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Development of uni-stretch woven fabrics with zero and negative Poisson's ratio

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Abstract

The fabrics with zero, or negative Poisson's ratio, are referred as auxetic fabrics which have unusual property of lateral expansion or zero expansion upon stretch. The use of conventional materials and machinery to produce auxetic fabrics has gained curiosity of researchers in recent years. However, this approach is limited to knitted fabrics only. The development of auxetic fabric using conventional yarns and weaving technology is a research area that is still unaddressed. This paper reports a study on the development of a novel class of stretchable auxetic woven fabrics by using conventional yarns and weaving machinery. The phenomenon of differential shrinkage was successfully employed to realize auxetic geometries capable of inducing auxetic behavior into woven fabrics, and a series of auxetic woven fabrics were fabricated with elastic and non-elastic yarns and a dobby machine. The uni-axial tensile tests showed that auxetic woven fabrics developed exhibited zero or negative Poisson's ratio over a wide range of longitudinal strain.

Key words: Auxetic fabric, interlacement pattern, negative Poisson's ratio, weaving

1. Introduction

Auxetic materials are those materials which possess zero or negative Poisson's ratio (NPR). Such materials possess the unusual property of either preserving their dimensions or expanding in lateral direction[1, 2]. In contrast to most conventional materials, auxetic materials become fatter when stretched or narrower when compressed as shown in Figure 1.The term auxetic was derived from the Greek word (auxetos) which means "that which tends to increase" by Evans K of the University of Liverpool[3]. The Poisson's ratio is an elastic constant and is independent of the material scale. Therefore, auxetic materials can be single molecules or a particular structure of macroscopic to micro level [4-10]. It is claimed that auxetic materials have enhanced mechanical properties like shear modulus, energy absorbance, vibration damping[11-15], sound absorption [16], indentation resistance [17]and synclastic behavior for better formability [18]. As a special type of auxetic materials, auxetic textiles have become a point of focus for many researchers during past ten years. The auxetic textiles that have been developed and investigated include fibers, moisture sensitive yarn and helical auxetic yarns [19-22], monofilaments [23], woven fabrics [24, 25], weft knitted[26-31] and warp knitted fabrics [18, 32-35], 3D textile structure[36, 37], fiber reinforced laminated composites[8, 38, 39] and non-woven fabrics [40].

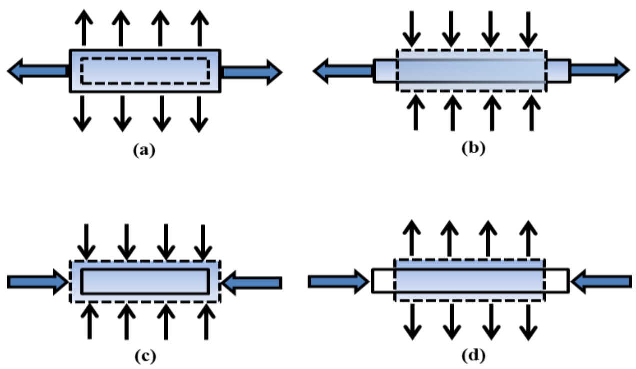


Figure 1.Deformation behavior of materials when stretched: (a) auxetic; (b) conventional; deformation behavior of materials when compressed: (c) auxetic; (d) conventional

Since the inception of auxetic textiles up till today, woven and knitted auxetic fabrics have been produced based mainly on two approaches. The first one is using auxetic fibers or yarns to fabricate the auxetic fabrics and the second one is to fabricate auxetic fabrics from conventional yarns, as the auxetic behavior is purely linked with the geometrical arrangements of structural units[41-43].

Various types of auxetic woven fabrics have been produced by using helix auxetic yarns (HAY) [24, 25, 44].The first one was produced by using the HAY yarn in the weft direction and non auxetic yarn in the warp direction[25]. This type of fabric produced an out of plane NPR and an in-plane positive Poisson’s ratio. However, when the fabric was tested with thickness constrained between two glass plates, an in-plane NPR of -0.1 was observed. The second one was also produced by using the HAY in weft direction and non auxetic yarns in warp direction with three weave patterns, which are plain, 2/2 twill and 3/5(3) satin[24].It was found that while both the plain and twill fabrics exhibited most auxeticity, the satin woven fabric was significantly less auxetic. The third one was the 2-ply plain woven narrow auxetic fabric produced with HAY in the warp direction and non auxetic yarn in the weft direction[44]. The fabric exhibited an in-plane NPR in a strain range of 15–40%, reaching a maximum NPR value of –0.1 at approximately 32% strain. It should be pointed out that Poisson's ratio value is significantly important for the clothing materials and applications where lateral contraction, due to stretch, might be problematic. Such applications may include clothing for periods of growth such as maternity, clothing and child development, possibilities for promoting clothing permanency due to adaptability in sizing, under garments, shape wear, under wears, leggings and sportswear. In case of fashion clothing, the smocking and pleating are two recognized techniques used to overcome the problem of lateral contraction. Smocking is used to gather the fabric so that it can stretch when required and pleating is used to add fullness from the waist or hips. Smocking is also suggested as a solution to longevity problem of maternity wear [45-47]. These two techniques are labor intensive and require specialized machinery; auxetic fabrics can also be used as alternative of these two techniques.

Up till today auxetic woven fabrics were only produced by using auxetic yarns. The demerits of this approach are the availability of very few auxetic fibers and yarns. The development of auxetic woven fabrics by using conventional yarns is still unaddressed. Furthermore, due to the limitations like low structural stability, low elastic recovery, higher thickness and difficulty in the fabrication because of their complicated geometrical structures, mostly auxetic knitted structures have not yet been produced on larger scale. The fabrication of auxetic woven fabrics from conventional yarns with reduced thickness and better formability that can easily be shaped into garments is still a great challenge for weaving specialists. This paper reports a study on the development of a novel class of stretchable auxetic woven fabrics for clothing material by using readily and inexpensively available conventional elastic and non-elastic yarns and weaving machinery. The phenomenon of differential shrinkage is created to realize specially designed auxetic geometries into woven architecture to produce auxetic woven fabrics with zero or NPR.

2. Materials and methods

2.1. Design concept, fabrication and post weaving treatment of auxetic fabrics

Auxetic fabrics for clothing applications must have two key properties, the elasticity and auxetic effect. The elasticity in the fabric structure facilitates the deformation at different parts of the garment during movement or exercise while the auxetic effect helps the garment to take the continuously changing body shape during movement or exercise. Woven fabrics with these two features are possible to fabricate. Since the auxetic effect is purely linked to the geometrical shape of the fabric structural units, realizing the auxetic geometries capable of inducing auxetic behavior into a woven fabric is important. Such geometries can be realized by creating the phenomenon of differential shrinkage into fabric structure in order to enable different sections of fabric unit cell to endure different level of shrinkage upon relaxation.

The differential shrinkage effect can be created in both warp and weft directions or in one direction only, by using elastic and non-elastic yarns with different stretch properties, and by employing interlacements patterns with combinations of loose and tight weave having different contraction properties. In this study, the elastic yarns are only used in weft direction. As the fabrics have extensibility only in one direction, they are named as uni-stretch fabrics. In such kind of fabrics, the elastic yarns induce elasticity into the fabric structure and act as a return spring. The non-elastic yarns are used as stabilizing component, and the interlacement pattern with combinations of loose and tight weave is capable of inducing auxeticity into the fabric structure and helps to retain the transverse dimensions of the fabric upon stretching. Therefore, the auxetic effect is resulted due to the interplay between the interlacement pattern of warp and weft, different stretch properties of elastic and non-elastic yarn and the mechanism of deformation of the fabric.

The specially designed interlacement patterns based on auxetic geometries, for this kind of uni-stretch auxetic fabrics are combination of different weaves and are not regular. Such patterns can only be weaved by using a weaving machine equipped with dobby shedding or Jacquard shedding mechanism. Further, in order to create differential shrinkage along weft direction, elastic and non-elastic yarns have to be used alternately or in different combinations depending upon the geometry which is needed to be realized into fabric structure. Therefore, a weaving machine capable of inserting more than one kind of weft yarn or with more than one weft supplies can only be used to produce these fabrics.

The computerized rapier weaving machine manufactured by CCI Intech Taiwan with option of eight weft supplies and dobby shedding mechanism with 22 heald frames can meet these requirements and was used to weave uni-stretch auxetic fabrics based on the three different kinds of geometrical structures, namely, foldable structure, rotating rectangles and re-entrant hexagons. The woven fabrics obtained, were then subjected to hot washing for about 45 minutes at 60°C followed by tumble drying for 60 minutes at 70°C temperature. After washing and drying, the fabrics were allowed to relax for 24 hours in order to facilitate the creation of the differential shrinkage effect of elastic and non-elastic yarn into woven fabric structure and to realize the shapes of auxetic geometries. These geometries are capable of inducing auxetic behavior into the fabric. The testing samples were then cut and prepared for measurement of Poisson's ratio.

