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Design and Evaluation of Auxetic E-textile Stretch Sensors for Wearable Technology Applications

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Abstract

Electronic textiles (e-textiles) provide a great platform for creating stretch sensors in wearable applications as they are inherently flexible and stretchable allowing them to conform to the shape and movements of the human body. This study explores the integration of laser cut and 3D printed auxetic patterns into textile-based stretch sensors, investigating their design, fabrication, and sensing capabilities to develop a novel approach for creating flexible and highly sensitive e-textile stretch sensors for wearable applications. We employed two different biostable auxetic patterns to realize the stretch sensor structures and tested impedance change of the samples under repeated movements of stretching and relaxing. 3D printing of conductive filaments directly on fabric in an auxetic pattern resulted in reliable and repeatable stretch sensing capability. The study demonstrated that the stable and repeatable performance of e-textile stretch sensors depends on a combination of factors such as the fabrication method, conductive material, optimized auxetic geometry, base fabric recovery characteristics and the application of pre-stretching during fabrication.

Key words: E-textile, Stretch sensor, Auxetic, 3D printing, Laser cutting

I. Introduction

Electronic textiles (e-textiles) are fabrics embedded with electronic components such as sensors, actuators, and conductive materials, enabling them to sense and respond to environmental stimuli (Komolafe et al., 2021). E-textiles have garnered increasing attention in wearable technology due to their inherent flexibility and stretchability, which allow them to conform to the human body's shape and movements (Sazonov & Neuman, 2014; Stoppa & Chiolerio, 2014). A stretch sensor is a type of sensor that is designed to measure and quantify the amount of strain or deformation experienced by an object when subjected to mechanical stretching, straining or bending (Mattmann et al., 2008). E-textiles provide a great platform for creating stretch sensors in wearable applications as they are inherently flexible and stretchable allowing them to conform to the shape and movements of the human body. E-textile stretch sensors integrated into fabrics and garments, offer the ability to monito and measure human body movements, providing valuable data for applications ranging from healthcare to sports and rehabilitation (Lorussi et al., 2005).

In the field of health sciences, the measurement of human movement is commonly conducted using motion capture laboratory equipment. However, this approach is associated with certain limitations such as high costs, the need for specialized expertise, and the inability to capture movement in real-life environments (Pacelli et al., 2006). Traditional methods like optical motion capture systems, while accurate, are often cum-

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bersome, expensive, and limited to controlled environments (Qui et al., 2022). By contrast, textile-based stretch sensors embedded in wearable garments can provide an affordable and versatile alternative capable of operating in real-life settings (Shi et al., 2024).

To address these challenges, this study introduces an innovative stretch sensor embedded in textiles, offering the potential to accurately measure human movement within smart clothing applications. In this paper, we explore the integration of auxetic structures—materials with a negative Poisson's ratio which become wider when stretched and narrower when compressed—into e-textile stretch sensors using 3D printing and laser cutting technologies. Auxetic materials, which expand perpendicularly when stretched, offer unique increased stretchability. By incorporating auxetic patterns into textile-based stretch sensors through direct 3D printing of flexible filaments onto textiles and laser cutting, this research aims to develop e-textile stretch sensor suitable for wearable applications. We specifically investigate their design, fabrication, and sensing capabilities to develop a novel approach for creating flexible and highly sensitive e-textile stretch sensors.

II. Literature Review

1. Stretch Sensors

Stretch sensors work by detecting and measuring mechanical deformation such as stretch, strain, or bending. These sensors convert physical movement into an electrical signal, which is then analyzed to quantify the amount of strain or deformation. The functionality of stretch sensors is based on several key principles, depending on their design and material composition. The most common mechanisms include resistive, capacitive, and piezoresistive sensing. Resistive stretch sensors change their electrical resistance in response to mechanical stretching. As the sensor stretches, the conductive material elongates, increasing its resistance. The relationship between elongation and resistance allows the sensor to quantify the stretch (Amjadi et al., 2016). Capacitive sensors operate by measuring changes in capacitance when the sensor is deformed. Capacitance is the ability of a material to store an electric charge. As the sensor stretches, the distance between its conductive layers changes, altering its capacitance. The degree of the capacitive change correlates with the amount of mechanical strain. Capacitive stretch sensors are often made with flexible conductive layers separated by dielectric (non-conductive) materials like silicone or rubber (Lipomi et al., 2011). Piezoresistive stretch sensors rely on materials whose electrical resistance changes in response to mechanical pressure or strain. When a force is applied to the material, it deforms, causing a measurable change in electrical resistance. This method is commonly used in flexible sensors embedded into textiles (Teyeme et al., 2020).

