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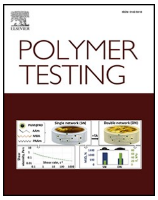

Exploring re-entrant auxetic silicone structures to design bra pads

Yin-ching Keung, Kit-lun Yick [*], Annie Yu, Joanne Yip

School of Fashion and Textiles, The Hong Kong Polytechnic University, Hong Kong, China

A R T I C L E I N F O

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A B S T R A C T

Auxetic materials, known for their negative Poisson's ratio and unique form-fitting deformation, are proposed in this study for designing bra pads to accommodate different bra cup sizes. The deformation elasticity behaviour of re-entrant auxetic structures with a bow-tie shape, made of silicone elastomer, is systematically analysed for size accommodation and shape conformity, and compared with traditional polyurethane foam and spacer fabric used in bra pads. The results indicate that the auxetic structures exhibit desirable mechanical properties, including superior elasticity and stable deformation under tensile loading. Additionally, these structures facilitate 3D shape conformity to breast shapes, thereby improving overall bra fit. Amongst the 4 different unit cell dimensions studied, the auxetic elastomer with a cell size of 9.14 mm is the most promising candidate, which has superior elasticity, linear expansion, and excellent shape conformity. This auxetic elastomer enables increases in area from an A to D cup thus offering the potential to realize a one-size-fits-more concept. The findings provide the grounds for future research endeavours that aim to develop support in different areas of bras and optimize the arrangement of unit cells to enhance the functional aspects of bras.

1. Introduction

As women today are increasingly prioritizing their self-image and seek products that enhance their body shape, lingerie such as bras have become a significant expenditure, which account for almost 20 % of spending on women's clothing in the US [1]. This market is further enhanced by lifestyle changes, as women are becoming more health-conscious and require a bra that provides a high degree of support yet allow physical freedom during fitness related activities. Breasts naturally lack anatomical support, so bras are designed to protect their structure and provide external support to hold them in place. The design and construction of bras are highly intricate and have unique fit requirements to enhance the shape of the body. Amongst these different components, bra pads play a crucial role by enhancing the shape of the breasts, lifting them, and overall better supporting them. Previous studies on bra design have highlighted the importance of the curvature and fit of bra pads to the 3D shape and geometry of the breasts for optimal fit and support [2].

Bra pads are traditionally fabricated by using elastomeric microcellular polyurethane (PU) foam and/or spacer fabric in a 3D knitted structure for increased breathability and wear comfort. A contour molding machine is utilized with a pair of aluminum male and female molds designed to match specific 3D breast shapes. Even though smooth and seamless molded bra pads provide a 3D fit and unlimited designs for different softness and thickness, the control of the molding process and quality of different types of foams and sizes of bra pads are largely based on time-consuming trial-and-error processes during the molding tests. Given the wide range of bra sizes and variations in breast contours, manufacturers face significant challenges in designing and producing well-fitting bra pads which require a number of engineering stages and specialized technologies [2]. Precise anthropometric measurements and the morphology of the breasts are critically challenging factors because breast tissues are pliable and readily deformable, and breasts have different 3D shapes and profiles [3]. Despite extensive research on bra fit-related issues, little progress has been made in resolving this problem. McGhee and Steele [4] found that over 85 % of the women in their study wear ill-fitting bras, which means that a poor fitting bra will continue to impact wear comfort, support, and overall well-being. Researchers have also made efforts to investigate the root causes of these long-standing bra fitting issues [5,6].

Auxetic structures are best known for their intriguing geometric and mechanical properties, primarily due to their negative Poisson's ratio (NPR). In 1991, the Greek word "auxetos" was introduced which conveys the concept of expansion, and the term "auxetic" was thus derived [7]. Two of the significant features of an NPR suggest that auxetic materials can be used to change the size of bra pads, including structure

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[*] Corresponding author.
E-mail address: tcyick@polyu.edu.hk (K.-l. Yick).

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expansion under applied force and out-of-plane bending when stretched. Unlike conventional materials that contract when stretched, auxetic materials expand in the cross-sectional area perpendicular to the applied force [8–11]. Bra pads constructed with an auxetic structure can stretch and accommodate larger breasts by increasing the coverage of the breasts in multiple directions, thus adapting to different breast shapes and volume. As for the bending properties, the out-of-plane bending of auxetic structures enables materials to fit a viscoelastic body by conforming to a synclastic curvature [7,12]. Therefore, auxetic bra pads can readily accommodate different breast shapes and their contours, and even improve the fit and retain the position of bra pads during dynamic movement. The distinctive properties of structures with auxetic behavior have been shown to provide superior comfort, support and fit because they adapt to different curvatures [13,14]. It is anticipated that the unique form-fitting deformation of auxetic structures allow flexible fit of curved target surfaces and body regions to meet different needs due to differences in breast morphology, age, and physiological conditions. Yet, there is a paucity of scientific knowledge on the structural configurations of auxetic materials in relation to the required mechanical properties and synclastic behavior to accommodate the complex shape of breasts.