2.2. Measurement of Poisson's ratio

The developed fabrics are uni-stretch fabrics, which mean that they have extensibility only in one direction that is weft direction; therefore, tests were carried out along this direction only. However, the fabrics can also be tested along warp direction but due to the limited extensibility in this direction, the fabrics may break at smaller strains and cannot be tested over a wider strain range. Furthermore, the folded structures cannot fully open at smaller strains and do not exhibit auxetic effect.

The tensile tests were conducted on an Instron 5566 tensile machine. The capacity of the load cell used was 500N.The gauge length and tensile speed was set as 150mm and 50mm / min, respectively. The schematic of the testing setup is shown in Figure 2(a). Three fabric strips of dimension (50mm×150mm) were cut for each sample as shown in Figure 2(b). The central point of the fabric strip was first located and then four points were marked with the central point at a distance of 5mm in order to facilitate the recording the information of fabric deformation during the tensile test.

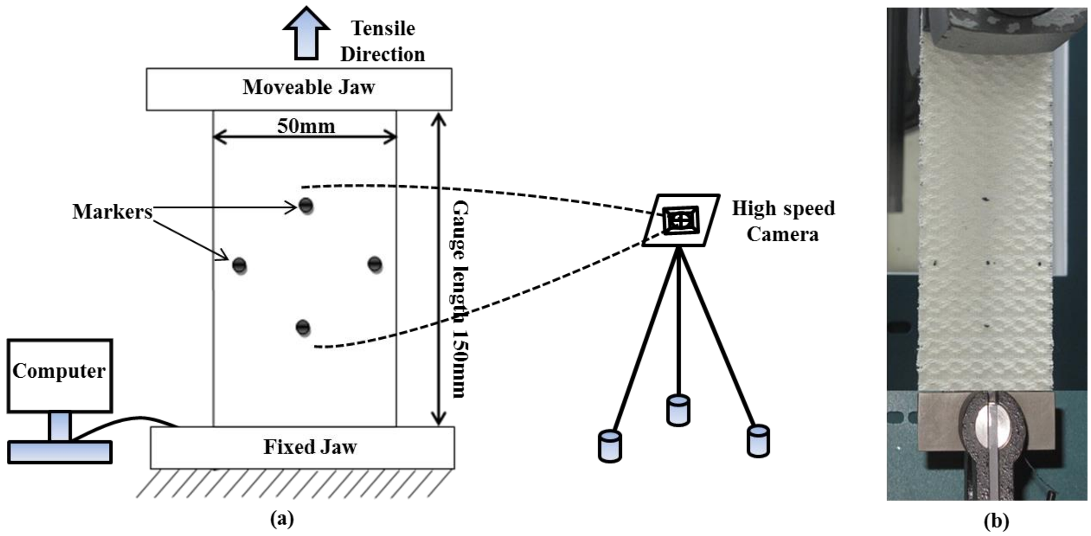


Figure 2. Tensile test for the auxetic fabric: (a) Schematic of testing setup; (b) Fabric with oblique foldable stripes in stretched state

The distances of two marks in the tensile and transversal direction were first photographed by camera with a time interval of 3s or after each 3mm extension for each sample until the sample broke. Then, the distances of the marks in the photos were measured via a screen ruler to calculate the engineering strains of the fabric structure in both tensile direction and transversal direction. Finally, Poisson's ratio was calculated using Eq.1[48].

$$v = -\frac{\varepsilon_y}{\varepsilon_x} \qquad (1)$$

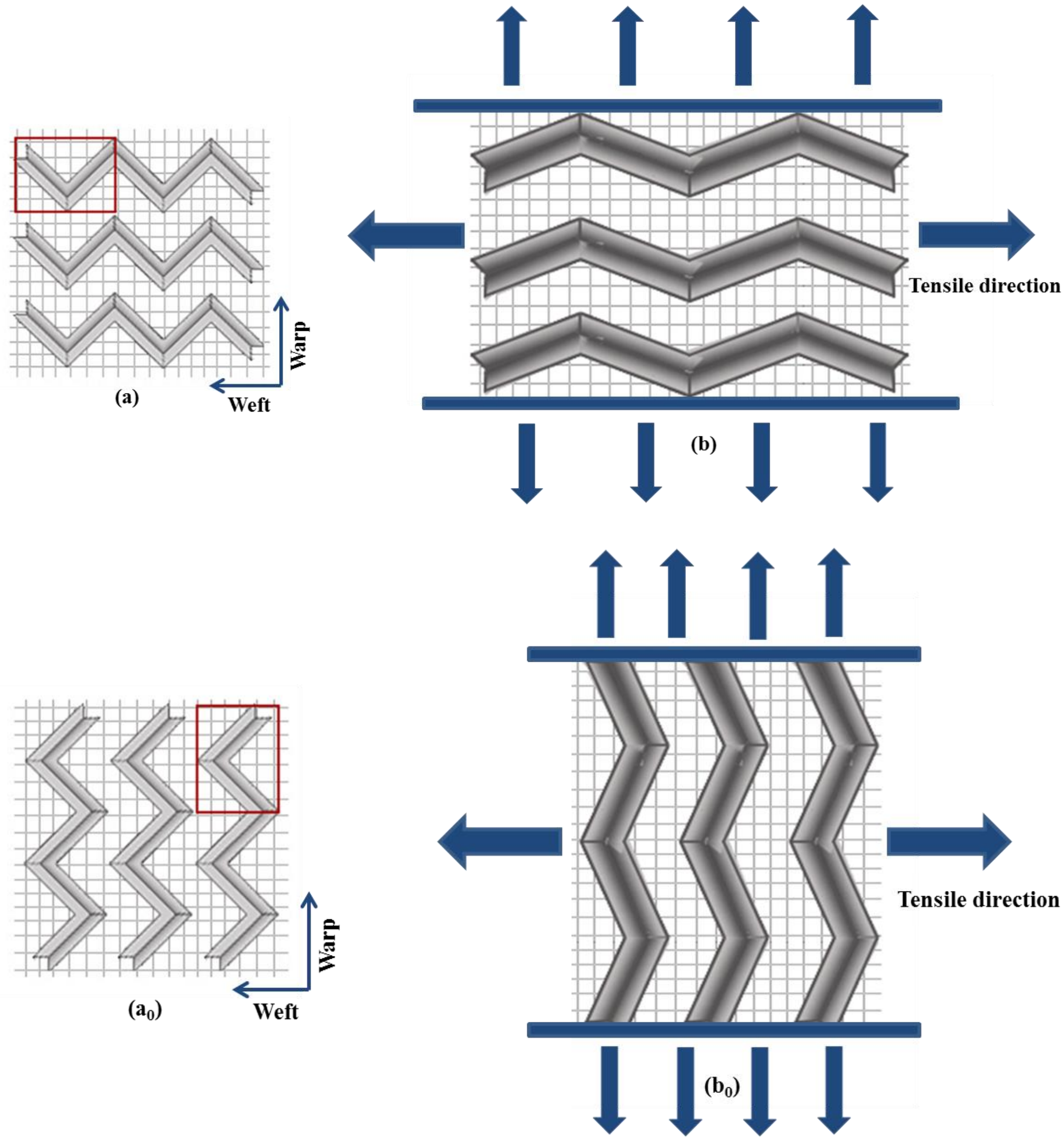
Where ε_x is the longitudinal strain and ε_y is the transverse strain. Poisson's ratio vs longitudinal strain curves were then generated and presented.

3. Auxetic fabrics developed and their auxetic behavior

3.1 Auxetic fabrics developed based on foldable geometries

The principle of using foldable structures to create an auxetic effect is that a folded structure can be unfolded when stretched in one direction, increasing the dimensions in the lateral direction. Foldable structures can be produced by exploiting the phenomenon of differential shrinkage. The characteristics of the interlacement pattern together with different stretch and shrinkage properties of elastic and non-elastic weft yarns enable the sections of fabric with different tightness of weave to undergo different levels of shrinkage for the creation of folds. Based on this approach, three different kinds of fabrics with foldable geometries were designed and fabricated. The first one was with foldable stripes created in parallel in-phase zig-zag fashion. The architecture of this fabric consists of alternate folded stripes and flat stripes placed in parallel in-phase zig-zagmanner runing along weft direction or warp direction as shown in Figure 3(a) and 3(a_0). The second one was foldable stripes created in oblique fashion. This fabric has a geometry formed by placing folded stripes in oblique fashion which means that the stripes intersect each other in diagonal fashion. The spaces formed between these stripes are flat and may form a parallelogram shape as shown in Figure 3(c). The third one was foldable stripes in form of convexities running along warp direction. Thisfabric has an architecture comprising of folded abrupt convexities or protuberance along warp with flat portion of fabric between two consecutive convexities as shown in Figure 3(e). The minimal repeating unit or unit cell of each geometry is highlighted by red color box in each of the corresponding figures. In case of folded stripes arranged in parallel in-phase zig-zag fashion along warp or weft direction and folded stripes in oblique fashion, when these folded structures are subjected to an extension in one direction, the structures also expand in lateral or transversal direction due to the flattening of folded sections, resulting in NPR ratio effect as shown in Figure 3(b), 3(b_0) and 3(d). While in case of folded stripes in the form of convexities, upon extension the transposition of convexities in tensile direction tends to retain their lateral dimensions resulting in the zero Poisson's ratio effect as shown in Figure3(f).

