NASA Public Access

Author manuscript

Proc ASME Conf Smart Mater Adapt Struct Intell Syst. Author manuscript; available in PMC 2020 February 20.

Published in final edited form as:

Proc ASME Conf Smart Mater Adapt Struct Intell Syst. 2019 September 9; 2019: . doi:10.1115/smasis2019-5661.

EXPERIMENTAL INVESTIGATION OF THE MECHANISMS AND PERFORMANCE OF ACTIVE AUXETIC AND SHEARING TEXTILES

Rachael Granberry¹, Brad Holschuh

Department of Design, Housing, and Apparel, University of Minnesota, Saint Paul, MN

Julianna Abel

Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN

Abstract

Anisotropic textiles are commonly used in wearable applications to achieve varied bi-axial stress-strain behavior around the body. Auxetic textiles, specifically those that exhibit a negative Poisson's ratio (ν), likewise exhibit intriguing behavior such as volume increase in response to impact or variable air permeability. Active textiles are traditional textile structures that integrate smart materials, such as shape memory alloys, shape memory polymers, or carbon nanotubes, to enable spatial actuation behavior, such as contraction for on-body compression or corrugation for haptic feedback. This research is a first experimental investigation into active auxetic and shearing textile structures. These textile structures leverage the bending- and torsional-deformations of the fibers/filaments within traditional textile structures as well as the shape memory effect of shape memory alloys to achieve novel, spatial performance. Five textile structures were fabricated from shape memory alloy wire deformed into needle lace and weft knit textile structures. All active structures exhibited anisotropic behavior and four of the five structures exhibited auxetic behavior upon free recovery, contracting in both x- and y-axes upon actuation ($\nu = -0.3$ to -1.5). One structure exhibited novel shearing behavior, with a mean free angle recovery of 7° . Temperature-controlled biaxial tensile testing was conducted to experimentally investigate actuation behavior and anisotropy of the designed structures. The presented design and performance of these active auxetic, anisotropic, and shearing textiles inspire new capabilities for applications, such as smart wearables, soft robotics, reconfigurable aerospace structures, and medical devices.

Keywords

active auxetics; auxetic textiles; shape memory alloys; knitted textiles; smart materials; smart structures

¹Contact author: granb017@umn.edu.

1. INTRODUCTION

Active materials and textiles are integrated into wearables to enable garments and body-worn devices to respond to and even assist user capabilities. Active fibers, such as shape memory polymers, carbon nanotubes, and shape memory alloys, have been successfully integrated into traditional textile structures to enable surface-wide functionalities, such as contracting for dynamic fit or medical compression, morphing topology for responsive haptics, or structural realignment for modular thermal insulation [1]–[4]. When interacting with the human body, these active textiles are expected to maintain function while the user assumes multiple postures (e.g., sitting, standing). Consequently, dynamic, multi-posture anthropometry requires actuators that exhibit anisotropy, biaxial extension, biaxial contraction, or even shear to maintain body proximity in areas such as shoulders, wrists, knees, hips, and ankles. Active textiles integrated into body-worn systems may require complex active auxetic behaviors – for example, auxetic fabric contraction and expansion behind knees or shear at hip flexors.

Auxetic materials and textiles are those that exhibit a negative Poisson's ratio (ν). In 2D, the Poisson's ratio (ν) is the ratio of the strain in the x (ϵ_x) and strain in the y (ϵ_y).

$$\nu = -\frac{\epsilon_x}{\epsilon_y} \quad (1)$$

As shown in Figure 1a, non-auxetic materials and structures exhibit a negative strain in the x-axis ($-\epsilon_x$) in response to tensile force and subsequent positive strain in the y-axis ($+\epsilon_y$). Likewise, a compressive force and subsequent negative strain in the y-axis ($-\epsilon_y$) produces a positive strain in the x-axis ($+\epsilon_x$). Alternatively, passive auxetic structures (Figure 1b) exhibit x-axis positive strain ($+\epsilon_x$) in response to y-axis positive strain ($+\epsilon_y$) and x-axis negative strain ($-\epsilon_x$) in response to y-axis negative strain ($-\epsilon_y$).

Auxetic behavior is enabled by auxetic materials (e.g., auxetic polymeric fibers) integrated into non-auxetic structures or by non-auxetic materials configured into auxetic structures that enable internal restructuring [5], [6]. Common auxetic structures include re-entrant, rotating polygon, chiral, crumpled sheet, and perforated sheet models, shown in Figure 2. For a thorough review of auxetic models, refer to [7].

