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Development of an Auxetic-Based Elbow Wrap with the Aid of Resin 3D Printing

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Abstract:

In this work, an elastic elbow wrap is developed to press a cotton ball against the skin after a blood draw during an annual medical checkup, helping to stop bleeding. The wrap is made entirely from elastic material and incorporates an auxetic structure with hollow, re-entrant patterns that produce a negative Poisson's ratio. Consequently, when stretched, the wrap becomes wider rather than thinner, which helps prevent buckling and maintains a smooth surface. Combined with its elasticity, this design ensures the cotton ball remains in firm contact with the skin. In this work, the internal geometry of the auxetic structure is first designed based on geometric constraints. To link the two ends of the wrap around an elbow, a self-locking mechanism is then developed that relies on both friction and the material's elasticity. Finally, the prototype is fabricated using resin 3D printing. Testing results demonstrate that the wrap effectively resolves the issues of loose contact and over-tightening, which are frequently observed when conventional bandages or adhesive tapes are employed to secure a cotton ball following venipuncture.

1. INTRODUCTION

In clinical practice, blood is typically drawn from a vein in the elbow region [1]. After the blood draw, a medical cotton ball is placed over the puncture site, and either a bandage or tape is used to apply pressure and stop the bleeding. When a bandage is used, it can effectively press the cotton ball against the skin while the arm is fully extended (Figure **1a**). However, when the elbow is flexed (angle < 180°), the bandage is pressed between the upper arm and forearm. Due to its small bending stiffness, it may buckle [2,3], lifting the cotton ball and reducing contact between the cotton ball and the skin (Figure **1b**).

If a tape is used instead (Figure **2a**), the cotton ball generally maintains contact with the skin even during arm movement. However, pressing tape directly against the skin may leave a noticeable crease after removal (Figure **2b**). The crease appears paler than the surrounding skin, suggesting that the blood in the skin's capillaries may have been displaced by the tape. It was reported in [4] that the pressure required to stop blood flow in the human skin's capillary beds is approximately 4.3 kPa (≈ 32 mmHg). Therefore, the medical tape might have exerted a pressure higher than 4.3 kPa on the skin. For comfortable long-term wear, the applied pressure should be kept below 2.7 kPa (≈ 20 mmHg) [5]. In addition, instead of using a bandage or tape, pressure may be applied with the fingers, which is inconvenient and impractical, particularly when the other hand is occupied.

To address the issues of losing contact with the skin and applying excessive pressure, we propose a specialized elbow wrap that maintains consistent pressure on the cotton ball regardless of arm position, while ensuring gentle contact with the skin with the applied pressure less than 2.7 kPa. Although commercial elbow wraps, such as the elbow neoprene wrap [6], are available, they are primarily designed to protect injured elbows by limiting joint motion and absorbing external impacts. Such products are unnecessarily bulky and costly for the simple task of securing a cotton ball after a blood draw.

Auxetic materials are a unique class of materials that exhibit a negative Poisson's ratio. They expand laterally when stretched and contract when compressed, contrary to most conventional materials [7]. This unusual behavior arises from their internal structure, often engineered with re-entrant or chiral geometries, which enables enhanced mechanical

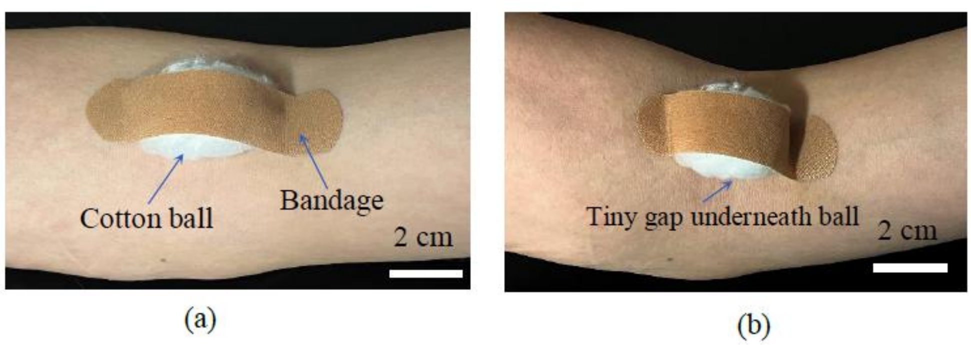


Figure 1: Demonstration of bandage application. (**a**) Cotton ball pressed against the elbow; (**b**) loss of contact with the blood-draw site during elbow flexion.