It is important to mention that, the geometries illustrated in Figure 3 can be realized either into single layer fabric or double layer fabric. In case of single layer fabric, the face and back of the fabric will not be truly flat due to the formation of folded sections, whereas in case of double layer fabric, the back of the fabric can be made flat and the folded section can be created on the face of the fabric. In this study, single layer fabrics were produced with the geometries including folded stripes in parallel in-phase zig-zag and oblique fashion. In order to produce double layer fabrics with these geometries, more number of heald frames are required as the size of the unit cell of interlacement pattern becomes larger. Therefore, weaving machine shedding mechanism is a limitation in fabrication of double layer fabrics with these geometries. For this reason, the double layer fabric was only produced with folded stripes in the form of convexities on the face of the fabric, due to the fact that the size of the unit cell of interlacement pattern is smaller and more simple, which makes it easy to realize this geometry into double layer fabric.



Warp
Weft
(a)
Tensile direction
(b)
Warp
Weft
(a0)
Tensile direction
(b0)

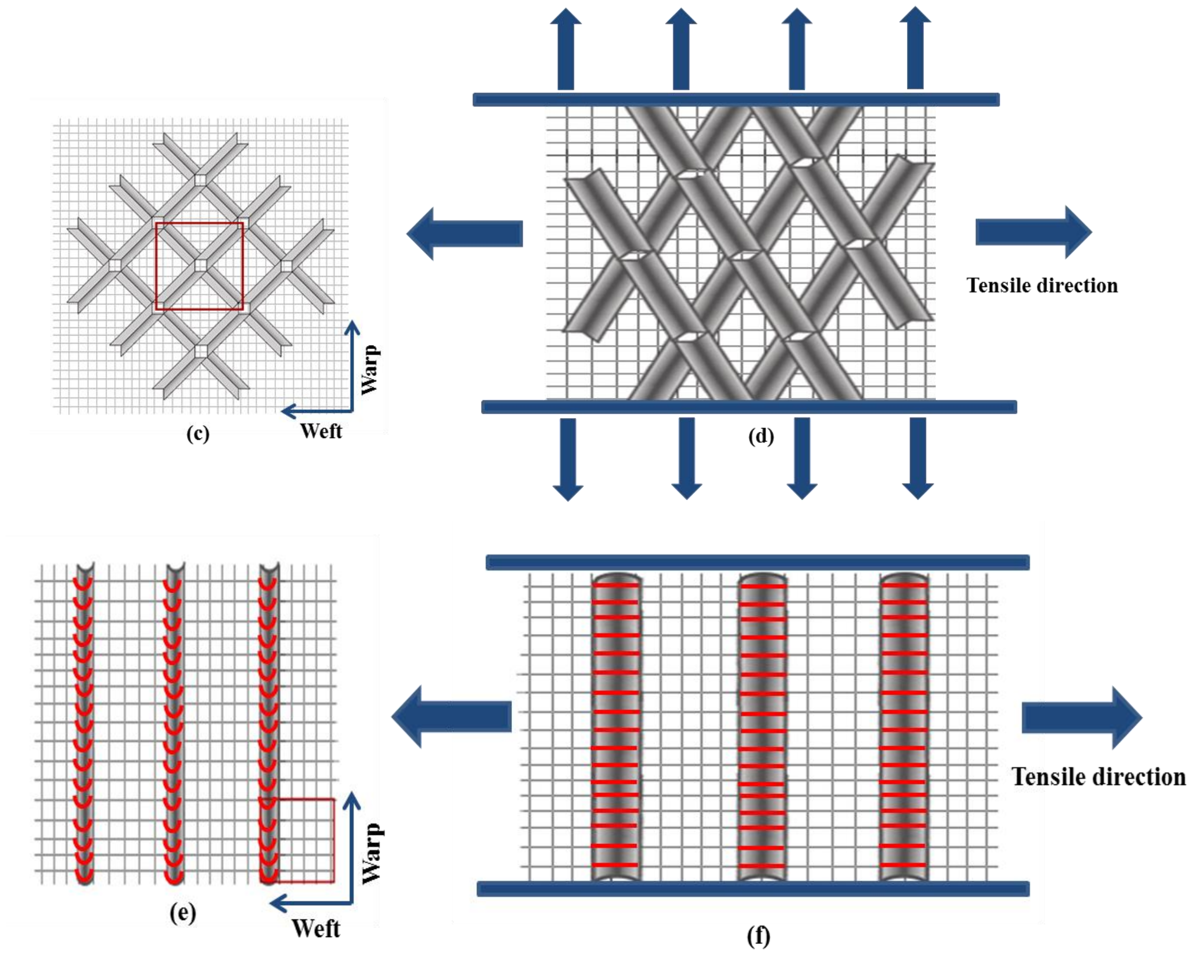


Figure 3.Foldable geometries: (a) and (b) folded stripes in parallel in-phase zig-zag fashion along weft in ree state and stretched state;(a_0) and (b_0) folded stripes in parallel in-phase zig-zag fashion along warp in free state and stretched state; (c) and (d) folded stripes in oblique fashion in free state and stretched state;(e) and (f) folded convexities along warp in free state and stretched state.

3.1.1 Transformation of foldable geometries into interlacement patterns and fabrication of auxetic fabrics

The schematics of the foldable geometries formation for folded stripes in parallel in-phase zig-zag fashion along weft, folded stripes in parallel in-phase zig-zag fashion along warp and folded stripes in oblique fashion are shown in Figures 4(a), 5(a) and 6(a),respectively. In these figures, the dashed lines represent loosely woven area with long floats of weft yarns while the solid lines represent the tightly woven area. The black lines represent non-elastic weft yarns and the red lines represent elastic weft yarn. In order to create differential shrinkage effect, the loose weave and tight weave are arranged in parallel in-phase zig-zag pattern running along warp direction or weft direction and in oblique fashion. The yarn sections of warp and weft within the structure of stripes are loosely woven with long floats, while the yarn sections of warp and weft which are not in the structure of stripes are woven by employing a firm and tight weave.

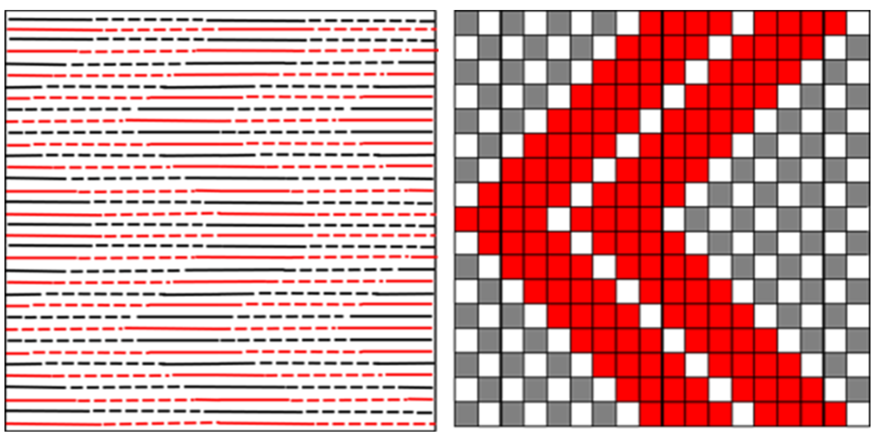
Two single layered fabrics based on parallel in-phase zig-zag folded stripes in alternate fashion running along warp and weft direction were developed. The unit cells of interlacement patterns are shown in Figure 4(b) and 5(b). The real fabrics are shown in Figure 4(c) and 5(c). In these fabrics, alternate elastic yarn (core spun spandex Ne 16/s) and non-elastic yarn (cotton Ne 30/s) were used in the weft direction in order to exploit differential shrinkage effect. The non-elastic yarn (cotton Ne 20/2) was used in the warp direction. The warp and weft densities were set at 40/inch. One single layered fabric based on folded stripes in oblique fashion was also developed. The interlacement pattern is shown in Figure 6(b) and the real fabric is shown in Figure 6(c). In this fabric, a bi-component rubber elastic yarn was used. The wrapping component was of 86D polyester multifilament yarn with 46 filaments and the core was of polyurethane monofilament with a diameter of 0.5mm and stretch of 300%. The non-elastic yarn used was (cotton Ne10/s). The elastic and non-elastic yarns were used in alternate fashion in weft, and non-elastic yarn (cotton Ne20/2) was used in the warp direction. The warp and weft densities were set at 48/inch and 40/inch, respectively.