Traditional textile structures have utilized auxetic models to induce auxetic textile behavior, specifically weft and warp knitted fabrics [8]. Auxetic weft knit structures, for example, have been fabricated using the principles of rotating polygons and re-entrant structures depicted in Figure 2 [9]. Alternatively, auxetic warp knit structures have utilized manufacturing guide bars to inlay limiting yarns into open chain or pillar stitches [10]. An example of an auxetic inlay wrap knit structure is depicted in Figure 3.

Few auxetic structures, textile or non-textile, have been made from or incorporated active materials. Active auxetic structures (Figure 1c) are those that exhibit both x- and y-axis negative strain ($-\epsilon_x, -\epsilon_y$) or both x- and y-axis positive strain ($+\epsilon_x, +\epsilon_y$) in response to the active material element's external stimulus (e.g. heat, magnetic field). Prior work in active

auxetic structures includes re-entrant, honeycomb, or chiral models fabricated with shape memory alloy foil or ribbon [11]–[13]. There has not been prior work that presents methods of leveraging bending and torsion inherent to traditional textiles structures to design actuating auxetic textile structures with active material filaments. Likewise, there has not been prior work that investigates anisotropy (i.e. directionally dependent stress-strain behavior) or shear in the design and performance of active textiles.

This research identifies geometric textile features induced during the textile manufacturing process that, when implemented with active materials, enable active auxetic, anisotropic, and shearing behaviors. While this work has immediate implications in the field of smart wearables, the creation of active auxetic, anisotropic, and shearing textiles will enable advancements for soft robots, reconfigurable aerospace structures, and medical devices.

2. MATERIALS AND ARCHITECTURES

The mechanisms and performance of each textile structure are dependent on the material deformations imposed during the manufacturing process. Consequently, shape memory alloy (SMA) materials are discussed in relation to the manufacturing process of each textile architecture.

2.1 Textile Architectures

Five textile architectures were evaluated for auxetic behavior, including needle lace and weft knit textile architectures, both bending- and torsion-dominant structures composed of interlocking, looped filaments in an open, web-like pattern. These architectures, which were inspired by prior work on SMA knitted actuators [14], include (1) needle lace with buttonhole stitches, (2) needle lace with ceylon stitches, (3) weft knit with ceylon stitches, (4) unbalanced weft with knit ceylon stitches, and (5) garter knit with twisted filament (Figure 4).

1. Needle Lace with Buttonhole Stitches (Sample #1)—Needle lace architectures composed of buttonhole stitches are primitive forms of lace achieved by interlocking looped filaments in an open, web-like pattern (Figure 4a). The textile was manufactured overtop a foamboard backing so that the structure could be pinned in place while successive rows of loops were formed using a hand sewing needle. Each row of loops was connected to the previous row between loops, rather than around loops. The mechanical performance of the structure is defined by the applied deformations imposed during the manufacturing process. Detached buttonhole stitches are primarily bending-dominant structures. As shown in Figure 5a, for a given filament ABCDE, an applied moment about the z-axis (M_z) initiates the loop structure. Subsequently applied filament tension (T) creates a reaction at C (R) in response to a mounted pin.

2. Needle Lace with Ceylon Stitches (Sample #2)—Needle lace composed of ceylon stitches is similar to needle lace with buttonhole stitches in both their manufacturing method and architectures. The key distinction between the two lace structures is the connection point. Successive rows of ceylon stitches connect around the loops of the

previous row, rather than between loops, as shown in Figure 4b. Like buttonhole stitches, Ceylon stitches are bending-dominant structures produced by an applied moment about the z-axis (M_z) and a reaction at C (R) from filament tension (T) that produces a bending moment, shown in Figure 5a.

3. Weft Knit with Ceylon Stitches (Sample #3)—Ceylon stitches can be made on a weft knitting machine as well as with a hand sewing needle. Weft knit ceylon stitches were manufactured on a Taitexma-860, a manual weft knitting machine that produces highly organized rows of loops with consistent loop lengths through regular and repeatable applied bending deformations. These deformations, which characterize the knitting loop dimensions, are depicted in Figure 5b. For a given filament ABCDE, a concentrated load at C (P) under filament tension (T) initiated reactions (R) at from mounted pins. These knitted loops, characterized by bending deformations depicted in Figure 5b (left), are then twisted by hand to reverse the loop apex and form the ceylon stitch. As shown in Figure 5b (right), the torsion is initiated by an applied moment about the y-axis (M_y). The direction of the twisting moment (M_y , M_{-y}) alternates in each successive row of loops to mimic needle lace with ceylon stitches. With sufficient applied loads, weft knit ceylon stitches appear identical to needle lace with ceylon stitches; however, without sufficient load, the torsion built up from the applied moment about the y-axis (M_y) forces a partial recovery shown in Figure 4c.