One key aspect of e-textile stretch sensors is the choice of conductive materials which enable the sensors to maintain their functionality even when subjected to mechanical deformation. Common materials for resistive stretch sensors include conductive polymers, silver-coated fibers, or carbon-based materials such as graphene, carbon nanotubes (Amjadi et al., 2016). Teyeme at al. (2020) examined a stretchable conductive fabric sensor sourced commercially, with a specific focus on its potential applications in pressure and stretch sensing. Authors explored various sample lengths and evaluated their ability to measure strain as well as their electromechanical properties. Capacitive stretch sensors utilize flexible conductive layers separated by dielectric (non-conductive) materials like silicone or rubber. For example, the e-textile stretch sensor developed by Amjadi et al. (2016) utilized a sandwich structure with conductive fabrics and elastomers, exhibiting a high sensitivity to strain variations.

Researchers have explored different integration method of stretch sensors into textiles such as stitching, embroidering, knitting, weaving, or laminating conductive materials into fabrics. Several researchers explored overlock and cover stitch structures using conductive thread on fabric substrate to test a looped conductor approach where more loops come in contact with one another, causing the resistance to decrease (Gioberto & Dunne, 2012, 2013; Greenspan et al., 2018).

Yu et al. (2019) studied how the resonant frequency and sensitivity of embroidered meander line dipole (MLD) antennas vary with the elongation of antenna geometry and proposed the utilization of this property of embroidered antenna as a stretch sensor. Liang et al. (2019, 2021) explored knitted stretch sensors with varying conductive yarn, wale and course density that change their electrical resistance when under strain and evaluated the sensor placement locations on the body for monitoring movement during dance performance.

2. Rapid Prototyping of Stretch Sensors

In recent years, rapid prototyping technologies such as 3D printing and laser cutting have opened up new possibilities for the development of sensors with enhanced functionalities. Materials such as carbon nanotube-based filaments, graphene-infused filaments, and metallic filaments have been extensively investigated for their electrical conductivity and compatibility with 3D printing techniques (Choi et al., 2022; Wong et al., 2019). In addition, laser cutting offers another precise and customizable fabrication of method for e-textile stretch sensors. Laser cutting conductive fabric can be utilized to create intricate patterns that can flex and stretch. The design and geometry of e-textile stretch sensors play a crucial role in determining their sensing characteristics. The ability to customize the sensor geometry during the laser cutting and 3D printing processes allows for the optimization of sensor performance based on specific application requirements (Choi et al., 2022).

Structures with auxetic geometries, characterized by their unique mechanical behavior of expanding in multiple directions when stretched, demonstrate great potential for development of stretch sensors. When auxetic materials are deformed, they create changes in the structure that affect the conductive pathways, resulting in resistance or capacitance changes that reflect the amount of strain (Ren et al., 2018). Also, since auxetic materials exhibit a negative Poisson’s ratio under tension or compression, and such counter-intuitive behavior leads to enhanced mechanical properties such as shear resistance, impact resistance, and shape adaptability (Dong & Hu, 2023). As stated earlier, resistive sensors detect variations in stress or strain by measuring the changes in resistance exhibited by conductive materials. When an external force is applied to a conductor acting as the sensing element, its resistance undergoes modifications due to alterations in length, cross-sectional area, or interaction with other materials. These resistance changes effectively capture and reflect the corresponding physical variables being measured (Jiang et al., 2018). The utilization of 3D printing technology is frequently employed in the production of resistive auxetic sensors. A common approach involves applying coatings of conductive materials, such as graphene and carbon nanotubes (CNTs), onto the 3D-printed auxetic structures (Choi et al., 2022; Li et al., 2022; Wong et al., 2019).