In recent years, there have been advancements in the design of molded bra pads. Molded pads are popular due to their ability to provide a smooth shape and support, and offer different cup designs. However, the manufacturing process of molded bra pads is complex and time-consuming due to the large variety of cup sizes, styles, and material properties [15,16]. Besides, the 3D shape characteristics of breasts contribute to the complexity of developing parameters for molding pads. Scholars have shown by categorizing 3D scanned images of breasts that breasts are very diverse in shape and size [17–22]. In addition, even though the use of 3D scanning can provide more comprehensive anthropometric information of the breasts, consumers find it difficult to categorize their breasts accordingly. Since breasts vary so much from individual to individual, poor bra fit remains an ongoing issue despite continuous efforts and advancements in molded bra pads as the problem is closely related to the misalignment of the shape of the breasts and the molded pad [23]. The alignment between breast shape and molded pads is an important aspect that remains a gap in the current understanding and implementation of bra pad design. In light of these challenges, this study takes a different approach to address the alignment gap by proposing a novel solution—a bra pad that can fit multiple breast sizes and shapes, rather than relying on individuals to select the correct fit from existing bra products, this approach aims to provide a more flexible and adaptable solution that can accommodate a range of breast sizes and shapes. By utilizing auxetic structures in bra pad development, a better alignment can be achieved between the pad and the wearer's breasts, regardless of their individual shape and size. This alternative approach focuses on creating a versatile pad that can conform and adapt to different breast shapes, thereby improving the overall fit and comfort for a broader range of individuals.

Among the auxetic structures, the re-entrant structure is widely recognized as the most utilized structure due to their superior mechanical properties and their convenient fabrication compared to alternative forms of auxetic units [11,24,25]. It is characterized by multiple sides converging at a point or line, which form angles or curves that create a narrowing region within the cell structure. Re-entrant structures are notably flexible, have enhanced energy absorption, better conformity and enhanced mechanical properties such as tensile strength. These characteristics render them suitable to create different sizes of bra pads in bra pad design.

Despite that re-entrant auxetic structures have immense potential to improve garment fit, there are few studies in the literature that provide accurate guidelines for related applications. The focus of this paper is to explore the use of re-entrant auxetic structures in bra pad construction, primarily in 2 areas: (i) size accommodation and (ii) contour conformity. It is hypothesized that an auxetic elastomer, due to its NPR, has higher deformation elasticity compared to laminated PU foam and spacer fabric. Its performance in size accommodation and contour conformity is associated with the size of the unit cells in the auxetic structures. This study proposes a solution to the problem of poor bra fit by offering a "one-size-fits-more" concept in bra pad design. The findings contribute with valuable knowledge and insights into the application of auxetic structures in the engineering design of bra pads and size simplification in bra production.

2. Materials and methods

In this study, a series of re-entrant auxetic structures with a bow-tie shape are first designed and fabricated by using silicone elastomer. In consideration of the 3D bra pad design, the tensile elongation behavior, elastic deformation, and 3D shape conformability of the proposed auxetic structures were systematically evaluated. Their deformation and form-fitting performance were further compared with those of a traditional PU foam pad and spacer fabric material.

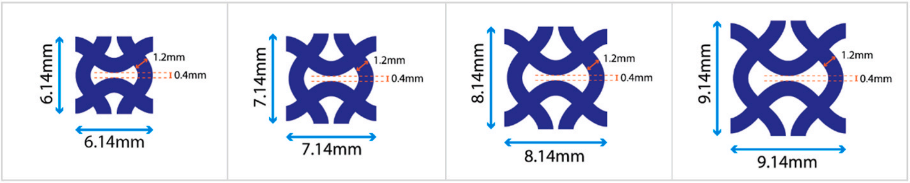
2.1. Re-entrant auxetic structures with a bow-tie shape

A re-entrant auxetic structure with a bow-tie shape, which is a typical auxetic structure, was generated to model the mechanical properties of a bra pad with an auxetic structure. Prior to constructing the sample, CAD models of the bow-tie honeycomb structure were established with 4 different unit cell dimensions. The line width and void height were kept constant at 1.2 mm and 0.4 mm respectively for all of the unit cells. The 4 unit cells which are 6.14 mm (Sample A), 7.14 mm (Sample B), 8.14 mm (Sample C) and 9.14 mm (Sample D) in size are shown in Fig. 1.

Silicon elastomer (KE-1300T), which cures with the addition of 10 % of the corresponding curing agent was used as the specimen material for its superior tensile strength, high tear strength and elongation characteristics. To create the specimen models, CAD models with dimensions of 160 mm in length, 100 mm in width, and 3 mm in thickness were established using Autodesk Fusion 360. These models were then converted into STL files, as depicted in Fig. 2(a). Subsequently, the geometric structures were 3D printed using a stereolithography (SLA) process, resulting in molds with embedded cavities. This allowed for the casting of the auxetic specimens during the curing process. The 3D-printed mold casts for the 4 auxetic specimens are illustrated in Fig. 2 (b). To achieve precise and accurate dimensions in the intricate patterns and details of the specimens, a vacuum casting technique was utilized. The process involved pouring silicon elastomer into the cavities of the cast molds and carefully removing any excess silicon from the surface. Subsequently, the silicon-filled molds were placed inside the vacuum chamber and subjected to a controlled vacuum environment. The vacuum chamber created a reduced pressure environment by removing air and other gases, thereby facilitating the elimination of trapped air bubbles and ensuring a more uniform distribution of the silicon elastomer within the molds. After the completion of the vacuum casting process, the specimens were carefully placed in a controlled environment at room temperature and left undisturbed for a minimum of 12 h. This duration was necessary to ensure the complete curing of the silicon elastomer, allowing it to attain its optimum mechanical properties and structural integrity. Once the silicon elastomer had fully cured, the specimens were carefully taken out of the molds and were ready for subsequent testing and evaluation.

