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Development of auxetic warp knitted fabrics based on reentrant geometry

Zhao Shuaiquan, Hu Hong*, Chang Yuping
Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hung Hom, Hong Kong
*The corresponding author: hu.hong@polyu.edu.hk

Abstract

This paper reports a novel method to fabricate auxetic warp knitted fabrics on a tricot warp knitting machine based on a special structure design and knitting process. Three auxetic warp knitted structures were successfully developed and all of them were designed to form a reentrant hexagonal geometry to acquire auxetic effect. To provide the fabrics with reentrant frames, both elastomeric yarns and stiff yarns were used to form the elastic underlaps and stiff underlaps, respectively. While the elastic underlaps can keep the reentrant structures stable, the stiff underlaps can support the reentrant structures to keep their reentrant frames. To alleviate the transfer of yarns in the loops under tension, an additional front yarn guide bar was used to feed binding yarns to basic reentrant structures. After knitting, all the fabrics were subjected to a heat setting process to keep their shape and a tensile test to assess their auxetic behavior. Experimental results showed that all the fabrics exhibited an obvious auxetic behavior within a wide range of strain. Especially, the fabrics kept an auxetic behavior till breaking when stretched in wales direction and the Poisson's ratio of the fabrics could be as low as -0.5. On the other hand, the fabrics exhibited a large tensile elongation when stretched in courses direction and their Poisson's ratio was changed from negative to positive after the tensile strain exceeded a certain value.

Key words

Negative Poisson's ratio, auxetic fabrics, knitting, auxetic textiles

1. Introduction

Poisson's ratio is defined as the minus value of materials' lateral strain to longitudinal strain under tension [1]. Although most materials possess positive Poisson's ratio theoretically and practically, materials with negative Poisson's ratio (NPR) do exist in nature [2]. Materials with NPR are also known as auxetic materials [3]. They have received increasing attention since the report of the first man-made auxetic foam in 1987 [4]. Auxetic materials, usually with a special structure being of either macroscopic or microscopic, will expand under unidirectional tension [5-7]. Due to this counter-intuitive behavior, properties of auxetic materials, such as shear resistance [8], indentation resistance [9], sound absorption [10] and crashworthiness [11, 12] can be enhanced [7, 13, 14], making them ideal materials for many interesting applications such as personal protection [15], biomedicine, aerospace and even military use [16]. So far a lot of structures have been proved to be auxetic [17-20] and many of them have been found to have similar deformation mechanisms [21].

There are mainly two methods to achieve auxetic fabrics. The first one is to use auxetic yarns to fabricate fabrics with normal structures. Miller et al. [22] reported a type of auxetic woven fabric made of auxetic yarns for composite reinforcement and proved that the composite manufactured from two layers of the auxetic fabrics showed auxetic effect. Wright et al. [23] proposed a woven structure fabricated with helical auxetic yarns. Although the Poisson's ratio of the auxetic yarns used was as low as -1.5, the fabrics made from these auxetic yarns only obtained a Poisson's ratio of -0.1. Using the same principle, Ng et al. also [24] fabricated auxetic woven fabrics with different types of auxetic yarns and found that the auxetic effect of the fabrics depended on several parameters including yarn arrangements, woven structures and types of helical yarns used. The limitation of using auxetic yarns to produce auxetic fabrics is that their auxetic behavior could be restrained by fabric structures.

The second method is to directly fabricate auxetic fabrics from non-auxetic yarns by realizing special auxetic geometrical structures in fabrics. Several woven fabrics have been proposed using this method [25-27]. Knitting has also shown its advantage in fabricating auxetic fabrics using different auxetic geometries. Through flat knitting, Liu et al. [28] produced auxetic weft knitted fabrics based on a foldable structure comprised of parallelogram planes. Hu et al. [29] also designed and fabricated three types of auxetic knitted fabrics based on foldable structures, rotating rectangles and reentrant hexagons, respectively. In regard to warp knitting, Ugbolue [30, 31] et al. proposed a type of auxetic structures with the use of thicker soft yarns to form open chain wales and high stiffness yarns as inlaid yarns. They also suggested a reentrant hexagonal warp knitted structure by using inlaid elastomeric yarns. Alderson et al. [32] developed another type of warp knitted fabric with double arrow head structure and found that NPR could be achieved under $\pm 45^0$ tension. Wang and Hu [14] developed a special type of auxetic warp knitted spacer fabrics with in-plane auxetic behavior through the modification of a non-auxetic hexagonal geometry to an auxetic geometry formed with parallelograms by using thermo-mechanical method. Chang et al. [33] proposed another type of warp knitted fabric with NPR based on a rotational hexagonal structure and further applied it to warp knitted spacer fabrics [34]. Although a few auxetic warp knitted fabrics have been proposed based on different geometries, the number is still limited and more auxetic warp knitted fabrics can be achieved using novel method to enlarge their range.

This paper reports the design and fabrication of a novel type of planar auxetic warp knitted structure based on a modified reentrant hexagonal geometry by using a conventional high-speed tricot warp knitting machine. It is expected that the newly proposed auxetic warp knitted structure would have a great potential for practical applications.

2. Experimental

2.1 Geometry design

The well-known reentrant hexagonal structure, as shown in Figure 1(a), was adopted as the basic geometry to form auxetic warp knitted fabrics. As illustrated in Figure 1 (b), there are two types of ribs in a basic unit of the structure, namely the horizontal ribs and the diagonal ribs. When subjected to tension in either vertical or horizontal direction, the horizontal ribs will keep straight, but the diagonal ribs tend to rotate towards the vertical direction, leading to the lateral extension of the basic unit. As a result, the auxetic effect is achieved. It should be noted that the ribs can be designed to have different lengths to achieve different *θ* for obtaining different auxetic effect.

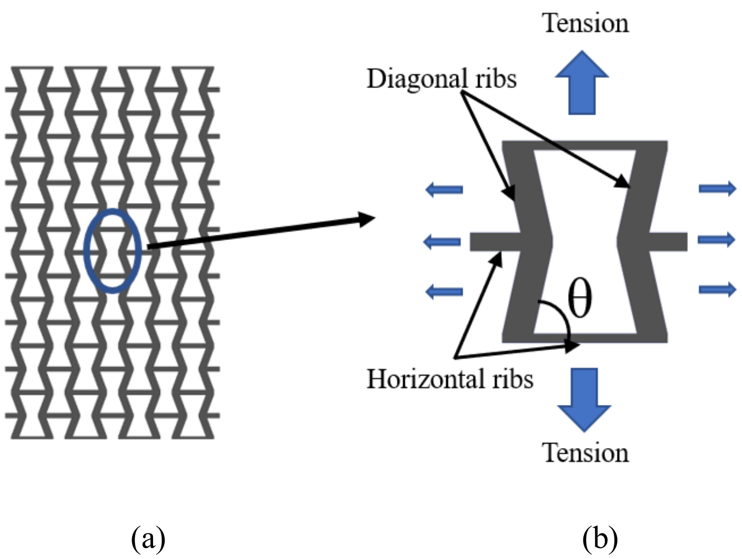


Figure 1 Reentrant hexagonal geometry (a) and basic unit (b).

