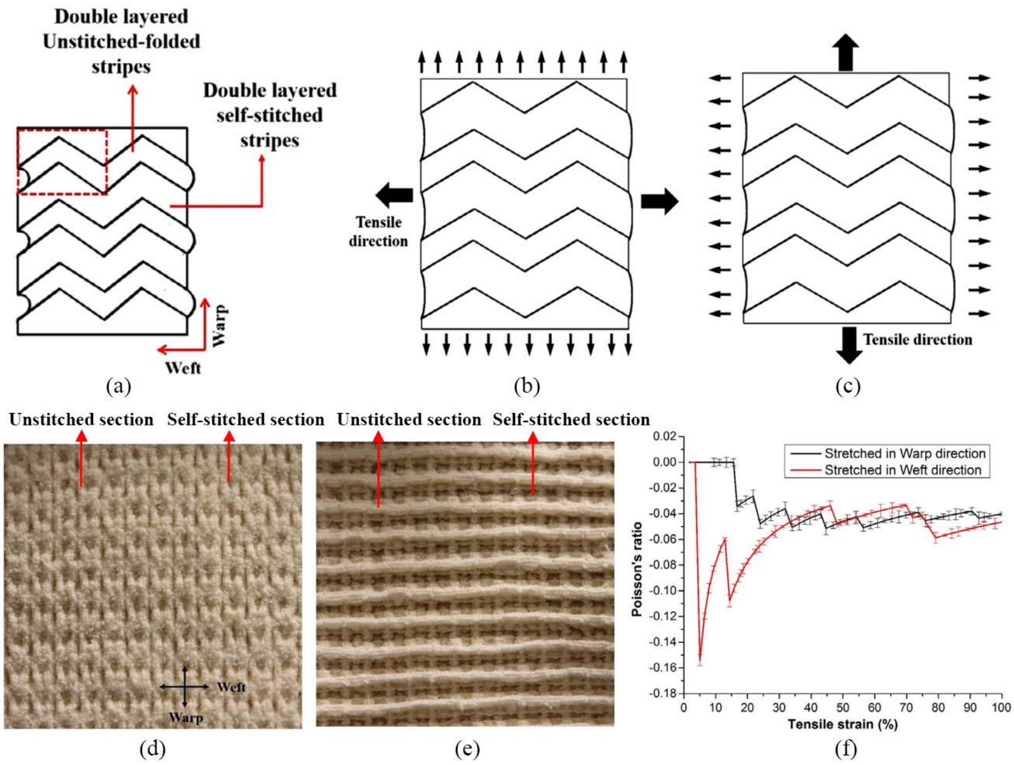

Fig. 5 Double-layered auxetic woven fabric. **a** zigzag foldable geometry at initial state. **b** when stretched along weft. **c** when stretched along warp. **d** fabric face. **e** fabric back. **f** Poisson’s ratio - tensile strain curves (with permission of John Wiley and Sons) [46]

A new approach was proposed to develop a double-layered auxetic woven fabric [46]. As shown in Fig. 5(a), the fabric is designed based on a zigzag-shaped foldable geometry, consisting of unstitched folded stripes where two layers are detached, and self-stitched flat strips where two layers are attached together. When it is stretched along the weft or warp direction, the folded strips will unfold exhibiting an auxetic behaviour as shown in Fig. 5(b) and (c). To fabricate the double-layered woven fabric, alternate elastic and non-elastic yarns were used in both warp and weft directions. The face and back sides of the produced fabric under relaxed state is shown in Fig. 5(d) and (e) respectively. It can be seen that the fabric turned out to be flat where self-stitched either on the face or on the back, while folds appeared where unstitched due to the shrinkage of elastic weft yarns, and abrupt convexities were formed where unstitched due to the shrinkage of elastic warp yarns. The tensile tests were conducted on the fabric samples along the warp and weft directions, with the Poisson's ratio results with the change of tensile strain shown in Fig. 5(f). It was concluded that the double-layered woven fabrics designed based on the folded geometry are auxetic in both warp and weft directions, and a higher NPR effect was obtained when stretched along the weft direction.

4 3D non-woven fabrics with NPR

4.1 3D orthogonal fabric structure

A novel type of 3D auxetic fabric structure with three sets of non-interlacing yarns was proposed by Ge and Hu [47]. Its formation principle resembles that of the bi-axial warp knitted structure. Sets of warp yarns and sets of weft yarns are first alternately arranged along two orthogonal directions of the fabric plane in a straight form. The stacked warps and wefts are then bound together by stitch yarns through the thickness direction, forming a 3D auxetic fabric structure. The alternately arranged voids are formed between adjacent layers of weft yarns and adjacent warp yarns. When compressed along the thickness direction, the structure contracts in the weft direction due to the bending of weft yarns, thus an auxetic behaviour is obtained. The cross-sectional views of the fabric structure at the initial state and under compression are shown in Fig. 6(a) and Fig. 6(b), respectively. It can be seen that the originally straight weft yarns turn curvy under compressive forces, and the rectangular void marked in Fig. 6(a) turns into a re-entrant hexagonal geometry marked in Fig. 6(b) under the compression along the thickness direction, leading to the contraction of the structure in the weft direction.