4. Weft Knit with Unbalanced Ceylon Stitches (Sample #4)—Weft knit with unbalanced ceylon stitches are identical to weft knit with ceylon stitches in the manufacturing process and similar in architectures. Rather than alternating the direction of the applied moment about the y-axis (M_y , M_{-y}) every row, the moment is applied in the same direction every time (i.e. either y or -y direction). Like weft knit with ceylon stitches, weft knit with unbalanced ceylon stitches look like needle lace with ceylon stitches under sufficient load and, upon the release of that load, reverse loop face orientation (z to -z) to recover the imposed torque. See Figure 4d and Figure 5b.

5. Garter Knit with Twisted Filament (Sample #5)—Garter knits are weft knit structures composed of alternating rows of knit and purl stitches. Like previously described weft knit architectures, garter knit structures are dominated by imposed bending deformations detailed in Figure 5c. Rather than manufacturing the structure with a straight filament, a filament in pure torsion was used. The filament was held in tension with an applied load and rotated to achieve 4.5 twists per inch. The filament under pure torsion was then fed through a Taitexma TH-860 manual weft knitting machine and a local force at C (P) under filament tension (T) produced reactions (R) at fixed pins to form a row of knitted loops, as shown in Figure 4e and Figure 5c.

2.2 Shape Memory Alloys

Each textile architecture previously described was manufactured with shape memory alloy (SMA) wire. SMA is an energy dense metal alloy that exhibits large actuation displacements (~6–8%) through solid-solid, diffusionless phase transformations in response to changes in temperature, making the material widely used in the design of smart actuators and soft

robots [15]. This characteristic thermomechanical coupling enables two novel material behaviors, the shape memory effect (SME) and superelasticity (SE). The SME, or the ability to recover large mechanical deformations, is demonstrated when SMA is deformed in a lower-temperature, less stiff martensite state and recovers that deformation through a thermally-induced transition to a higher-temperature, higher-force austenite state [15]. SE behavior enables SMA to maintain constant forces/stresses over large plateau strains, making the material an excellent mechanical damper [15].

Textile samples were manufactured with Flexinol® wire (0.008", $A_f = 90^\circ\text{C}$, Dynalloy, Inc.), which is a commercially available and widely-used material manufactured in wire, sheet, and ribbon formation. Flexinol®, manufactured by Dynalloy, Inc., is a near equiatomic NiTi metal alloy with the following transition temperatures gathered through in-house differential scanning calorimetry (DSC) testing: austenite start, $A_s \approx 66^\circ\text{C}$; austenite finish, $A_f \approx 77^\circ\text{C}$; martensite start, $M_s \approx 42^\circ\text{C}$; martensite finish, $M_f \approx 26^\circ\text{C}$. Flexinol® undergoes significant thermomechanical cycling during the manufacturing process to reorient self-accommodated martensite variants to highly aligned martensite variants for repeatable linear actuation [16], [17]. Due to the trained orientation of martensite variants, imposed bending and torsion of Flexinol® through architectural reconfiguration induces significant energy storage through shear stresses. Consequently, the designed active auxetic and shearing textiles were evaluated in terms of actuator thermomechanical performance as well as free recovery behavior to evaluate the shape memory effect (SME) that enables active auxetic features.

3. METHODS

Active textile structures were initially evaluated for free recovery behavior through 2D image analysis to investigate the magnitude of shape change upon actuation. Free recovery analysis was followed by x- and y-axis bias load under controlled temperatures (i.e. above the austenite finish temperature and below the martensite finish temperature) to observe structural isotropy/anisotropy. One sample only was used in the initial analysis to observe behavioral trends and future work should be conducted on multiple identical textile samples to evaluate performance variability due to manufacturing.

3.1 2D Imaging of Free Recovery

Each active textile was photographed using a standard 2D camera (50 MP at 50 fps CMOS camera). Split rings were placed around the first and last knitted loop of each textile swatch to prevent unraveling. The split rings were then slid through a supporting rod. This partially constrained configuration allowed free displacement in the x-axis and minimal supporting load in the y-axis to prevent significant z-axis motions, such as curling. The partially constrained configuration was designed to observe free recovery in x- and y-axes to mimic a condition in which fabrics are adjacent to the body surface. The setup was placed on a tabletop next to a measuring tape. The camera was mounted overtop the setup and locked in place for consistent data collection.

