Compliant, Large-Strain, and Self-Sensing Twisted String Actuators

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Abstract

Twisted string actuators (TSAs) convert rotational motion from twisting into linear motion. They are known for high energy efficiency, and large linear strain and stress outputs. While they have been successfully applied as the moving mechanism for different robot applications, their potential in soft robotics is mainly challenged by two aspects: Firstly, the conventional strings of TSAs are stiff and strong but not compliant. Secondly, precise control of TSAs predominantly relies on external position or force sensors. Due to these, TSA-driven robots are often rigid and bulky. In this study, we propose the design, modeling, and robotic application of TSAs that are compliant, can produce large strain, and are capable of self-sensing during twisting-induced actuation. The design is realized by replacing conventional stiff strings with compliant, thermally-activated, and conductive supercoiled polymer (SCP) strings. Experiments show that the developed TSAs have normalized stiffness of less than 50 N, strain larger than 30%, and position self-sensing capability during twisting. The quasi-static actuation and self-sensing properties are accurately captured by the Preisach hysteresis operators. In particular, both the twisting-induced actuation and thermally-induced actuation are considered. Finally, the proposed TSAs are successfully demonstrated in a low-cost three-dimensionally printed compliant robotic gripper.

Keywords: supercoiled polymers, twisted string actuators, self-sensing

1. Introduction

Although rigid robotic actuators have high precision, strength, and speed for performing repetitive tasks in structured environments, it is often difficult to use them for soft robotic applications and in unstructured environments. Therefore, soft actuators are increasingly studied for their advantages over rigid ones. Soft actuators make robots inherently safe. Other advantages include low cost, low mass, and high power-to-weight ratio. In robotic applications such as collaborative robots, medical robots, and robotic exo-skeletal suits, soft actuators prove to be very beneficial.

For soft actuators, compliance, maximum strain, and self-sensing capabilities are among the most important performance metrics. Compliance is important for robots that move along soft surfaces or are used around soft materials, such as the human body. The maximum strain of the actuator directly affects a robot’s range of movements, and consequently the types of robots that can be created. For example, a soft bending actuator may be used in a robotic gripper if the actuator can make sufficiently large motions. Self-sensing actuators are important for creating compliant, compact, and lightweight robots. Rigid external sensors are undesirable because they add mass and complexity while lowering the compliance of the system.

The twisted string actuator (TSA) is an artificial muscle demonstrated to have high energy efficiency, and large strain and stress outputs. The essential components of a TSA are a motor and two or more strings. A TSA usually consists of a load attached to the strings as well. One end of the strings is attached to the load and the other end is twisted by the motor. The twisting of the strings reduces their length to create linear contraction customarily up to 30%, without entering the over-twisting phase. Utilizing the over-twisting phase as well as more than two strings can lead to strains up to 81%, but also create unwinding problems. It is noted that the length of the actuator was not taken into account to calculate that contraction percentage, due to the specific TSA design.

The TSA actuation mechanism also allows for high output forces with relatively low input torque, due to their high transmission ratio. The transmission ratio typically varies across the actuation range, but can be made constant with variable radius pulleys. The required motor torque can be accurately calculated by accounting for the stiffness and friction of the strings. The TSA is strong, efficient, and...
mechanically simple. Its thin and long strings resemble biological muscle fibers. Several studies have been published on their robotic applications, such as in robotic exosuits, assistive gloves, and tensegrity robots. However, TSAs have generally been difficult to use in soft robotic applications for the three main reasons discussed below:

Firstly, the existing TSAs predominantly rely on strings with high stiffness but low compliance (with some exceptions). Previous studies used strings such as braided ultra-high-molecular-weight polyethylene (UHMWPE) strings, commonly referred to as Dyneema string. The stiffness of these strings, normalized to their unit length, is often over 3000 N. Highly stiff strings allow for simpler modeling by considering the strings as inextensible. Those strings can lift high loads and reliably perform for thousands of cycles or more. TSAs with compliant strings have been realized before. For example, a robotic joint designed utilized compliant and elastic strings. In soft robots, compliant actuators are more desirable.

Secondly, recent studies showed that the maximum strain of TSAs decreased when their compliance was increased. Greater loads on the TSA decreased the maximum strain even more significantly. We recently realized compliant TSAs by replacing stiff Dyneema strings with compliant supercoiled polymer (SCP) strings that are made by twisting and coiling conductive silver-coated nylon threads. However, the linear contraction of the TSAs with two 4-ply and 8-ply strings only reached 9.1% and 8.4% under 250 g and 700 g, respectively, while conventional TSAs can generate up to 30% strain.

Thirdly, closed-loop control of TSAs predominantly requires external rigid sensors that are not based on self-sensing. This is undesirable for soft robotic applications due to the increased stiffness, mass, and volume. Important advantages of soft robots over their rigid counterparts are compliance, compactness, and low mass. Therefore, maintaining system compliance and reducing the need for external sensors is desired. Previous studies developed models that related the number of motor rotations to the linear contraction of the TSA. However, the utilization of those developed models often requires externally-attached motor encoders or other external sensors for closed-loop control. In addition to being rigid, adding external sensors increases system mass, volume, and complexity.

To achieve self-sensing, the strain of the TSA should be estimated with a signal that is easier to obtain, such as an electrical one. Self-sensing has been realized for other soft materials. For realizing self-sensing TSAs, utilizing conductive and stretchable strings can enable strain sensing via the strings’ resistance change. When two conductive strings are utilized, resistance changes would come from the changes of individual string’s cross-sectional area and length, as well as the increased contact between strings as the TSA contracts.

In this study, a new TSA that is compliant, can produce large strain, and capable of self-sensing during twisting is proposed (Fig. 1). This is realized by replacing regular stiff strings with compliant, thermally-activated, and electrically conductive SCP strings. SCP actuators are a recent invention, first reported in 2014. Their unique geometry allows the polymer fibers’ radial thermal expansion to be converted into linear contraction of the overall string when thermally activated. The SCP string is chosen for the proposed TSA with the following considerations:

- SCP strings are highly stretchable, which makes the resulting TSA more compliant;
- SCP strings’ contraction under applied heat increases the overall strain of the TSA besides twisting-induced strain; and
- when stretched or twisted, SCP strings have demonstrated measurable change in electrical resistance, which can be used for strain self-sensing during twisting without external sensors.