Designing and fabricating auxetic structures for stretch sensing requires careful consideration of geometric patterns and assembly methods. 3D printing and laser cutting can create intricate and scalable auxetic structures. For example, laser cut auxetic conductive fabric stretch sensors can combine the unique mechanical properties of auxetic structures with the conductivity of fabric-based materials, enabling accurate and reliable detection of strain and deformation (Dong & Hu, 2023). Similarly, the direct 3D printing of conductive filaments in auxetic patterns on fabric to develop stretch sensors opens up new possibilities for wearable technology and smart textiles. The design parameters, such as cell size, shape, and orientation, directly impact the sensor's sensitivity and range. The choice of material influences the sensor's stretchability, linearity, and response time. The conductivity of laser cut and 3D printed auxetic e-textile stretch sensors relies on the presence of conductive pathways within the fabric structure. The deformation of the auxetic structure modulates the conductive pathways, leading to changes in electrical resistance or capacitance, enabling strain sensing capabilities. In this study we present development and testing of 3D printed and laser cut stretch sensor samples with different auxetic patterns.

III. Materials and Methods

1. Sensor Development

We developed 25mm × 50mm × 0.5mm sensor samples utilizing 3D printing and laser cutting technologies. We employed two different bistable auxetic patterns to realize the stretch sensor structure as shown in <Fig. 1>. Bistable auxetic patterns involve a specific arrangement of cells that allows the material to switch between two stable states with contrasting mechanical properties. The two particular auxetic patterns were selected after experimenting with numerous other patterns as shown in <Fig. 2> based on their suitability for both 3D printing and laser cutting manufacturing methods and ability to stretch in two directions. Auxetic patterns displayed in <Fig. 2> were 3D printed and laser cut in different repeat and cut thickness configurations, were then eliminated from further testing due to reasons such as elongating only in one direction when stretched (Fig. 2-a), not uniformly expanding when stretched and challenges in 3D printing (Fig. 2-b), structural deformation of narrow linked when stretched (Fig. 2-c, d), lack of meaningful sensing performance (Fig. 2-e).

For 3D printed sensor sample development, two polyester and spandex blend jersey knit fabrics (W and B) with different stretch and recovery characteristics were utilized as the base to print the auxetic structure on (Fig. 3). To get a practical estimate of the base fabric's stretch and recovery properties, two points are marked 10 cm apart on a fabric swatch, which is then stretched using a manual tensile tester with 10N load. The distance between the marks is measured in the stretched state, and the stretch percentage is calculated by subtracting the original length from the stretched length, dividing by the original length, and multiplying by 100. The process was repeated 3 times, after the base fabric is allowed to relax afterward to assess recovery. Based on the manual testing of stretch, Fabric W displayed 76% stretch while Fabric B stretched 28% under same amount of force. Fabric W recovered back to %18 increased length while Fabric B recovered to its initial length immediately after removing the force.

Fig. 3. Base fabric W (a) and Base fabric B (b).

NinjaTek Eel conductive filament was used to di-

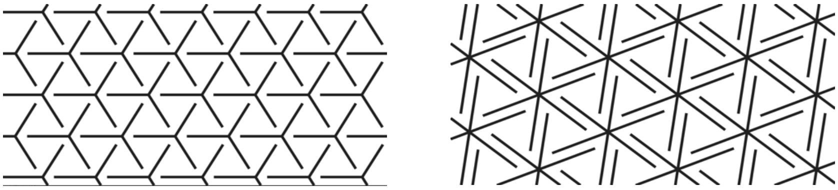

Fig. 1. Auxetic pattern 1 (P1) and auxetic pattern 2 (P2).

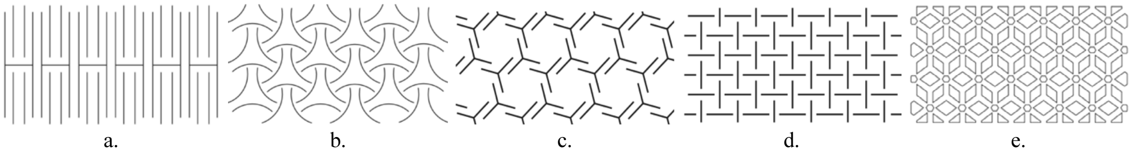

Fig. 2. Eliminated auxetic patterns due their low performance in sensing or unsuitability for 3D printing and laser cutting.

Table 1. Electrical resistance of NinjaTek Eel conductive filament

Sample (Length: 10mm)	Avg. Resistance (kΩ)
NinjaTek Eel filament	0.75
NinjaTek Eel filament 3D printed	12.80
NinjaTek Eel filament 3D printed on Fabric	18.17

rectly 3D print the auxetic structure on the base fabrics using Raise N1 dual extruder FDM printer. NinjaTek Eel conductive filament was chosen due its shore hardness value of 90A and therefore stretchability and conductivity (Table 1). The base fabric was 50% pre-stretched and stabilized on the printing bed for direct printing of the conductive filament.