The active textile samples were first photographed in room temperature ($T \approx 23^\circ\text{C}$) to gather textile dimensions in a martensite state. The samples were then actuated by increasing the

thermal load with a heat gun ($T > 77^{\circ}\text{C}$). The samples were subsequently photographed in an actuated state. The process was repeated three times to calculate a standard error for the dimensional measurements. Between each cycle, samples were gently pulled in the x- and y-axes to return the textile swatches to their relaxed martensite dimensions. Three images of a sample in a martensite state and three images in the austenite state were used to calculate x- and y-axis dimensions (i.e. mean $\pm$ standard deviation) for each textile sample. The mean x- and y-axis values were used to calculate the engineering strain in the x- (ϵ_x) and y-axes (ϵ_y). Poisson's Ratio (ν) was calculated using the calculated strain values, as shown in Equation 1.

3.2 Temperature-Control Bias Load Testing

Prior work has evaluated contractile SMA knitted actuator performance with cycled thermal loads under fixed applied forces (i.e. force-control testing) or fixed applied displacements (i.e. displacement-control testing) [18]. Here, temperature-control testing is used as an alternative to generate quick loading and unloading curves for each sample in both austenite and martensite states. Temperature control tests use fixed thermal loads (i.e. temperature above the austenite finish temperature, $T > A_f$ or temperature below the martensite finish temperature, $T < M_f$) and controlled displacements to generate force-displacement data. Temperature-control tests do not provide high resolution actuator performance data as do force- and displacement-control tests; however, temperature control tests quickly provide the minimum and maximum bounds of a material's force-displacement relationship when used as an actuator [18]. Consequently, the inclusion of the temperature-control testing is intended to provide a comparison of force-displacement behavior between samples rather than a full study of actuator performance.

A tensile testing machine (Instron, model 3365) equipped with a thermal chamber and 25-lb load cell (0.05% accuracy) was used to gather force-displacement data for each sample under controlled thermal loads. Pneumatic side action grips pressurized to 50–60 psi were used to grasp a custom coupling. The coupling was designed to support an aluminum rod that translated tensile force to the textile via the split rings. The setup improved the distribution of tensile force across the sample by translating force evenly across each column of loops.

The samples were first tested for force-displacement performance in an austenitic state. The thermal chamber temperature was set above the austenite finish temperature ($T = 120^{\circ}\text{C}$) and each sample soaked above the austenite finish temperature for 10 minutes before testing. The samples were then displaced in the y-axis at a rate of 2 mm/sec. Upon reaching an applied load of 8 N, the samples were unloaded at a rate of -2 mm/s. After each sample had been tested in the y-axis, the samples were rotated and the same test was performed with x-axis displacement. Force-displacement data in a martensite state was then collected for each sample below the martensite finish temperature ($T = 23\text{--}25^{\circ}\text{C}$) in both x- and y-axes.

4. RESULTS

4.1 2D Imaging of Free Recovery

The results of the 2D imaging are depicted in Figure 6. The mean dimensional values along with calculated standard deviation of the three actuation cycles is depicted in Table 1. While y-axis lengths had relatively consistent measurements, specifically low calculated standard deviations, x-axis lengths had high standard deviations due to boundary conditions.

The mean x- and y-axis values were used to calculate the engineering strain in the x- and y-axes (ϵ_x and ϵ_y) for each sample. As shown in Table I, these calculated strain values were used to determine each sample's Poisson Ratio (ν) according to Equation 1. The results in Table I show that four of the five samples exhibit auxetic behavior, with Poisson's Ratios (ν) between -0.3 and -1.5 . Only weft knit with ceylon stitches (sample #3) does not exhibit auxetic behavior.

All samples were relatively symmetrical about the x-axis, with the exception of sample #4, weft knit with unbalanced ceylon stitches. The angle (θ) of each knitted column was measured from the 3 repeated measures. Table II presents the mean angle of columns in the martensite state ($\overline{\theta_M}$) along with the mean angle in of columns the austenite state ($\overline{\theta_A}$). The average measured angle difference ($\Delta\theta$) was 7° upon actuation.

