A Study of Tubular Braided Structure with Negative Poisson's Ratio Behavior

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Abstract:

Textile structures with negative Poisson's ratio (PR) behavior are called auxetic textile structures. They have received increasing attention in recent years and have been designed and fabricated through spinning, knitting, weaving and non-woven methods. However, auxetic textile structures fabricated using braiding method have not been reported so far. This paper reported a novel type of auxetic braided structure based on a helical structural arrangement. The geometry of the structure and its deformation mechanism were first introduced and described. Then a special manufacturing process was developed by the modification of commonly used tubular braiding technology. Various auxetic braids were fabricated with different structural parameters and yarns and tested under uniaxial extension condition. The results showed that all manufactured braids exhibited high negative PR behavior and maintained this behavior until the fracture of the component wrap yarn. Among three structural parameters discussed, namely wrap angle, braiding angle and braiding yarn diameter, the wrap angle had more effects on the tensile properties of auxetic braided structure than the other two parameters. The success of fabricating auxetic braids with commercially available yarns in this study provides an alternative way to manufacture auxetics from positive PR materials.

Key words: Auxetic braided structure, Tensile properties, negative Poisson's ratio, braiding

1. Introduction:

It is a common phenomenon that when a material is stretched, it tends to be thinner, one of example is the rubber band. Whereas most of the materials behave like this, some materials in rare cases will actually expand in the transverse direction when stretched or contract when compressed, displaying a negative value of Poisson's ratio (PR). The materials and structures with negative PR are called 'auxetics' [1]. The positive side of being negative is that the negative PR results in a significant improvement of mechanical properties, such as a rise in toughness [2, 3], better permeability after stretching [4], high energy absorption [5], and excellent indentation resistance [6, 7]. Thus, over the past three decades, a considerable number of auxetic materials and structures, ranging from the macroscopic down to the molecular levels, have been proposed, fabricated, or synthesized through various approaches [8-16]. In addition, auxetics that exhibit negative coefficients of thermal expansion have also been designed and manufactured recently, including the chiral negative PR lattices [17] and the bi-material star-shaped re-entrant planar lattice structure [18]. The introduction of this unique property could further apply auxetics in different areas, such as precision instruments and tooth fillings.

In textile, the development of auxetic structures could be traced back to the fibers developed by Alderson et al. in 2002 [19]. By using a thermal process technique, they produced auxetic polypropylene fibers with a PR low to -0.6. The category of auxetic textile then was extended to yarns when Hook patented a novel helical auxetic yarn (HAY) exhibiting negative PR effect in 2006 [20]. This yarn structure is constructed by wrapping a lower diameter stiffer wrap fiber to a low modulus straight core fiber and was capable of achieving a NPR of -6.8 as indicated by Miller's findings [21]. This auxetic yarn structure is later proved to be a huge success as it is simple to be achieved and have great potential to maximize the auxetic effect. Numerous studies have been conducted on its performance as well as on the influence of the structural parameters [22-26]. In addition, other structures developed from this structure have also been reported, including double helical yarn (DHY) and auxetic woven fabric with the warp being the HAY or the weft being the DHY [27, 28]. More recently, Hu et al. exploited knitting technology for manufacturing auxetic structures and have successfully fabricated both auxetic weft- and warp-knitted fabrics [29-31] and thereby furthering the range of auxetic textile structures. Since negative PR effect can be achieved in fibers [19, 32, 33], yarns [20, 34, 35], knitted and woven fabrics [29-31, 36, 37], a stretch of the thought is to introduce this novel and counterintuitive behavior into a braided structure which has not been done yet according to our knowledge.

Braid is a minor but distinctive form of textile fabric which consists of three or more flexible materials interlaced diagonally with each other [38, 39]. The textile manufacturing technology of it is called *braiding* which has existed for thousands of years [40, 41]. Compared with other three classical textile processes, namely weaving, knitting and nonwoven, braiding employs a method of intertwining instead of interlacing (for weaving), interlooping (for knitting) and interlocking (for nonwoven fabrics) to fabricate a thicker and stronger product from yarns or fibers. For example, ropes and candles. Braided structures are known for their exceptional mechanical properties, including excellent bending strength, impact resistance, torsional integrity and energy absorption [39, 42-44]. As a result, braided textile composites are quite suitable to be utilized in civil engineering, aerospace, transportation or medical industries and various structures have been developed to date [38, 45-47]. Recently, Subramani et al. attempted to employ braided composite rods (BCRs) in manufacturing a novel auxetic structure which could be applied in civil engineering construction [48]. Totally five different structures were fabricated by assembling the BCRs in the form of 'missing rib' in the research. Later on, they conducted a systematic study on this auxetic structure to investigate influences of materials and structure [49] and proved that structure designed on a basis of 're-entrant' also exhibit auxetic effect [50]. It is indicated that these attempts successfully developed macro-scale auxetic structures from braided composites for the first time while the BCR itself is non-auxetic. Thus, auxetic braids are still lacking currently and the production of an accessible auxetic braided structure is needed in the industry.

To fill in this void, here, we would like to propose a novel type of tubular braided structure exhibiting negative PR behavior. The geometry features and deformation mechanism to realize the negative PR effect of proposed structure were first described in this paper. A special manufacturing process based on tubular braiding technology was developed to fabricate the structures with various parameters, including initial wrap angle, initial braiding angle and braiding yarn diameter. The effects of these parameters on tensile properties and negative PR behavior of auxetic braided structure were carefully examined and discussed. With the proposed auxetic braided structure, it is hoped that the problem of unsolid knots that exist in practical applications could be solved. For example, the unsolid knot of the sutures resulting a secondary infection in a medical practice. But by applying negative PR behavior into it, this problem can be tackled. Thus, auxetic braided structures may find great applications in shoelaces or secure threads where solid knots are highly preferred. It is expected that such a study could promote further development of auxetic structures using textile technology.

2. Experimental

2.1 Structure and deformation mechanism

The auxetic braided structure proposed in this study is schematically illustrated in Figure 1(a). It consists of a fine stiff wrap yarn, a tubular braid formed with low modulus braiding yarns and a large diameter core yarn inserted inside. As shown in Figure 1(a), the wrap yarn is helically wounded around the tubular braid and fixed with the braiding yarns at four evenly distributed points in each repeating helical turn. This fixation not only makes the wrap yarn to be uniformly wrapped onto the outside of the braid, but also avoids possible slippage problem which could happen in auxetic helical yarn [23]. In addition, the adding of the core yarn provides support to the whole structure to prevent the irregular distortion of the structure when it is stretched, thus, leading to a better auxetic behavior.

The deformation mechanism of the structure under the axial extension is schematically presented in Figure 1(b), from which we can see how the negative PR behavior is achieved. In the initial state (Figure 1(a)), the base braided structure is in a straight line with the wrap yarn helically winding around it. Upon application of an axial tensile strain, the wrap yarn straightens and displaces the base structure laterally due to its relatively higher modulus. The whole auxetic braid which is of a tubular shape in the initial state is then converted into a wave shape when stretched, as shown in Figure 1(b). This shape change increases the cross-sectional contour size of the structure H and thereby leading to the realization of negative PR effect of the structure. The shape change continues with the applied stretching until H reaches its maximum value, as shown in Figure 1(c). If we continue stretching, H will be decreased due to the extension of the wrap yarn, the reduction of braid wave form as well as the reduction of the cross-sectional size of the core yarn. The reduction of braid wave form is accompanied by a reduction in the braiding angle of braiding yarns. However, since H in this state is still larger than H_0 in the initial state, the proposed braided structure maintains negative PR behavior during the whole stretching process.