2.2. Laminated polyurethane foam and spacer fabric

Conventional bra pad materials including laminated PU foam and a spacer fabric were sourced. The microscopic view of these two types of materials are presented in Figs. 3 and 4 respectively. Material specifications are listed in Table 1.



(a) (b) (c) (d)

Fig. 1. Size of unit cells of re-entrant auxetic structures with a bow-tie shape: (a) 6.14 mm, (b) 7.14 mm, (c) 8.14 mm, and (d) 9.14 mm.

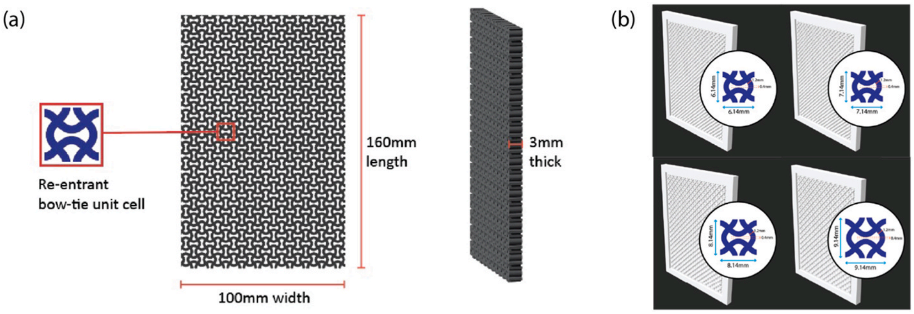
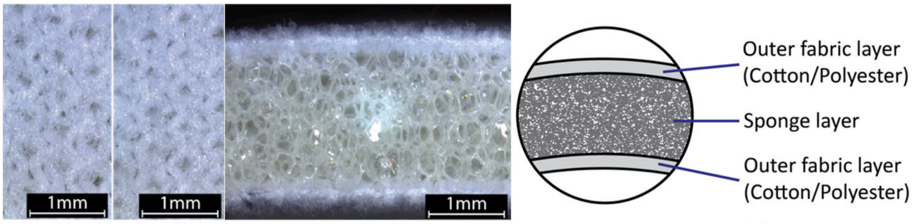
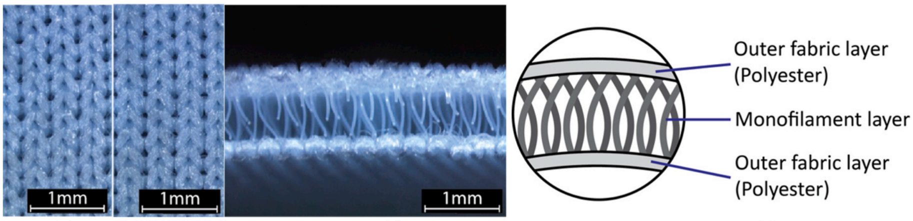


Fig. 2. (a) Illustration of CAD model dimensions for auxetic specimen with bow-tie shape and honeycomb structure; (b) Mold cast with cavity in auxetic pattern in dimension 6.14 mm, 7.14 mm, 8.14 mm and 9.14 mm.



(a) (b) (c) (d)

Fig. 3. Microscope views of (a) front, (b) back, and (c) cross section, and (d) schematic of laminated PU foam.



(a) (b) (c) (d)

Fig. 4. Microscope views of (a) front, (b) back, and (c) cross section, and (d) schematic of spacer fabric.

Table 1
Specifications of PU foam and spacer foam specimens.

	Density (g/cm^3)	Thickness (mm)	Hardness (°ShD)
Test method	Weight/Volume	ISO7231-1984	ASTM D 2240-05
PU foam	0.13	3.08	37.5
Spacer foam	0.16	2.04	29.5

2.3. Experimental design

In this study, the deformation elasticity and elongation behavior of the proposed silicone sheet that has a re-entrant auxetic structure with a bow-tie shape were systematically evaluated and were compared to traditional bra pad materials. Their performance in size accommodation and contour conformity was assessed across bra sizes that ranged from 75A to 75E (Fig. 5).

2.3.1. Tensile and deformation behavior

A total of 8 specimens including 4 auxetic silicone sheets, laminated PU foam and spacer fabric were subjected to tensile testing in both the wale and course directions to assess the load required for a specific amount of elongation. 3 samples were prepared for each specimen in the two directions to ensure repeatability and reliability of the experimental results. To evaluate the effect of the NPR, tensile testing was conducted by using an Instron 4411 tensile strength tester. Based on the experimental settings in Wang and Hu [26], specimens with dimensions of 150 mm × 100 mm were extended at a rate of 30 mm/min with an initial gauge length of 100 mm. The specimens were gradually elongated from

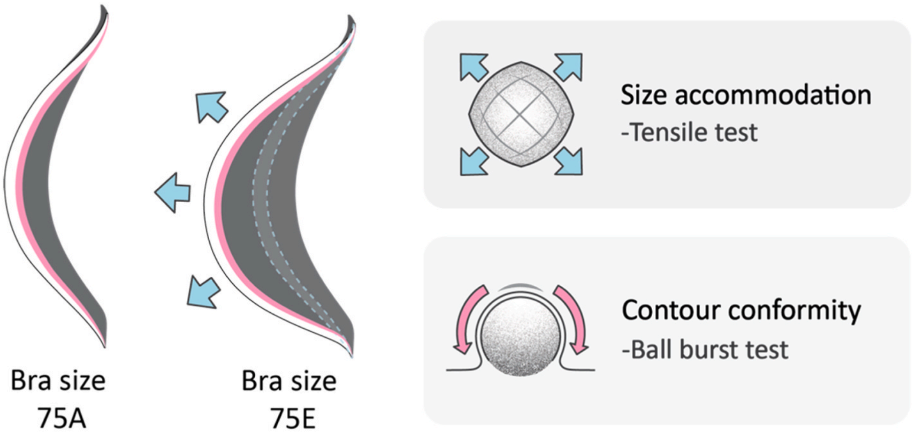


Fig. 5. Evaluation of bra fit performance across different bra sizes.