For laser cut sensor sample development, the base fabric B that led to better results from 3D printed sample acquisition due to its compatibility with filament adhesion and good recovery characteristics, was used. Shieldex Bremen plain weave, silver conductive fabric was adhered on the full surface of the base fabric and then laser cut in the identical auxetic patterns as the 3D printed sensor samples. Laser cutting parameters were optimized so that only the conductive fabric layer was cut but not the base fabric (Fig. 4, 5).

2. Sensor Characterization

For characterization of the stretch sensor samples, we employed a bench LCR/ESR meter (BK Precision, Inc) and measured the impedance at 100kHz with the 1 peak-peak voltage. We found that when we measure the impedance value for each sensor under alternative current, it has higher sensitivity compared to measuring resistance under direct current. Since there are many equivalent capacitors existing in the gaps of auxetic patterns of the sensor samples, the higher the frequency, the higher sensitivity we could achieve in measuring impedance. Therefore, we measured impedance at 100 kHz which is the highest frequency we could integrate into a wearable technology application.

To evaluate the performance of the stretch sensor samples, we employed repeated movements of stretching and relaxing using a manual tensile tester. The sensor samples were gradually stretched while clamped to the tensile tester up to 5 mm elongation (Fig. 6). The bench LCR/ESR meter probes were also clamped to the samples and impedance data was recorded every 0.5mm elongation. For each sample the testing procedure was repeated two times after 3 minutes of waiting time.

In order to determine the sensitivity of the sensor

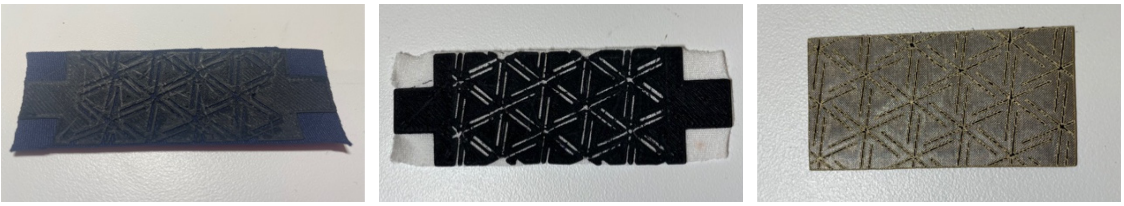

Fig. 4. 3D Printed and laser cut sensor samples (P1B 3D Print, P1W 3D Print, P1B Laser cut).

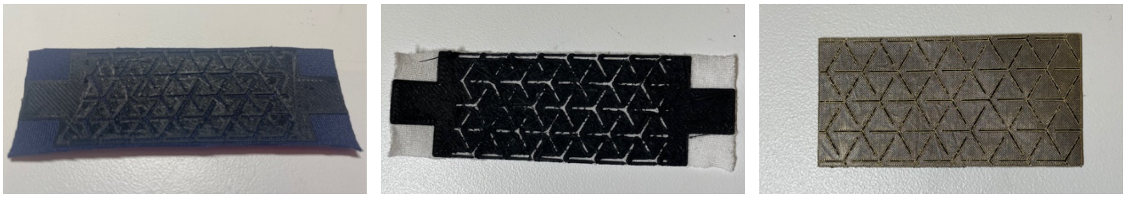

Fig. 5. 3D Printed and laser cut sensor samples (P2B 3D Print, P2W 3D Print, P2B Laser cut).

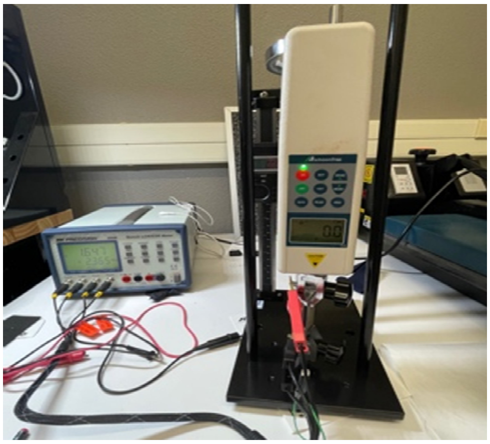

Fig. 6. Sensor sample testing set-up.

samples we calculated how much the resistance changed per elongation distance during the extension using the below formula where RN = the resistance at N mm elongation; R0 = resistance at 0 mm elongation; LN = length at elongation N mm; L0 = length at 0 mm elongation (Eq. 1).