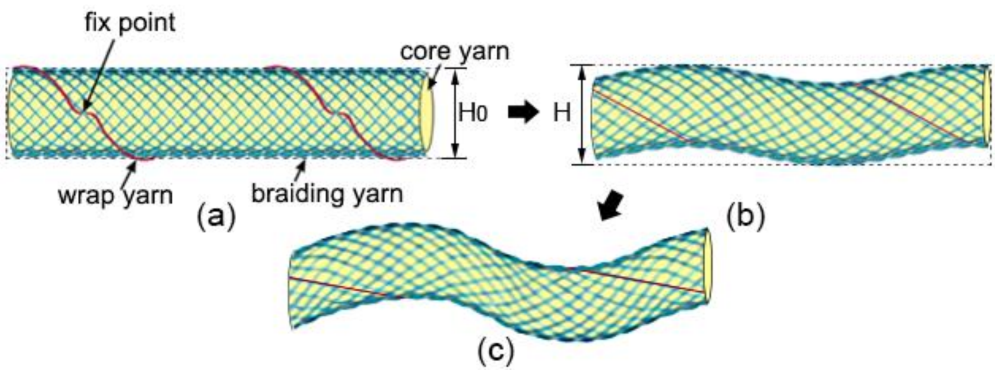
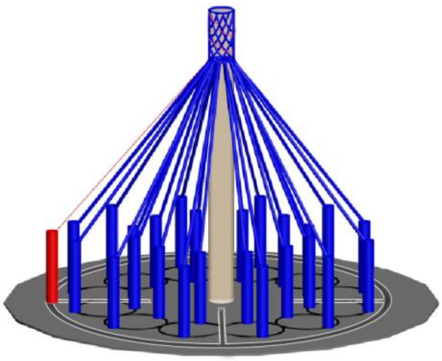


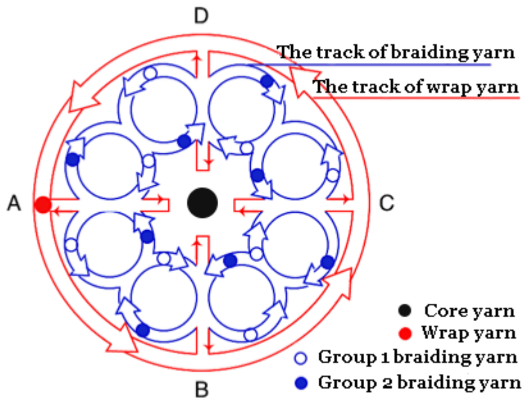
Figure 1. Auxetic braided structure proposed: (a) in the initial state; (b) under extension; (c) maximum cross-sectional contour size.

2.2 Fabrication of auxetic braids

A special manufacturing process was developed to fabricate this auxetic braided structure based on the modification of tubular braiding technology. As shown in Figure 2, the whole process involves two steps, i.e., the formation of the base braided structure and the fixation of the wrap yarn. At the initial process (Figure 2(a)), the wrap yarn is located outside of the braiding yarns at point A. The first step is to form the base tubular braid around the core yarn by moving two groups of braiding yarns in opposite directions, one in the clockwise direction and the other group in the counter-clockwise direction, as shown in Figure 2(b). At the same time, the wrap yarn also circularly moves from point A to point B around the base tubular braid. Changing the moving speed of the braiding yarns and that of the wrap yarn, auxetic braided structures with different braiding angles of the braiding yarns and different wrap angles of the wrap yarn can be produced. The first step finishes when the wrap yarn reaches point B. Then the second step starts. As shown in Figure 2(c), the second step is to fix the wrap yarn with the braiding yarns by first moving it from outside of the braiding yarns to the inside of the braiding yarns and then moving out after two neighboring braiding yarns around it making an interlacement. During the moving in and out of the wrap yarn, the braiding yarns temporarily stop their movements. After the second step finishes, the next braiding process starts with the movement of the wrap yarn from point B to point C. Four braiding processes will be completed when the wrap yarn returns to point A and a turn of helical geometry of the wrap yarn is formed. To achieve this unique manufacturing process, a specially designed prototype then was built, as shown in Figure 3.



(a)



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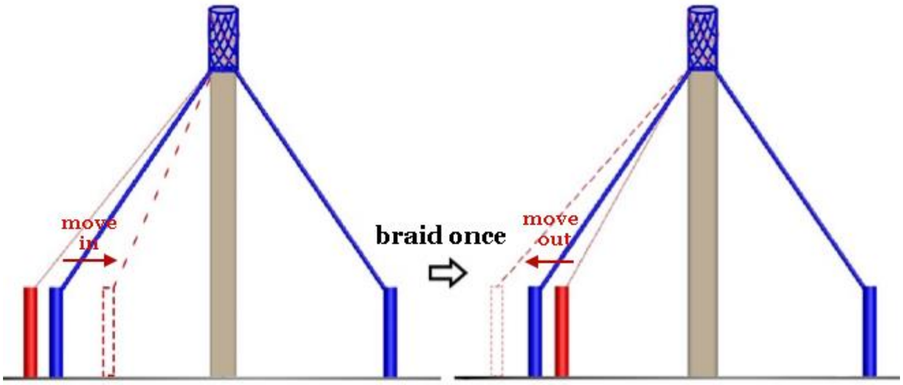


(c)

Figure 2. The manufacturing process developed: (a) set-up of the braiding system; (b) the moving paths of two groups of braiding yarns and wrap yarn; (c) fixation of the wrap yarn.