These artificial muscles have shown high power density (up to 27 W/g) and low mass. For example, a 20-cm, 8-ply SCP string has a mass of only 1.2 g. The ply number is the number of threads used to fabricate the actuator. SCP actuators have been used to drive robotic hands, assistive gloves, and soft robots, although a common limitation is that they often generate low force outputs. Because of this relationship, SCP strings were proposed to be useful as sensors. Abbas and Zhao showed that SCP strings’ resistance can be used to determine the externally applied load and length change. Another study realized self-sensing of deflection and force for Joule-heated SCP actuators. These examples of sensors with individual SCP strings imply that SCP-based TSAs have promising self-sensing potential.

Although SCP-based TSAs have useful self-sensing properties, this study also takes advantage of SCP strings’ thermal actuation. SCP actuators integrated into other compliant and soft actuators have enabled improved functionality and performance. For example, SCP strings combined into a soft pneumatic actuator allowed for a soft robot with variable stiffness. In another study, combining an SCP actuator with a shape memory alloy (SMA) actuator led to a large-stroke and powerful soft actuator. To our best knowledge, there have been no reports by other researchers that implement thermally-actuated SCP strings into TSAs.

This study proposes the design, modeling, and robotic demonstration of compliant and large-strain TSAs with promising self-sensing potential. This is realized by replacing conventionally stiff Dyneema strings with SCP strings to firstly increase the compliance of the resulting TSA. To compensate for the decreased maximum strain resulting from the utilization of compliant strings, two actuation modes, namely, twisting-induced actuation and thermally-induced actuation, are utilized. These two modes bring the maximum strain of the proposed TSA to up to 34.7%, which is comparable to or more than that of many existing TSAs. Furthermore, the length of the proposed TSA is predicted by its SCP strings’ electrical resistance during twisting. In this study, the self-sensing correlations are obtained for twisting-induced actuation, but not for thermally-induced actuation.
However, the tendency for resistance to change according to the length indicates strong self-sensing potential during thermal activation as well. The design and fabrication procedures for the proposed TSA are detailed. Experiments confirm increased compliance, maximum strain, and self-sensing potential of the proposed TSA. To model the quasi-static actuation and self-sensing behaviors, a Preisach operator is proposed and experimentally validated. Finally, the proposed TSA is implemented into a compliant three-fingered robotic gripper. Recently, we realized self-sensing TSAs using SCP strings. However, the strain of the TSA made from two SCP strings never exceeded 10% and the actuator’s compliance was not quantified. In another work, we realized compliant and large-strain TSAs using SCP strings. However, neither modeling nor robotic applications were considered. The main contributions of this work are:

- The design and modeling of SCP-based TSAs with large strain, high compliance, and promising potential in strain self-sensing by replacing typical stiff TSA strings with compliant, active, and self-sensing SCP strings.

- Experimental characterizations and validation of the proposed TSA in terms of improved compliance, actuation, and potential self-sensing capacities under different configurations and conditions.

- A proof-of-concept demonstration of the proposed TSAs in a custom-designed compliant robotic gripper.

The rest of the paper is organized as follows. Section 2 discusses design considerations and the fabrication procedure for compliant, large-strain, and self-sensing TSAs. Section 3 discusses actuation performance during twisting-induced and thermally-induced actuation. The next section details the self-sensing results when the TSA is only twisted. Section 5 details the modeling results of the TSA during actuation and self-sensing. Section 6 showcases the application of the proposed TSA to a compliant robotic gripper. Finally, Section 7 concludes this study and proposes future directions to explore with the proposed TSA.

2. Actuator Design and Fabrication

Below, decisions on the materials, string thicknesses, fabrication processes, and experimental procedures for the proposed TSA are discussed.

Firstly, the compliance of the SCP strings means increased loads elongate the TSA. Stiffness measurements are taken to quantify the compliance of the resulting TSAs. Because the TSAs may have different lengths, the stiffness normalized to the length is reported, consistent with existing studies. Instead of N/m, the normalized stiffness has units of N.

Secondly, TSAs consisting of two strings of equal length will be adopted in this study. TSAs can be fabricated from different numbers of strings, but using two strings is most common. For combined twisting-induced and thermally-induced actuation, the TSA is fabricated from one or two conductive SCP strings, as shown in Fig. 1 (left). It is observed that TSAs made from one UHMWPE string and one SCP string underwent negligible length change under applied voltage. For self-sensing, two string configurations are studied during twisting-induced actuation. In the first configuration, the TSA is fabricated from one regular Dynema string and one conductive SCP string. The SCP string undergoes detectable resistance change as the TSA contracts. The inextensible string made from braided UHMWPE allows the TSA to support heavier loads. In the second self-sensing scheme, the TSA is fabricated from two SCP strings.

Thirdly, for actuation and self-sensing, TSAs with different diameters are studied, which is determined by the ply number. The ply number is the number of silver-coated nylon threads used to fabricate each string. This study utilized silver-coated nylon 66 threads (110/34 dtex Z turns High Conductive Yarn, V Technical Textiles). When the TSA is utilized for combined twisting-induced and thermally-induced actuation, relatively thin strings are utilized. Thin strings allow for quicker Joule heating and therefore quicker actuation. 3-ply and 4-ply strings are tested with diameters of 0.72 mm and 0.89 mm, respectively. The diameter of the resulting TSA depends on the amount of actuation – its diameter increases as the TSA linearly contracts via motor rotations or Joule heating. When the TSA is utilized purely for self-sensing, both thin and thick strings are studied. In this study, 4-ply strings are considered thin and 8-ply strings are considered thick. Thick strings are tested for self-sensing because of their ability to support heavier loads, making them suitable for practical robotic applications where high strength is necessary.

Finally, the TSA will contract when the motor rotates, but only up to a limited amount. The maximum contraction is reached at the maximum input voltage and maximum motor rotations. The maximum voltage is the greatest voltage at which the SCP string does not overheat and break. The maximum number of motor rotations is when additional rotations do not cause additional actuation, but instead buckle and eventually snap the strings.