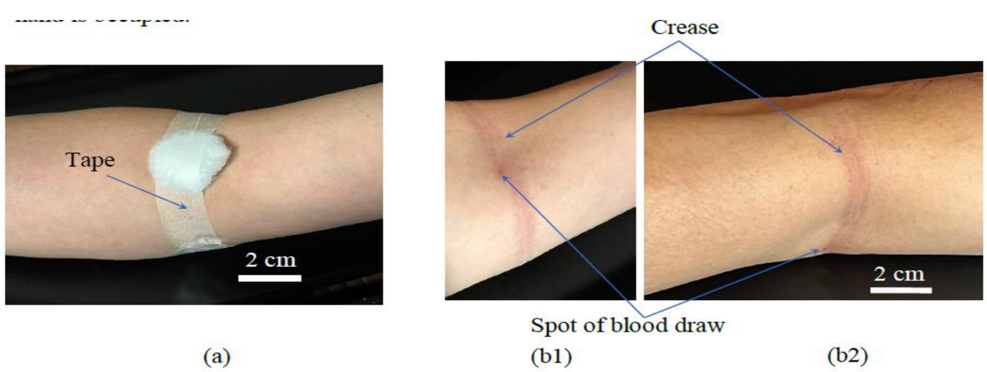


Figure 2: (**a**) Demonstration of using a tape to press a cotton ball against the elbow. Its consequence after a real blood draw for medical checkup: (**b1**)-(**b2**) perspective views of a crease around an elbow after the elbow is taped for around 1 hour.

properties such as improved energy absorption, indentation resistance, and fracture toughness [8,9]. In the case of a re-entrant structure, when stretched, the inclined bars rotate outwards. As a result, as illustrated in Figure **3**, the lateral distance between two neighboring bars increases, leading to an overall increase in the width of the structure. For comparison, their lateral distances before and after stretching are labeled "*a*" and "*b*," respectively, in Figure **3**.

Auxetic materials have found innovative applications in various fields due to their distinctive mechanical properties. In protective gear, their ability to expand laterally under tension enhances energy absorption and impact resistance, making helmets, body armor, and padding more effective at dissipating forces and reducing injury risk [8,10]. In biomedical devices, auxetic materials improve conformability and comfort in implants and prosthetics, while their enhanced fracture toughness contributes to durability in load-bearing applications such as stents and orthopedic supports [11,12]. For flexible electronics, the high stretchability and resistance to indentation of auxetic materials enable flexible and wearable electronic components that can withstand bending and twisting without damage, supporting advances in soft robotics, sensors, and foldable displays [9,13]. In this work, an auxetic structure is applied in a different way. It is employed to ensure that the wrap remains taut in both directions, preventing buckling and maintaining full surface contact with the cotton ball. In addition, stretching a film with a positive Poisson's ratio generates wrinkles within the film, causing it to contact the skin only at the wrinkle peaks. Consequently, the effective contact area between the film and the skin is reduced, resulting in higher localized pressure. Using an auxetic structure at the location of direct skin contact avoids this problem. For these reasons, as to be detailed in Section 2.1, auxetic structures are incorporated into both the presser and the belt of our proposed wrap.

Auxetic structures come in various geometric designs that enable their characteristic negative Poisson's ratio behavior. Common auxetic configurations include re-entrant honeycombs, where inwardly angled cell walls unfold under tension to expand laterally [3] (Figure **3**); rotating units, such as rotating squares or triangles, which pivot around their connections causing the material to widen when stretched [9]; and chiral structures, composed of nodes connected by ligaments arranged in a spiral or helical pattern that allows expansion in multiple directions [8]. Each structure's unique mechanism influences properties like stiffness, stretchability, and energy absorption, allowing designers to tailor auxetic materials for specific applications [12]. Due to the simplicity of re-entrant honeycombs (Figure **3**), such structures are adopted here for the proposed wrap.