Generally, warp knitted fabrics do not have reentrant geometry. However, warp knitted technology shows its advantage in fabricating net structures which can be transferred into reentrant ones by using special yarn arrangements and lapping movement. In order to design fabrics based on the above proposed reentrant geometry, a conventional fabric structure with rectangular nets, as shown in Figure 2(a), was used as the basic frame and each rectangular net is comprised of two horizontal ribs a and b formed by stiff underlaps, and four vertical ribs c, d, e, f formed by stiff wales. To achieve the reentrant geometry as shown in Figure 1(a), additional underlaps formed by elastomeric yarns were introduced to connect two adjacent stiff underlaps horizontally. As shown in Figure 2(b), stiff underlaps and elastic underlaps are alternatively distributed along both the wale and course directions. The length and width of both the horizontal and vertical ribs could be designed through the change of the number of wales or courses in a repeating unit and the threading way of warp yarns. As shown in Figure 2(c), elastomeric yarns will shrink after finishing, narrowing the distance between two adjacent vertical ribs while stiff yarns will support the adjacent vertical ribs to keep a distance between them due to their high stiffness. As a result, the conventional rectangular nets were converted into an auxetic reentrant ones. The vertical ribs also become diagonal ribs. Due to the use of elastomeric yarns, the designed auxetic geometry can exhibit much better elastic recovery after the load is released.

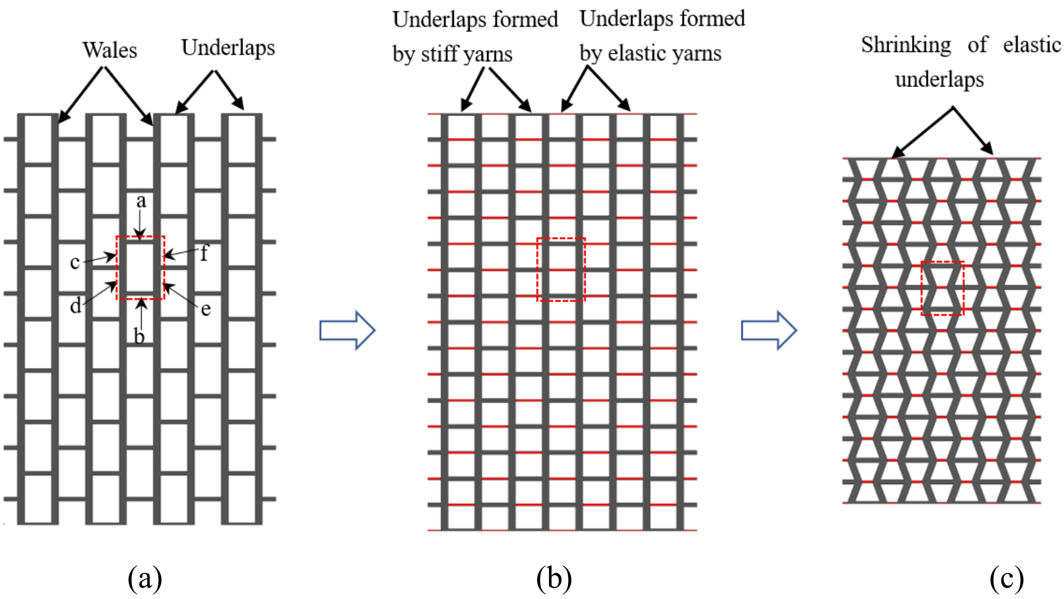
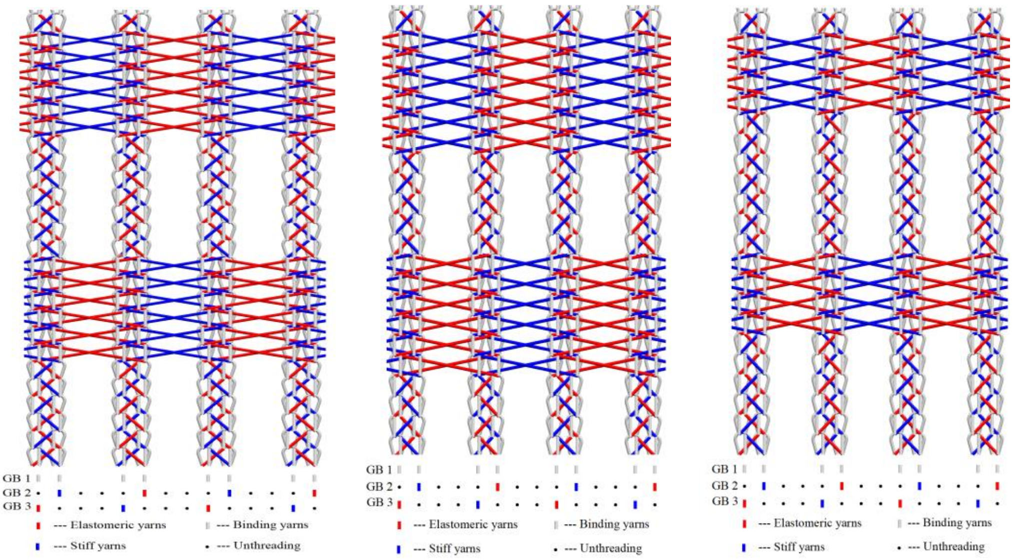


Figure 2 Schematic illustration of structural design: (a) conventional rectangular nets; (b) introducing of elastomeric yarns during knitting process; (c) conversion of conventional nets into auxetic geometry due to shrinkage of elastomeric yarns.

2.2 Knitting of auxetic warp knitted fabrics

The above designed auxetic geometry can be fabricated with special yarn arrangement and lapping movements using conventional warp knitting machine. Rigid warp knitted wales and long underlaps are used to form the vertical ribs and horizontal ribs, respectively. It should be noted that the width and length of both the vertical and horizontal ribs can be varied by changing the yarn threading methods and number of knitting courses in a repeating unit. In this study, to avoid re-threading of yarns which is time-consuming, the same yarn threading method (2 needles knitting and 2 needles non-knitting in a repeating unit) were used to produce the auxetic fabric samples with different numbers of knitting courses for the vertical ribs (*V*) and horizontal ribs (*H*) in a repeating unit to study the influence of the rib size on the auxetic behavior of fabrics.



(a) (b) (c)

Figure 3 Schematic illustration of fabric structures: (a) Fabric 1; (b) Fabric 2; (c) Fabric 3.

The loop structures of the three fabrics were schematically shown in Figure 3 and their corresponding chain notations are listed in Table 1. For easy reference, the values of *V* and *H* for each fabric structure are also provided in Table 1. It can be seen that three yarn guide bars (GBs) were used. While the first yarn guide bar (GB1) was used to knit open chain stitches to stabilize the ground structure for the realization of the targeted reentrant geometry, the yarn second guide bar (GB2) and the yarn third guide bar (GB3) were used to knit tricot stitches for the vertical ribs (cross two-needles space) and the horizontal ribs (cross six-needles space) with the symmetrical lapping movements. The use of tricot stitches can enhance the structural stability and stiffness of the vertical ribs.

In order to reduce the number of yarn guide bars and beams to smoothly fabricate auxetic fabrics on the available warp knitting machine with only 4 yarn guide bars and 4 beams, the same type of yarns were wound on the same beam and the yarns with the same lapping movement were threaded on the same yarn guide bars. As a result, three beams and three yarn guide bars were used. The yarns from the first beam was the binding yarns and they were threaded on GB1. The yarns from the second beam were monofilament yarns and they were divided into two groups. Half of them were threaded on GB2 and another half of them were threaded on GB3. The yarns from the third beam were elastomeric yarns and they were also divided into two groups. Half of them were threaded on GB2 and another half of them were threaded on GB3. Therefore, the monofilament yarns and elastomeric yarns were alternatively threaded on GB2 and GB3.