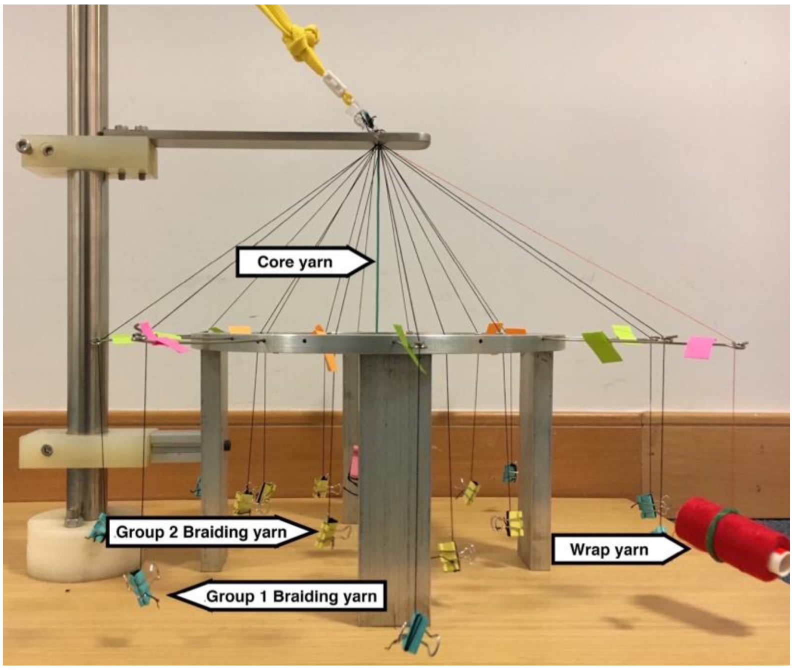
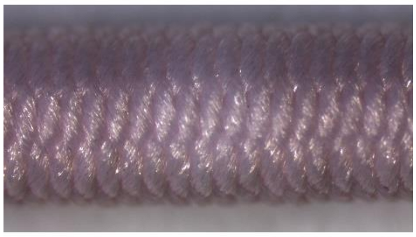
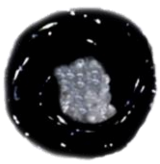
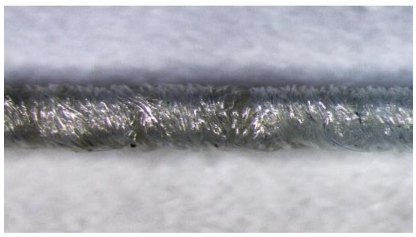
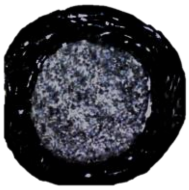
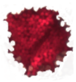


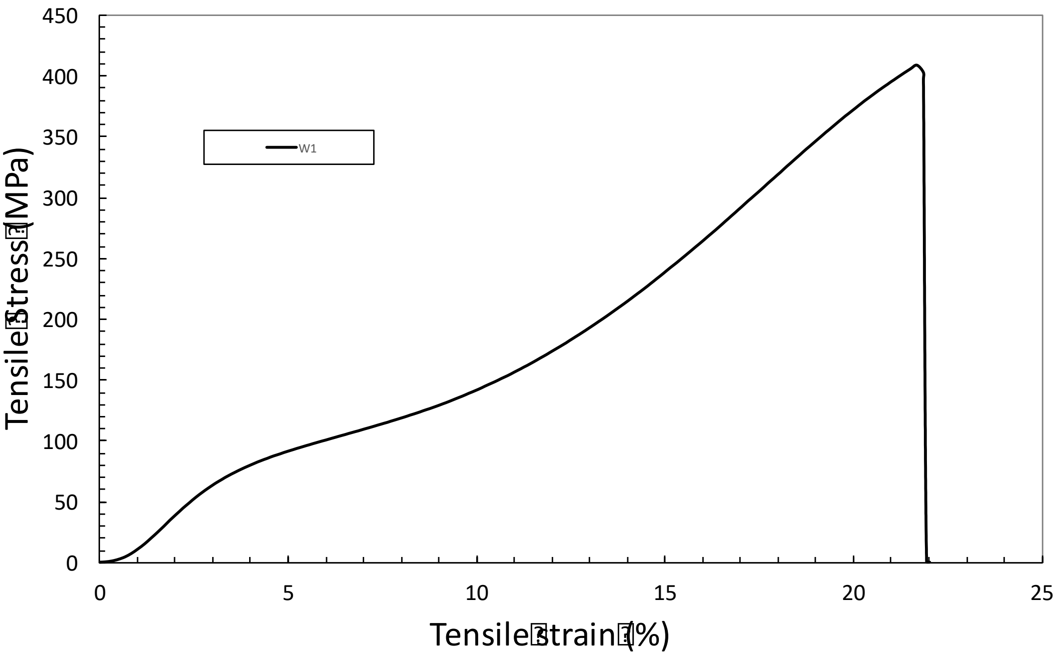
Figure 3. The prototype developed

Totally six yarns, including two different core yarns, three different braiding yarns and one wrap yarn were utilized to fabricate the auxetic braids in this study. The details of these yarns are listed in Table 1. The wrap yarn used was spun polyester thread, while the braiding yarns and core yarns were bi-component rubber elastic yarns formed with the cover of polyester multifilament and the core of polyurethane monofilament. The stress-strain curves of these six yarns then are shown in Figure 4. Since the initial modulus of the wrap yarn is significantly higher than other yarns, its stress-strain curve is plotted alone, as shown in Figure 4(a). The stress-strain curves for core yarns and braiding yarns are demonstrated in Figure 4(b), from which it can be seen that the tensile properties of core yarns and braiding yarns are quite similar.

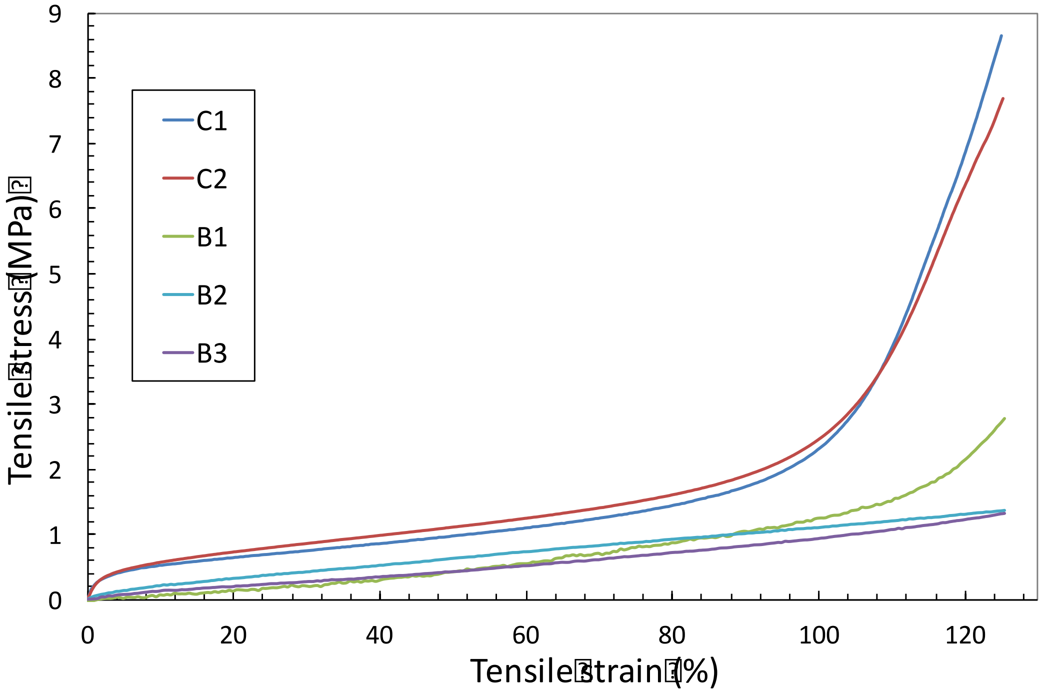
Table 1 Details of yarns.