The prototype of an elbow wrap will be formed entirely from F39 white flexible resin [14]. It will be manufactured via resin 3D printing [15-17]. Resin 3D printing, also known as stereolithography or masked stereolithography, is an additive manufacturing process that builds objects layer by layer by curing liquid photopolymer resin with ultraviolet (UV) light. Unlike the commonly used fused-filament 3D printing [18], which is suitable only for fabricating rigid polymer structures, resin 3D printing enables the fabrication of flexible structures. In resin 3D printing, a light source, such as a laser, digital light processing projector, or a liquid crystal display (LCD) masked UV array, selectively hardens the resin according to each cross-sectional slice of the 3D model. The build platform moves incrementally, allowing successive layers to cure on top of each other with high precision, often achieving layer heights as fine as 20μm. This method produces parts with smooth surfaces, intricate details, and sharp edges, making it ideal for fabricating prototypes.

A strap will be used to connect the two ends of the wrap, allowing it to encircle the elbow. However,

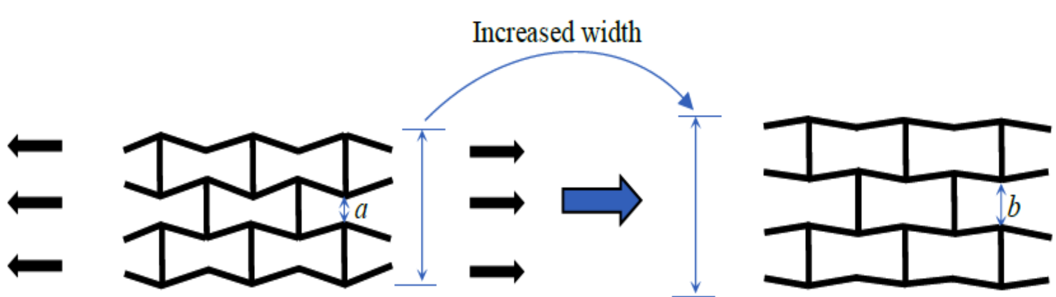


Figure 3: Auxetic behavior of a re-entrant hexagonal structure: when stretched, its width increases, in contrast to the width decrease observed in structures with a positive Poisson's ratio.

because both the strap and the wrap are elastic, they cannot be tightened in the same manner as two non-stretchable cords. To overcome this limitation, a specialized fastening mechanism will be developed to securely link the components together.

This article will be outlined as follows. In Section 2, the design and dimensions of the proposed wrap will be presented. In Section 3, experimental methods and materials will be introduced. In Section 4, experimental results will be presented and discussed. Finally, in Section 5, this work will be summarized and concluded.

2. DESIGN AND DIMENSIONS OF THE WRAP

2.1. Design

There are two requirements about the wrap: (i) it should be able to stretch over the elbow area and apply continuous pressure to the cotton ball even during arm movement, and (ii) it should apply minimal pressure on the skin to avoid discomfort. To meet these two requirements, the wrap will be made from an elastic material. It will consist of two main components (Fig. 3): the presser and the belt. The presser is intended to press a cotton ball against the skin, while the belt secures the presser around the elbow.

The belt includes two links and two ends (Figure **4a**). The belt links feature standard re-entrant structures (Figure **3**), allowing them to conform to the contours of the elbow. As will be detailed later, the belt ends are specifically designed to fasten the wrap around the elbow. The presser employs a reinforced version of the standard featured re-entrant structure to enhance its pressing function. A central bar is added to the presser's unit cell for two reasons (Figure **4a**): (i) its placement at the center of the cell reduces the size of the hole within the unit; and (ii) it limits deformation of the unit cell when the wrap is stretched, providing greater structural stability. As shown in Figure **4b**, when the arm bends and the wrap stretches, the belt segment lengthens considerably to fit the larger elbow circumference, whereas the presser extends only slightly so it can continue to exert pressure on the bleeding site.