4.2 Temperature-Control testing

The force-displacement results of the temperature-control tests are depicted in Figure 7. Loading and unloading curves collected above the austenite finish temperature ($T = 120^\circ\text{C}$) are depicted in red while data gathered below the martensite finish temperature ($T = 23\text{--}25^\circ\text{C}$) are depicted in blue. Red and blue circles indicate the mean length measurement observed in the 2D free recovery analysis. For clarity, force-displacement data collected in x- and y-axis are depicted in separate plots. The initial observation is that all active textile samples exhibit anisotropic behavior – stress-strain behavior in x- and y-axes are dissimilar. The results also show that, in an austenitic state, all weft knit textile architectures (i.e. samples #3, #4, and #5) are stiffer than needle lace textile architectures (i.e. samples #1 and #2) in both x- and y-orientations at lower applied loads. Needle lace structures (#1, #2) exhibited strain hardening behavior at initial low stiffness. While loading and unloading of samples in a martensitic state are similar in the y-axis, x-axis testing reveals weft knit structures (i.e. samples #3, #4, and #5) exhibit relatively large hysteretic unloading.

Figure 8 provides additional insight into the data by presenting textile length as engineering strain to enable performance comparisons. Figure 8 confirms that weft knit textile architectures are stiffer textile architectures in both x- and y-orientations while austenitic; however, Figure 8 further reveals samples #3 and #5 are stiffer than sample #4 (weft knit with unbalanced ceylon stitches) in the y-axis while samples #4 and #3 are stiffer than sample #5 (garter knit with twisted filament) in the x-axis. While Figure 8 shows that needle lace architectures require higher strain to reach 8 N in an austenite state, samples #1 and #2 require comparatively little strain to reach 8 N in a martensite state. Sample #5 (garter knit

with twisted filament) exhibited the largest amount of strain to reach maximum forces in the x-axis.

5. DISCUSSION

The results of the free recovery tests demonstrate that active auxetic and shearing textiles can be accomplished through imposed bending and torsional deformations inherent to traditional textile architectures. Figure 9 investigates the mechanics of each textile loop structure upon actuation.

Sample #1 and #2 function through a recovery of a bending deformation about C, which generates an x-axis widening and y-axis shortening of each loop (Figure 9a and 9b). Due to the applied moment (M_z), loop x-axis widening increases the length of filament (s) within the enclosed loop, thus shortening the distance between adjacent loops. Consequently, needle lace structures contract rather than widen in the x-axis unlike prior y-axis contracting SMA textile structures, such as weft knit garter structures [14]. Additionally, vertical loop sliding shortens the overall y-axis length.

While torsional moments are imposed on sample #3 during the manufacturing process, the applied torque is reversed and lost upon post-manufacture structural equilibrium. Through structural resettling, sample #3 also becomes a bending dominant structure. Upon actuation, bending deformations about A, C, and F attempt to recover, creating a widening of each loop (Figure 9c). Loop broadening causes sample #3 to increase x-axis length. As observed in prior SMA knit structures, sample #3 contracts in the y-axis as loop height decreases slightly and loops slide vertically, similar to weft knit garter structures [14].

Unlike sample #3, sample #4 retained the applied torque post-manufacture; therefore, actuation behavior is caused by a recovery of both bending and torsional deformations. As shown in Figure 9d, upon actuation, the applied moment about the y-axis (M_y) reverses such that the loop legs B and D no longer cross. At the same time, the bending deformation about C attempts to recover, forcing a slight broadening of the loop width. Structural shear appears to be caused as these stacked loops twist open and lock at an angle related to the untwisted loop geometry.

Sample #5, which is fabricated with a wire in pure torsion, similarly experiences a twisting moment about the x-axis upon actuation (Figure 9e). Depending on the direction of applied tension (i.e. Figure 5c), row twist alternates between y and -y. Fully actuated loops become nearly planar with the z-axis.

In addition to the mechanisms that produce auxetic and shear behavior, the bias loading tests under controlled temperatures provide insight into the performance of each presented active textile. Needle lace architectures required high strain to reach 8 N in an austenite state and relatively low strain to reach 8 N while in a martensite state, suggesting samples #1 and #2 exhibit little actuation contraction (ξ), defined by the percent difference between the austenite length and the martensite length at a given applied load [19]. While true actuation contraction (ξ) will not reach the austenite loading curve due to structural friction, the

thermomechanical path provides a bounding box for actuator performance. Additionally, large, x-axis martensite relaxation suggests large actuation contraction (ξ) of weft knit architectures (samples #3, #4, #5) in the x-axis. Future work could tailor these actuation behaviors through structural modification of geometric design parameters, as previously explored in prior work [19].