$$\frac{\frac{RN-RO}{RO}}{\frac{LN-LO}{LO}} \qquad \text{...... Eq. 1}$$

IV. Results

In this study, we developed 3D printed and laser-cut e-textile stretch sensor samples and tested them under gradual elongation to evaluate their stretch-sensing performance. <Fig. 7> presents the impedance changes for laser-cut samples with two different auxetic patterns, Pattern 1 and Pattern 2. At an initial stretch of 0.5 mm elongation, the impedance change observed in both laser-cut samples was minimal, and beyond this point, no significant change in impedance was detected, indicating nonfunctional sensor behavior. This outcome suggests that neither auxetic pattern type provided effective sensing capabilities in the laser-cut samples.

In <Fig. 8>, the impedance change results for 3D printed samples using Pattern 1 on two different base fabrics (W and B) are shown side by side. The Pattern 1 sample on base fabric W exhibited minimal impedance change—less than 0.5 kΩ—and inconsistent behavior during the second elongation cycle. In contrast, the Pattern 1 sample printed on base fabric B demonstrated a stable and repeatable impedance response during both the first and second elongations. This difference highlights the influence of base fabric characteristics on sensing behavior.

To further assess the performance, <Fig. 9> illustrates the sensitivity of Pattern 1 sensor samples on both base fabrics W and B. Sensitivity is expressed as the change in impedance (kΩ) per millimeter of elongation. For the Pattern 1W sample, sensitivity values lower than 0 indicate abnormal readings, underscoring its nonfunctional status. In contrast, the Pattern 1B sample exhibited consistent sensitivity values, confirming the sensor’s functionality. While minor fluctuations were observed, these results are considered promising, given that textile-based sensors inherently exhibit

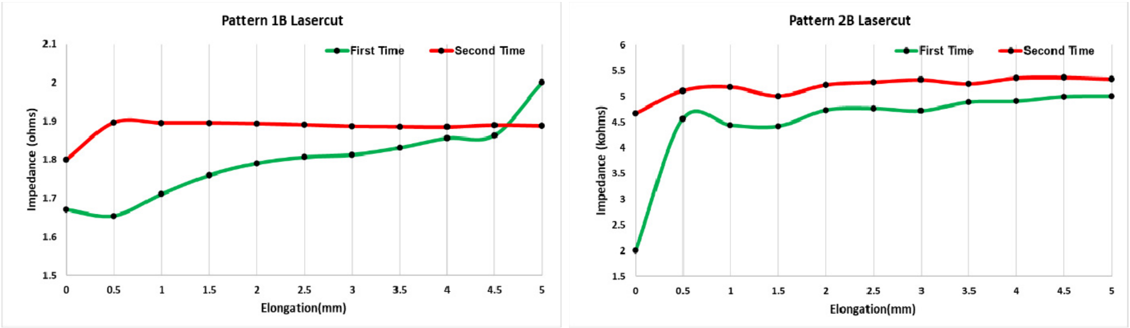

Fig. 7. Impedance change of laser cut sensor sample with Pattern 1 and Pattern 2 configurations.

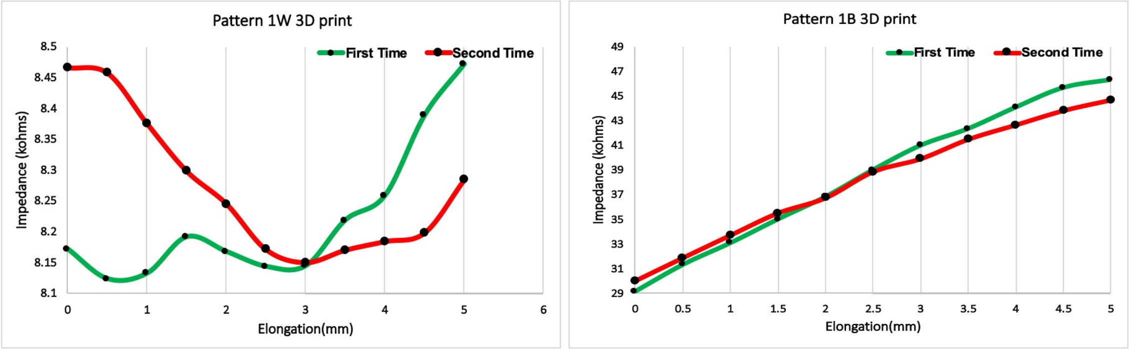

Fig. 8. Impedance change of 3D printed sensor sample with Pattern 1 on base fabric W and B.