2.2. Dimensions of Auxetic Structures

The bars in both the belt and the presser are designed to have the same width (t) and thickness (t_1). Consider a unit cell in the presser, as shown in Figure **5**. The same analysis applies to a unit cell in the belt, with the only difference being that the presser's unit cell includes an additional horizontal bar. An *xy*-coordinate system is established in Figure **5** to aid in the geometric analysis.

The flatten cotton ball has a diameter from 2.5 to 3.5 cm. In this work, the height (h) of the unit cell is set to 8 mm to ensure that at least three unit cells in the presser can press against the cotton ball along the y direction. To maintain both structural robustness and design simplicity, the bar width t and structural thickness t_1 are both set to 1 mm.

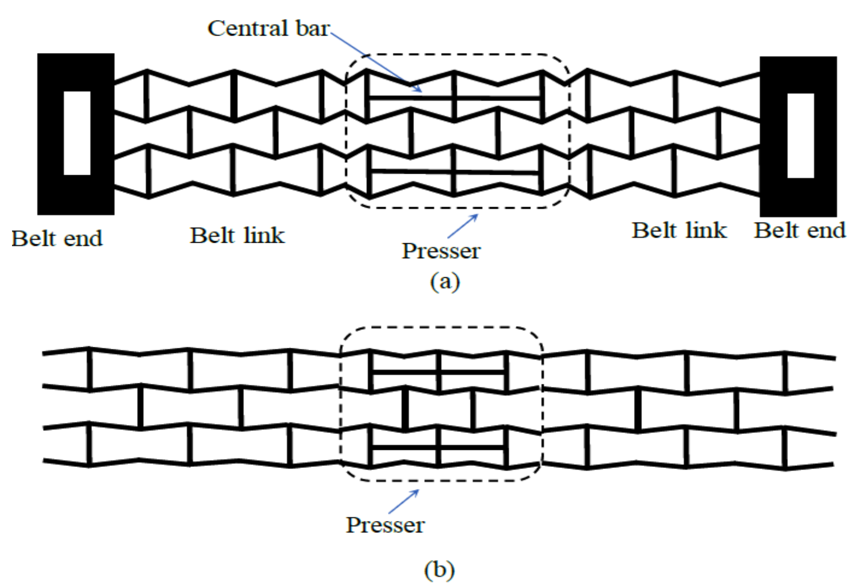


Figure 4: (**a**) Design of the elbow wrap, and (**b**) relatively large and small elongations of the wrap's belt and presser when the wrap is stretched (not to scale).

As shown in Figure **5**, in addition to h, t and t_1, there are two key geometric parameters to determine: the width (w) of the unit cell, and inclined angle (θ) of the inclined bars. Geometrically, w must exceed the combined widths of two vertical and two inclined bars:

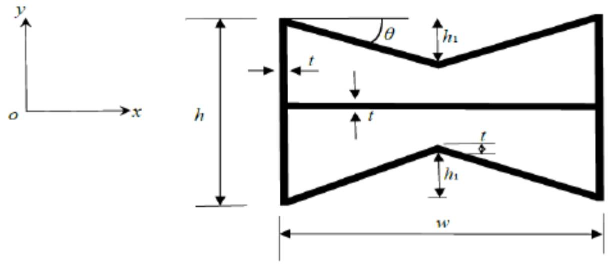


Figure 5: Dimensions of a unit cell in the presser.

$$w > 4t \tag{1}$$

The intersection point between a pair of inclined bars has an approximate height of t. Let h_1 denote represent the vertical distance from this intersection to the adjacent edge of the unit cell. To prevent overlap between the top and bottom intersections within a single unit cell, the following condition must be met:

$$2h_1 + 3t < h \tag{2}$$

Since

$$h_1 = \frac{w \tan\theta}{2} \tag{3}$$

it follows from Eq. (2) that

$$w \tan\theta < h - 3t \tag{4}$$

Eq. (4) thus defines a geometry constraint on w and θ. Given that h=8 mm and t=1 mm, it follows from Eqs. (1) and (4) that

$$w > 4\ mm \tag{5}$$

$$w \tan\theta < 5\ mm \tag{6}$$

Substituting Eq. (5) into Eq. (6) yields

$$\tan\theta < 1.25 \tag{7}$$

Accordingly,

$$\theta < 51.3^0 \tag{8}$$

The maximum strain before the inclined bars are fully extended horizontally is:

$$\varepsilon = \frac{\frac{w}{2\cos\theta} - \frac{w}{2}}{\frac{w}{2}} = \frac{1-\cos\theta}{\cos\theta} \tag{9}$$