Yarn type	Code	Diameter (mm)	Initial modulus (KPa)	Photograph	
				Cross-section	Side view
Core yarn	C1	1.45	12.06		
	C2	2.20	12.22		
Braiding yarn	B1	0.4	1.05		
	B2	0.7	1.39		

	B3	0.73	1.17		
Wrap yarn	W1	0.18	1588	 or 	 or 



(a)



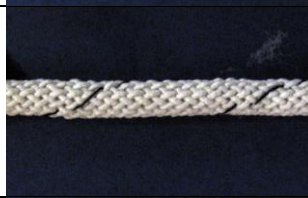
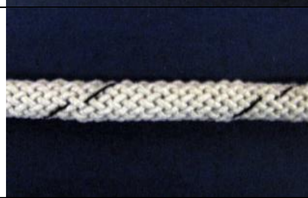
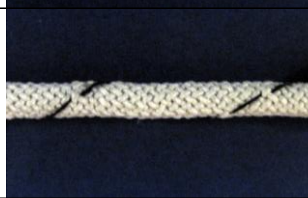
(b)

Figure 4. Stress-strain curves of the yarns used: (a) wrap yarn; (b) core yarns and braiding yarns.

By using yarns mentioned above, seven types of auxetic braids plus one normal braid were fabricated. Details of their yarn combination and structural parameters are presented in Table 2, in which both the initial braiding angle and the wrap angle are defined by the angle formed between the central axial line of the braid and braiding yarn or wrap yarn. The fabricated auxetic braids can be split into three groups. The first group includes samples 1-1, 1-2 and 1-3 which are produced with the same braiding yarn, the same core yarn, the same initial braiding angle and the same braid diameter, but with different initial wrap angles. The second group includes samples 1-1, 2-1 and 2-2, which are produced with the same braiding yarn, the same core yarn, the same initial wrap angle and the same braid diameter, but with different initial braiding angles. The third group includes 3-1 and 3-2, which are produced with the same initial braiding angle, the same initial wrap angle, the same core yarn, but with different diameters of braiding yarns. In this group, the change of the braiding yarn diameter also results in the change of auxetic braid diameter. For all the auxetic braids, the fine and stiff wrap yarn is kept unchanged.

Table 2. Details of auxetic braids.

Sample code	Yarn combination	Diameter (mm)	Initial braiding angle (degree)	Initial wrap angle (degree)	Photograph

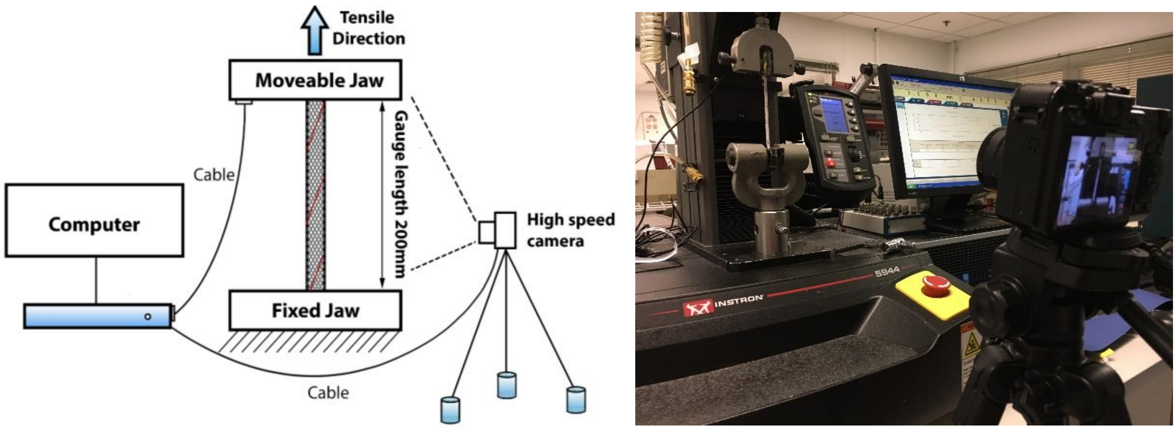
0-0	C2+B2	4.10	20.6	21.7	
1-1	C2+B2+W1	4.10	20.6	21.7	
1-2	C2+B2+W1	4.10	20.6	17.5	
1-3	C2+B2+W1	4.10	20.6	12.1	
2-1	C2+B2+W1	4.10	24.5	21.7	
2-2	C2+B2+W1	4.10	35.7	21.7	
3-1	C1+B3+W1	3.18	35.7	21.7	
3-2	C1+B1+W1	2.22	35.7	21.7	

2.3 Tensile test and calculation of Poisson's ratio

In order to assess the negative PR behavior of the auxetic braids produced, the tensile tests were conducted on an Instron 5944 tester (Instron Worldwide Headquarters, Norwood, Massachusetts, USA). The gauge distance and the test speed were set as 200 mm and 100 mm/min, respectively. The pair of jaws used was mechanical and the size of jaws faces was

2.5cm x 2.5cm. The whole tests were performed in an environment of 20 °C and 65% relative humidity and ended when the wrap yarn failed.

To measure the transversal deformations of the braids, an in-situ photograph system consisting of a high-resolution CMOS camera and a computer was used as shown in Figure 5. A photograph of the tested sample was taken at every 6/5 second during the stretching process, which was correspondent to the time of 1% elongation. After the tensile test, each photograph obtained was processed via a software called Photoshop with the noises removed and edges detected as shown in Figure 6. The threshold and color refill were then applied to the objectives so that the edges of the sample could be distinguished from the background. At the same time, the upper and lower boundary curves of the sample were smoothed by using the meaning filter in the Matlab. At last, the cross-sectional sizes of the samples in the initial state H_0 and in the stretching state H were measured by counting the pixels existing between left and right boundaries. Figure 6 illustrates the digital image processing and the measurement of the cross-sectional sizes of auxetic braid.



(a) (b)

Figure 5. The in-situ photograph system used for measuring the auxetic behavior of braids: (a) schematic of set up; (b) photograph of the system.

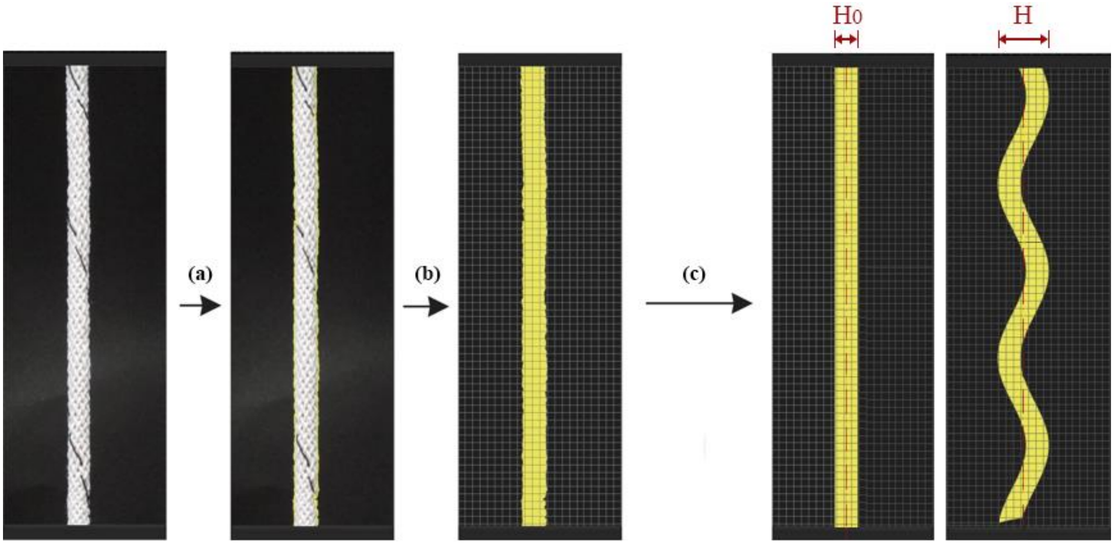


Figure 6. The digital image processing of sample photograph: (a) edge detection and emphasis; (b) threshold and color refill; (c) curve smoothing and pixel measurements.