0 % to 15 %, 30 %, 70 % and 100 % respectively as shown in Fig. 6. Applied loads for different elongations were obtained. The specimens were then held at 100 % elongation for 5 min and returned to the initial gauge length for another 5 min to rest. The tensile elongation behaviour and Poisson's ratio (PR) of the samples were measured. To evaluate the increase in cup area across different bra sizes to accommodate fit, nine dots that form a square of 40 mm by 40 mm were first marked on the specimens to record the change in size of the material in both the tensile and transversal directions during testing. A camera was used to capture the deformation of the specimens during the testing. The change in size of the specimens and their PR (ν) under different applied loads were obtained and calculated by measuring the distances of the points on the captured photographs with a screen ruler.

2.3.2. *Increased cup area for size accommodation*

Bra pads vary in size and shape depending on the bra size. Yet, there is limited information available on the complex 3D shape of breasts and bra cups. In this study, bra sizes 75A, 75B, 75C, 75D and 75E of a typical full cup bra are commercially sourced. Their size increments in the cup pad area in comparison with the cup size of a 75A bra were measured and compared (Fig. 7). With reference to the change in percentage in cup pad area, the required deformation elasticity of the cup pad materials was determined to achieve optimal fit across different bra sizes. Compared to the cup pad for a 75A bra, the pattern area increases by 19.12 % for 75B, 35.18 % for 75C, 53.73 % for 75D and 99.83 % for 75E.

2.3.3. *Bursting behavior for contour conformity*

A ball burst test was conducted to evaluate the ability of the auxetic elastomer to conform to contours. The objective of this test is to observe and measure how well the specimen conforms to the contour of the underlying surface. During the test, the specimens were held in the ring clamp which has an inner diameter of 70 mm, see Fig. 8. The specimens were then subjected to an applied load with a spherical indenter that has a diameter of 50 mm at a moving speed of 100 mm/min, which simulates the external forces that the bra pad may withstand on the breast. The maximum vertical displacement of the indenter is 80 mm with reference to the depth of the breasts. The load required for the progressive extension to 80 mm was recorded at a constant interval of 10 mm. It was observed that as the dimensions of the auxetic cell increased, the load needed for extension decreased. The curves that show the load required for the extension were compared for each unit dimension of the auxetic structures.

3. Results and discussion

3.1. *Tensile deformation of auxetic structures*

In this study, the specimens were uniaxially deformed until 100 % extension. As shown in Fig. 9(a), the auxetic elastomer expands in the lateral direction during stretching, which demonstrates NPR behavior. The laminated PU foam and spacer fabric show lateral shrinkage when stretched, see Fig. 9(b), (c), 9(d) and 9(e).

During tensile testing, the load required for material extension in the tensile direction was recorded. Each of the 8 curve plots shown in Fig. 10 (a) is the average of the 3 samples tested, given variations of test results for each specimen are less than 5 %. It shows the large difference between the load needed for the laminated PU foam and the other materials. When the tensile strain is 100 %, the load required for the laminated PU foam in the wale and course directions reaches 904.4 N and 392.1 N, respectively, while a load of 79.6 N and 117.3 N is required

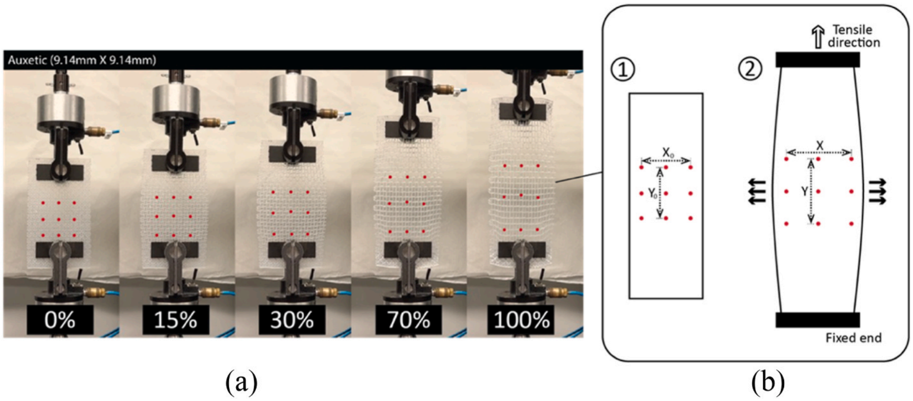


Fig. 6. (a) Specimens deform at 15 %, 30 %, 70 % and 100 % elongation under applied load; (b) Nine dots marked on specimen (1) before and (2) during stretching.