Table 1 Details of designed fabric structures

No.	Chain notations	Yarn threading	*H*	*V*
Fabric 1	GB 1: (1-0/0-1) × 13//	2 C ,2*	6	7
	GB 2: (5-6/5-4) × 3/ (5-6/1-0) × 3/ (5-6/5-4) × 4/ (9-10/5-4) × 3//	1 A, 3*,1 B, 3*		
	GB 3: (5-4/5-6) × 3/ (5-4/9-10) × 3/ (5-4/5-6) × 4/ (1-0/5-6) × 3//	1 B, 3*,1 A, 3*		
Fabric 2	GB 1: (1-0/0-1) × 11//	2 C ,2*	6	5
	GB 2: (5-4/5-6) × 2/ (5-4/9-10) × 3/ (5-4/5-6) × 3/ (1-0/5-6) × 3//	1 A, 3*,1 B, 3*		
	GB 3: (5-6-5-4) × 2/ (5-6/1-0) × 3/ (5-6/5-4) × 3/ (9-10/5-4) × 3//	1 B, 3*,1 A, 3*		
Fabric 3	GB 1: (1-0/0-1) × 11//	2 C ,2*	4	7
	GB 2: (5-4/5-6) × 3/ (5-4/9-10) × 2/ (5-4/5-6) × 4/ (1-0/5-6) × 2//	1 A, 3*,1 B, 3*		
	GB 3: (5-6/5-4) × 3/ (5-6/1-0) × 2/ (5-6/5-4) ×	1 B, 3*,1 A,		

4/ (9-10/5-4) × 2//	3*

* represents unthreading of yarns. GB represents yarn guide bar. × means the repeating times for the same chain notations within '()'. *V* and *H* represent knitting courses for the vertical ribs and horizontal ribs respectively.

In this study, the objective was to propose a novel method to fabricate warp knitted fabrics with NPR. Therefore, only the available common yarns as shown in Table 2 were used for knitting auxetic fabric samples. However, it should be noted that, in addition to polyester, other types of monofilaments, elastic yarns and multi-filaments can also be used to replace the yarns used in this research to form stiff underlaps, elastic underlaps and binding stitches, respectively. While the stiff and elastomeric yarns in GB2 and GB3 were used to fabricate the basic reentrant geometry, and the binding yarns in GB1 were used to knit chain stitches for preventing yarn slippage under tension in wales direction. In order to avoid the bending of underlaps due to the shrinking of elastomeric yarns, polyester monofilament with a diameter of 0.1mm (108dtex), which was considered to be stiff enough, was selected as the stiff yarn.

Table 2 The yarns used for producing auxetic warp knitted fabrics

No.	Type	Role	Linear density	Tenacity (cN/dtex)	Breaking elongation (%)
A	Polyester monofilament	Stiff yarn	108 dtex	5.08	17.8
B	Polyester wrapped PU	Elastomeric yarn	116 dtex	2.9	20
C	Polyester multifilament	Binding yarn	83 dtex	4.05	17.5

dtex: the weight in gram of every 10000 m yarn.

The machine used was a conventional high-speed tricot warp knitting machine. The details of the machine are shown in Table 3. It should be pointed out that a multi-speed electronic letting-off system is necessary for the tension control of warp yarns to help the knitting process go smoothly. For all three fabrics, two-needle space tricot, six-needle space tricot and chain stiches were knitted with let-off values of 1850, 3000 and 1500 mm/rack, respectively. To facilitate the analysis, all the fabrics were fabricated with the same loop course density of 16 courses/cm. Although the speed of warp knitted machine can reach 1100 rotations per minute (rpm), to fabricate the fabrics safely and smoothly, the speed for fabricating the proposed fabrics was set as 800 rpm.

Table 3 Details of the machine used for producing auxetic warp knitted fabrics

Machine type	Manufacturer	Gauge	Machine width (inch)	Let-off system	Shogging system	Speed (rotations/min)
HKS 4	Karl Mayer (Germany)	28	42	Electronic	Electronic	800

After knitting, all fabrics were subjected to a heat setting process under a temperature of 160 ^{0}C for 5 minutes to stabilize the reentrant structure. The underlaps formed with elastomeric yarns shrank due to their internal stress, and those formed with stiff yarns kept straight due to their high stiffness. As a result, a reentrant hexagonal geometry was formed in the fabrics. Figure 4 shows the fabrics obtained after finishing process. It can be seen that the expected reentrant unit cell as designed were achieved and the angles between the horizontal ribs and diagonal ribs are different due to the different diagonal rib lengths in the fabrics.

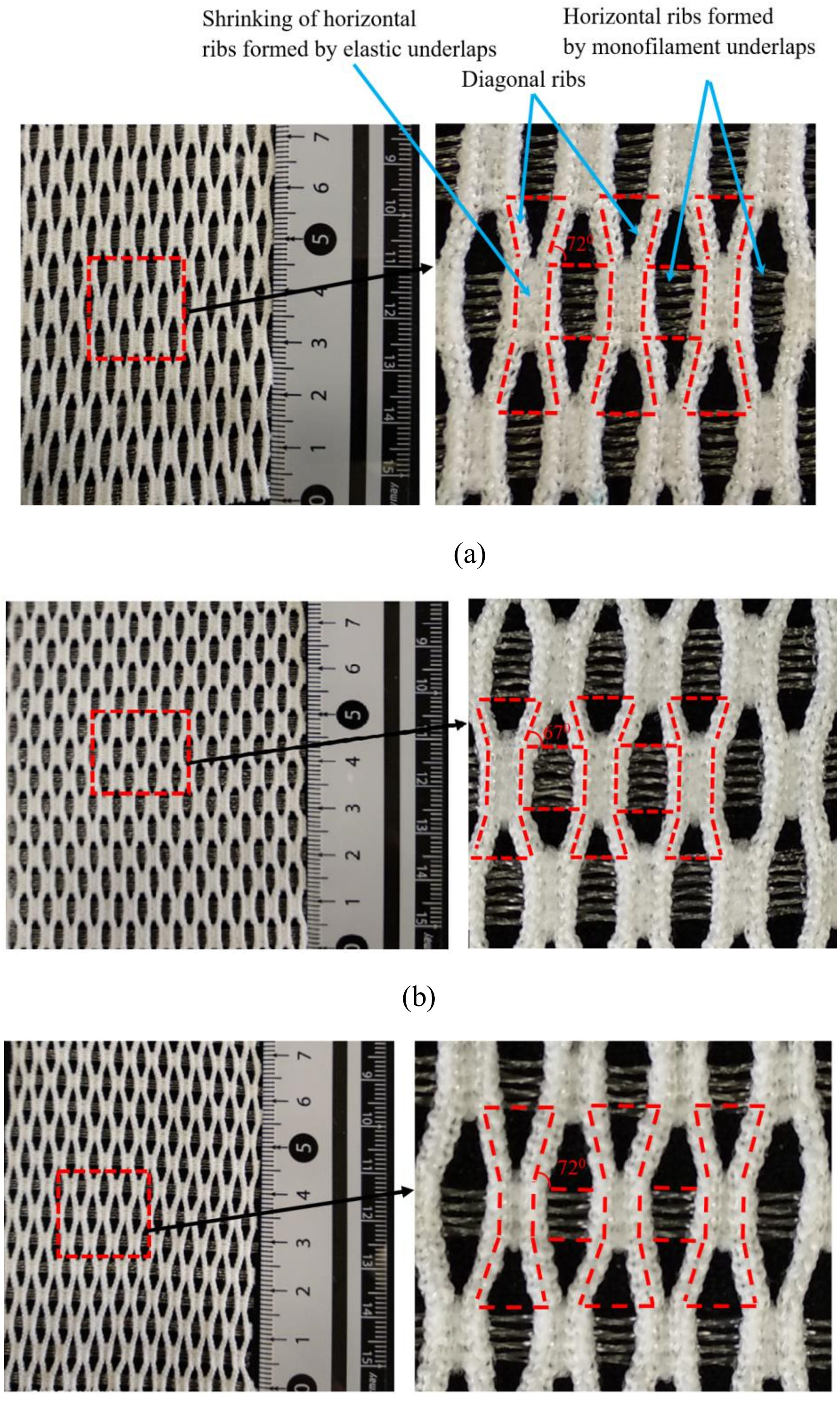


Figure 4 Photographs of auxetic warp knitted fabrics produced at unloaded state: (a) Fabric 1; (b) Fabric 2; (c) Fabric 3.