When H_0 and H were obtained, the transversal strain ε_t could be calculated using Eq. 1.

$$\varepsilon_t = \frac{H-H_0}{H_0} \tag{1}$$

As the tensile strain ε_l is directly provided by the tensile tester, the PR was then calculated from Eq. 2.

$$\vartheta = -\frac{\varepsilon_t}{\varepsilon_l} \tag{2}$$

3. Results and discussion

3.1 Tensile behavior of a typical auxetic braided structure

As shown in Figure 7, Sample 1-1 was selected as an example to investigate the tensile behavior of a typical auxetic braided structure. While Figure 7(a) and 7(b) respectively show its cross-sectional contour size H and PR as a function of tensile strain, Figure 7(c) compares its stress-strain curve with that of the normal braid (Sample 0-0) made with the same structural parameters as Sample 1-1 but without the use of wrap yarn. Figure 7(d) demonstrates its shape changes at different critical strains. Referring to the curves displayed in Figure 7, we could divide the whole stretching process into three stages and discuss the typical tensile behavior of auxetic braided structure in each stage.

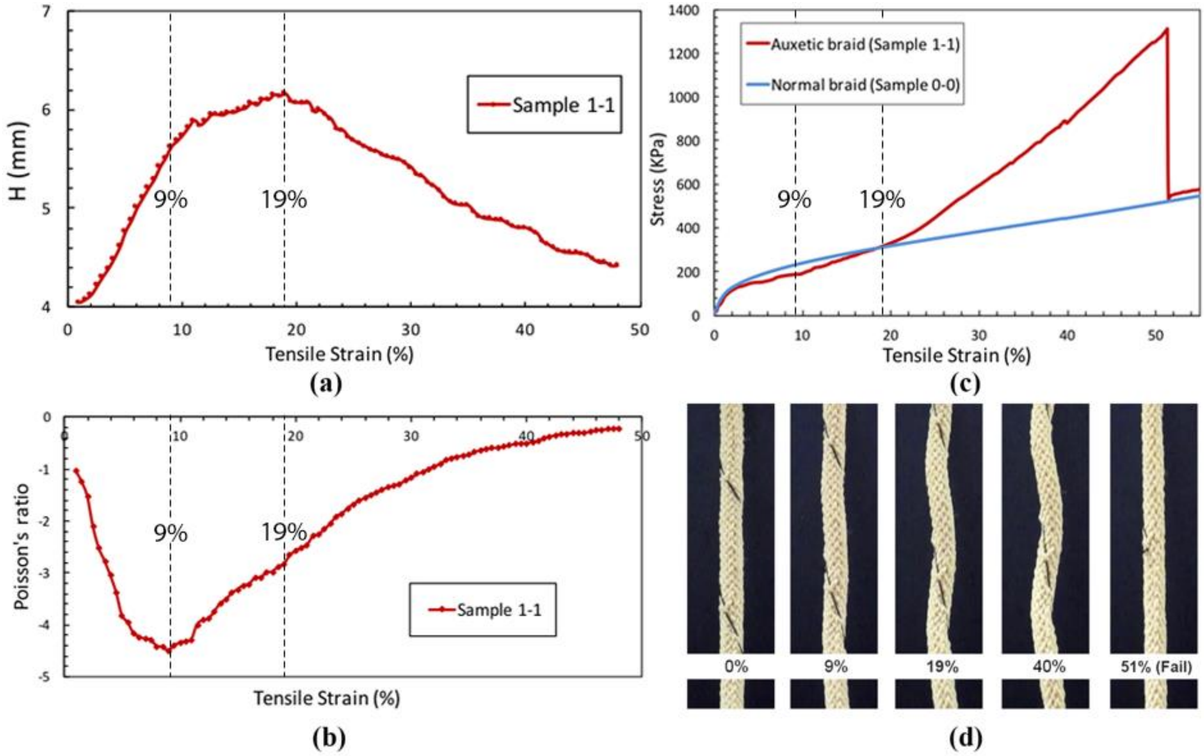


Figure 7. Tensile behavior of a typical auxetic structure: (a) H and (b) Poisson's ratio as a function of tensile strain; (c) stress-strain curves; (d) shape changes at different tensile critical strains.

The first stage starts from the initial state and ends when the auxetic braid reaches its highest negative PR effect, which corresponds to a tensile strain range from 0 to 9%. In this stage, upon application of stretching, H quickly increases with tensile strain due to rapid shape change from a straight form to a wave form (Figure 7(d)). Meanwhile, the PR quickly reaches its maximum negative value. However, compared with the normal braid, although the auxetic braid has an additional wrap yarn, its tensile stress is lower than that of the normal braid as the straightening of the wrap yarn converts the braided structure into a wave form, leading to a loss of stiffness of the auxetic structure along the axial direction.

The second stage starts from the maximum negative value of PR to the maximum H value (Figure 7(d)), which corresponds to a tensile strain range from 9% to 19%. In this stage, although H is still in growth, the increasing rate is slowing down. This may be attributed to the interaction forces between the wrap yarn and the base braided structure that hampered the rapid shape change of the auxetic structure in the transversal direction, and thus causing less increase of H. As the PR is a comparison of the changes in both the transversal and longitudinal directions, the decrease in increasing rate of H causes a reduction of negative PR effect of auxetic braided structure. Meanwhile, the tensile stress of the auxetic braid continued to increase and be able to reach the same level of that of the normal braid at the end of the second stage due to the straightening of the wrap yarn.

The last stage starts from the maximum value of H to the failure of the auxetic braid, which corresponds to a tensile strain range from 19% to about 52%. In this stage, H starts to decrease due to diameter decrease of both the core yarn and braiding yarns. Although the base braid gets more waved with the further increase of the tensile strain, the decreasing rate of the yarn diameter becomes much higher, leading to a decrease in H value. It should be pointed out that although H decreases, its value was still bigger than H_0. Therefore, the negative PR effect is still maintained, but is decreased with the increase of tensile strain. Regarding the tensile stress of auxetic braid, it increases with a much higher rate than that of the normal braid in this stage and maintains this trend until the fracture of the wrap yarn. As the only difference between the auxetic braid and normal braid is with or without wrap yarn, the tensile stress of the auxetic braid is almost the same as that of the normal braid after the failure of the wrap yarn, see Figure 7(c). The result indicates that the wrap yarn plays a more important role in the determination of tensile behavior of the auxetic braided structure.