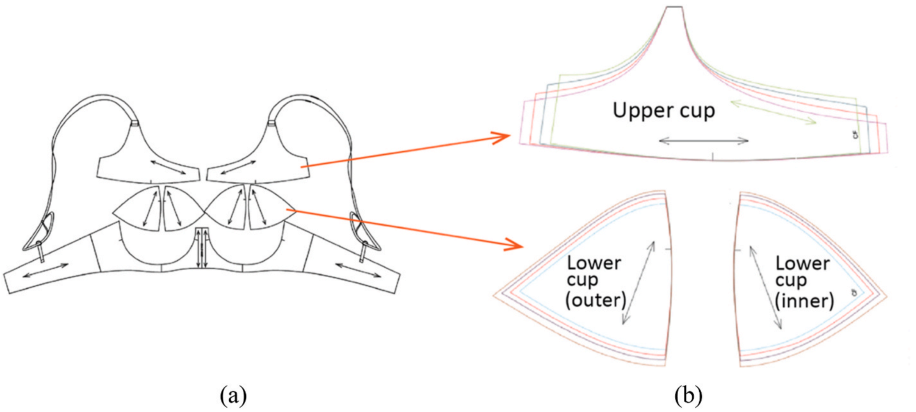


Fig. 7. Draft 2D pattern of full cup bra: (a) full set and (b) cup pieces.

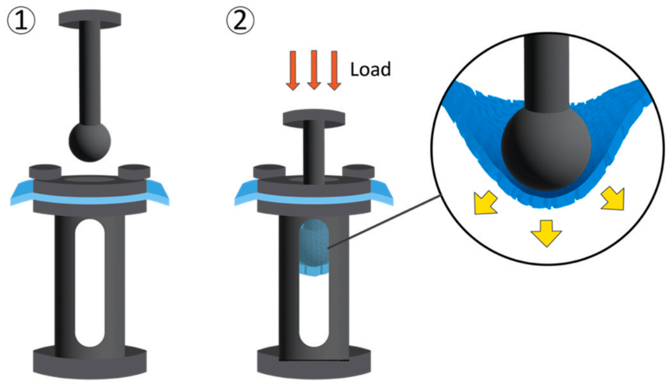


Fig. 8. Ball burst test.

for the spacer fabric in the wale and course directions, respectively. For the auxetic elastomer, the load required under 100 % tensile strain ranges from 53.4 N to 97.7 N. This shows that 9 to 16 times of load is applied on the laminated PU foam in the wale direction compared to the auxetic elastomer. This reveals the low elasticity of laminated PU foam compared with the spacer fabric and auxetic elastomer, as a larger load is required for the same amount of extension. Laminated PU foam is widely used to fabricate bra cups due to its softness and flexibility which are two good molding process parameters [27,28]. Despite its low tensile elasticity, PU foam can be easily shaped due to its molecular structure, which allows this material to be molded into specific 3D shapes for different breast sizes. Spacer fabric is similar to PU foam, and typically molded into the desired shape that accommodates the body contours. The tensile strain results reveal that the tested spacer fabric exhibits a relatively high level of elasticity. Higher elasticity is known to provide a better fit and more wear comfort when the garment is worn, thus making a more elastic material desirable for intimate apparel to achieve a closer fit with the body contours. However, note that achieving higher elasticity with the use of spacer fabric requires higher molding energy to maintain the desired shape [29]. This presents a contradiction between material elasticity and the molding parameters, which can impact both wear comfort and contour fitting.

The tensile strain results for the auxetic elastomer show the highest level of material elasticity. This reflects the advantage of higher elasticity in better accommodating the contours, and improved wear comfort specifically for bra pad applications. Fig. 10(b) shows the effect of the unit cell dimensions on the deformation elasticity of the auxetic elastomer. The 4 upward curves have a consistent pattern with a gradual increase in the applied load as the tensile strain increases.

Additionally, the opposite relationship between the unit cell size and load required for deformation suggests that the dimensions of a material impact its mechanical properties. The results revealed a negative linear relationship between the dimensions of the auxetic unit cell and the tensile strain of the material, with an R square of 0.9692. At 100 % tensile strain, the relationship can be mathematically described by using:

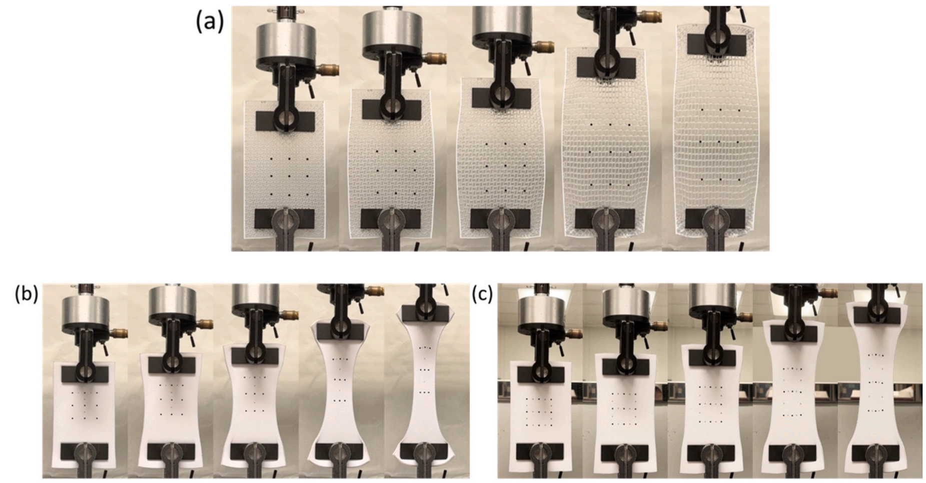


Fig. 9. Deformation under applied tensile load: (a) auxetic elastomer-9.14 mm; (b) laminated PU foam-wale direction; (c) laminated PU foam-course direction; (d) spacer fabric-wale direction; and (e) spacer fabric-course direction.