It can be shown that, as the derivative of ε with respect to θ is positive, ε increases monotonically with θ. Therefore, to maximize stretchability without risking buckling, θ should be as large as possible. Based on Eqs. (9) and (10),

$$\varepsilon < 60\% \tag{10}$$

This sets 60% as the upper bound for the stretch the wrap can accommodate during use. Figure **6** illustrates the relationship between ε and θ, which allows the designer to choose an appropriate θ based on the expected maximum strain in practical applications.

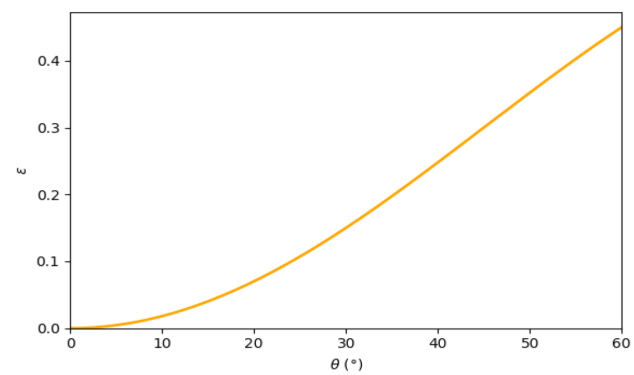


Figure 6: Relationship between ε and θ.

Based on the above considerations, the following parameters are selected for the auxetic structures of the presser (Figure **7**): h=8 mm, t=1 mm, t_1=1 mm, θ=30^0, and w=6mm. For this design, a flattened cotton ball with a diameter of at least 3.0 cm will be pressed by 3 unit cells along the y-direction and 5 unit cells along the x-direction, resulting in a total of 15 unit cells providing contact and pressure.

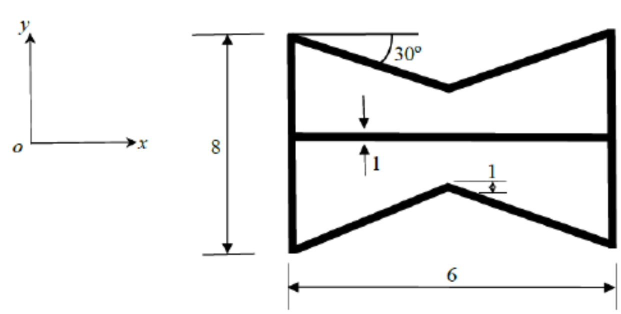


Figure 7: Dimensions used in the auxetic structures of the presser. Unit for the dimensions is mm. The membrane is also 1 mm thick.

3. EXPERIMENTAL METHODS AND RESULTS

The Elegoo Saturn 3 printer and F39 white flexible resin were used in this work to fabricate the prototype of the elastic elbow wrap. This printer uses an LCD masked UV array with wavelength of 405 nm as its light source. It offers a build volume of 219 x 1223 x 260 mm^3 (length x width x height). According to its manual, it offers resolutions of 19, 24, and 10 μm along the *x*, *y* and *z* directions, respectively. These high resolutions enable the structure to be printed with good accuracy and surface finish.