The fabrication of the proposed TSA consists of four steps. The schematic of the procedure is shown in Fig. 2.

Figure 2. The fabrication process of the proposed TSA is composed of four steps: coiling, heat treatment, twisting, and a second heat treatment.
2.1. Step 1: Coil Conductive Nylon Threads

Firstly, a given number of conductive nylon threads are attached to a motor shaft and hung vertically. A load suspended from the threads keeps them under tension while ensuring they remain fixed at the bottom. Previous studies found that SCPs achieve poor performance under low amounts of tensions or no tension at all.\textsuperscript{20,24} The motor rotates clockwise until the threads form spring-like coils. The coiled structure is then stabilized by double-backing the threads, which balances the torque induced from twist insertion. This process follows our previous approaches.\textsuperscript{33,34} If SCP strings are not thermally actuated and only used for self-sensing in TSAs, the fabrication of the SCP string is finished in this step. In that case, the SCP strings from this step can be combined to form a TSA, as long as the strings have equal length and diameter. If the strings will be actuated thermally, additional steps are required.

2.2. Step 2: Heat Treat SCP Strings

Next, the SCP strings from Step 1 are annealed via Joule heating, in which voltage pulses are applied to the strings while the strings suspend a load.\textsuperscript{20,21} An alternative method is oven heat treatment.\textsuperscript{20} Approximately 10 cycles of heat treatment are necessary, with voltage on for 7 s to 10 s and off for 90 s. The peak voltage was 24 V. The peak current depended on the electrical resistance of the SCP string. 3-ply and 4-ply SCP strings had peak currents of 0.53 A and 0.70 A, respectively. The optimal load during heat treatment also depended on the diameter of the SCP string. For 3-ply and 4-ply SCP strings, 150 g and 200 g were used, respectively. An SCP string is sufficiently heat treated when its resting length no longer increases between cycles. The SCP string should generate approximately 15% strain consistently. Attempts to heat treat past 15% strain led to increased chances of breakage. The maximum attainable strain may depend on various factors, such as the string material, thickness, voltage pulse width, and pulse amplitude. Because SCP-based TSAs have not (to our knowledge) been realized by other research groups, there is no direct comparison to other research groups’ studies. However, the maximum thermally-induced strain of an individual SCP string in the literature (not twisted in the TSA configuration) vary between approximately 10%\textsuperscript{21} and 20%.\textsuperscript{20}

2.3. Step 3: Fully Twist Two SCP Strings

After heat treating individual SCP strings in Step 2, two SCP strings can be used to form a TSA. In a TSA, the top ends of the string are fixed to a motor’s shaft. At the bottom ends of the strings, linear movement toward or away from the motor must be permitted but rotation must be restricted. To keep the compliant strings taut, a load is also suspended from the bottom of them. During preliminary experiments, it was observed that SCP-based TSAs loaded with no mass exhibited negligible thermal-based actuation. The magnitude of the load is the same amount used during experiments. The motor then rotates until the TSA achieves its maximum possible strain. Because the motor rotates clockwise in Step 1, the motor also rotates clockwise in this step. When the two SCP strings are fully twisted about each other, contact between them is maximized and another heat treatment process can be conducted.

2.4. Step 4: Heat Treat Twisted SCP-Based TSAs

Lastly, the fully-twisted SCP-based TSA is heat treated. In addition to heat treatment in Step 2, the SCP strings in this configuration were found to require additional heat treatment. This is likely because the strings are now in a new configuration. Instead of hanging individually, the two SCP strings hang together, twisted in tight physical and electrical contact. As in Step 2, voltage pulses heated the strings in cycles. Heat treatment in this step is also complete when the TSA demonstrates consistent 15% thermally-activated strain. The amount of cycles and peak voltage needed to obtain this strain varied. For two 3-ply SCP strings, five cycles were sufficient. Each cycle consisted of voltage on for 10 s and off for 100 s. The peak voltage was 10 V and the peak current was 0.86 A. The peak voltage in this step is lower than in Step 2. In this step, the overall structure is thicker and shorter because the SCP strings are fully twisted together. Consequently, the electrical resistance between each end of this structure is lower than in Step 2. Lower electrical resistance means greater electrical power when the same voltage is applied. To compensate and prevent the actuators from burning, the peak voltage was lowered based on experiments.

2.5. Experimental Setup

A model and photograph of the experimental setup is shown in Fig. 3. The timing and magnitude of inputs (rotations to the motor and voltage across the SCP strings) are controlled through a 16 MHz microcontroller based on the ATmega2560 microchip. The stepper motor (NEMA 17HS4401) is driven by an A4988 driver. The constant voltage for Joule heating to the TSA is regulated with a
P-channel MOSFET and pulse-width modulations (PWM) from the microcontroller. An analog magnetoresistive position sensor (SPS-L225-HALS, Honeywell) with a sensing range of 225 mm and a resolution of 0.14 mm tracked the actuators’ contractions. Analog-to-digital conversions of the sensor’s position measurements were conducted at 20 Hz with a 14-bit National Instruments USB-6001 data acquisition device and a LabVIEW virtual instrument. Electrical resistance measurements were taken with a digital multimeter (NKTECH VICI VC480C+) at a resolution of 0.01 Ω. Resistance measurements were conducted at 20 Hz with a 14-bit National Instruments USB-6001 data acquisition device and a LabVIEW virtual instrument. Electrical resistance measurements were taken with a digital multimeter (NKTECH VICI VC480C+) at a resolution of 0.01 Ω. Resulting resistance values were recorded, and the system setup can be observed, but this is also consistent with previous work. The results in Fig. 4 exhibit mild hysteresis, which is consistent with previous studies.

The stiffness of the SCP string was found by approximating the Length – Load relationship with a linear fit. Fig. 4b shows the strain modeling error as a percentage of the experimentally-obtained strain. The average absolute modeling errors were computed to be 0.37±0.57 cm and 0.27±0.42 cm for 3-ply and 4-ply strings, respectively. Based on the linear model, the 3-ply and 4-ply strings were computed to have normalized stiffnesses of 24.61 N and 31.88 N, respectively. “Index” in Fig. 4b is the numbering of experimentally-obtained length values. Because it is normalized to the length unit, normalized stiffness has units of N instead of N/m. SCP strings are shown to be significantly more compliant than conventional TSA strings. Previous work has considered the viscoelastic properties of SCP strings. However, applying viscoelastic theory to model the compliance of the individual SCPs and SCP-based TSAs is beyond the scope of this study.