2.3 Tensile test

According to the previous studies [14, 26, 29, 32, 35], Poisson's ratio values of fabrics can be obtained through measuring both the lateral and longitudinal dimensional changes of the samples. To facilitate the measurement of dimensional changes, marks should be made at proper positions on the surface of the fabric samples and a better and more effective method was to record the dimensional changes during the test by video. After the test, the photos with marks were extracted from the video for measuring of the lateral and longitudinal dimensional changes of the marks by screen ruler, through which the Poisson's ratio at a certain tensile strain can be calculated. It should be noted that the lateral dimensional changes can be measured at any positions of the samples along the tensile direction. However, the largest lateral dimensional changes are obtained at the middle of the samples due to the constraint of clamps.

In this study, the tensile tests were conducted based on the method adopted in [26]. As the designed reentrant geometry usually has in-plane auxetic effect in horizontal and vertical direction as shown in Figure 1(b), the tensile tests were conducted in the wale direction and the course direction and each test was conducted for three times. The size of testing samples was 200 mm × 50 mm, and all of them were marked with five points, as shown in Figure 5.

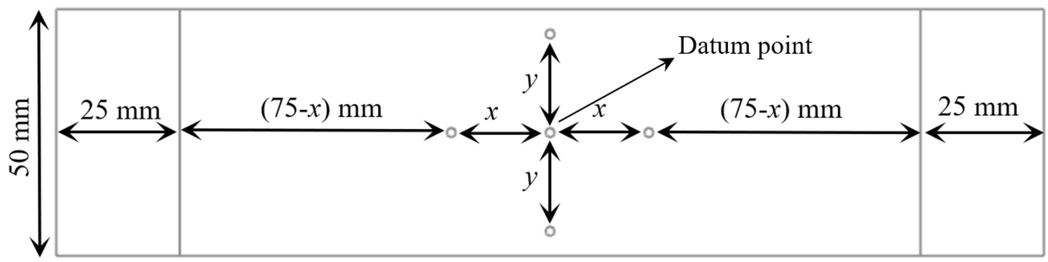


Figure 5 Sample size and marks for tensile test.

The center point was set as the datum point and the other four points were set along the tensile direction with a distance of x and the lateral direction with a distance of y to the central point. Values of x and y do not affect Poisson's ratio. However, they must be marked parallel to the tensile direction and the lateral direction, respectively. As shown in Figure 6, an INSTRON 5566 machine was used and the tensile tests were conducted with a tensile speed of 50 mm /min and a testing gauge of 150 mm. During the test of each sample, a Canon camera was installed in the front of INSTRON to video-record the deformations of the sample. After the tests, the videos were processed in a software named KMPlayer to extract the pictures of fabrics under tension with a time interval of 500 ms. A screen ruler of another software named FastStone Capture was used to precisely measure the changes of pixel number between the marks.

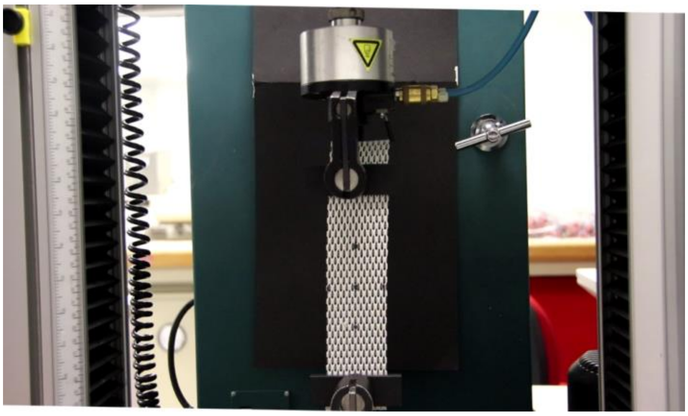


Figure 6 Tensile test on an Instron machine.

For each sample, the pixel numbers between the marks in tensile direction and lateral direction of the sample picture before testing were measured as the initial pixels v_0 and h_0, respectively. The pixel numbers between the marks in tensile direction and lateral direction of the sample pictures during tensile process were measured as v and h, respectively. Based on these values obtained, the tensile strain ε_y and the lateral strain ε_x can be calculated using Eq. (1) and Eq. (2), respectively.

$$\varepsilon_y = \frac{v - v_0}{v_0} \quad (1)$$

$$\varepsilon_x = \frac{h - h_0}{h_0} \quad (2)$$

From here, the Poisson's ratio v_{yx} can be calculated using Eq. (3).

$$v_{yx} = -\frac{\varepsilon_x}{\varepsilon_y} \quad (3)$$

3. Results and discussion

3.1 Tensile behavior

Since all the three fabrics fabricated were produced based on the same geometry, their auxetic behaviors should be similar. In this regard, one of the fabrics could be selected as a representative fabric to analyze the typical auxetic behaviors of the auxetic warp knitted fabrics in different tensile directions. In this study, Fabric 3 was selected as an example for discussion and its stress-strain curves are illustrated in Figure 7. It can be seen that the fabric has a much higher extensibility and a lower slope when stretched in course direction. The main reason is that when the fabric is stretched in the course direction, the yarns can be easily transferred from loops in the wales to underlaps. Figure 8 illustrates how a yarn marked in red color is transferred from the wale to the underlap when the tensile strain is increasing. The transfer of yarns causes yarn slippage, which results in a lower slope of stress-strain curve in the course direction. However, when stretched in the wale direction, as the yarn transfer is more difficult to take place, the fabric shows a lower extensibility but with a higher slope. In this case, the yarns in the fabric start to bulk and then break after the tensile strain exceeds 50%, causing the breaking of the fabrics.

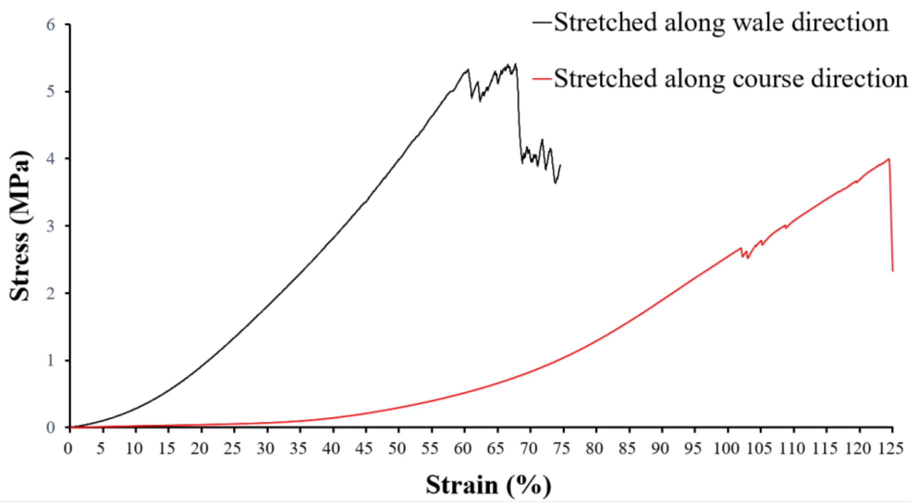


Figure 7 Stress-strain curves of Fabric 3.