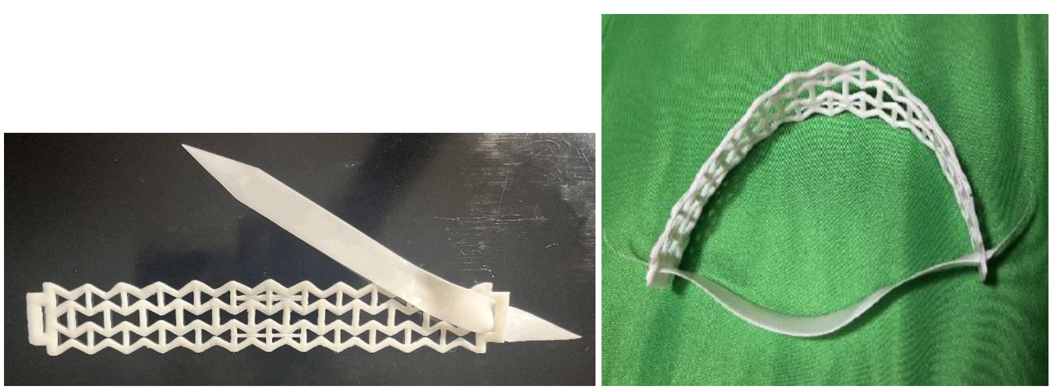
In our experiments, the 2-mm-thick wrap was printed by stacking 20 layers, each layer with a thickness of 20μm. The bottom 5 layers, which were in the intimate contact with the build plate, had longer exposure (i.e., 19 s), to ensure strong adhesion to the build plate. The remaining layers were each exposed by 2.5 s. After the F39 resin was cured by the UV light, the printed wrap was rinsed in isopropyl alcohol (IPA) for about 3 min to dissolve and remove uncured resin from the surface. If uncured resin was not completely removed, the sample felt sticky, and the hollow portions of the wrap might still be blocked by the resin. After that, it was further rinsed with clean water around 1 min to remove any residual IPA.

Figure **7** shows the fabricated prototype of the wrap. The wrap itself is 2 mm thick, 22 cm long, and 3.2 cm wide. In addition, a 0.5-mm-thick strap was fabricated from F39 resin to fasten the wrap around the elbow (Figure **7**). The strap measures 21.5 cm in length and 1.75 mm in width and incorporates two triangular ends that facilitate insertion through the apertures at the wrap ends, as will be demonstrated later.

According to [19], the elbow circumferences of adult males and females typically range from 24–30 cm and 22–28 cm, respectively. The linked wrap can extend to a maximum length of approximately 40 cm, and its adjustable design ensures applicability across a broad spectrum of adult users. Furthermore, the wrap can readily be shortened for applications involving children.

Figure **8a** illustrates the self-locking mechanism used to secure the strap within the receiving apertures of the two belt ends. The triangular tip of the strap is first inserted through the aperture of one belt end and then pulled completely through (Figure **8a**). Repeating the process on the opposite belt end links the two ends together (Figure **8b**). The rectangular portion of the strap is approximately 35% wider than the receiving aperture, and therefore must be compressed as it passes through (Figure **8a**). This compression

Figure 7: Fabricated prototype of the wrap and strap.



(a) (b)

Figure 8: (**a**) Illustration of the self-locking mechanism used to secure the strap through the receiving apertures, and (**b**) the wrap linked at both ends.

increases the frictional resistance between the strap and the aperture.

Testing confirmed that the resulting friction was sufficient to lock the strap in place and prevented slippage during arm movement. The lock can be intentionally released by pulling on the strap head with the fingers. Once pulling ceases, the strap automatically re-locks in the apertures. This configuration allows the strap length between the two belt ends to be locally adjusted, thereby improving the fit of the wrap around the elbow and reducing localized pressure on the joint.

Figure **9** shows that, when the belt was stretched horizontally, the inclined bars of the auxetic lattice rotated outward without buckling, and the structure remained planar. This response is consistent with the expected auxetic (negative Poisson's ratio) behavior illustrated in Figure **3**. However, when the fabricated lattice was elongated by approximately 15%, several bars fractured, indicating that F39 resin has limited elasticity. Thus, while suitable for proof-of-concept prototyping, this material is not appropriate for final, real-world applications.