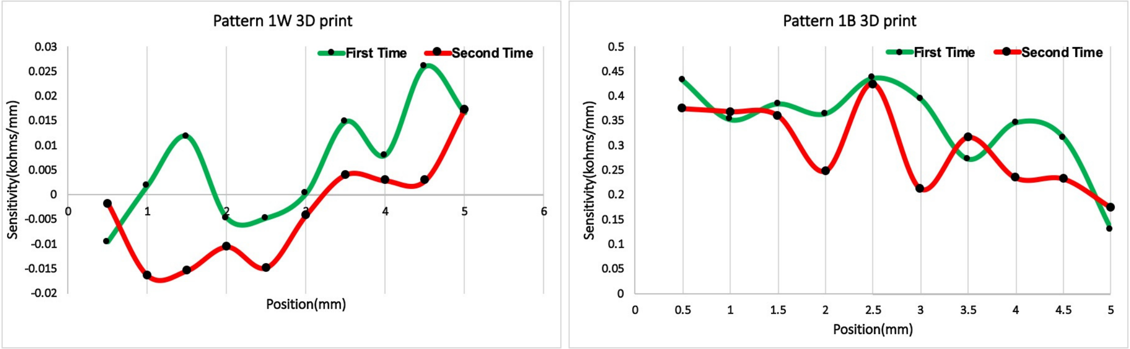

Fig. 9. Sensitivity of 3D printed sensor sample with Pattern 1 on base fabric W and B.

non-linear responses due to the complex interplay of mechanical and structural characteristics in both the fabric and the auxetic pattern unlike a semiconductor force sensor.

The 3D printed Pattern 2 samples showed similar performance trends to the Pattern 1 samples in terms of impedance change per elongation and sensitivity, as displayed in <Fig. 10, 11>. These results underscore the importance of the base fabric's recovery characteristics on the sensing capability of e-textile-based sensors. A comparative analysis of auxetic patterns reveals additional insights: Pattern 2 exhibits a steady impedance change and sensitivity up to 2 mm elongation, followed by a plateau, while Pattern 1 maintains a steady impedance change across all levels of elongation. This pattern-dependent behavior suggests that the geometric structure of the auxetic pattern significantly influences sensor performance.

V. Discussion

By comparing two fabrication methods of laser cutting and 3D printing of auxetic patterns, we can see that 3D printing holds a potential for creating reliable stretch sensors while laser cutting fails to deliver functionality based on the impedance measurements. This lack of functionality may be attributed to several factors. Firstly, the mechanical properties of the conductive fabric in laser cut samples itself might not support functional sensing under the conditions applied here. Furthermore, the laser-cutting process introduces localized heat and thermal stress at the contact points of the auxetic cells, potentially damaging or altering the conductive properties of the fabric. These changes at the microscopic level could disrupt conductive pathways within the material, compromising its functionality as a stretch sensor. Additionally, unlike the 3D

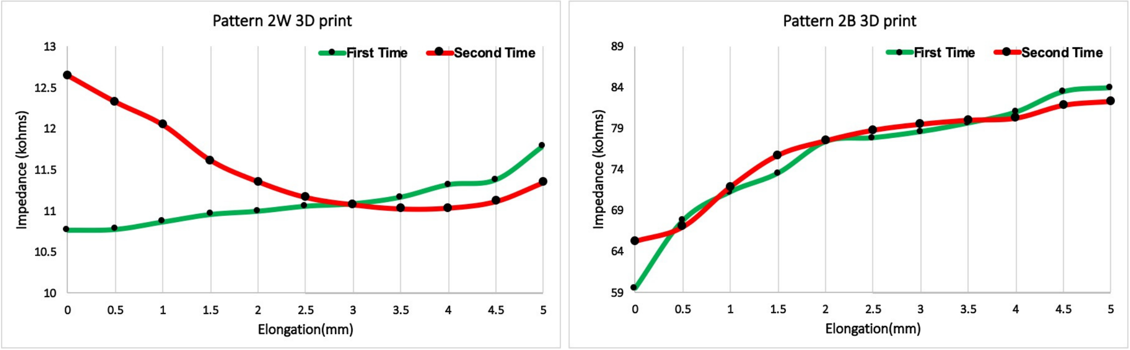

Fig. 10. Impedance change of 3D printed sensor sample with Pattern 2 on base fabric W and B.