The face and back of all the fabrics differs greatly in appearance. On the face of the fabric, at the loose weave stripes sections the long floats of warp yarns are prominent and elastic weft yarn undergo high shrinkage due to the loose weave structure or longer float than non-elastic weft yarn. Meanwhile, at the tight weave sections both the elastic and non-elastic weft yarns are firmly woven and undergo less shrinkage. On back of fabric, at the loose weave stripes sections, the long floats of weft yarns are prominent and as a result of high shrinkage of elastic weft yarns due to the loose weave structure, the warp yarns tend to come closer to each other. Moreover, at the tight weave stripes section in case of fabrics with parallel in-phase zig-zag folded stripes, and at the tight weave tetragonal section held between oblique folded stripes in case of fabric with folded oblique stripes; the texture of the fabric is not truly flat. Due to the high shrinkage of elastic weft yarns at loose weave stripes section, the tightly woven section is slightly rucked up and a bulge is formed. This rucking up and bulge formation is even more in fabric with parallel in-phase zig-zag folded stripes along weft than the other two fabrics. This might be due to the fact that the loose weave stripes in this fabric run along weft direction which is also the direction of elastic yarn. In addition to this, if the interlacement patterns of all three fabrics are compared, it is clear that though the size of repeating unit of the interlacement patterns is almost same, in case of interlacement pattern of fabric with parallel in-phase zig-zag folded stripes along weft, the longer floats along elastic weft are more and it endured more shrinkage and larger bulge formation than other two fabrics.

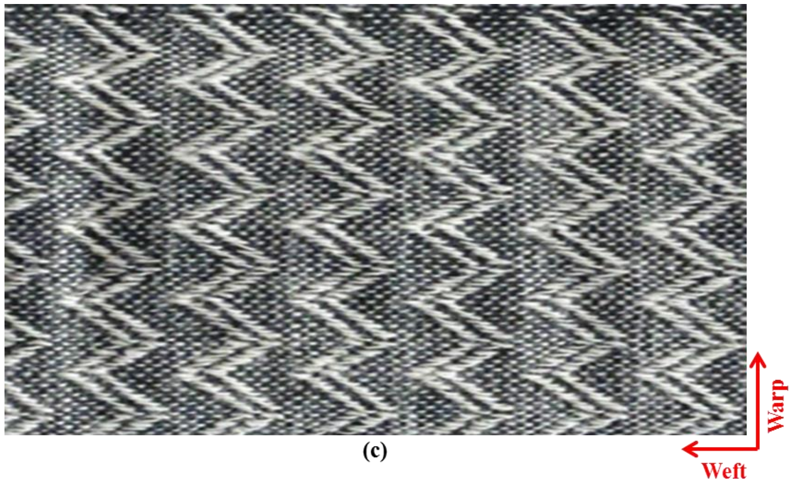
The geometry with folded convexities is transformed into interlacement pattern for a double layered fabric. The schematic for the formation of folded convexities along warp is shown in Figure 7 (a). This geometry comprises of two layers and yielded a texture with a flat portion (where the two layers are self-stitched) and a portion with an abrupt convexity or protuberance (where the two layers are not self-stitched) in an alternate fashion. In the structure of fabric, two sets of warp yarn are interlaced with two set of weft yarns. In order to produce differential shrinkage among two layers, one set of warp yarn is interlaced with elastic yarn in the lower layer of the fabric and the second set of warp yarns is interlaced with non-elastic yarn in the face layer of the fabric. The core spun spandex Ne 20/s elastic yarn is used as weft for lower layer, cotton Ne 20/s non-elastic yarn is used as weft for face layer and cotton Ne 20/s non-elastic yarn is used as warp. The warp and weft densities were set at 60/inch.

The interlacement pattern of non-elastic weft in the face layer is shown in Figure 7(b). The shaded cells in red color shown in Figure 7(c) is depiction of loose weave with longer floats for elastic weft in the lower layer. The shaded cells in black color shown in Figure 7(d) represent the points where two layers are self-stitched. Figure 7(e) shows the mechanism of convexities formation. The blue solid line represents the non-elastic weft yarn and the dashed black line represents the elastic weft yarn. Due to the characteristics of the interlacement pattern together with different stretch and shrinkage properties of two sets of weft yarns (elastic and non-elastic), the two layers of fabric with different kind of weft yarns endured different levels of shrinkage. The real fabric is shown in Figure 7(f).

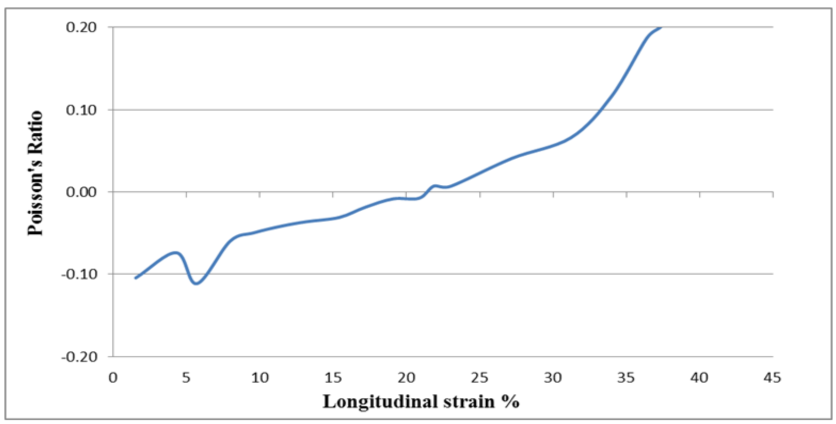
The face and back of the fabric realize different appearance. In the face layer of the fabric, forced by higher shrinkage of the lower elastic filling due to the loose weave structure or longer float, the upper non-elastic yarns tend to form a convexity with protuberance appearing on the face of the fabric as shown in Figure 7(e). Meanwhile, the back of the fabric which is consisted of elastic filling appears truly flat and shows normal behavior of elastic fillings. In shorts, the face layer of the fabric with non-elastic yarns is with regular convexities formed in alternate fashion, while the back layer with elastic yarn appears smoother and tidier. The fabrics with parallel in-phase zig-zag folded stripes yielded NPR up to 20% of longitudinal strain and the fabric with folded oblique stripes exhibited NPR up to 38**%** of longitudinal strain, as shown in Figure 4(d), 5(d) and 6(d) respectively. The double layer fabric with folded convexities produced zero Poisson's ratio up till 29% of the longitudinal strain when stretched along the weft direction, as shown in Figure 7(g).



(a) (b)

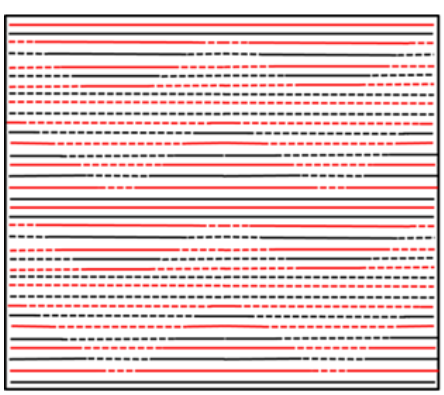


(c)

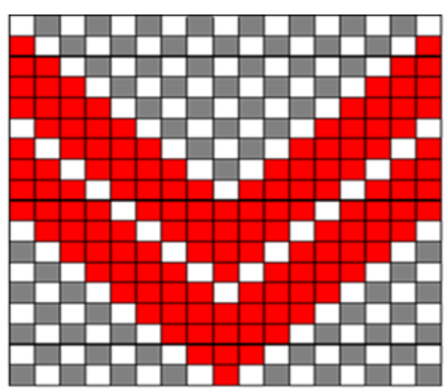


(d)

Figure 4. Fabric with parallel in-phase zig-zag folded stripes along warp: (a) schematic of fabric showing loosely and tightly woven parallel in-phase zig-zag stripes; (b) interlacement pattern; (c) real fabric; (d) Poisson's ratio as a function of longitudinal strain when stretched along weft direction.