Figure **10** demonstrates the application of the wrap to press a cotton ball against the elbow. The cotton ball remained securely in place even during arm movement. Because no instrument was available to measure local pressure, the absence of any crease or the presence of only a shallow crease, along with the wearer's comfort during one hour of continuous use, was used as an indirect indication that the applied pressure was below the threshold of 2.7 kPa [5]. Owing to the adjustable effective length of the wrap and the elasticity of both the wrap and its strap, the wearer experienced minimal discomfort while using it. Furthermore, no creases were observed on the elbow after continuous wear for one hour, supporting the conclusion that the pressure applied by the wrap was below 2.7 kPa.

SUMMARY AND CONCLUSIONS

In summary, this study introduces an elastic elbow wrap with auxetic architecture, specifically designed to keep a cotton ball in place following blood draw, regardless of elbow motion. Its prototype was fabricated using resin 3D printing. As confirmed by the testing results, its re-entrant structures expand laterally

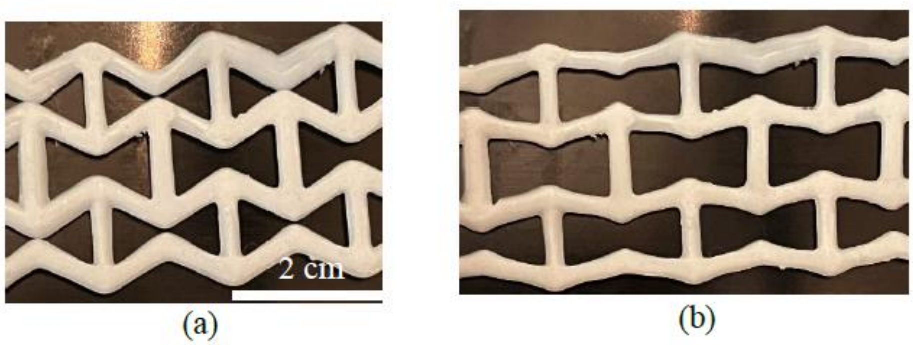


Figure 9: Auxetic structure in the belt (**a**) before and (**b**) after they are elongated by 12%.

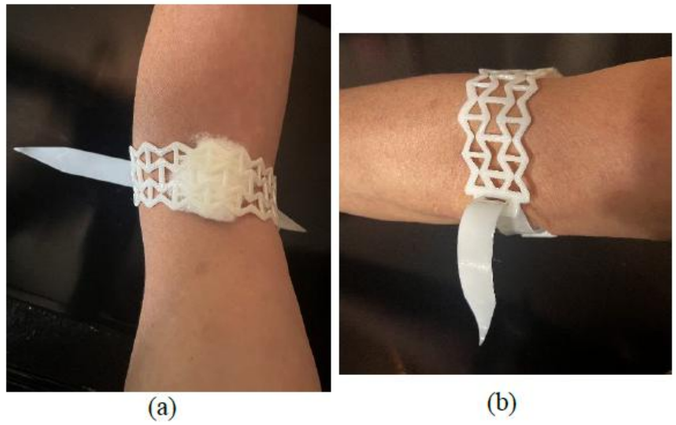


Figure 10: Pressing of a cotton ball against the elbow using the prototype of the wrap: (**a**) top and (**b**) back views of the wrap on the elbow.

when stretched and contract when compressed. Consequently, it avoids the buckling problem that a bandage experiences due to arm movement and keeps the cotton ball in close contact with the skin. Furthermore, due to its elasticity and length adjustability, it applies much less pressure on the skin than medical tape and leaves only a faint mark on the skin after wear. The wrap may be further mass manufactured via compression molding [20] or injection molding [21].

The prototype was fabricated using F39 resin, which has a Shore hardness of approximately 70A. As this material is not biocompatible, it was employed solely for proof-of-concept testing. For improved comfort and safety in practical applications, the resin may be replaced with a medical-grade silicone possessing a lower Shore hardness, which would provide greater elasticity, reduced pressure, and improved biocompatibility.

AUTHOR CONTRIBUTIONS

O.L. designed the wrap, conducted the experiments, and prepared the figures. E.M. assisted O.L. with these activities. C.L. supervised the project, carried out the theoretical analysis, and drafted the manuscript. Both O.L. and E.M. contributed to manuscript preparation and editing.

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