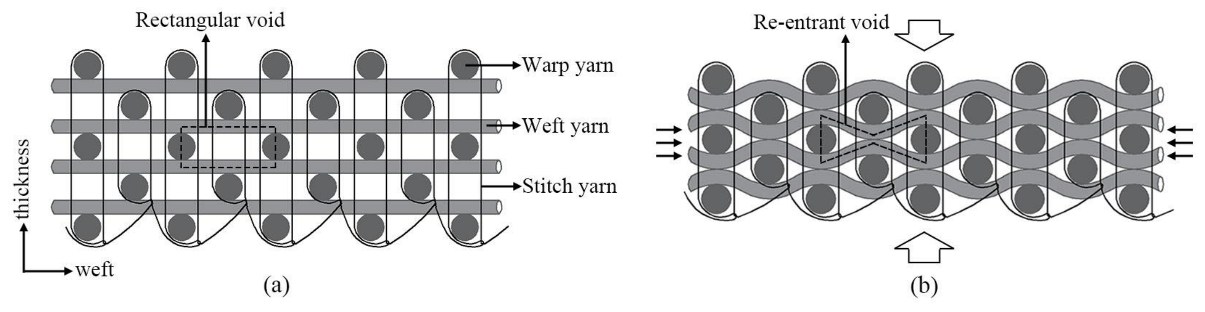

Fig. 6 The cross-sectional view of 3D orthogonal fabric structure with NPR. **a** at initial state. **b** under compression

The 3D orthogonal fabric structure was manufactured using rigid braided yarns as warps, flexible braided yarns as wefts, and thinner elastic yarns as binding stitch yarns. Clearly, the diameter of the warp yarns determines the size of voids inside the fabric structure, thus affecting the value of Poisson's ratio of the fabric structure under the thickness compression. For this reason, samples with warp yarns of various diameters were produced for comparison [47]. Experimental results confirmed the NPR effect of the structure, and showed that a larger fineness ratio between the warp and weft yarns could lead to a higher NPR effect. A theoretical analysis was conducted to predict the effects of different structural parameters and elastic modulus of yarns on the auxetic behaviour of the 3D auxetic textile structure under compression [48]. A finite element model was also established to demonstrate the deformation process of the orthogonal fabric structure at different compression strains, which was validated by experimental results. And a numerical analysis was further conducted and confirmed that the main factors that affect the deformation behaviour of the 3D orthogonal structure under compression are the bending stiffness and radius of the weft and warp yarns. The finite element analyses could successfully simulate the auxetic behaviour of the orthogonal fabric with different structural parameters, showing the effects of ratio of radii and moduli between warp and weft yarns on the auxetic behaviour of the structure [49-50]. Further, the composite reinforced with the 3D orthogonal auxetic structure was fabricated using polyurethane foam as matrix [51-52]. Its NPR effect and mechanical behaviour were evaluated through quasi-static compression tests. Results showed that an obvious NPR effect was obtained. Compared with non-auxetic composite, the auxetic composite has a larger deformation strain range before failure, which makes it more suitable as damping material or energy absorbing material. To investigate the mechanical properties of the auxetic composite under low-velocity impact, single and repeating impact tests at different impact energy levels were also conducted [53]. Better transmitted force reduction and higher energy absorption were found in the auxetic composite under single impact test, and higher structural stability was shown under repeating impact tests, revealing a better impact protective performance in the composite reinforced with auxetic orthogonal textile structure.

4.2 3D non-woven fibre network

In the domain of non-woven fabrics, a 3D stochastic fibre network was firstly analysed using a finite element modelling approach to study the effects of parameters on its out-of-plane auxetic behaviour [54]. The simulation showed that the auxetic behaviour is determined by the degree to which the fibre network is compressed during manufacturing, and the out-of-plane fibre orientation angle distribution. Based on the numerical modelling, compressed stainless steel mats with NPR were produced and investigated experimentally, confirming the critical significance of the amount of compression to the out-of-plane auxetic behaviour of the non-woven fabrics [55]. It also proved feasible to produce composites with NPR by embedding the auxetic fibrous network in a conventional polymer matrix, under the condition that the ratio of reinforcing network stiffness to matrix stiffness is sufficiently high. The out-of-plane auxetic behaviour of the heat-processed nonwovens is found arising from the tilted and buckled vertical fibre bundles, which may be re-orientated under uniaxial tensile strains, thus causing an increase in thickness, as shown in Fig. 7(a) [33]. In another research, the fundamental principle of the out-of-plane auxetic behaviour of paper is revealed [32], which is intriguing to inspire the design of 3D non-woven fabrics with NPR. One of the critical elements that lead to the out-of-plane auxetic response is the interwoven organization of fibres as shown in Fig. 7(b). When an in-plane tensile force is applied to the structure, the intertwining fibres will be extended so as to push other fibres that lie above and below, thus leading to an increase in thickness.