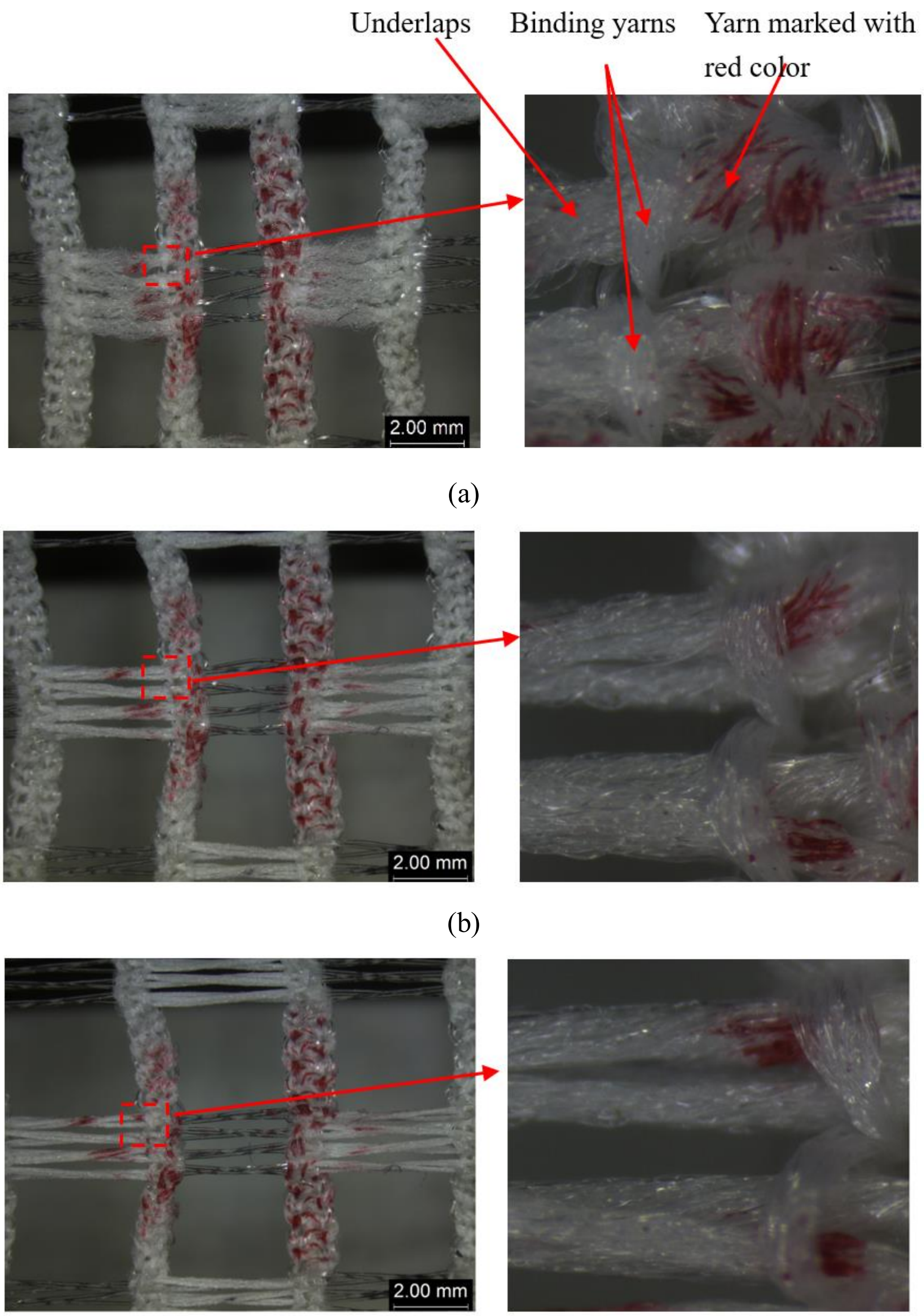
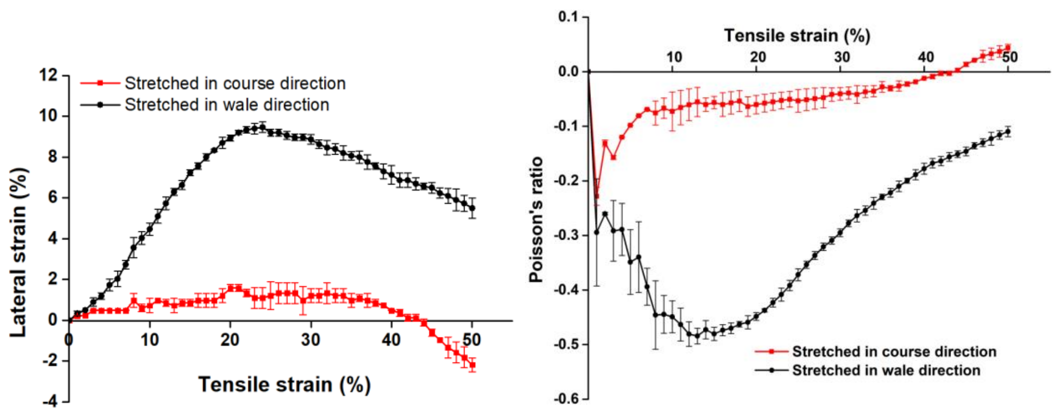


Figure 8 Yarn transfer process under different tensile strains: (a) 30%; (b) 60%; (c) 90%.

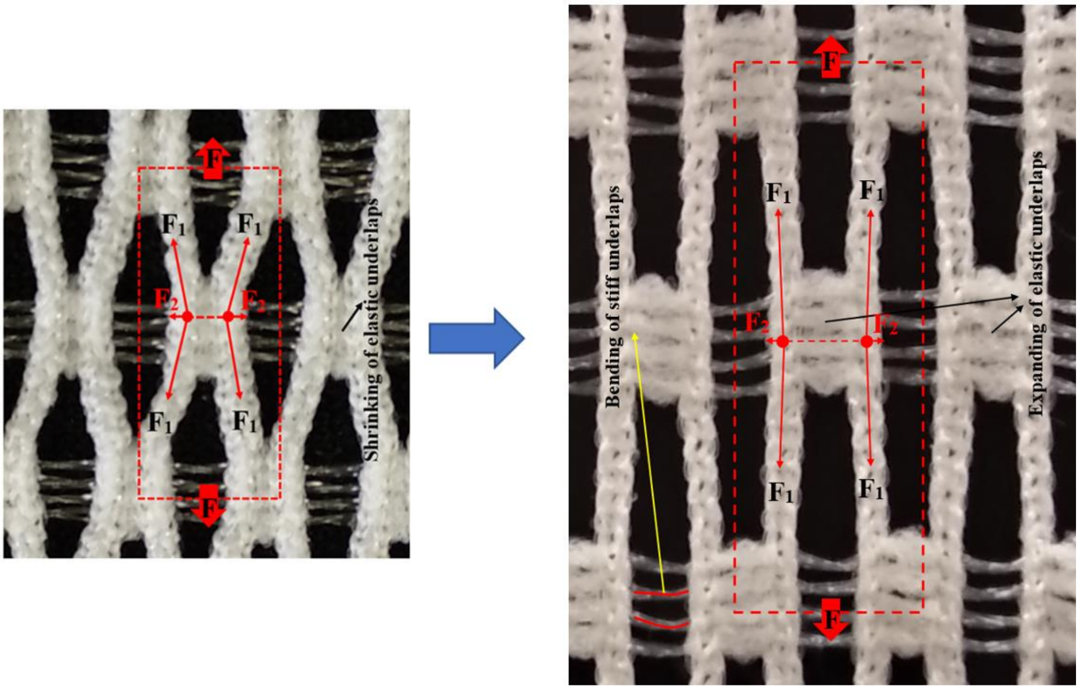
The lateral strain and Poisson’s ratio as a function of tensile strain when stretched in the course and wale direction are shown in Figure 9(a) and 9(b), respectively. As the yarns in the fabric start to break causing the breaking of the fabric when the tensile strain in the wale direction exceeds 50%, the measurement of Poisson's ratio in this direction is no longer effective after 50% of tensile strain. On the other hand, when the tensile strain exceeds 45% in the course direction, the Poisson's ratio values change from positive to negative. Therefore, only the testing results within tensile strain of 50% in both directions are shown in Figure 9(a) and 9(b). It can be seen that auxetic effect is achieved in both directions in a large range of tensile strain. However, due to the difference in the lateral strain changes as shown in Figure 9(a), the auxetic behaviors of the fabric in two directions are very different, as shown in Figure 9(b). In addition to having the much higher auxetic behavior in the wale direction, the variation trends of the auxetic behaviors in both directions are also different. While the auxetic behavior of the fabric stretched in the course direction decreases with changes of Poisson's ratio value from negative to positive in a monotone way, the auxetic behavior of the fabric stretched in the wale direction first increases and then decreases but keeping negative value of Poisson's ratio until the breaking of the fabric. These different behaviors can be explained by analyzing tensile loading which leads to the stretch and rotation of ribs.