The normalized stiffnesses of 3-ply and 4-ply TSAs are given in Fig. 4c as a function of contraction percentage. While the stiffness is mildly hysteretic (Fig. 4c), the stiffness of each TSA generally decreases as contraction increases. This relationship is consistent with stiff strings in existing studies. Mild fluctuations in stiffness due to noise and the system setup can be observed, but this is also consistent with previous work. A previous study by Palli et al. on the modeling and control of TSAs obtained the normalized stiffness as a function of motor rotations. Palli et al. found that the stiffness of 20 N-loaded and 30 N-loaded TSAs peaked at approximately 16 motor rotations, then generally decreased as motor rotations increased. In this study, the stiffness was calculated by measuring the changes in length due to changes in loading. It is shown that the stiffness of each TSA is generally lower than the stiffness of corresponding 3-ply and 4-ply strings. TSAs made from 4-

![Figure 4](image_url)

**Figure 4.** (a) The measurements of length and load of single SCP actuators used to calculate their stiffness. (b) The error of the linear model of the stiffness of the SCP strings calculated at each data point. (c) The calculated normalized stiffness of the 3-ply and 4-ply TSAs as a function of contraction percentage.

## 3. Actuation Performance

### 3.1. Performance Metrics

For TSAs actuated by heat and motor rotations in this section, the contraction of the TSA, \( \Delta x_u \), is evaluated according to the equation below:

\[
\Delta x_u = \frac{x_1 - x}{x} \times 100\%,
\]

(1)

where \( x_1 \) is the length of the loaded TSA with no twists or voltage inputs. \( x \) is the length of the TSA after twisting and/or voltage inputs.

The stiffness of the proposed TSAs is quantified by the equation below. Stiffness is inversely proportional to length, so in this study the normalized stiffness with respect to length is reported.

\[
K = \frac{F \cdot L_0}{L - L_0},
\]

(2)

where \( K \) is the normalized stiffness with respect to length, \( F \) is the applied load, \( L_0 \) is the length of the actuator with no load, and \( L \) is the length of the actuator under the loading force of \( F \).

### 3.2. Compliance

Firstly, the compliance of the SCP strings was quantified by their normalized stiffness. To obtain this metric, loads were suspended from the strings in increasing and decreasing sequences. Each load remained on the string for 60 s, to ensure the length reached its steady state. The length of the SCP string was then recorded, similar to our previous work. The results in Fig. 4a exhibit mild hysteresis, which is consistent with previous studies.

In this study, the stiffness of each TSA is quantified by the equation below:

\[
K \text{ (N)} = \frac{F \cdot L_0}{L - L_0},
\]

(2)

where \( K \) is the normalized stiffness with respect to length, \( F \) is the applied load, \( L_0 \) is the length of the actuator with no load, and \( L \) is the length of the actuator under the loading force of \( F \).

**Figure 4.** (a) The measurements of length and load of single SCP actuators used to calculate their stiffness. (b) The error of the linear model of the stiffness of the SCP strings calculated at each data point. (c) The calculated normalized stiffness of the 3-ply and 4-ply TSAs as a function of contraction percentage.
ply strings notably have greater stiffness because they are thicker. Utilizing relatively small changes in loading may decrease the fluctuations observed in Fig. 4c.

3.3. Twisting-Induced Actuation

In this case, SCP strings are passively used in TSAs and no heat is applied. The length of the TSA is measured at each corresponding number of motor rotations. The input motor rotations change as a function of time. Fig. 5a shows both the input motor rotations and corresponding contraction of a 4-ply TSA loaded with 250 g. The data shows the presence of mild disturbances that may have been caused by unaccounted friction in the setup. However, accounting for noise and disturbance is beyond the scope of the study.

TSAs made from thin 3-ply SCP strings were tested with three different loads: 100 g, 150 g, and 200 g. TSAs made from 4-ply strings are able to withstand slightly higher loads. Therefore, they were tested with 150 g, 200 g, and 250 g. The results for 3-ply and 4-ply strings are shown in Fig. 5b and 5c, respectively. Hysteresis between motor rotations and linear contraction exists in all experiments. This is likely due to the physical properties of the silver-coated nylon strings.\(^3\) In addition, friction likely exists between the two strings, as well as between plies within each string as the TSA is twisted.

3.4. Combined Twisting-Induced and Thermally-Induced Actuation

In this case, both motor rotations and Joule heating are applied to the TSAs to obtain a larger amount of strain. The SCP strings are considered active because of their ability to contract under applied heat, which is also utilized to further actuate the proposed TSA.

The experiment to obtain the maximum strain is conducted as follows: after fully twisting the strings, voltage inputs are monotonically applied in steps from zero to maximum, then back to zero, and the strings finally fully untwist. The maximum voltage varied according to the thickness and tension of the actuator. Too much voltage would burn and snap the actuator, while too little voltage would yield little movement. The maximum voltage is chosen as follows: first a number of extreme tests are conducted, then the maximum voltage is chosen to be slightly less than the extreme experiments. The voltage input sequence and resulting TSA contraction are plotted in Fig. 6a with respect to time. Note that the voltage sequence is slow, and it is expected that the steady-state temperature is obtained. For example, the pair of 4-ply SCP strings loaded with 250 g achieved a maximum contraction of 14.1\% via thermal actuation after initially twisting 81 full rotations. The contraction mildly fluctuates, which may have been due to small environmental disturbances or friction in the setup. Accounting for this was beyond the scope of the work. More work will be done in the future to improve the response of the TSA’s length to the input voltages to be smoother and more consistent.

Fig. 6b and 6c show the complete actuation of TSAs made from 3-ply and 4-ply strings, respectively. To compare the performance of each TSA fairly, each TSA was tested with the same loading and input motor rotations as when SCP strings were only used passively. As an example, for the TSA with 3-ply strings under 200 g load, the TSA achieved 13.49\% strain with passive strings and 27.01\% strain with active strings, showing a 13.51\% increase in maximum strain with thermally-induced actuation.