(a)



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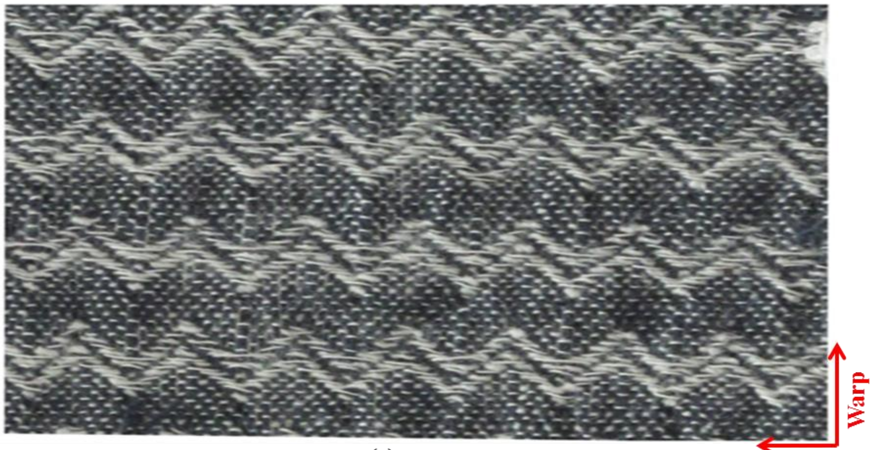

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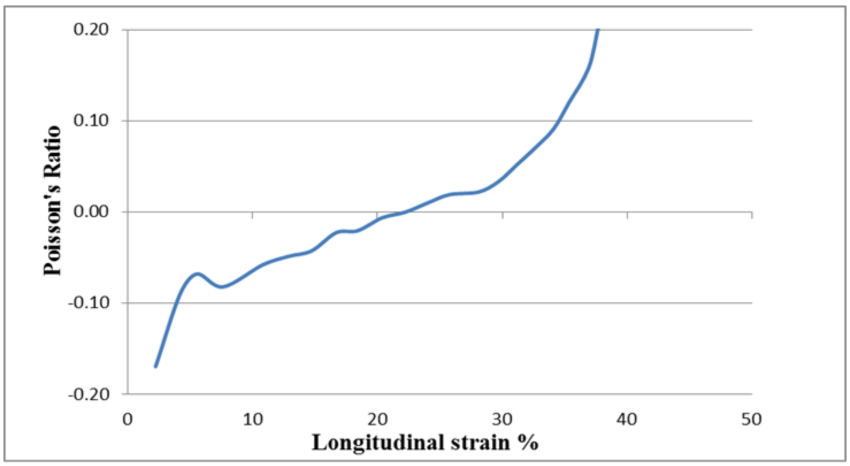
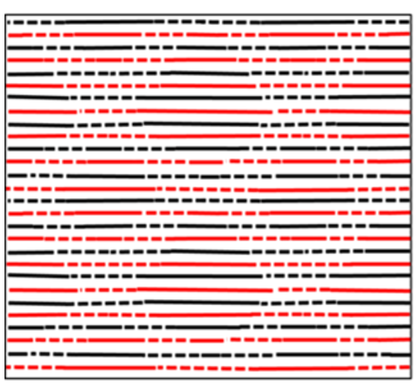
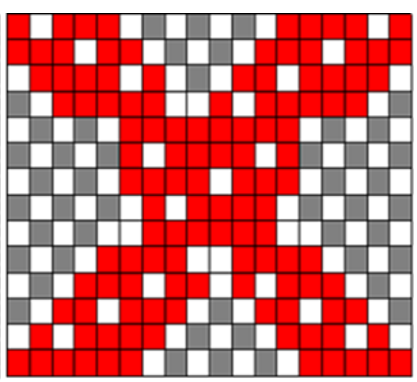


(d)

Figure 5. Fabric with parallel in-phase zig-zag folded stripes along weft: (a) schematic of fabric showing loosely and tightly woven parallel in-phase zig-zag stripes; (b) interlacement pattern; (c) real fabric; (d) Poisson's ratio as a function of longitudinal strain when stretched along weft direction.



(a)



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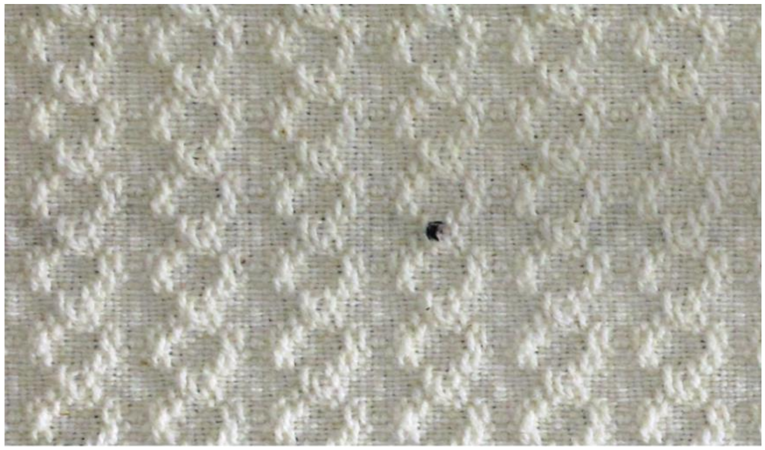

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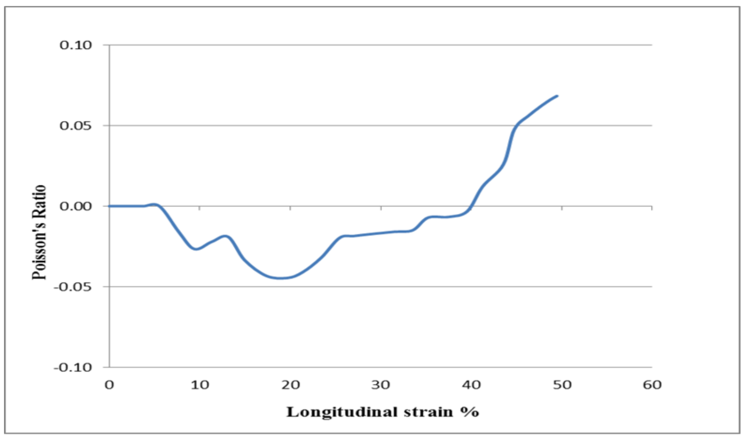
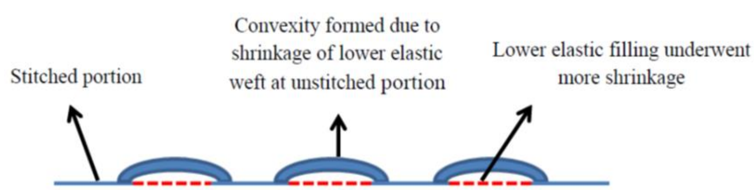
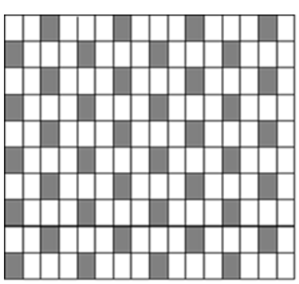


(d)

Figure 6. Fabric with oblique folded stripes: (a) schematic of fabric showing loosely woven oblique stripes; (b) interlacement pattern; (c) real fabric; (d) Poisson's ratio as a function of longitudinal strain when stretched along weft direction



(a)



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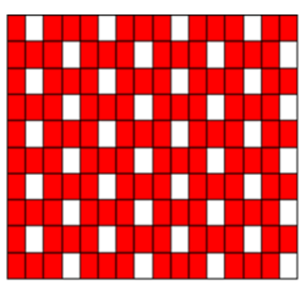

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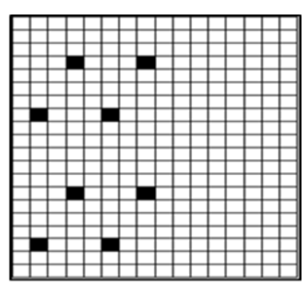
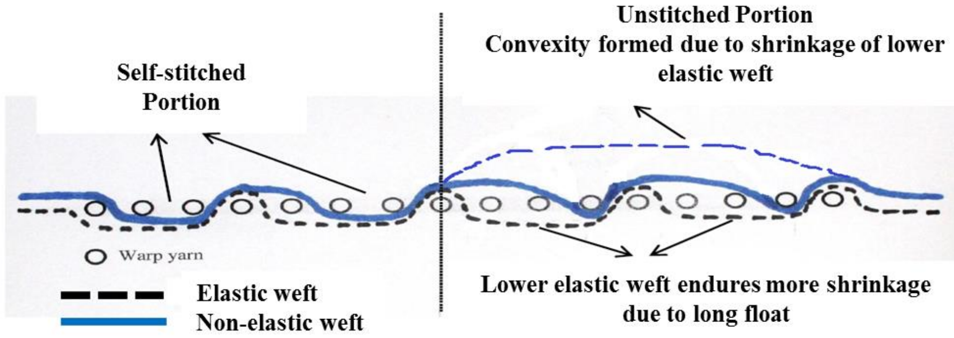
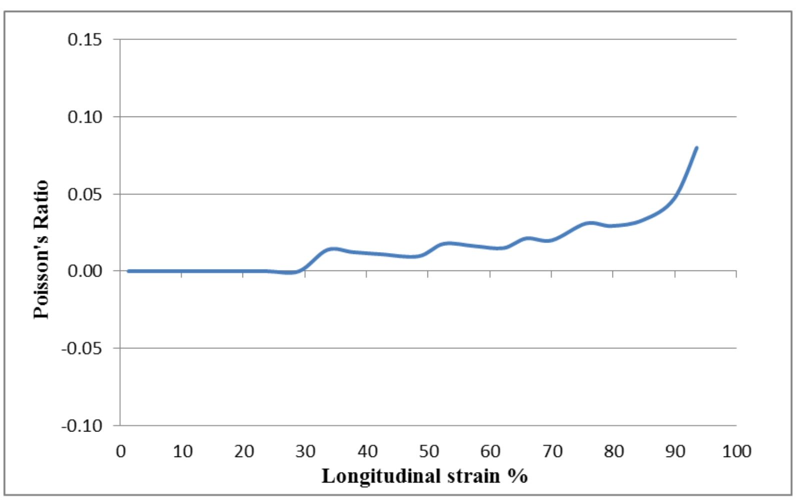