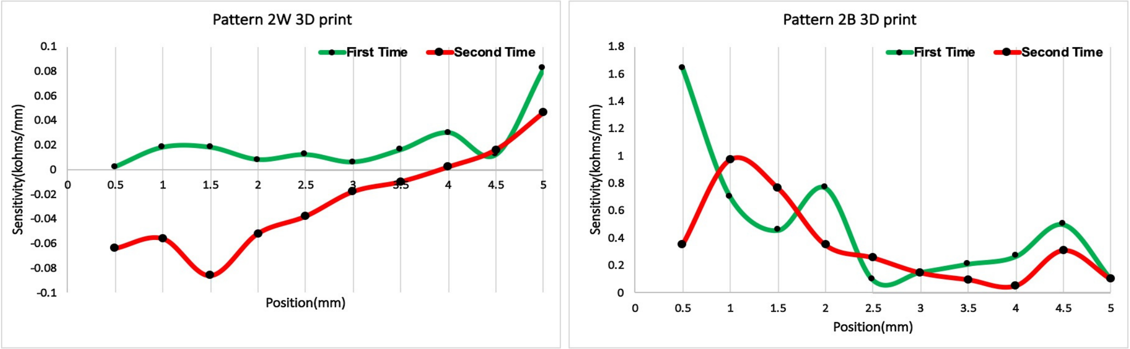

Fig. 11. Sensitivity of 3D printed sensor sample with Pattern 2 on base fabric W and B.

printed samples, no pre-stretch was applied to the base fabric of the laser cut samples before adhering the conductive fabric layer, which may have contributed to the absence of measurable sensing behavior. Thus, pre-stretching the fabric could improve the alignment and contact of conductive points, enhancing performance.

By comparing two distinct auxetic patterns (Pattern 1 and Pattern 2) in both 3D printed and laser-cut samples, we can see that auxetic geometry cell size on conductive contact points impact sensor functionality. Pattern 1, with its smaller, densely packed cells, creates more frequent contact points throughout the auxetic structure. This results in a higher number of conductive pathways that can respond to stretching and recovery cycles. These additional contact points enable continuous conductive connectivity, as the small cells within the pattern maintain contact across a broader range of elongation levels.

When we compare only 3D printed samples, Pattern 1, with its smaller geometric cells and greater repetition, has more contact points, which enables continuous conductive connectivity under elongation. Pattern 2, on the other hand, features larger cells with fewer repetitions and consequently fewer contact points, which results in decreased conductivity beyond a certain level of stretch. This observation suggests that larger, less frequently repeating auxetic cells limit the range and consistency of impedance change, potentially rendering Pattern 2 less effective for applications requiring sustained sensitivity under higher elongations. The higher repetition frequency in Pattern 1 facilitates a more reliable and consistent impedance response. With more units of the pattern repeating across the sensor surface, the stretch-induced changes are more evenly distributed, reducing localized stress on individual cells. This uniform distribution of stress results in a more stable and repeatable sensing performance across multiple cycles of elongation and recovery. The greater repetition also minimizes the potential for gaps or disconnections in conductive pathways, which can occur if the pattern stretches unevenly. Pattern 2 has a lower repetition frequency due to its larger cell size, leading to more pronounced fluctuations in impedance change at higher elongations. This variability in response can be attributed to the reduced redundancy in conductive pathways, where fewer cells are present to distribute the stress of elongation. When the larger cells lose contact, the impedance change becomes less predictable, compromising the sensor's reliability over extended use.

Additionally, Pattern 1 exhibited a steady and consistent impedance change across all levels of stretch, making it suitable for applications where a continuous and predictable sensing response is required. Pattern 2, in contrast, consists of larger cells with fewer repetitions within the same surface area. The larger cell size means fewer contact points overall, reducing the conductive interactions as the material stretches. This structure caused the sensor to show an initial change in impedance at lower elongation levels (up to approximately 2 mm) but then plateaued, as the fewer contact points limited further conductive interaction. This plateau effect indicates that Pattern 2 is less sensitive to changes in stretch beyond a certain threshold, making it less ideal for applications requiring a broader sensing range.