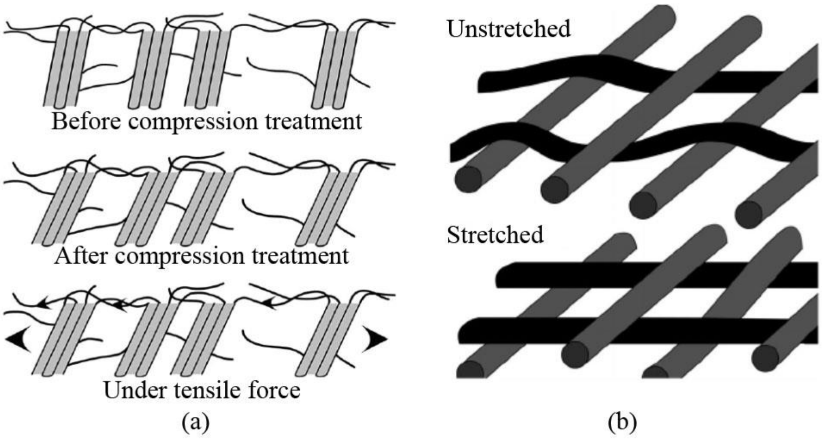

Fig. 7 Schematic diagram of out-of-plane auxetic effect in nonwovens under in-plane tensile force. **a** reorientation of tilting fibre columns (with permission of John Wiley and Sons) [33]. **b** straightening of interlaced fibres (with permission of John Wiley and Sons) [32]

5 Application prospects

The 3D fabrics with NPR have the potential to revolutionize the protective equipment, from personal defence garments to blast-proof upholstery textiles. The materials used for personal protective equipment are required to be light in weight, high in impact resistance, and easy to conform to the human body. Defence clothing with moulded pads, which are commonly used now, are inhibitive to the body movement, and unideal in breathability and conformability. The 3D fabrics with NPR are expected to be a good candidate for such applications like knee pads, shoulder pads, elbow pads, gloves or helmet lining. Experimental researches have been done on sports tops attached with auxetic foam and non-auxetic foam for shoulder protection, but few progresses have been made on the functional benefits of the 3D auxetic fabrics applied to personal protective garments. In the area of upholstery textiles, the application of auxetic fabrics to the blast-proof curtain has been reported. Auxetic woven fabrics made of helical auxetic yarns were selected to undergo explosion tests in a vented room to measure the energy absorption when exposed to blasting conditions [56]. Results showed that the deflection decays faster for auxetic fabrics than for the reference plate under the same gas pressure impulse, and the auxetic fabric with the highest energy absorption in response to the pressure impulse was also identified.

Composites reinforced with 3D auxetic fabric structures are also a promising application field. The auxetic behaviour could effectively prevent the pull-out of the reinforcement, and the 3D fabric structure of the reinforcement could provide a high resistance to the delamination of composite. Relevant researches have been done mainly on composites reinforced with 3D orthogonal woven fabrics with NPR. Larger deformation strain of auxetic composites under quasi-static compression tests, and their better energy absorption property under impact loading make them very suitable as damping material or energy absorbing material [45, 51].

Another application prospect of 3D auxetic fabrics lies in the biomedical area. 3D auxetic fabrics containing healing agents can be used as wound dressing materials. Not only a perfect coverage on the curvy human body will be provided, but also the healing agent could be released to the wound in a dynamic manner. The auxetic tubular fabrics in a smaller size are expected to be applied to palliative treatment of dysphagia, or the vascular occlusion. Auxetic stents were produced based on the rotating square network using various methods, among which the laser cutting of polyurethane tubes was proved to be both effective and efficient [57]. But tubular fabrics with NPR have not yet been developed in such a size that can be used inside the oesophageal or vessel.

6 Conclusion

3D fabrics with NPR are a novel type of textile materials that exhibit an unconventional deforming ability under uniaxial tensile or compression forces. There are generally three principal directions, orthogonal to each other, in a 3D fabric structure. When the external force is applied to the 3D fabric along one of principal directions, the auxetic behavior could either be in plane or out of plane, and could exist either in a single direction or in multiple directions. Researches on various types of 3D auxetic fabrics have shown that the NPR characteristic could induce many enhanced properties like fracture resistance and energy absorption. The excellent formability of 3D auxetic fabrics makes them suitable as reinforcement in composites that are curvy or irregular, such as aircraft head or wings. With careful selection of yarn materials and fabrication technique, 3D fabrics with NPR could also be used in functional garments to lengthen the longevity or to improve the fit and comfort of the products. 3D auxetic fabrics in tubular shape are also a novel and intriguing research topic, because the tubular auxetic material has biomedical application potentials such as auxetic stent that can help open the blockage and allow the smooth flow of blood when treating coronary artery and vascular diseases.

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Data Availability

Data sharing not applicable to this article as no new data were generated during the study.

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