(a) (b)

Figure 9 Lateral strain (a) and Poisson's ratio (b) of Fabric 3 as a function of tensile strain.

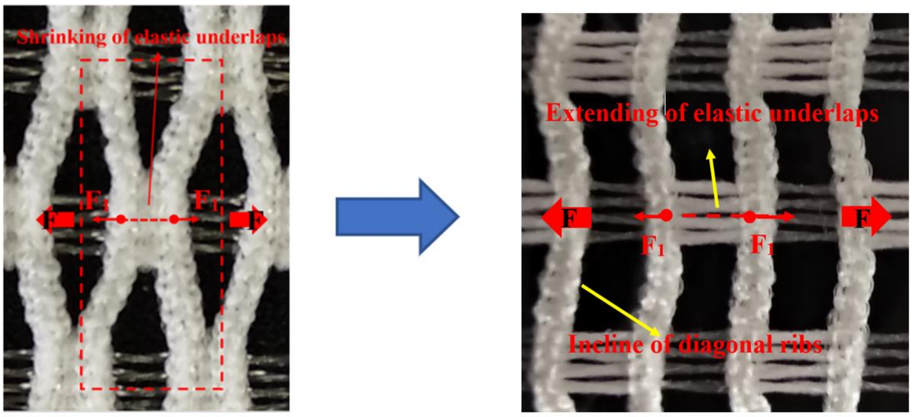
Figure 10 shows the deformations of the fabric under tension in the wale direction, in which the dashed box in red color represents one basic unit. It can be seen that when subjected to tension in the wale direction, forces F_1 created by tensile stress will be exerted along the diagonal ribs. As F_1 is not parallel to the loading direction, two resultant forces F_2 with opposite directions in each basic unit will be produced along the horizontal direction. Under the action of F_1, the diagonal ribs will be stretched causing their elongation in length. Under action of F_2, the shrunk ribs made of elastomeric yarns will be extended, causing the rotation of the diagonal ribs and an expansion of the fabric in the lateral direction. As shown in Figure 10(a), under lower tensile tension, the rigid ribs (underlaps) made with monofilaments can bear pressure of F_2 keeping their straight shape. Therefore, a high auxetic behavior is obtained due to the high extension of elastic ribs. However, with the increase of tensile strain, the pressure applied by F_2 on the rigid ribs increases. High pressure makes the rigid ribs bend, as shown in Figure 10(b), resulting in a decrease of the fabric size in the lateral direction but an increase of size through-the-thickness direction. In addition, with the increase of tensile strain, the stress exerted on wales by F_1 also increases causing the stretching of diagonal ribs. As a result, the auxetic behavior of the fabric decreases. It should be noted that the bending of the stiff underlaps also provides the fabric with out of plane auxetic effect due to the increase of the fabric thickness. As this work is focused on the in-plane auxetic behavior of the fabric, detailed discussion on the auxetic behavior in the fabric thickness direction will not be conducted here.



(a) (b)

Figure 10 Fabric deformation when stretched in wale direction: (a) deformation at strain below 5%; (b) deformation at strain of 40%.

When stretched in the course direction, as shown in Figure 11, both the rigid and elastic ribs (underlaps) will bear the main tensile load. As the loading direction is parallel to the course direction, there is no additional force exerted along wales. In this case, the extension of elastic underlaps and straightening of stiff underlaps will cause the rotation of diagonal ribs, resulting in a size increase of the fabric in the lateral direction. As a result, the auxetic behavior is produced. However, as diagonal ribs made with loops are not very rigid, they can bear tension rather than compression. At lower tensile strain, as shown in Figure 11(a), the rotation of the diagonal ribs can easily increase the size of the fabric in the lateral direction, producing a higher auxetic behavior. However, with the increase of tensile strain, the diagonal ribs which have been rotated to the vertical direction start to incline and bend due to the flexibility of ribs and different extensibilities between rigid and elastic underlaps (horizontal ribs), causing a decrease of fabric size in the lateral direction, as shown in Figure11(b). In addition, as explained before, the transfer of yarns from loops to underlaps under tension in the course direction can also cause the decrease of auxetic effect.



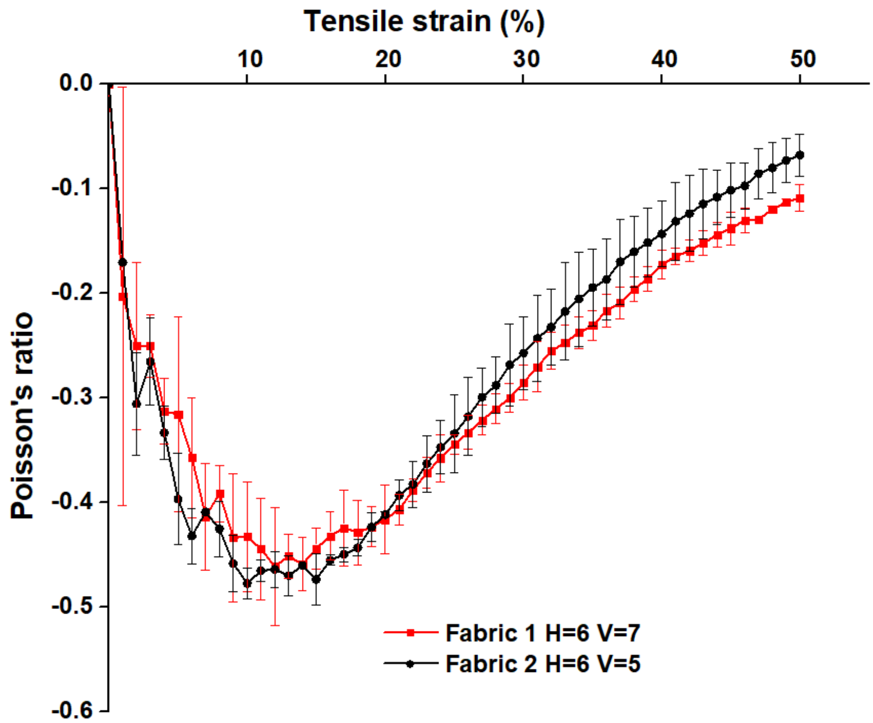
(a) (b)

Figure 11 Fabric deformation when stretched in course direction: (a) deformation at strain below 5%; (b) deformation at strain of 50%.