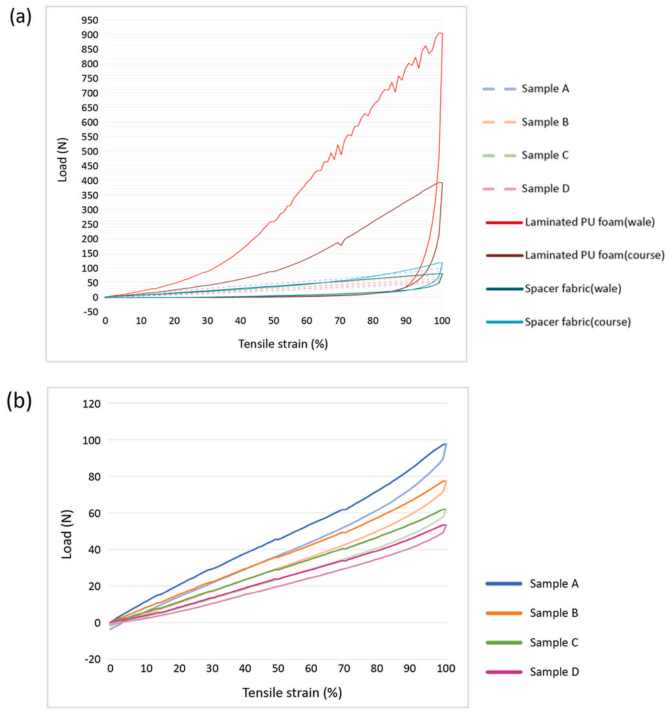


Fig. 10. Tensile strain curve: (a) all specimens and (b) only auxetic elastomer samples.

$$y = - 14.82x + 185.82$$

where x and y denote the unit cell dimensions and tensile strain, respectively.

In this case, smaller unit cell dimensions correspond to higher density. The results are in agreement with those in Kabir et al. [30] who found that auxetic specimens with a higher density, or smaller unit cell dimensions, require a larger load to achieve elongation compared to specimens with lower density.

These findings emphasize the significant impact of density and unit cell size on the mechanical behavior of auxetic materials. Specifically, a higher density is achieved through smaller unit cell dimensions, leading to an enhanced resistance against deformation and necessitates a larger load for elongation. When considering the use of such materials for bra pads, the load applied is derived from the volume of the breast and the force generated through breast motion. Higher breast volumes correlate with greater forces exerted, as larger masses generate increased loading. In the context of breast support or bra design, the size and weight of the breasts play a significant role in determining the level of support required to minimize discomfort and provide adequate support during physical activities. Therefore, the desirable amount of material tensile strength is further investigated.

3.2. *Poisson's ratio*

Fig. 11 presents the distribution of the average PR for each individual specimen across different elongation percentages (15 %, 30 %, 70 %, and 100 %). The PR typically ranges from −1 to 0.5 amongst textile structures [31]. The results depicted in Fig. 10 reveal a diverse range of PR values between the auxetic elastomer and conventional bra pad materials. The curves in Fig. 11 demonstrate the PR behavior of the auxetic elastomers across various dimensions during elongation. Amongst them, Sample D exhibits the lowest PR with elongation, followed by Samples C, B, and A. This indicates that as the unit cell dimension decreases, the PR increases. All four samples have upward curves as the percentage of elongation increases, thus suggesting that the effect of the PR is gradually reduced as the material reaches 100 % elongation.

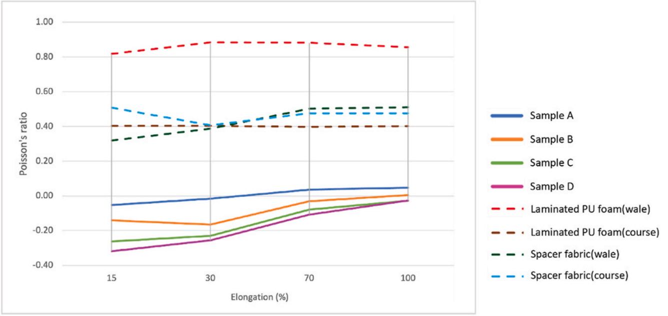


Fig. 11. PR of study specimens.

Table 2 lists the specific PR values for each sample for the four elongation percentages. Sample A retains an NPR up to 30 % elongation with a value of −0.02, while Sample B has an NPR up to 70 % elongation with a value of −0.03. Both Samples C and D maintain an NPR up to 100 % elongation with a value of −0.03. Among the four samples, the effect of NPR is more constant for Samples C and D. The findings provide valuable insights into the PR behavior of auxetic structures, which highlight the variations in the PR with elongation and stability of the effect of NPR as shown by Samples C and D.

3.3. *Increased cup pattern area*

The size of the 2D cup pattern pieces of a full cup bra was used as the benchmark. The increment rate of the auxetic elastomers of different unit cell dimensions was measured and compared against that of the cup area for various bra sizes. Fig. 12 shows the correlation between the increase in area of the different bra cups and the deformation of the auxetic elastomer under loading.