(d)



(e)

(f)



(g)

Figure7.Fabric with folded abrupt convexities: (a) schematic of fabric showing self-stitched portion and unstitched portion with convexities or protuberances on face of fabric and flat back of fabric; (b) weave of face non-elastic wefts; (c) weave of lower elastic wefts; (d) stitching weave of face and lower layer; (e) mechanism of convexities or protuberances formation on face of fabric; (f)real fabric; (g) Poisson's ratio as a function of longitudinal strain when stretched along weft direction

3.1.2 Deformation behavior of developed auxetic fabrics with foldable geometries

As the foldable structure are formed by the creation of differential shrinkage effect, which enable different sections of fabric with different tightness of weave to endure different levels of shrinkage upon relaxation. The fabric sections with tighter weaves undergo less shrinkage while the sections with loose weave experience more shrinkage and the folds in predesigned patterns are created. In addition, it was also observed that the warp yarns and weft yarns do not occupy the same path at tightly woven sections and loosely woven section, in reality as a result of more shrinkage at the loosely woven section; they deviate from the position held by both yarn at the tightly woven sections and tend to come closer. Therefore, in relaxed state the warp and weft yarns are not truly straight.

In case of fabric with parallel in-phase zig-zag folded stripes along weft or warp and fabric with folded stripes in oblique fashion, upon stretching in the weft direction that is also the direction in which there are alternate elastic yarns, the bulged or folded sections tend to open up, expanding in the transversal direction and the yarns in tensile direction tend to get straight. Furthermore, due to frictional binding forces between the yarns at the cross over points, the yarns in transversal direction also experience a persuasive force and tend to get straight to the position which they held at the tightly woven section until there is yarn slippage at the cross over point. Thus, the stretching force is consumed in flattening of the bulge or folds formed due to the differential levels of shrinkage followed by straightening of warp and weft yarns until slippage point is reached. Consequently, the yarn systems get more in order to achieve more consolidated form that is the straight form and the width of the fabric increases due to the opening of the bulge or folds in transversal direction giving rise to NPR effect.

In the fabric with folded convexities or protuberances the convexities are created along warp direction with elastic yarn along weft direction. It is also observed that both of the yarns (warp and weft) deviate from their original right-angled position, and some kind of undulation is occupied by both of the yarns in the fabric structure as shown in Figure 7(f). When the fabric is stretched along the weft direction, the convexities run along transversal direction and opened up in tensile direction and some of the stretching force is also consumed by yarns in tensile direction in order to adopt the consolidated form. Therefore, no expansion in transversal direction arises and the width of the fabric remains unchanged which resulted in zero Poisson's ratio. After the yarns slippage is reached at the cross over point, the yarns in tensile direction come closer and the fabric undergo contraction in the transversal direction giving rise to positive Poisson's ratio or behave conventionally.

3.2 Auxetic fabrics developed based on rotating rectangles geometry

The architecture of this geometry is a rotating quadrilateral illustrated in Figure 8(a). Its unit cell is highlighted in black color. In the unit cell, four rigid rectangles are connected together at their vertices by hinges, in such a way that the empty spaces between the rectangles form rhombi. It is assumed that these rectangle units are rigid and do not change their shape, and are allowed to rotate freely under loading and collapse in relaxed state. When the structure is subjected to an extension in one direction, due to the free rotation of the rectangle units the structure ascent from collapsed state and expands in transverse direction as shown in Figure 8(b), resulting in a NPR effect, which depends on the strain and dimensions of the rectangles.

In order to produce a single layer fabric with this rotating rectangles geometry, an interlacement pattern was designed. The schematic of this interlacement pattern is shown in Figure 8(c). The individual rectangle units were woven continuously by employing tight plain weave and connected together at their vertices (area shaded with grey color). The sections between two tightly woven rectangular units were woven with a loose weave (non-shaded area). While the central rhombi section (formed by joining corners of four plain woven rectangle units) is kept free of interlacements of warp and weft (area shaded with red color). The elastic yarn (core spun cotton spandex Ne 16/s) and non-elastic yarn (cotton Ne 20/1) were used in weft. The non-elastic yarn (cotton Ne 20/2) was used in the warp direction. The non-elastic yarn was used to impart stability to the structure, especially to the tightly woven rectangular sections. The warp and weft densities used were 40/inch and 50/inch respectively. The real fabric is shown in Figure 8(d).

During fabrication, only elastic weft yarn was inserted at central part of the rhombi, while at other sections elastic and non-elastic weft yarns were inserted alternately. It was assumed that the use of elastic yarn can increase the axial deformation and recovery capacity of the structure after release from extension. In addition, the elastic yarn facilitates the rectangular units to collapse upon relaxation. The three sections of fabric unit cell with different tightness of weave undergo different levels of shrinkage. The higher shrinkage of elastic weft yarns together with the absence of interlacements at the central rhombi section compels the plain woven rectangular units to collapse. Though, the individual rectangular units are weaved by employing tight plain weave but still, they are not stable enough to withstand with the shrinking force of elastic weft yarns and lose their shape. The rectangular units are gathered in the direction of elastic yarn, shrinking and slight bumps are formed on the face of the fabric at tightly woven rectangle sections. On the face of the fabric, the elastic weft yarns are prominent at sections, with absence of interlacements. On the back of the fabric the warp yarns are prominent at sections, with absence of interlacements and slight depressions are formed at plain woven rectangle sections. This fabric produced smaller values of NPR over a smaller range of longitudinal strain. The NPR effect is achieved up till 11% of longitudinal strain when stretched in the weft direction as shown in Figure 8(e).

Upon stretching, the bumps resulted from the higher shrinkage of elastic weft yarn at tightly woven rectangle units are transposed in the transversal direction and then the rectangle unit ascent from their collapsed state. The yarns in the tensile direction tend to get straight. Therefore, the stretching force is mainly consumed in transposition of the bumps, in ascending of rectangular units from the collapsed state due to the free rotation of rectangular units to some extent and straightening of yarns in the tensile direction until slippage point is reached. However, the true rotating rectangles effect could not be achieved in this development. In order to achieve a true rotating rectangles effect, the rectangular units should collapse or rotate freely in both directions. Conversely, due to the absence of elastic yarn in warp direction, the tightly woven rectangular units collapsed only in weft direction. The rectangular units were also not stable enough to resist change of shape and due to higher shrinkage caused by elastic yarns in weft direction, they lose their rectangular shape. The free rotation is also restricted due to the warp and weft yarns passing from one rectangle to the other. All these factors resulted in smaller transversal expansion and smaller NPR effect.