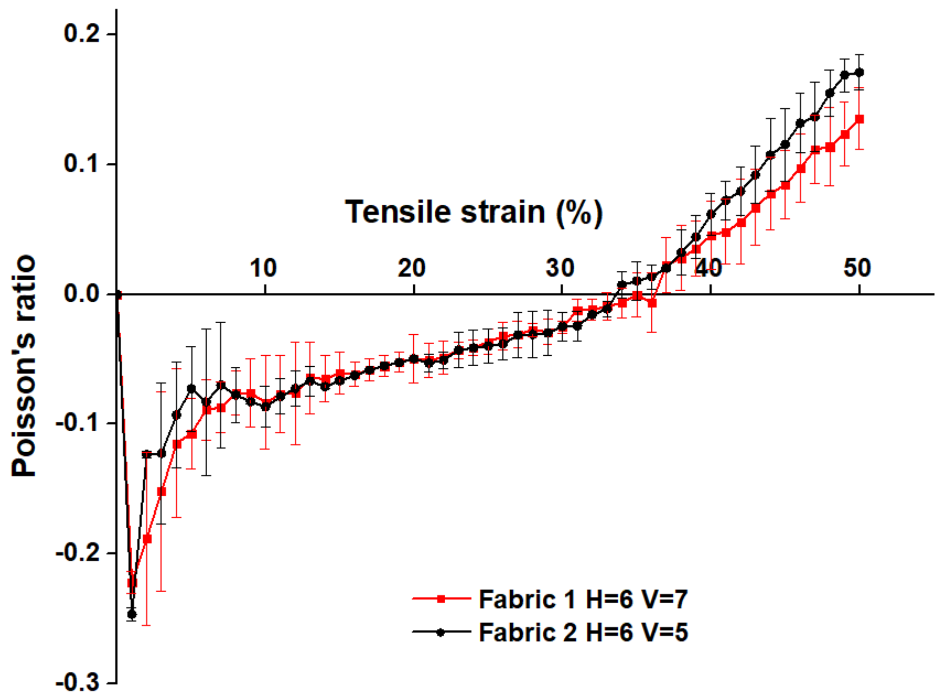
3.2 Effect of knitting parameters

Effect of knitting courses for diagonal ribs (*V*)

To study the effect of knitting courses for the diagonal ribs (*V*) on auxetic behavior of the warp knitted fabrics, as shown in Table 1, Fabric 1 and Fabric 2 were fabricated with the same knitting courses for horizontal ribs (*H*) but with different knitting courses for diagonal ribs (*V*). The testing results of their Poisson's ratio as a function of tensile strain when stretched in the wale direction and the course direction are shown in Figure 12(a) and (b), respectively.



(a)



(b)

Figure 12 Effect of V on auxetic behavior: (a) stretched in wale direction; (b) stretched course direction.

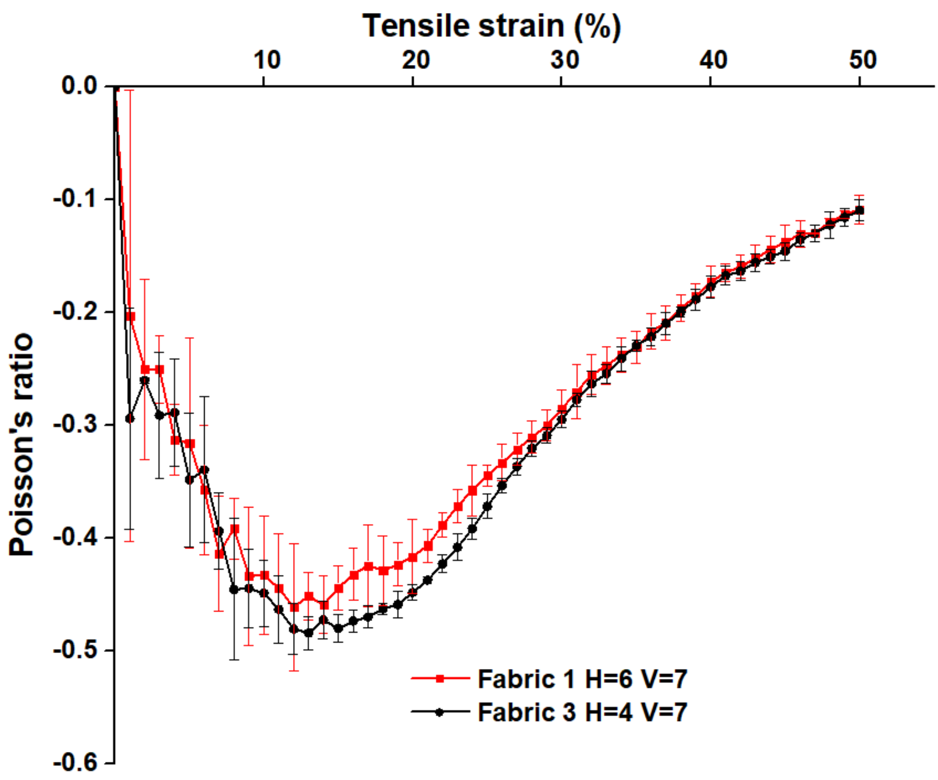
When stretched in the wale direction, as shown in Figure 12(a), at the initial stage, Fabric 2 shows a slightly higher auxetic effect than that of Fabric 1. However, with the increase of tensile strain, the auxetic effect of Fabric 1 becomes better than that of Fabric 2. When stretched in the course direction, as shown in Figure 12(b), the two fabrics show almost the same auxetic effect and the lateral strain of Fabric 2 decreases much faster than that of Fabric 1 after the Poisson's ratio turns to be positive. The above differences in auxetic behavior of the two fabrics can also be explained by analyzing the tensile loading applied in different directions.

As shown in Figure 1 (b), θ is the angle formed between the adjacent horizontal ribs and diagonal ribs. As H is kept constant, the horizontal ribs (underlaps) in the two fabric structures are the same. As shown in Figure 4, Fabric 1 has a bigger θ than Fabric 2 according to the measurement due to longer diagonal ribs. Due to the smaller value of θ in Fabric 2, when stretched in the wale direction, the angle between F_1 in Fabric 2 is smaller than that of Fabric1, which leads to a bigger F_2, as shown in Figure 10. Under action of F_2, the shrunk ribs made of elastomeric yarns will be extended and larger value of F_2 causes larger expanding of the elastic ribs. Since at the initial stage the lateral strain change mainly comes from the expanding of elastic underlaps or the rotation of the diagonal ribs, a better auxetic effect is obtained for Fabric 2. However, with the increase of the strain, the lateral strain change mainly comes from the bending of stiff underlaps. As F_2 in Fabric 2 is higher than that in Fabric 1, the bending of stiff underlaps of Fabric 2 is higher than that of Fabric1, which results in a less lateral expanding of Fabric 2. As a result, the auxetic effect of Fabric 1 becomes better than that of Fabric 2.