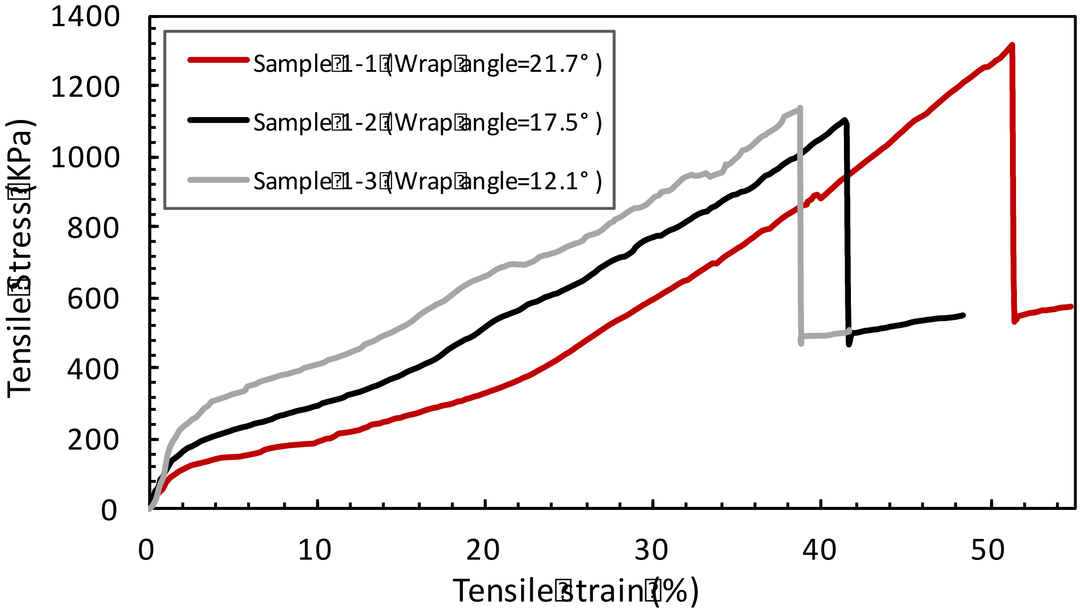
When it comes to the comparison between auxetic braid and helical auxetic yarns, it is interesting to note that with the braided structure, the positive PR value does not increase in the beginning of the traction as it is the case for helical auxetic yarn. There may be two reasons. The first one is that the fixation processes of sample ends between auxetic braids and helical auxetic yarns were different. In manufacturing the braided structure, knots were employed to secure the ends of samples before they were taken down from the machine. This fixation process not only avoided the possible slippage of the wrap yarn, but aslo caused it straightened. Though this straightening effect was small and could not be observed with eyes, it would lead to decrease of the PR of braids in the beginning of the traction. The second possible reason then is that the diameter ratio of the wrap yarn to the mandrel in the manufactured braids is low while their tensile modulus ratio is high. As indicated by previous studies [22, 24, 26], this yarn combination may lead to the early activation of the auxetic effect and increase the auxetic effect at the same rate of strain.

3.2 Effects of structural parameters

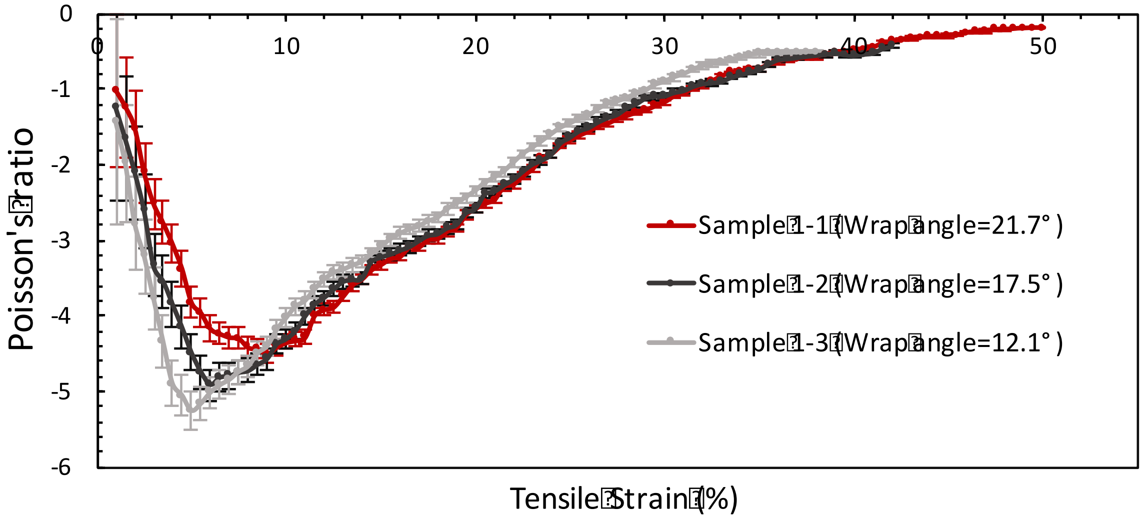
The tensile behavior of an auxetic braided structure, however, is greatly influenced by its parameter settings. Different parameter settings will lead to different tensile properties of the braid. Here, we evaluate the influences of three critical structural parameters, namely the initial wrap angle, the initial braiding angle and the braiding yarn diameter, and discuss the possible causes of their influences.

3.2.1 Effects of initial wrap angle

The initial wrap angle is the first structural parameter that can be employed to tailor the tensile behavior of auxetic braids. Both the stress-strain curves and PR-strain curves of three different types of auxetic braids made with the same braiding yarns, the same core yarn and the same initial braiding angle, but with different initial wrap angles are shown in Figure 8(a) and 8(b), respectively. It can be seen that the initial wrap angle has obvious effects on both the tensile behavior and negative PR effect.



(a)



(b)

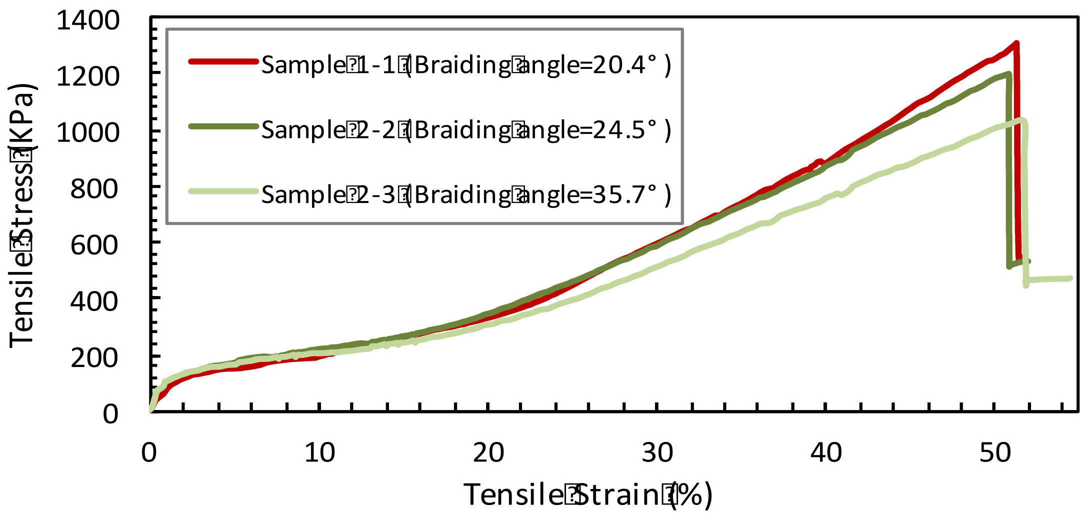
Figure 8. Effects of initial wrap angle: (a) stress-strain curves; (b) PR-strain curves.