6. CONCLUSION

This research introduces an innovative use of traditional textile structures and highlights the potential of these structures, when combined with smart materials, to produce complex actuation behaviors. Prior work on SMA knitted actuators has explored axial contraction, curling, or corrugation [14]. This work introduces the design of five new textile structures (i.e. weft and needle lace structures) fabricated with SMA wire as an integrated filament. Each textile structure exhibited shape memory recovery of mechanical deformations imposed in the manufacturing process to produced novel actuation behaviors, such as biaxial contraction ($\nu = -0.3$ to -1.5) and shear ($\theta = 7^\circ$). Force-displacement testing suggests that these active structures have the potential to be powerful actuators with unique, anisotropic behaviors that could be tailored for a given application.

Such novel, reconfigurable structures contribute to a new actuation paradigm that impact innumerable applications, touching wearables, medical devices, soft robotics, or aerospace structures. Future work will examine these active auxetic architectures in relation to wearables applications, such as active compression and self-fitting garments, as well as evaluate their behavior when embedded into larger systems designs. The introduction of active auxetic and shearing textiles is intended to inspire interest in active textiles and highlight the flexibility of architectural manipulations to design new motions.

ACKNOWLEDGEMENTS

This work was supported by a NASA Space Technology Research Fellowship (grant # 80NSSC17K0158) and MnDRIVE Robotics, Sensors, and Advanced Manufacturing through Dr. Julianna Abel's Design of Active Materials and Structures Lab in the Department of Mechanical Engineering at the University of Minnesota. Thank you to Charles Weinberg for conducting DSC testing. Thank you to Heidi Woelfle and the Wearable Technology Lab for time on the Instron Machine.

NOMENCLATURE

ν	Poisson's Ratio
ϵ_x	x-axis strain
ϵ_y	y-axis strain
$\overline{\theta_A}$	mean textile shear angle in austenite
$\overline{\theta_M}$	mean textile shear angle in martensite
θ	mean textile shear angle difference

SMA shape memory alloy

REFERENCES

- [1]. Eschen K, Granberry R, Holschuh B, and Abel J, "Active-Contracting, Variable-Stiffness Fabrics for SelfFitting Wearables," in ASME Conference on Smart Materials, Adaptive Structures & Intelligent Systems, 2018.
- [2]. Granberry R, Abel J, and Holschuh B, "Active knit compression stockings for the treatment of orthostatic hypotension," in Proceedings - International Symposium on Wearable Computers, ISWC, 2017, vol. Part F1305.
- [3]. Hu J and Narayana H, "Review of Memory Polymeric Fibres and Its Potential Applications," Adv. Res. Text. Eng, vol. 1, no. 2, 2016.
- [4]. Di J, Zhang X, Yong Z, Zhang Y, Li D, and Li R, "Carbon-Nanotube Fibers for Wearable Devices and Smart Textiles," Adv. Mater, vol. 28, pp. 10529–10538, 2016. [PubMed: 27432521]
- [5]. Alderson K et al., "Auxetic warp knit textile structures," Phys. Status Solidi, vol. 249, no. 7, pp. 1322–1329, 2012.
- [6]. Simkins VR, Alderson A, Davies PJ, and Alderson KL, "Single fibre pullout tests on auxetic polymeric," J. Mater. Sci, vol. 40, pp. 4355–4364, 2005.
- [7]. Ren X, Das R, Tran P, Ngo TD, and Xie YM, "Auxetic metamaterials and structures: a review," Smart Mater. Struct, vol. 27, 2018.
- [8]. Ma P, Chang Y, Boakye A, and Jiang G, "Review on the knitted structures with auxetic effect," J. Text. Inst, vol. 5000, p. 0, 2017.
- [9]. Hu H, Wang Z, and Liu S, "Development of auxetic fabrics using flat knitting technology," Text. Res. J, vol. 81, 2011.
- [10]. Ugbolue SC et al., "The formation and performance of auxetic textiles. Part I: theoretical and technical considerations," J. Text. Inst, vol. 5000, 2010.
- [11]. Kuribayashi K, Tsuchiya K, You Z, and Tomus D, "Self-deployable origami stent grafts as a biomedical application of Ni-rich TiNi shape memory alloy foil," Mater. Sci. Eng, vol. 419, pp. 131–137, 2006.
- [12]. Hassan MR, Scarpa F, and Mohamed NA, "In-plane Tensile Behavior of Shape Memory Alloy Honeycombs with Positive and Negative Poisson ' s Ratio," J. Intell. Mater. Syst. Struct, vol. 20, no. May, 2009.
- [13]. Hassan MR, Scarpa F, Ruzzene M, and Mohammed NA, "Smart shape memory alloy chiral honeycomb," Mater. Sci. Eng, vol. 482, pp. 654–657, 2008.
- [14]. Abel J, Luntz J, and Brei D, "Hierarchical architecture of active knits," Smart Mater. Struct, vol. 22, no. 12, p. 16, 12 2013.
- [15]. Rao A, Srinivasa AR, and Reddy JN, Design of Shape Memory Alloy (SMA) Actuators. 2015.
- [16]. V. R Nicholson DE, Padula SA, Benafan O, "Texture evolution during isothermal, isostrain, and isobaric loading of polycrystalline shape memory NiTi," Appl. Phys. Lett, vol. 110, no. 6, 2017.
- [17]. Miller DA and Lagoudas DC, "Influence of cold work and heat treatment on the shape memory effect and plastic strain development of NiTi," Mater. Sci. Eng, vol. 308, pp. 161–175, 2001.
- [18]. Eschen K, Granberry R, and Abel J, "Guidelines on the Design, Characterization, and Operation of Shape Memory Alloy Knitted Actuators," (under Rev., 2019.
- [19]. Eschen K and Abel J, "Performance and prediction of large deformation contractile shape memory alloy knitted actuators," Smart Mater. Struct, vol. 28, no. 2, p. 25014, 2019.