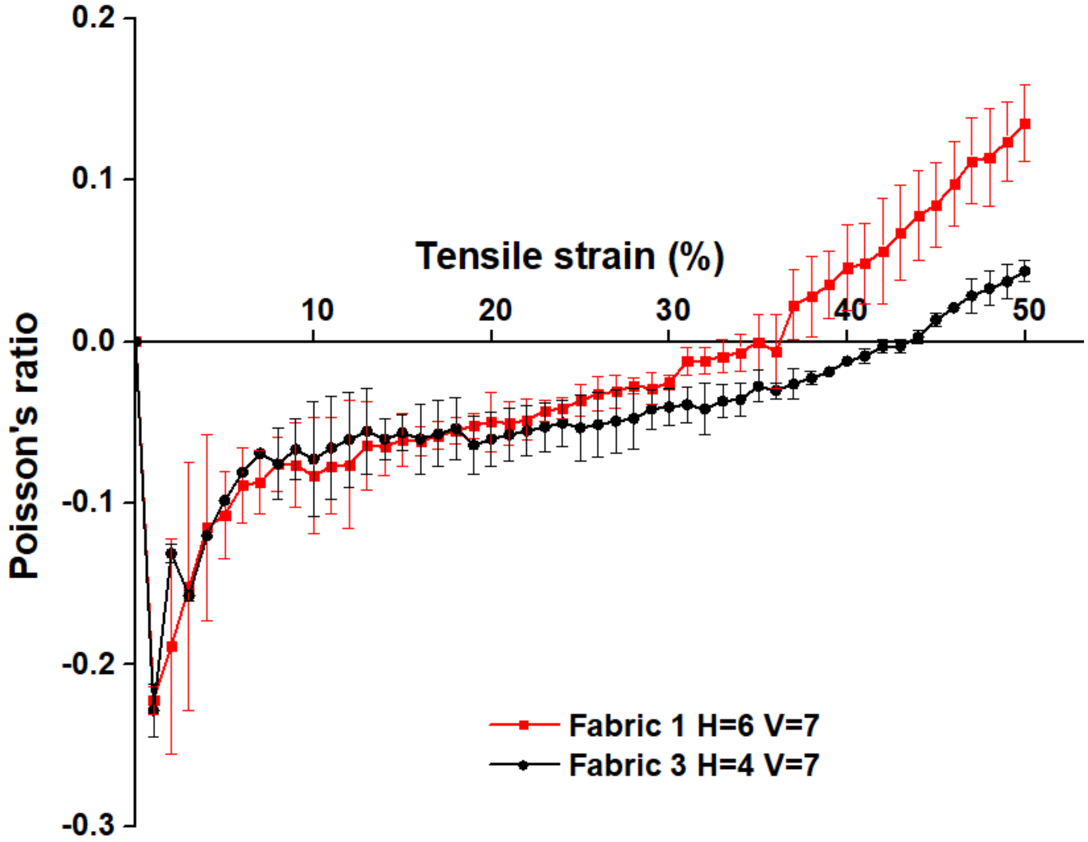
When stretched in the course direction, at the initial stage, the lateral strain change mainly comes from the rotation of the diagonal ribs. As mentioned above, the diagonal ribs are comprised of flexible loops which are very easy to be deformed. Although the length of diagonal ribs is different in the two fabrics, the flexibility of the diagonal ribs in the two fabrics is the same. Therefore, the lateral expansion effects of two fabrics due to the rotation of diagonal ribs are not very different, which result in almost the same auxetic behavior. With the increase of the strain, the transfer of yarns from loops to underlaps becomes the main factor. The shortening of diagonal ribs due to yarn transfer causes the change of Poisson's ratio from negative to positive. Due to the smaller value of *V* of Fabric 2, the shortening effect of diagonal ribs in Fabric 2 becomes more important than in Fabric 1, which results in higher positive Poisson's ratio of Fabric 2.

3.3 Effect of knitting courses for horizontal ribs (*H*)

To study the effect of the knitting courses for horizontal ribs on auxetic effect, Fabric 1 and Fabric 3 were fabricated with the same knitting courses for diagonal ribs (*V*) but with the different knitting courses for horizontal ribs (*H*), as shown in Table 1. The test results of the two fabrics in the wale and course direction are shown in Figure 13 (a) and (b), respectively. It can be seen that the effect of *H* is quite evident in two tensile directions. When stretched in the wale direction, the auxetic effect of Fabric 3 is higher than that of Fabric1 when the tensile strain is lower than 30%. However, with the increase of tensile strain, the auxetic behavior of the two fabrics becomes almost the same. When stretched in the course direction, there is no big difference of auxetic effect in the two fabrics at the initial stage. However, with the increase of tensile strain, the auxetic effect of Fabric 1 decreases much faster than that of Fabric 3.



(a)



(b)

Figure 13 Effect of H on auxetic behavior: (a) stretched in wale direction; (b) stretched in course direction.

The different auxetic behaviors of the two fabrics when stretched in the wale direction can be explained by the different ability of diagonal rib orientation. When stretched in the wale direction, the lateral strain change mainly comes from the expanding of elastic underlaps at the initial stage. As the value of H is smaller in Fabric 3, the number of elastic underlaps of Fabric 3 in one basic unit is less than that of Fabric 1, which means less stress is needed for the same expanding of the underlaps. Therefore, the rotation of diagonal ribs in Fabric 3 is much easier than that in Fabric1. As a result, the degree of orientation for diagonal ribs in Fabric 3 for a given strain is larger than that in Fabric 1, leading to a larger expanding of elastic underlaps, producing a larger auxetic effect. With the increase of tensile strain, the lateral strain change mainly comes from the bending of stiff underlaps. In this stage, due to less stiff underlaps of Fabric 3 in one basic unit, the stiff underlaps are much easier to be bent to the outside of plane. As a result, the lateral strain of Fabric 3 decreases much faster than that of Fabric 1. However, with the further increase of tensile strain, the orientation degree of the diagonal ribs in the two fabrics tends to be almost the same. Therefore, two fabrics demonstrate almost the same auxetic behavior after the tensile strain exceeds 30%.

When stretched in the course direction, the difference of auxetic behavior may come from the transfer of yarns from loops to underlaps. As there are more underlaps within a unit cell in Fabric 1 than that of Fabric 3, more loops in Fabric 1 will shrink for a given tensile strain, leading to higher shrinkage in the lateral direction. As a result, the auxetic behavior of Fabric 1 decreases much faster than that of Fabric 3, with faster change of Poisson's ratio value from negative to positive.

Conclusions

A novel type of auxetic warp knitted structure was first designed based on the modification of a non-auxetic geometry to a reentrant auxetic structure. Various auxetic fabrics were then fabricated using a conventional warp knitting machine with different knitting parameters. The fabric samples obtained were finally tested to assess their auxetic behavior. Based on the test results, the following conclusions can be obtained.

1. Auxetic warp knitted structures can be achieved using elastomeric yarns and stiff yarns in a special arrangement on a warp knitting machine with more than three yarn guide bars. This technique not only enlarges the method of knitting auxetic fabrics using warp knitting technology, but also make it possible to manufacture auxetic fabrics using conventional machines with conventional yarns.
2. The use of binding yarn is necessary to fabricate auxetic warp knitted fabrics with stable structure. Binding yarns should be used in the front bar to get the binding effect.
3. The auxetic knitted fabrics have obvious auxetic behavior in both wale and course directions. When stretched in the wales direction, the fabrics can keep auxetic effect till breaking. However, when stretched in the course direction, the Poisson's ratio

can change from negative to positive when the tensile strain exceeds some limited values.

4. The knitting courses for the diagonal ribs and horizontal ribs (underlaps) in a unit cell have obvious effect on the auxetic behavior.

As this work is only a primary study, some limitations still exist. For example, the geometrical model used to study the relationships between the parameters and Poisson's ratio of the structures has not been set up and the auxetic behaviors in off-axis directions are not clear. Besides, the stability of the auxetic effect has not been tested. Therefore, future work will be focused on the establishment of geometrical models, the test of the fabrics in off-axis directions, and the study of auxetic stability. Finally, as the objective of this paper is to propose a novel method to fabricate auxetic warp knitted fabrics, only the available polyester yarns were used in this study. The comparison of using different types of yarns to realize the same warp knitted structure can also be another future research direction.

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