As shown in Figure 8(a), the effects of the initial wrap angle on the tensile stress and the tensile strain at the break of the wrap yarn are opposite. While the tensile stress at the same value of tensile strain increases with the decrease of the initial wrap angle, the tensile strain at the break of the wrap yarn decreases with the decrease of initial wrap angle. With the reduction of the initial wrap angle, the wrap yarn gets more oriented to the tensile direction. Therefore, its capacity to withstand the tensile load increases. As a result, the stress of the braided structure increases for the same value of tensile strain. However, the reduction of the initial wrap angle makes the wrap yarn shorter in a helical turn, and thus leading to the earlier failure of the structure.

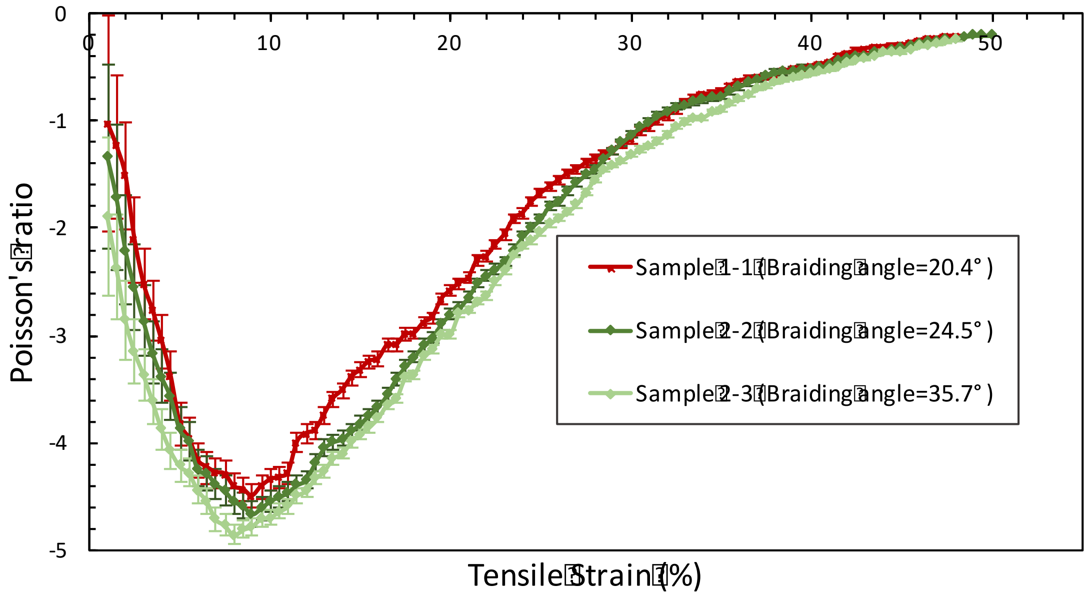
As shown in Figure 8(b), the effect of the initial wrap angle on negative PR behavior is clearly observed in the first stage of the stretching process. It can be seen that the maximum negative PR effect increases with the decrease of the initial wrap angle, but the tensile strain to reach the maximum negative PR effect decreases with the decrease of the initial wrap angle. As the shape change of the auxetic braided structure from a straight form to a wave form mainly comes from the straightening of the wrap yarn, it is normal that lower initial wrap angle can cause the early activation of shape change in structure and thereby resulting in a better negative PR effect. These results showed good agreement with previous findings on effects of wrap angle on HAY structures [22, 23, 25]. However, it is worth to note that these assumptions may become untrue under certain conditions as have been pointed out by Faisal et.al [26]. By employing the FEA method, they found a wrap angle of around 7° is an optimum choice for obtaining the maximum auxetic effect and the angle below it would not strengthen the auxetic performance of the structure. On the other hand, lower wrap angle makes the wrap yarn shorter, therefore making it easily straightened at a lower tensile strain. From Figure 8(b), it can be also seen that the effect of the initial wrap angle on negative PR becomes in-evident after the maximum negative PR point due to straightening of the wrap yarn.

3.2.2 Effects of initial braiding angle

Another important structural parameter in this unique auxetic braided structure is the initial braiding angle. Figure 9(a) and 9(b) illustrate the stress-strain curves and PR-strain curves of three different types of auxetic braids made with the same braiding yarns, the same core yarn and the same initial wrap angle, but with different initial braiding angles, respectively. It can be seen that the effects of the initial braiding angle are not so evident as those of the initial wrap angle.



(a)



(b)

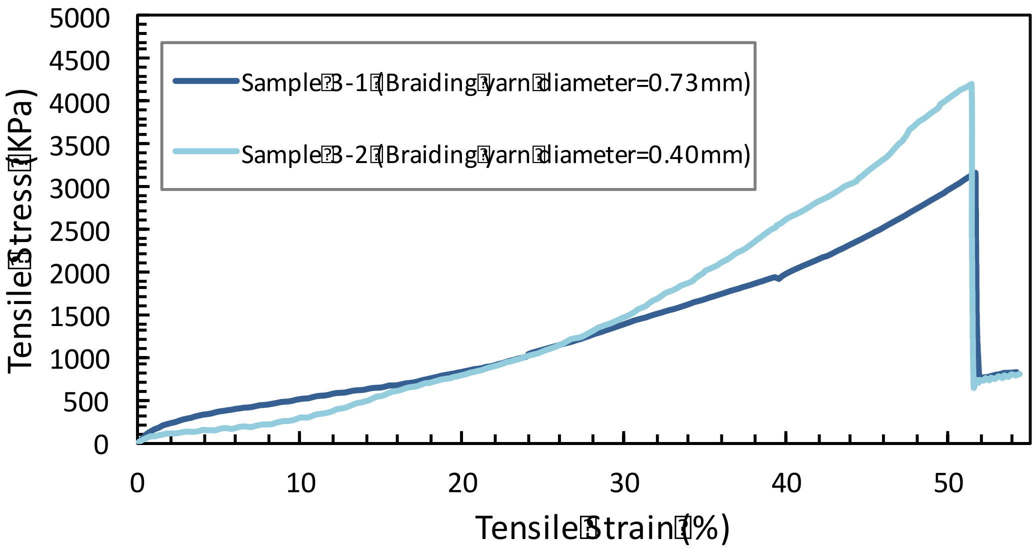
Figure 9. Effects of initial braiding angle: (a) stress-strain curves; (b) PR-strain curves.