FIGURE 1:

(a) TRADITIONAL MATERIALS CHARACTERIZED BY POSITIVE POISSON'S RATIO. (b) AUXETIC MATERIALS CHARACTERIZED BY NEGATIVE POISSON'S RATIO. (c) ACTIVE NEGATIVE POISSON'S RATIO. (c) ACTIVE NEGATIVE POISSON'S RATIO EXHIBIT BIAXIAL CONTRACTION (LEFT, RED) OR BIAXIAL EXPANSION (RIGHT, RED) UPON ACTUATION IN RELATION TO ORIGINAL UNACTUATED DIMENSIONS (BLUE).

FIGURE 2:
A SELECTION OF TYPICAL AUXETIC STRUCTURES UNDER COMPRESSION (TOP)
AND EXTENSION (BOTTOM).

FIGURE 3:
AUXETIC WARP KNIT TEXTILE ACCOMPLISHED THROUGH INLAY YARN
GEOMETRY THROUGHOUT A REPEATING OPEN CHAIN STITCH.
REPRESENTATION BASED ON STITCH PATTERN DEVELOPED BY [10].

FIGURE 4:

ACTIVE AUXETIC WARP KNIT TEXTILES FABRICATED WITH SHAPE MEMORY ALLOY WIRE. (a) NEEDLE LACE WITH BUTTONHOLE STITCHES ARE COMPOSED OF ROWS OF LOOPS THAT CONNECT TO THE PRIOR ROW BETWEEN LOOPS. (b) NEEDLE LACE WITH CEYLON STITCHES ARE COMPOSED OF ROWS OF LOOPS THAT CONNECT TO THE PRIOR ROW AROUND LOOPS. (c) WEFT KNIT WITH CEYLON STITCHES IS COMPOSED BY MACHINE KNITTING A ROW OF LOOPS AND TWISTING THE HEAD OF EACH LOOP TO FORM A CEYLON STITCH, ALTERNATING TWIST DIRECTION EACH ROW. (d) WEFT KNIT WITH UNBALANCED CEYLON STITCHES IS ALSO COMPOSED BY MACHINE KNITTING, MAINTAINING THE SAME TWIST DIRECTION FOR ALL ROWS. (e) GARTER KNIT WITH TWISTED FILAMENT IS COMPOSED BY MACHINE KNITTING SUCCESSIVE ROWS OF A FILAMENT IN PURE TORSION.

FIGURE 5:

(a) BENDING DEFORMATIONS IMPOSED ON NEEDLE LACE ARCHITECTURES (SAMPLES #1 & #2). (b) BENDING AND TORSIONAL DEFORMATION IMPOSED ON WEFT KNIT ARCHITECTURES (SAMPLES #3 & #4). (c) TORSIONAL AND BENDING DEFORMATIONS IMPOSED ON SPUN WEFT KNIT ARCHITECTURE (SAMPLE #5).