The comparison of maximum strain between active and passive strings is summarized in Fig. 6d (3-ply strings) and Fig. 6e (4-ply strings). TSAs made from 3-ply and 4-ply SCP strings averaged 29.10\% and 33.51\% maximum strain, respectively. These averages are 11.91\% and 8.05\% larger, respectively, than when TSAs are only twisted. When the strings are only twisted, 3-ply and 4-ply TSAs respectively achieved 17.19\% and 25.46\% maximum strain. As shown in Fig. 6d-e, when only twisting is used, the maximum strain of the TSAs depends significantly on their loading; however, when both heating and twisting actuated the TSA, the maximum strain changes less significantly with the amount of loading (except for the 100 g-loaded 3-ply TSA with active strings).

The temperature of the SCP-based TSA determines its length. The time for the proposed TSA to heat is relatively quick, but the time for it to cool is longer. Under a step voltage input, the SCP fully actuates within a few seconds, but the time for complete cooling is over one minute. This is because of the noticeable creep behavior due to inherent nylon material properties.\(^3\) This amount of time also increases as the thickness of the SCP strings increases. Capturing time-
dependent creep behavior is briefly discussed in Section 7 and accurate modeling is beyond the scope of this work.

4. Sensing Performance

The electrical resistance corresponding to each length was obtained for thin SCP string composed of four nylon threads. To cover the majority of the TSA actuation range, measurements were taken in the range of [20, 55] string twists, where each string twist equals one rotation of the motor. This rotation sequence, shown in Fig. 7a, led to a consistent Resistance – Length relationship, although other motor inputs can be used. For example, this input sequence led to approximately 25% strain of the TSA made from one Dyneema string and one thin SCP, as shown in Fig. 7b.

Two self-sensing schemes are studied: Scheme 1 and Scheme 2. The TSA in Scheme 1 consisted of one Dyneema string (approximately 1 mm thick) and one SCP string. The TSA in Scheme 2 consisted of two SCP strings. In general, TSAs were tested at masses appropriate for their string configuration. For example, TSAs made from 8 plies were tested with 700 g and 900 g load. In Scheme 1, 4-ply SCPs were tested at more weight than 4-ply SCPs in Scheme 2. The Dyneema string in Scheme 1 makes the TSA able to withstand greater loads than in Scheme 2.

4.1. Scheme 1: One SCP String and One Dyneema String

Resistance and length were measured at their steady states. Measurements were obtained at two different loading conditions: 450 g and 550 g. For both loading conditions, the self-sensing scheme was able to achieve approximately 25% contraction with thin strings. Results are shown in Fig. 7c for TSAs with 450 g and 550 g, respectively. It is noted that the contraction percentage is calculated with respect to the length at 20 twists. This method is chosen because the tested sensing range was [20, 55] turns. The initial lengths at 20 twists of the 450 g-loaded TSA and 550 loaded TSA were 28.0 cm and 28.1 cm, respectively.

As the TSA contracts, the resistance decreases. The self-sensing relationship between the length and resistance is evident with mild hysteresis. For this self-sensing scheme, this trend can be explained as follows: At a high number of motor rotations, the TSA becomes shorter. The distance between adjacent TSA coils also decreases, leading to less electrical resistance. At every contraction percentage, the 550 g loading condition has a higher resistance value than the 450 g loading condition at each corresponding contraction percentage. A larger loading makes the TSA longer, which also increases its electrical resistance. The experimental results are consistent with previous studies that utilized SCP strings as sensors.39

Similar to experiments with thin strings, experiments were also conducted with thick strings made from eight nylon threads. The same twisting range of [20, 55] rotations was utilized. The TSA in Scheme 2 consisted of two SCP strings. In general, TSAs were tested at masses appropriate for their string configuration. For example, TSAs made from 8 plies were tested with 700 g and 900 g load. In Scheme 1, 4-ply SCPs were tested at more weight than 4-ply SCPs in Scheme 2. The Dyneema string in Scheme 1 makes the TSA able to withstand greater loads than in Scheme 2.
Figure 7. (a) The input sequence of motor rotations as a function of time. (b) Linear contraction as a function of motor rotations for Scheme 1 with thin strings and attached 450 g and 550 g masses. The experimental results and polynomial modeling results modeling results for: Scheme 1 with (c) thin SCP strings, (d) Scheme 1 with thick SCP strings, (e) Scheme 2 with thin SCP strings, and (f) Scheme 2 with thick SCP strings.
strings is that while the 700 g loading allows 23.6% contraction, the TSA with 900 g only achieves 16.6% contraction. This is further evidence that increased loads decrease the maximum attainable strain, as previously shown in Fig. 6d–e.

4.2. Scheme 2: Two SCP Strings

In this self-sensing scheme, the TSA is composed of two SCP strings. This self-sensing TSA is of the same form as the compliant TSA with dual twisting-induced and thermally-induced actuation in Section 3.2 “Actuation”. Tests were conducted with TSAs made from thin strings (4-ply) and thick strings (8-ply).

The results for the thin-string TSAs are shown in Fig. 7e with attached weights of 250 g and 350 g. The initial lengths of these TSAs at 20 twists were 35.8 cm (with 250 g) and 36.1 cm (with 350 g). Similar to Scheme 1, resistance decreased as the contraction increased. Mild hysteresis is also present. Compared to the first self-sensing scheme, the correlation between length and resistance appears to be less hysteretic. This will be quantified by the Preisach hysteresis model and a third-order polynomial in Section 5, “Modeling”. The maximum contraction was greater with 250 g at 8.4%. With 100 g additional weight, the contraction decreased to 7.6%.

The tests with thick strings and weights of 700 g and 900 g are shown in Fig. 7f. For these experiments, the maximum contraction decreased even more. The initial lengths of these TSAs at 20 twists were 35.0 cm (with 700 g) and 36.1 cm (with 900 g). The TSAs with loads of 700 g and 900 g had maximum contractions of 7.0% and 6.9%, respectively. This low contraction further motivates the use of both thermal and twisting actuation to achieve large strains in Section 3, “Actuation Performance”.