As shown in Figure 9(a), the initial braiding angle almost has no effect on the stress from 0 to about 19% of the tensile strain. This range of the tensile strain just corresponds to the first and second stages of stretching process. As the main deformation of the auxetic braided structure in these stages is from a straight form to a wave form due to straightening of the wrap yarn, the tensile stress of the whole auxetic structure mainly depends on straightening of the wrap yarn. Therefore, the influence of the initial braiding angle is very low in the early stages of stretching process. However, with the increase of tensile strain, the base braid gets more oriented to the tensile direction and its role to withstand tensile load also increases. As a result, the effect of the base braided structure becomes evident. As the braided structure with higher initial braiding angle withstands lower tensile load, the increase of the initial braiding angle leads to decreasing of the stress of the auxetic braided structure when the stretching process enters the third stage. Since the auxetic braided structure fails when the wrap yarn breaks, the tensile strain at break mainly depends on the wrap yarn tensile property and wrap angle, not braiding angle. This can be confirmed by Figure 9(a) in which the tensile strains of three braids with different initial braiding angles are almost the same.

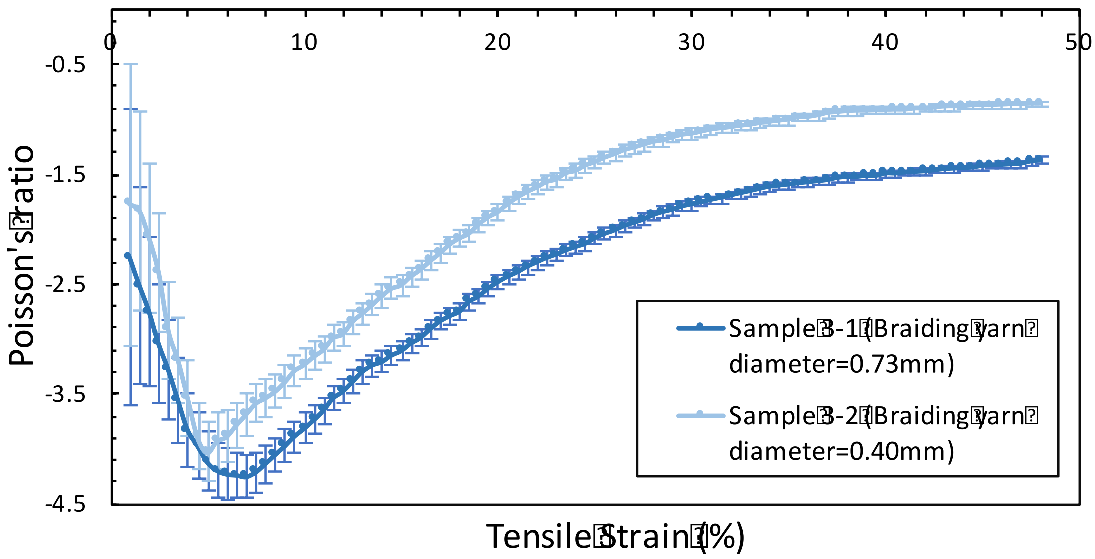
Regarding the effect of the initial braiding angle on negative PR behavior, it can be seen from Figure 9(b) that the negative PR effect of the auxetic braided structure is slightly increased with the increase of the initial braiding angle in the whole stretching process. This phenomenon can be explained by the fact that with the increase of the initial braiding angle, the base braid gets easier extended. This means its Young modulus gets decreased with the increase of the initial braiding angle. The lower modulus makes the base braid to be easier bent to form higher waves under the action of the wrap yarn, leading to higher negative PR effect.

3.2.3 Effects of braiding yarn diameter

The last structural parameter which can be used to tailor the tensile performance of the auxetic braided structure is the braiding yarn diameter. Figure 10(a) and 10(b) illustrates the stress-strain curves and PR-strain curves of the auxetic braids made with the same initial braiding angle, the same initial wrap angle and the same core yarn, but with different braiding yarn diameters, respectively. It can be seen that the braiding yarn diameter has obvious effects on both the tensile properties and negative PR behavior.



(a)



(b)

Figure 10. Effects of initial braiding yarn diameter: (a) stress-strain curves; (b) PR-strain curves.

From Figure 10(a), it can be seen that the stress-strain curve of the auxetic braid with larger braiding yarn diameter is higher than that of the auxetic braid with smaller braiding yarn diameter in the early stage of stretching process. As the auxetic braid with larger braiding yarn has larger braid diameter, it is more difficult to change its shape from the straight form to the wave form under action of the wrap yarn. As a result, its tensile stress gets higher than that of the auxetic braid with smaller braiding yarn diameter. However, after the tensile strain exceeds 24%, the situation gets inverse. In this case, the tensile stress of the auxetic braid with smaller braiding yarn diameter becomes higher than that of the auxetic braid with larger braiding yarn diameter. The likely reason is that the wrap yarn of the auxetic braid made with smaller diameter braiding yarn gets more oriented to the tensile strain as the braid diameter is smaller in that case, making it to withstand more tensile load and resulting in higher tensile stress. From Figure 10a, it can be also seen that the tensile strain at break is not affected by the braiding yarn diameter. As explained before, the tensile strain at break mainly depends on the wrap yarn tensile property and initial wrap angle. This result confirms again this phenomenon.

Regarding the effect of the braiding yarn diameter on negative PR behavior, it can be seen from Figure 10(b) that the effect is not very evident in the initial stage of the stretching process. This is because the auxetic braids have the similar shape change when the initial wrap angle is maintained the same. However, the maximum negative PR effect increases with the increase of the braiding yarn diameter. The possible reason is that larger braiding yarn diameter leads to a larger braid diameter so that the wrap yarn is longer in the structure and needs more stretching time to be straightened. The increased stretching time increases the tensile strain to reach the maximum negative PR, resulting in an increase of the maximum negative PR effect. The another reason is that the auxetic braid with larger braiding yarn diameter also has a larger braid diameter and thus the cross-sectional contour size increase in the structure is more significant. Because of these reasons, the negative PR effect of the auxetic braid with larger braiding yarn diameter is kept higher than that of the auxetic braid with smaller braiding yarn diameter from the maximum negative PR point to the fail of the structure.

4. Conclusion

A novel type of braided structure exhibiting negative PR behavior was proposed. Its geometry features and deformation mechanism were defined and described. A special manufacturing process based on tubular braiding technology was developed. The effects of three structural parameters, namely the initial wrap angle, the initial braiding angle and the braiding yarn diameter were systematically examined. It is hoped that this novel auxetic braided structure could satisfy the demands of applications requiring solid knots, such as medical sutures, shoelaces and secure threads.

Based on the results, the following conclusions can be reached:

1) The negative PR behavior can be achieved in a specially designed tubular braided structure with the use of a wrap yarn having higher modulus than that of the braiding yarns and core yarn.
2) The deformation process of an auxetic braided structure can be split into three stages and the maximum PR effect is reached at the end of the first stage.
3) All the structural parameters have influences on the tensile behaviors and the negative PR effect of the auxetic braided structure. Among three parameters discussed, the wrap angle has more evident influences than the initial braiding angle and the braiding yarn diameter.
4) Auxetic braided structure with a lower initial wrap angle, a higher initial braiding angle and a larger braiding yarn diameter has a better auxetic performance.

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