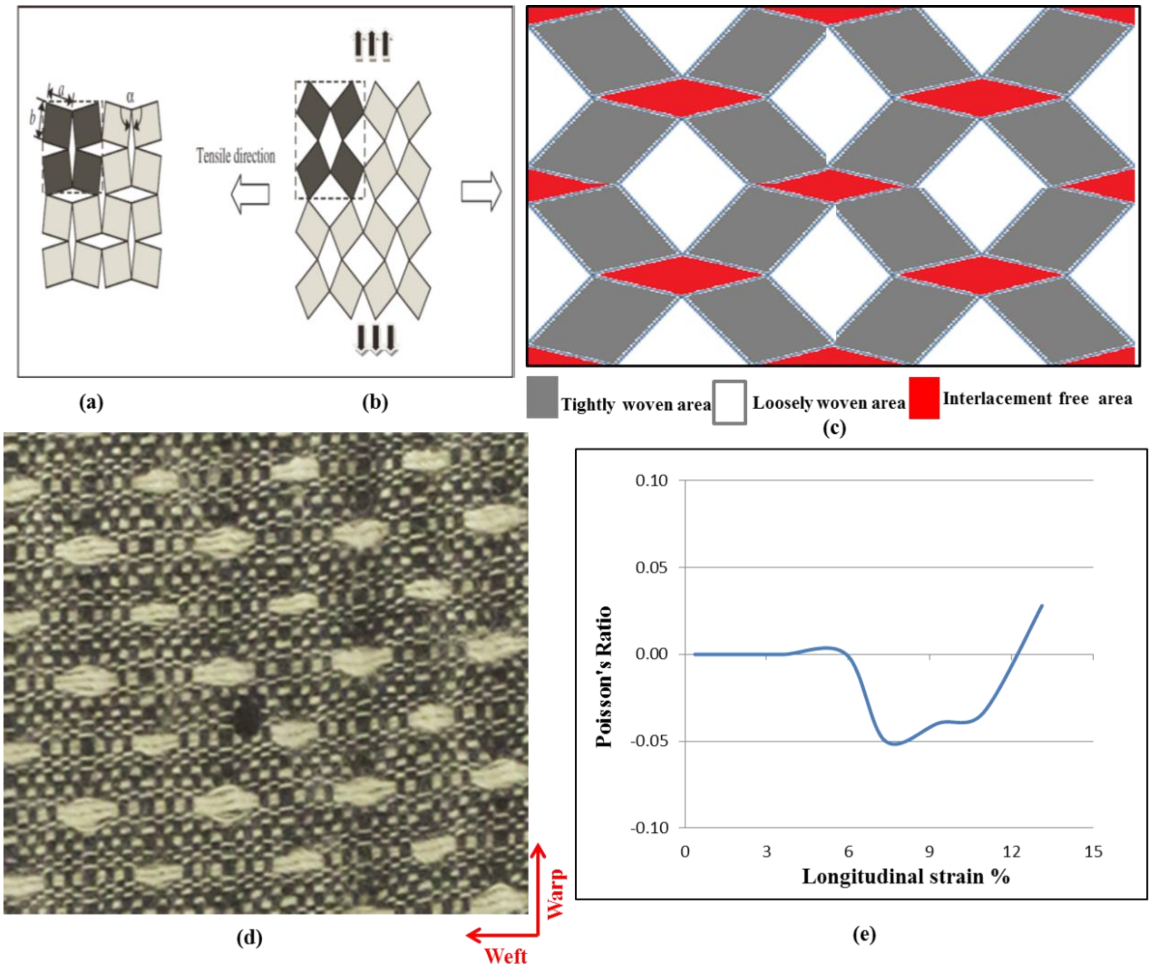


Figure 8. Development of fabric with rotating rectangles geometry:(a) free state of geometry; (b) extended state of geometry; (c) schematic of interlacement pattern; (d) real fabric; (e) Poisson's ratio as a function of longitudinal strain when stretched along weft direction

3.3 Auxetic fabrics developed based on re-entrant hexagonal geometry

This fabric is based on a re-entrant hexagone geometry as illustrated in Figure 9(a).The unit cell of this geometry is highlighted in red color. When this structure is subjected to an extension in a direction, the structure will expand in transverse direction due to the translation of the walls or the ribs of the hexagons, resulting in the NPR effect, as shown in Figure 9(b). In order to realize this geometry into woven fabric, the geometry was transformed into the interlacement pattern. The schematic of this interlacement pattern is shown in Figure 9(c). The unit cell of interlacement pattern has two vertical grids woven tightly, using plain weave and higher denting of reed. The single layered tightly woven sections, single layered loosely woven sections, double layered self-stitched woven sections and double layered un-stitched woven sections are arranged between the two tightly woven vertical grids. The double layered self-stitched woven sections and double layered un-stitched woven section are arranged in alternate fashion between each two loosely woven sections.

This arrangement creates a rectangular unit with double layered self-stitched woven sections at the edges of rectangle, double layered un-stitched woven section at the center of the rectangle and loosely woven sections between edges and center of rectangle as highlighted with solid black lines in Figure 9(c). The double layered sections have face layer with loose weave and back layer with tight weave. The single layered section also has loose weave. The aim of employing un-stitched double layer structure at the center of the unit cell is to facilitate the more shrinkage due to the loosely woven face layer and at the same time avoiding the creation of bumps and folds in thickness direction, which might be created if a single layer structure is used. Moreover, the two layers at the edges of the unit cell are self-stitched to impart rigidity and reducing shrinkage at the edges of the unit cell.

During fabrication, only elastic weft yarns were inserted at the double layered section, and alternate elastic and non-elastic yarns at the single layered loosely woven sections. The aim of inserting only elastic yarn at double layered section was to make fabric shrink more at this section so that the shape of re-entrant hexagon can be realized. The use of elastic yarn can increase the recovery capacity of the structure after release from extension and can also increase the axial deformation. It was assumed that upon relaxation different sections undergo different level of shrinkage and the unit cell realizes the shape of re-entrant hexagonal geometry.

The elastic yarn (core spun cotton spandex Ne 16/s) and non-elastic yarn (cotton Ne 20/1) were used in weft. The non-elastic yarn (cotton Ne 20/2) was used in the warp direction. The warp and weft densities used were 36/inch and 30/inch respectively and a uni-stretch fabric was produced by using this interlacement pattern as shown in Figure 9(d).

Upon relaxation, the four different sections of fabric unit cell with different tightness of weave undergo different levels of shrinkage. The face and back of the fabric is almost same in appearance after relaxation. The plain woven vertical grids appeared stiffer due to the use of tight plain weave and higher denting of reed. The un-stitched double layered section at the center of the rectangular unit undergo higher shrinkage due to loose weave in the face layer, while the double layered self-stitched section undergo lower shrinkage, due to the fact that the two layers are self-stitched together and the tightly woven back layer restricts shrinkage of loosely woven face layer. The loosely woven sections near the edges of the rectangular unit endure less shrinkage in comparison with the central double layered un-stitched section, but forced by the higher shrinkage of central double layered un-stitched section, these sections were rucked up, forming very prominent bumps. The tightly woven vertical grids will also bend at the center due to the higher shrinkage of the central double layer section and the rectangular unit takes the shape of a dumbbell like hexagon geometry as highlighted with dashed line in black color in Figure 9(c) and 9(d). The fabric produced NPR up to 52% of longitudinal strain as shown in Figure 9(e).

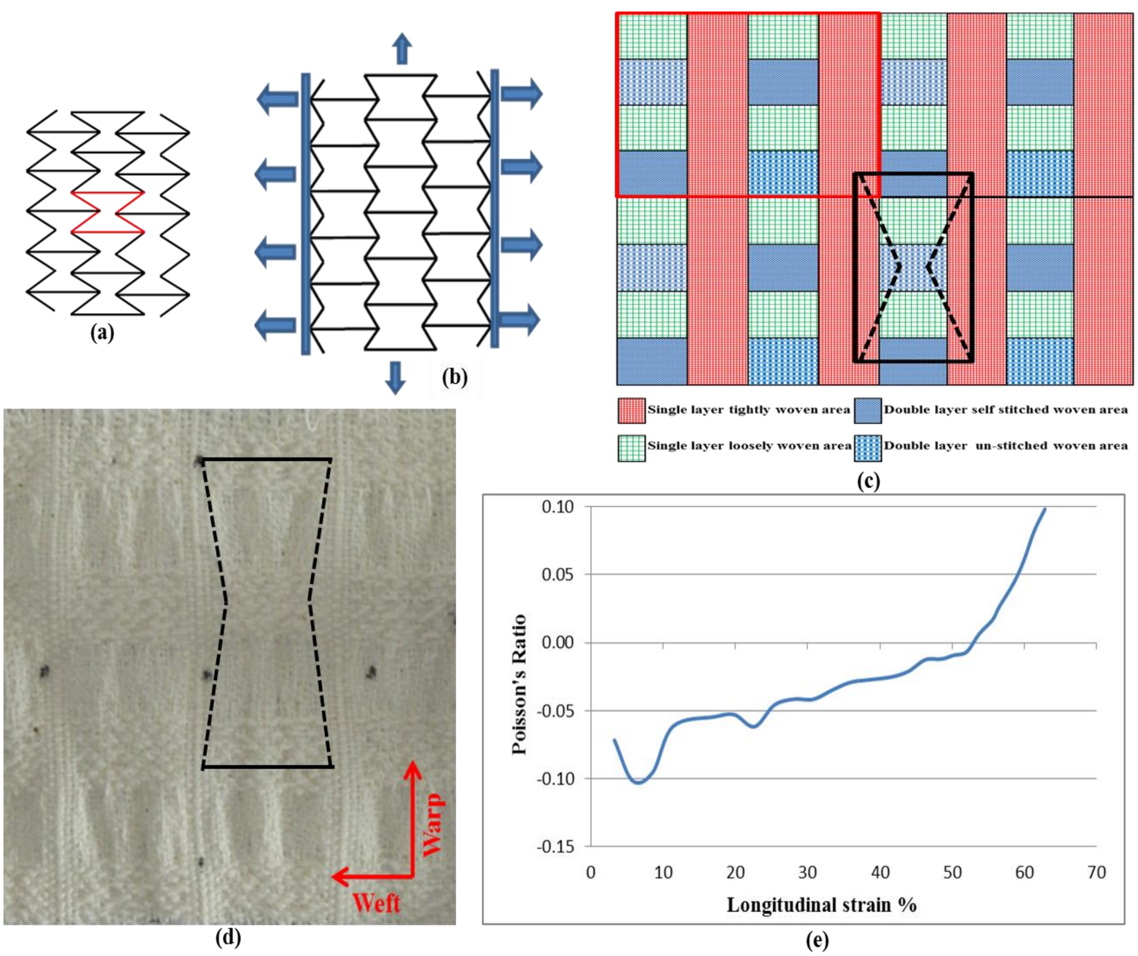


Figure 9. Development of fabric with re-entrant hexagon geometry:(a) free state of geometry; (b) extended state of geometry; (c) schematic of interlacement pattern; (d) real fabric; (e) Poisson's ratio as a function of longitudinal strain when stretched along weft direction

When the fabric is stretched, the bumps formed near the edges of unit cells at loosely woven single layered sections due to the higher shrinkage of double layered unstitched sections at center are transposed in transversal direction. In addition, the vertical grids adapting bend form due to the higher shrinkage of central un-stitched double layer section are translated to straight form and the width of the fabric increases in transversal direction, giving rise to NPR effect. Thus, the stretching force is consumed in transposition of the bumps near edges of unit cell and translation of bent vertical grids followed by straightening of yarns in the tensile direction until slippage point is reached. When the slippage point is reached at the cross over points, the yarns in stretch direction tend to come closer and the width of the fabric decreases which leads to a positive value of Poisson's ratio and the fabric behaves conventionally.