For the quasi-static experiments, additional twisting caused decreasing steady-state resistance whereas untwisting caused an increase in steady-state resistance, under the condition that the TSA had at least five twists. However, after the TSA’s motor stopped turning, we observed that the resistance of the TSA exhibited noticeable decay over approximately two minutes, regardless of whether the strings were twisting or untwisting. However, the length of the TSA instantly reached its steady state after the motor rotated. Fig. 8 shows the transient resistance behavior of the TSA immediately after the motor finished rotating. The total resistance decrease in Fig. 8 is only 0.13 Ω, or 2.2% of the initial resistance. The resistance values are overall less than the other self-sensing experiments because, with an untwisted length of 14.0 cm, this TSA is shorter than the TSAs tested in Fig. 7. While the transient resistance signals are not thoroughly studied in this work, brief discussion on future work is provided in Section 7, “Discussion and Conclusion”.

5. Modeling

Using the geometry of the strings, dynamical models of twists versus length and angular speed versus linear contraction speed have been developed and verified for TSAs.9 In addition, the required motor torque to compensate for the tension in the strings at every motor angle within the working range has been modeled.12 The dynamical model of torque versus twists that accounts for string friction and compliance showed significant improvement over the static model.12 In this work, we focus on the quasi-static relationship of actuation under twisting and thermal inputs, as well as self-sensing between length and resistance. To capture the actuation and self-sensing properties of TSAs, the Preisach operator is proposed. A linear model is considered for comparison purposes.

5.1. Hysteresis Modeling

The hysteresis nonlinearity occurs in many materials, such as smart materials, elastic materials, and ferromagnetic materials.40,41 Because previous studies have revealed hysteresis in both TSAs and SCP actuators,15,21,42 the SCP-based TSAs in this study are expected to exhibit hysteresis. Although there are many ways to model hysteretic materials and structures, the Preisach model is one of the most effective and widely used. This model is composed of a weighted superposition or integral of a continuum of delayed relays.40,41 The weight distribution is discretized to facilitate the real-time implementation and computation of the Preisach operator.41 The model’s computational complexity increases as the discretization level, M, increases. A discretization level between 10 and 40 is most commonly chosen.40

5.1.1 Actuation The hysteresis model of the twisting-induced and thermally-induced actuation is the sum of two distinct Preisach models. The discretized Preisach model for twisting-induced actuation is:

\[ L_{\text{Preisach}}(T) = \sum_{i=1}^{M} \sum_{j=1}^{M+1-i} \lambda_{ij} w_{ij}(T) + b_T, \]  

where \( T \) is the input twists and \( b_T \) is a constant offset. \( \lambda_{ij} \) is the discretized weight identified from experiments and \( w_{ij}(T) \) is fully dependent on the input twist history.

Similarly, voltage-induced actuation can be described as:

\[ L_{\text{Preisach}}(V) = \sum_{i=1}^{M} \sum_{j=1}^{M+1-i} \mu_{ij} y_{ij}(V) + b_V, \]

where \( V \) is constant input voltage and \( b_V \) is the constant offset. The discretized weight \( \mu_{ij} \) is often different than \( \lambda_{ij} \) in...
Figure 9. The Preisach and polynomial modeling errors for SCP-based TSAs for (a) twisting-induced and thermally-induced actuation and (b) self-sensing during twisting based on the resistance measurement. (c) An example of the Preisach density function for heated 3-ply strings under 100 g load. (d) An example of the identified Preisach weights for Scheme 2 with thin strings and attached 250 g mass. (e) An example of the percentage modeling error from the Preisach and polynomial models for Scheme 2 with thick strings and attached 700 g mass.

Eq. 3. \( y_{ij}(V) \) fully depends on the input voltage history. The discretization level \( M \) remains the same as in Eq. 3. It is noted that the constant voltage can be considered as a surrogate of temperature, and the correlation between constant voltage and length of SCP strings has been considered in our recent studies.\(^{34,43}\) Other artificial muscles also require the use of temperature surrogate when a direct temperature measurement is not available. For example, a 2016 study used electrical current as a temperature surrogate in self-sensing of vanadium oxide microactuators.\(^{44}\) A first-order thermoelectric model can also relate the electrical power across an SCP to its temperature.\(^{21}\)

To find the overall length of the TSA, the outputs from twisting-induced and voltage-induced actuation are summed:

\[
L = L_{\text{Preisach}}(T) + L_{\text{Preisach}}(V),
\]

where \( L \) is the overall length of the TSA. In reality, the effects of voltage and twists on the length of the TSA may be coupled. However, during this study, the TSA is heated only after being fully twisted. In other words, this model does not apply when heat and twists are applied to the TSA simultaneously or in an arbitrary order. Future work on the coupling between voltage and twists would allow for a more robust model.

5.1.2 Self-Sensing Similar to actuation, self-sensing during twisting can be captured by a Preisach operator with different values of parameters. The equation for the relationship between electrical resistance and length is given below:

\[
L_{\text{Preisach}}(R) = \sum_{i=1}^{M} \sum_{j=1}^{M+1-i} \xi_{ij} z_{ij}(R) + b_R,
\]

where \( R \) is the electrical resistance and obtained experimentally. \( b_R \) is a constant offset. The discretized weight is \( \xi_{ij} \) and \( z_{ij} \) depends fully on the experimentally obtained resistance history. The identification of the Preisach model can be worked out as a linear least-squares problem and solved with the MATLAB function \texttt{lsqnonneg}. The Preisach model is explained in more detail in previous studies.\(^{41,45,46}\)

5.2. Polynomial Modeling

The polynomial model, given by the equation below, is used to predict the length of the string under a certain input (voltage, motor rotations, or electrical resistance).

\[
L_{\text{Poly}}(q) = \sum_{i=0}^{k} p_i q^i,
\]

where \( L_{\text{Poly}} \) denotes the TSA’s length predicted by the
model. Depending on the experiment, \( q \) can be the input voltage \( V \), motor turns \( T \), or electrical resistance \( R \). The order of the polynomial is \( k \) and the coefficient of the \( i^{th} \) term is \( p_i \). An order of up to \( k = 3 \) was chosen to model every relationship for low error yet low computational complexity. The coefficients of the polynomial are identified with the MATLAB function \textit{polyfit}. The results of the polynomial model are compared to the Preisach models that account for hysteresis.