FIGURE 6: 2D IMAGING RESULTS FOR FIVE TEXTILE ARCHITECTURES MANUFACTURED WITH FLEXINOL® WIRE. (LEFT) UNACTUATED SAMPLES IN ROOM TEMPERATURE, WHERE THE TEMPERATURE IS LESS THAN THE MAINTENISTE FINISH TEMPERATURE ($T < M_f$). (RIGHT) ACTUATED SAMPLES HEATED WITH A HEAT GUN SUCH THAT THE TEMPERATURE IS GREATER THAN THE AUSTENITE FINISH TEMPERATURE ($T > A_f$).

FIGURE 7:
RESULTS OF TEMPERATURE-CONTROL TESTING OF FIVE SMA TEXTILES. RED
CIRCLE INDICATES MEAN AUSTENITE MEASUREMENT OBSERVED FROM 2D
IMAGING WHILE BLUE CIRCLE INDICATES MEAN MARTENSITE
MEASUREMENT.

FIGURE 8:
COMPARISON OF RESULTS OF TEMPERATURE-CONTROL TESTING OF FIVE
SMA TEXTILE ARCHITECTURES.

FIGURE 9: RECOVERED BENDING AND TORSIONAL DEFORMATIONS OF ACTIVE TEXTILE STRUCTURES. (a) NEEDLE LACE WITH BUTTONHOLE STITCHES BROADEN UPON ACTUATION TO FORM WIDER LOOPS THAT SLIDE CLOSER TOGETHER, (b) NEEDLE LACE WITH CEYLON STITCHES ALSO BROADENED UPON ACTUATION, CAUSING THE LOOPS TO OVERLAP ONE ANOTHER. (c) WEFT KNIT WITH CEYLON STITCHES BROADENS UPON ACTUATION; HOWEVER, THE LOOP CONTACT POINTS STAY RELATIVELY CONSISTENT. (d) WEFT KNIT WITH UNBALANCED CEYLON STITCHES TWIST ABOUT THE Y-AXIS AND BROADEN UPON ACTUATION, CAUSING LOOPS TO SLIDE AND LOCK IN PLACE AT A NEW ANGLE. (e) GARTER KNIT WITH TWISTED FILAMENT ALSO TWISTS ABOUT THE Y-AXIS AND BROADEN; HOWEVER, THE DIRECTION OF TWIST CAUSES THE LOOPS TO STACK ABOUT THE Z-AXIS AND SLIDE CLOSER TOGETHER.

TABLE I:

FREE RECOVERY TEST RESULTS. MEAN DIMENSIONAL VALUES FOR X- AND Y-AXES ALONG WITH CALCULATED STANDARD DEVIATED FOR THREE REPEATED MEASURES ARE USED TO CALCULATE AXIAL STRAIN (ϵ_x , ϵ_y). EQUATION 1 IS USED TO CALCULATE POISSON'S RATIO (ν).

	Rows (#)	Columns (#)	Mean x-axis length [cm]		Mean y-axis length [cm]		ϵ_x	ϵ_y	ν
			Martensite	Austenite	Martensite	Austenite			
#1	12	12	5.9 ± 0.5	4.3 ± 0.9	4.6 ± 0.2	2.6 ± 0.1	28%	45%	-0.6
#2	10	14	6.5 ± 0.6	5.8 ± 1.1	3.6 ± 0.1	2.3 ± 0.1	11%	38%	-0.3
#3	12	15	7.7 ± 0.8	7.8 ± 0.5	3.9 ± 0.4	2.7 ± 0.1	-2%	31%	+0.1
#4	15	15	7.8 ± 0.6	6.2 ± 0.6	4.2 ± 0.2	3.6 ± 0.1	20%	13%	-1.5
#5	12	15	5.9 ± 0.4	4.0 ± 0.9	3.9 ± 0.5	2.1 ± 0.1	32%	45%	-0.7

TABLE II:

MEAN COLUMN ANGLES IN MARTENSITE ($\overline{\theta}_M$) AND AUSTENITE ($\overline{\theta}_A$) STATES AND CALCULATED SHEAR VALUE ($\overline{\Delta\theta}$) FOR SAMPLE #4.

	$\overline{\theta}_M$	$\overline{\theta}_A$	$\overline{\Delta\theta}$
#4	$114 \pm 5^\circ$	$121 \pm 4^\circ$	7°