3.4 Comparison among auxetic fabrics developed

Table 1 show the Poisson's ratio values and corresponding longitudinal strains for all the auxetic fabrics developed. A comparison of their auxetic behavior is illustrated in Figure 10. Among all six fabrics developed, five fabrics yielded NPR and one fabric exhibited zero Poisson's ratio. The fabrics with parallel in-phase zig-zag folded stripes along warp and weft produced auxetic effect over a smaller strain range, from 2% up to 20% of longitudinal strain. The fabric with folded stripes in oblique fashion showed NPR up to 38% of longitudinal strain. The double layer fabric with folded convexities generated zero Poisson's ratio up to 29% of longitudinal strain and. The fabric with rotating rectangle geometry produced NPR over a smaller longitudinal strain up to 11% only and the fabric with re-entrant hexagonal geometry exhibited NPR over a larger strain range, starting from 3% up to 52% of longitudinal strain.

Table 1. Poisson's ratio values and corresponding longitudinal strains of developed fabrics

Sr. No.	Fabric Name	Maximum Negative Poisson's ratio Exhibited	Corresponding Longitudinal strain (%)	Poisson's ratio is negative up to Longitudinal strain (%)	Poisson's ratio is zero up to Longitudinal strain (%)

1	Fabric with parallel in-phase zig-zag folded stripes along warp	-0.1	2	21	--
2	Fabric with parallel in-phase zig-zag folded stripes along weft	-0.17	2	20	--
3	Fabric with oblique folded stripes	-0.045	20	38	5
4	Fabric with abrupt convexities	0.0	--	--	29
5	Fabric with rotating rectangles geometry	-0.05	7	11	6
6	Fabric with re-entrant hexagon geometry	-0.1	9	52	--

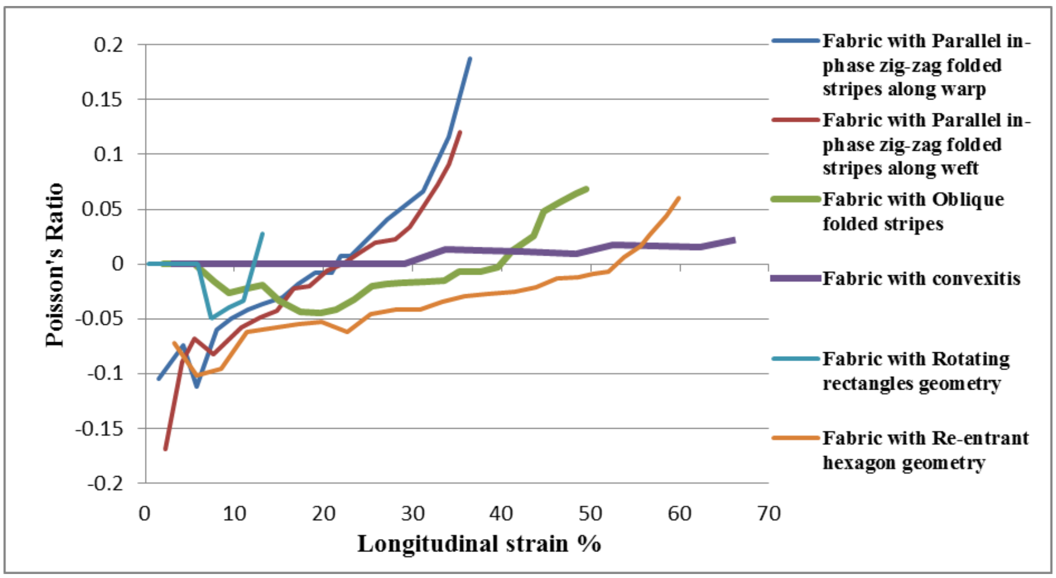


Figure 10. Comparison of auxetic behavior of fabrics developed

4. Potential applications of woven fabrics with auxetic behavior

The developed woven fabrics with auxetic behavior may find their potential applications in the area of fashion garments including girl's tops, stoles, long tops for girls, smocking stoles, round neck, V-neck tops cushion covers, smart maternity wear and sportswear, etc. For the fashion garment, two types of techniques are common smocking and pleating. Smocking can be used for dresses and a variety of outfits. Smocking is the process of putting a design of creases into fabric by using embroidery technique. Most importantly, it is used to gather the fabric so that it can stretch when required. Smocking reduces the dimensions of a piece of fabric to one-third of its original width and enhances the properties of form fitting and flexibility in the garment. Smocking is a complicated process. It cannot be easily used in mass produced clothing. The cost and complication have thus made smocking a relatively rare decorative device in fashion clothing but smocking has not entirely disappeared in our modern world[45, 46, 49].

Pleating is realized by machine. Pleating also involves a steam heating process to achieve permanency of pleat. Pleats of many types are extensively used into fashion garments including skirts, dresses and kilts, to add fullness from the waist or hips, or at the hem, to achieve design effects and to allow freedom of movement. For example, pleats near the hem of a straight skirt allow the wearer to walk comfortably while preserving the narrow style line. The disadvantage of some pleating techniques is added bulk to the seam[47].

The developed auxetic woven fabrics with folded geometries and double layer fabrics with abrupt convexities or protuberance can be employed as more economical seamless alternative for smocking and pleating techniques. The fabric with folded stripes and woven convexities can be used to gather a large amount of fabric into a small waistband without seam and the problem of added bulk to the seam as in case of traditional pleating can be resolved. Another advantage of using this fabric is that they allow the garment to drape straight down when standing and to expand its shape during movement without any lateral shrinkage.

Auxetic fabrics with NPR can also be used for sportswear and as solution to the longevity problem of maternity wear, as the defamation of the fabric will be consistent with body movement, therefore comfort and shape fitting of sportswear will be enhanced. Undoubtedly, auxetic woven fabrics have great potential to be classified as smart and intelligent textiles and to be incorporated into real life applications.

5. Conclusions

In this study a number of single layered and double layered uni-stretch auxetic woven fabrics were developed using conventional weaving machinery and conventional elastic and non-elastic yarns. The developed auxetic woven fabrics were based on foldable geometrical structures, rotating rectangle geometrical structure and re-entrant hexagonal structure. The basic principle used to realize these geometries into woven fabrics was differential shrinkage effect. The auxetic behavior of these fabrics was discussed in terms of tensile deformation, longitudinal strain, response of fabric geometrical structure and transverse strain. From this study, the following conclusions can be drawn:

- It is possible to produce auxetic woven fabrics by using conventional yarns and machinery. Differential shrinkage effect can induce auxetic behavior into woven fabrics and can be created by combinations of loose and tight weaves together with the use of elastic and non-elastic yarns having different stretch properties.
- The foldable structures can be produced by exploiting the phenomenon of differential shrinkage. The characteristics of the interlacement pattern together with different stretch and shrinkage properties of elastic and non-elastic weft yarns enable the sections of fabric with different tightness of weave to undergo different levels of shrinkage for the creation of folds. The foldable structures can be unfolded when stretched in one direction, preserving or increasing the dimensions in the transversal direction and giving rise to zero Poisson's ratio or NPR effect.
- The rotating rectangular geometry can be realized into uni-stretch woven fabrics. However, the true rotating rectangles effect could not be achieved due to the three major limitations. Firstly, the absence of elastic yarn in warp direction which makes rectangular units to collapse only in weft direction. Secondly, unstable rectangular units cannot resist change of shape and due to higher shrinkage caused by elastic yarns in weft direction, they lose their rectangular shape. And thirdly, free rotation of rectangular units is restricted due to the warp and weft yarns passing from one rectangle to the other. All these factors resulted in smaller transversal expansion and smaller NPR effect.
- With precise placement of loose and tight weave within the unit cell of fabric structure, it is possible to realize the re-entrant hexagonal geometry into woven fabrics. The longer ribs of the unit cell of hexagonal geometry can be made to bend upon relaxation due to differential shrinkage effect and to translate into straight form upon stretch, which will increase the transversal dimension, and a large NPR effect can be achieved over a larger longitudinal strain range.

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