### 5.3. Evaluation Metrics

The performance of each model was evaluated using the average absolute error, \( E_{\text{aver}} \) and standard deviation, \( \sigma \).

\[
E_{\text{aver}} = \frac{1}{N} \sum_{i=1}^{N} |e_i|, \quad (8)
\]

\[
\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (|e_i| - E_{\text{aver}})^2}, \quad (9)
\]

where \( N \) is the number of evaluated data points and \( e_i \) is the error of the \( i^{th} \) data point.

### 5.4. Actuation Modeling

Preisach operators and polynomials captured the quasi-static relationship between input (twisting or heating) and output (length). Models are obtained for the data collected in Section 3.4. Because each experiment applied two types of input to each actuator, each experiment requires two distinct Preisach or polynomial models. For all Preisach models, the level of discretization, \( M \), is chosen to be 20. Further increasing \( M \) will not generate appreciably better modeling results, but will further increase the computational complexity of the model. The modeling results are summarized in Fig. 9a. Polynomial coefficients for each loading condition, input mode, and string thickness are given in Table I.

#### 5.4.1 Input Mode 1: Twisting

The average Preisach modeling error due to twisting for all cases is 0.0265 ± 0.0346 cm. As seen in Fig. 9a, the maximum average modeling error occurred for the condition of 4-ply strings with 150 g load at 0.0622 ± 0.0601 cm. However, for all other cases, the average modeling errors were much less than 0.06 cm, which is extremely small compared to the mean length change of 3.927 ± 0.845 cm due to twisting.

Third order polynomials capture the relationship between length and twists reasonably well. Fig. 9a shows that for every loading condition, the average error is no more than 0.2131 ± 0.1304 cm. Considering all string thicknesses and loading conditions, the average polynomial modeling error is 0.1673 ± 0.0956 cm. The polynomial models have average errors more than six times larger than that of the Preisach hysteresis models in TSAs with twisting as the input mode. Much of the modeling error is due to the fact that the polynomial model does not capture the hysteresis in the SCP strings. The coefficient of the third-order term, \( p_3 \) was computed to have an absolute value of less than 4.1 × 10⁻⁶ cm/³ for all loading conditions and both string thicknesses (ply numbers) when twisting is the input mode. This means the strain may be effectively modeled through a second-order polynomial. Geometry-based models derived for stiff-string TSAs in the literature are also second-order.¹³

#### 5.4.2 Input Mode 2: Heating

The thermally-induced actuation demonstrates the benefit of the Preisach hysteresis model over third-order polynomial models. Although the modeling error varies over different cases, the Preisach modeling error of all heated and twisted strings averaged 0.0228 ± 0.0308 cm and 0.0265 ± 0.0346 cm, respectively (Fig. 9a). Since the average overall length change from heating is 3.117 ± 0.863 cm, the Preisach model can accurately capture the actuation behavior. As an example, the discretized weights \( u_{ij} \) are shown in Fig. 9c for heated 3-ply strings under 100 g load. As shown, most of the weight terms are located outside of diagonal regions, which are to describe the significance of the hysteresis.⁴⁴

Using third order polynomial models, the mean modeling error for heated strings is greater than that of twisted strings, as shown in Fig. 9a. The thermally-induced actuation (Length – Voltage) shows more significant hysteresis than the twisting-induced actuation (Length – Twisting). Although second-order polynomials were sufficient to capture the twisting-induced actuation, the thermally-induced actuation requires the third order term, \( p_3 \). Table I shows \( p_i \) for the heated strings. The third-order terms are quite low. The greatest value of \( p_3 \) is 0.034 cm/³, which was obtained for 4-ply strings under 150 g load. The lowest value of \( p_3 \) is only 0.001 cm/³, which was obtained for for 3-ply strings under 200 g load. The value of \( p_0 \) increases as the applied load increases for both 3-ply and 4-ply strings. This is because the low stiffness of the SCP strings makes their lengths increase significantly as the applied load increases.

### Table 1. Identified parameters of the third-order polynomials for TSAs with twisting and heating inputs.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Load</th>
<th>( p_0 )</th>
<th>( p_1 )</th>
<th>( p_2 )</th>
<th>( p_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-ply (Twisting)</td>
<td>100 g Load</td>
<td>28.54</td>
<td>-0.010</td>
<td>-0.001</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>150 g Load</td>
<td>30.01</td>
<td>-0.024</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>200 g Load</td>
<td>34.56</td>
<td>-0.029</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>4-ply (Twisting)</td>
<td>150 g Load</td>
<td>28.38</td>
<td>-0.002</td>
<td>-0.001</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>200 g Load</td>
<td>30.93</td>
<td>-0.011</td>
<td>-0.001</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>250 g Load</td>
<td>32.32</td>
<td>-0.017</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>3-ply (Heating)</td>
<td>100 g Load</td>
<td>23.69</td>
<td>-0.10</td>
<td>-0.08</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>150 g Load</td>
<td>25.71</td>
<td>0.32</td>
<td>-0.19</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>200 g Load</td>
<td>32.14</td>
<td>-0.32</td>
<td>-0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>4-ply (Heating)</td>
<td>150 g Load</td>
<td>23.94</td>
<td>0.673</td>
<td>-0.398</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td>200 g Load</td>
<td>26.51</td>
<td>0.082</td>
<td>-0.184</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>250 g Load</td>
<td>31.68</td>
<td>-0.331</td>
<td>-0.046</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Table 2. Identified parameters of the third-order polynomials for the self-sensing behavior in TSAs.