The deformation behavior of the elastomer samples exhibits a consistent pattern across the four elongation rates, thus indicating expansion due to the effect of the NPR. A comparison of the performance of the four unit cell dimensions showed that Samples C and D have a more linear expansion with elongation. At 15 % and 30 % elongation, the increase in area is greater than 19.12 % and 35.18 %, respectively, which is sufficient to accommodate the increase in area required for bra sizes 75B and 75C, respectively. At 70 % elongation, all four unit cell dimensions can cover the area required for a D bra cup, which is more than a 53.73 % increase in area. At 100 % elongation, only Sample D (9.14 mm) can expand enough to accommodate an E cup, or over 99.83 % of the required increase in area.

Samples A to C with unit cell dimensions that range from 6.14 mm to 8.14 mm can only accommodate up to a D cup, while Sample D with a unit cell dimension of 9.14 mm can easily expand and fully accommodate an E cup. Sample D can sufficiently expand to accommodate different cup sizes with optimal fit and coverage.

3.4. *Shape conformity*

In this study, only the auxetic elastomer samples were subjected to the ball burst test to assess their shape conformity capability, as

Table 2
PR of auxetic specimens at various percentages of elongation.

Specimen	Elongation			
	15 %	30 %	70 %	100 %
Sample A (Auxetic- 6.14 mm)	**−0.05**	**−0.02**	0.04	0.05
Sample B (Auxetic- 7.14 mm)	**−0.14**	**−0.17**	**−0.03**	0.00
Sample C (Auxetic- 8.14 mm)	**−0.26**	**−0.23**	**−0.08**	**−0.03**
Sample D (Auxetic- 9.14 mm)	**−0.32**	**−0.26**	**−0.11**	**−0.03**

Note: bolded text indicates negative PR value.

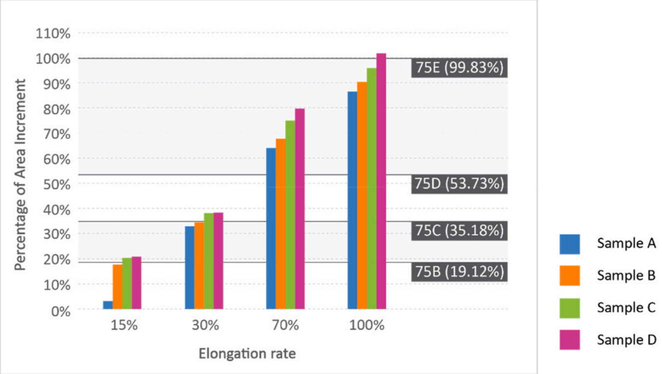


Fig. 12. Correlation of auxetic elastomer deformation and increase in bra cup area.

laminated PU foam and spacer fabric require heat-setting to achieve the required 3D cup shape for fitting purposes. Fig. 13 shows the average load measurements at various extensions for each of the four different unit cell dimensions as the variations of the test results within each specimen are less than 5 %. The 4 samples have a similar pattern in terms of the load required for extension, and show a gradual increase from 10 mm to 80 mm. The results are in agreement with those obtained from the tensile test; i.e., as the cell dimensions increase, the extension load decreases. The load required for achieving an 80 mm extension in Sample D was found to be 134.03 N. In contrast, Samples A, B and C can only be extended approximately 50 mm, 60 mm, and 70 mm, respectively. These findings indicate a clear correlation between the unit cell dimensions and the maximum achievable extension, thus highlighting the influence of the cell dimensions on the mechanical behavior and deformation capability of a material.

As the unit cell dimension increases, the length of each wall or rib of a unit cell increases, and the gap between the ribs also widens. This suggests that auxetic structures with larger unit dimensions can more easily deform to accommodate curved contours. When a downward load is applied from the spherical ball, it triggers the structural opening of the auxetic pattern due to the effect of the NPR. This expansion occurs in both directions, which allows the material to conform to the contours of the spherical ball. Notably, all the specimens successfully conform to the shape of the spherical ball during extension, thus indicating their capability for shape conformity. Amongst them, Sample D (9.14 mm) has the best performance in shape conformity. The sample requires the smallest load to fit the contours of the spherical ball.

Fig. 14 shows the appearance of Samples A and D, when they are affixed onto the molded bra cups for a bra size of (a) 75A and (b) 75D, which is used to visually assess their contour conforming performance. As shown in Fig. 14(a), both Samples A and D effectively conform to the curvature of the A cup, and shows a seamless fit without any noticeable gaps or wrinkles. However, Sample shows more openness as observed in Fig. 14(a)(ii). Conversely, when the samples are mounted onto the D cup in Fig. 14(b)–a substantial gap is found between Sample A and the bra cup. It is apparent that Sample A cannot conform to the curvature of a larger bra cup. In contrast, Sample D adheres to the contour of the bra cup, without any wrinkles or gaps. In comparison to Sample A, Sample D exhibits a higher degree of openness.

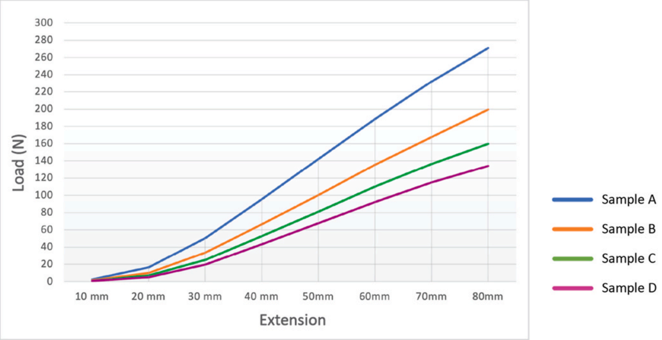


Fig. 13. Effect of unit cell dimensions on shape conformability of study samples.