When we compare Pattern 1 3D printed on two different two different base fabrics (fabric W and B) we can observe disparity in impedance response of the samples. This result indicates that the recovery characteristics of the base fabrics which were pre stretched before 3D printing is a critical parameter. Base fabric B, with its superior recovery, showed stable impedance and sensitivity readings, whereas base fabric W's poor recovery led to inconsistent results. Base fabric W, which displayed poor recovery, likely caused inconsistent contact between the auxetic pattern's conductive points as the fabric returned to its original shape. This variability affects the stretch-sensing mechanism, which relies on consistent resistance changes as a result of conductive material reorientation under stretch. When the fabric fails to recover effectively, the alignment and connectivity of conductive elements become erratic.

Conversely, base fabric B, with its superior recovery properties, maintained steady and reproducible impedance changes at all elongation intervals, indicating more reliable contact between conductive points. Conductive auxetic patterns that stretch and recover in sync with an elastic base fabric exhibit enhanced sensing capabilities. The 3D printed sensors, especially with Pattern 1 on a high-recovery fabric, demonstrated that synchronized elasticity between the auxetic structure and the base fabric leads to reliable impedance changes under elongation. This alignment allows for consistent shifts in conductive contact points, making the auxetic pattern more functional as a strain sensor. This result shows the good recovery characteristics of the base fabric leads to successful stretch sensing properties and underscore the need for base fabrics that can retain their structure and elasticity over repeated cycles to ensure sensor accuracy.

In addition, pre-stretching the base fabric before 3D printing conductive patterns onto it proved essential for developing a functional stretch sensor. This process helps establish a baseline alignment of conductive points, improving connectivity and response accuracy as the fabric stretches. Without pre-stretching, as observed in the laser-cut samples, the sensors exhibited minimal or no functional response, indicating that pre-stretching aids in maintaining stable conductive pathways under stress.

To summarize, auxetic pattern geometry plays in the performance of e-textile stretch sensors. The findings reveal that variations in auxetic pattern shapes, specifically in terms of cell size and frequency of repetition, significantly affect the sensor's impedance response and sensitivity under elongation. Second, the stretch and recovery characteristics of the base fabric directly influence the sensor's sensitivity and functionality. A fabric with good recovery allows the auxetic pattern's conductive contact points to consistently reconnect after each stretch, which is essential for reliable, repeatable sensor performance.

VI. Conclusion

This study focused on the development of 3D printed and laser cut e-textile stretch sensors with stretchable conductive auxetic patterns. We examined the impact of stretchability of the auxetic patterns applied on a base fabric on the conductivity/resistivity. The study demonstrated that the stable and repeatable performance of e-textile stretch sensors depends on a combination of factors such as the fabrication method, conductive material, optimized auxetic geometry, base fabric recovery characteristics and the application of pre-stretching during fabrication. Together, these design factors provide a foundation for creating advanced e-textile sensors with reliable and adaptive stretch-sensing capabilities.

This research provides foundational insights for developing e-textile sensors with customized auxetic geometries to meet diverse stretch-sensing performance tailored to specific applications. Auxetic geometry with smaller, closely spaced cells 3D printed on a pre-stretched base fabric with high recovery characteristics is ideal. Auxetic geometry with smaller, closely spaced cells is particularly advantageous for applications that require a high level of sensitivity and repeatability, as the frequent contact points offer a more refined control over the conductive pathways' engagement. Conversely, patterns with larger cells and fewer repetitions could be optimized for low-stretch applications or scenarios where a single, initial response is sufficient.

By focusing on optimizing auxetic geometries and considering the interactions between pattern shape, size, and base fabric properties, future research can unlock more sophisticated and adaptable e-textile sensors for wearable technology, health monitoring, and beyond. Future sensor designs could explore hybrid geometries that combine the benefits of both small and large cells, potentially creating a gradient of cell sizes within a single auxetic structure. Such designs could tailor impedance response across different elongation ranges, providing a more adaptive sensor for complex, multi-stage stretch requirements. Future research could further explore and refine these parameters, along with hybrid sensing mechanisms, to broaden the functionality of e-textile sensors in various real-world applications, especially for wearable technology and health monitoring.

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1. Acknowledgement

Not applicable.

2. Ethics and consent

Not applicable.

3. Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

4. Conflicting interests

Not applicable.

5. Funding

Not applicable.

6. Authors' contributions

RZ conducted experiments and the data analysis, AR developed and fabricated samples, GGB developed the research idea/hypotheses, designed experiments, developed and wrote the manuscript and supervised experiments and sample development.

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