The visual observations are in agreement with the analysis of the PR values. Sample A shows the effect of NPR, which enables the sample to expand and conform to the curvature of an A cup. However, as the elongation increases, the effect of the NPR diminishes. In contrast, Sample D consistently maintains an NPR value, which allows the sample to conform visually to the shape of both the A and D cups. This confirms the capability of Sample D to conform to shapes, thereby accommodating different sizes within a single bra pad.

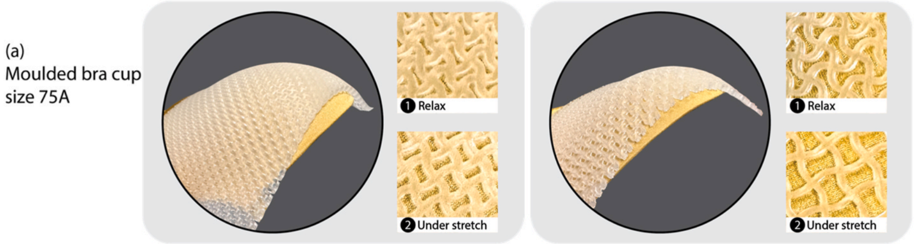
The issue of poor bra fit has persisted throughout the history of bra wear, despite advancements in bra cup manufacturing techniques and extensive evaluations of breast shapes and volumes. In this context, the use of auxetic materials which have unique properties presents an intriguing opportunity to address the problem of poor bra fit. As discussed above, auxetic elastomer with a unit cell size of 9.14 mm has superior elasticity, more linear expansion, and higher shape conformity. Based on the increase in area during structural deformation under applied tensile loads, the mechanical properties of Sample A facilitate covering an A to E bra cup. Additionally, the sample shows the ability to withstand a bursting depth of 80 mm without breakage, which points to its potential for use in a one-size-fits-more concept for bra pad applications. However, based on the results of the tensile test, stretching the specimen to a 100 % elongation is necessary to accommodate an E bra cup. At this percentage of elongation, the NPR decreases to −0.03, approaches 0 and shows a diminished effect. Therefore, expansion to 75E is not recommended. Taking into account the effect of the NPR, the auxetic elastomer can effectively expand to accommodate a 75A to 75D bra. It is noted that this study only investigates the mechanical properties of the materials. Incorporating auxetic structures into bra pads can present challenges, including complex manufacturing processes and the need to carefully choose appropriate materials. Ensuring the desired auxetic properties, as well as the necessary comfort and durability of the bra pads, becomes even more crucial in the context of long-term future production. Moreover, as wear comfort and support are crucial factors in bra design, further research is needed to investigate the pressure exerted on the breasts and the level of wear comfort when wearing an auxetic bra pad. A suitable unit size dimension becomes crucial in achieving the desired balance between accommodating multiple breast sizes and maintaining support and control.

4. Conclusion

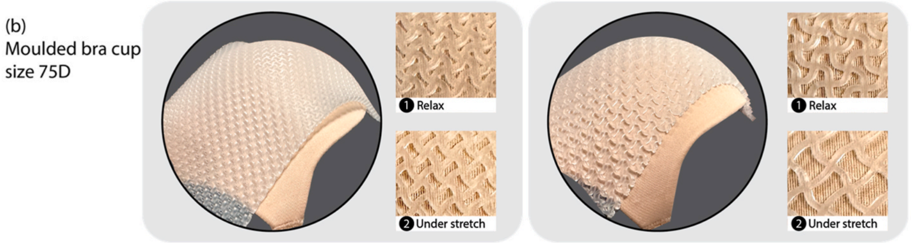
This study incorporates auxetic structures into bra pad design, leveraging the effect of Negative Poisson's Ratio (NPR) to address bra fit issues. A comprehensive evaluation of the mechanical performance of a re-entrant auxetic structure with a bow-tie shape has been illustrated, suggesting valuable insights unto the relationship between unit cell dimensions, mechanical properties, and the performance in terms of size accommodation and contour conformity.

The findings indicate that the unit cell dimension has a major influence on deformation elasticity and shape conformity capabilities of the bra pad. As compared to traditional laminated PU foam and spacer fabrics, the utilization of auxetic elastomer structures has shown

superior elasticity and fit performance across different bra cup sizes, enabling the realization of the one-size-fits-more concept in bra pad applications. It has been observed that the contour conformity of the auxetic elastomer is closely associated with the size of its individual cells. It can be found that when the unit dimension is too small, the structure fails to adequately conform to curved contours, resulting in decreased contour conformity compared to larger unit dimensions.



(i) Sample A (ii) Sample D



(i) Sample A (ii) Sample D

Fig. 14. Samples A and D on molded bra cup for (a) 75A and (b) 75D bra.

This study highlights the importance of exploring changes in unit cell dimensions and their arrangement as a future endeavour. By further investigating the relationship between configuration and mechanical properties, bra pad designs can be optimized to provide enhanced support in different areas of the bra. This research opens up new possibilities for developing innovative bra designs that offer improved comfort, fit, and support. In conclusion, our study contributes to the understanding of how the configuration of auxetic structures affects their mechanical properties and performance in bra pad applications. By leveraging this knowledge, future advancements in bra designs can be made to better meet the diverse needs and demands of individuals seeking comfortable and supportive undergarments.

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CRediT authorship contribution statement

Yin-ching Keung: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Kit-lun Yick:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Annie Yu:** Writing – review & editing, Supervision. **Joanne Yip:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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