<table>
<thead>
<tr>
<th>Scheme 1, Case 1</th>
<th>$p_0$</th>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$p_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 g Load</td>
<td>-506.75</td>
<td>62.87</td>
<td>-2.49</td>
<td>0.0330</td>
</tr>
<tr>
<td>550 g Load</td>
<td>-443.20</td>
<td>53.80</td>
<td>-2.07</td>
<td>0.0268</td>
</tr>
<tr>
<td>Scheme 1, Case 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 g Load</td>
<td>-170.84</td>
<td>39.14</td>
<td>-2.52</td>
<td>0.0544</td>
</tr>
<tr>
<td>900 g Load</td>
<td>-72.34</td>
<td>17.62</td>
<td>-0.99</td>
<td>0.0187</td>
</tr>
<tr>
<td>Scheme 2, Case 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 g Load</td>
<td>-40.54</td>
<td>12.63</td>
<td>-0.73</td>
<td>0.0148</td>
</tr>
<tr>
<td>350 g Load</td>
<td>-81.32</td>
<td>20.41</td>
<td>-1.22</td>
<td>0.0246</td>
</tr>
<tr>
<td>Scheme 2, Case 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 g Load</td>
<td>-21.36</td>
<td>16.66</td>
<td>-1.73</td>
<td>0.0625</td>
</tr>
<tr>
<td>900 g Load</td>
<td>-5.98</td>
<td>11.13</td>
<td>-1.03</td>
<td>0.0337</td>
</tr>
</tbody>
</table>

5.5. Self-Sensing Modeling

Preisach models and third-order polynomials captured the relationship between resistance and length for different self-sensing schemes with different loading conditions and string thicknesses. The resistance values were taken as inputs to predict the lengths of the TSAs. For all self-sensing models, the discretization level $M$ of the Preisach operator was chosen to be 20. The typical discretized weights $\xi_{ij}$ in the hysteresis models are shown in Fig. 9d. As shown, the major weights are mostly located in the diagonal region, which is responsible for describing the hysteresis-free correlation — the twisting-induced hysteresis is less evident. Each loading condition and string thickness is captured by the model.

Self-sensing models were realized only during twisting-induced actuation in this study due to the potential coupling between resistance and temperature during thermal actuation. For that reason, thermal actuation is recommended only when large actuation is required, because of three main reasons below.

1. It is difficult to ensure uniform temperature of the proposed actuator during thermal actuation.
2. The thermal model of this proposed actuator has not yet been studied.
3. Self-sensing during thermal actuation may depend on a number of factors, such as actuator temperature, ambient temperature, air flow, and humidity.

Previous studies have shown that the temperature of a single SCP actuator during thermal actuation is highly non-uniform. The proposed actuator in this study is more complicated because it is composed of two SCP actuators twisted about each other, with each Joule-heated via conductive silver coating. Thermal properties of individual SCP actuators have been studied, but for our proposed actuator, behaviors such as time constants during heating and cooling and voltage-temperature correlations have not yet been studied. The potential coupling between resistance and temperature is also indicated by the stress-deformation responses of a single SCP actuator at various temperatures.

The polynomial coefficients for the self-sensing experiments are provided in Table II. The modeling results are shown in Fig. 9b. Scheme 1 had greater modeling error than Scheme 2 for every string thickness and loading condition. That behavior occurs for both polynomial and Preisach hysteresis models. In particular, the TSAs of Scheme 2 with 8-ply SCPs and high loading had the least amount of polynomial modeling error, which indicates a relatively low amount of hysteresis (Fig. 9b). Although modeling errors are larger for Scheme 1 on average, the TSAs in Scheme 1 also have a larger range of contraction.

5.5.1 Scheme 1: One SCP String and One Dyneema String

For all loading conditions and thicknesses, the average Preisach modeling error is 0.0793±0.1536 cm for Scheme 1. Strings with lower loading had greater Preisach modeling error than strings with higher loading, similar to when polynomial models were utilized.

Third-order polynomials revealed an average modeling error of 0.2256±0.2093 cm for all loading conditions and string thicknesses, as shown in Fig. 9b. The average overall length change for this self-sensing scheme is 6.947±0.808 cm. For Scheme 1, thin and thick strings have less polynomial modeling error at the greater loading conditions.

5.5.2 Scheme 2: Two SCP Strings

The average Preisach modeling error was extremely low for Scheme 2 at only 0.0057±0.0159 cm for all strings with different values of thickness and under different loading conditions. On average, the overall length change of the TSA is 2.673±0.251 cm. This average length change is less than half that of Scheme 2. Thin strings with high loading have the most modeling error, at 0.0115±0.0282 cm. The lowest modeling error occurred for thick strings with low loading, at 0.0027±0.0063 cm. An example of the modeling errors from Preisach and polynomial models is given in Fig. 9e, in this case for two SCP strings with 700 g attached. "Index" is the numbering of quasi-static length values. In Fig. 9e, the modeling error is displayed as a percentage of the measured length, which changes slightly for each index.

The average polynomial modeling error for Scheme 2 is 0.0588±0.0366 cm, approximately one-fourth of the average polynomial modeling error of strings in Scheme 1. At high and low loading conditions, thick (8-ply) strings had less modeling error than thin (4-ply) strings, as shown in Fig. 9b. It is noted that Scheme 1 and Scheme 2 have, on average, comparable modeling error percentages, since Scheme 2 has less modeling error and a smaller contraction range.

6. Compliant Gripper

The SCP-based TSAs were applied to a robotic gripper (Fig. 10). Consisting of three robotic fingers, it is designed to gently yet securely grip objects. Each finger was designed based on a modified version of the Fin Ray® Effect, where applied force to the side of the structure causes it to bend inward to the object, thereby providing better grip. Each finger
Figure 10. (a) The gripper’s finger in the open and closed configuration. (b) The antagonistic configuration of the two TSAs attached to a hinge that rotates the finger. The gripper can gently grasp various objects, such as (c) a spool of fishing line, (d) a potato chip, and (e) an eggshell.
and twisting the SCP-based TSA. Another advantage is that self-sensing may be achieved by measuring the resistance of the SCP-based TSA.

When the finger is not actuated (both TSAs are fully untwisted), the resistance is 20.3 Ω. When the finger is rotated fully inward, the SCP string was found to have a resistance of 26.9 Ω. When the finger rotates inward, the SCP string stretches and its resistance consequently increases. Future work will include the control of the gripper based on self-sensing strain feedback. One possible future application of this type of robot is in food processing facilities, where the robot must safely interact with delicate food items. While heat may be generated to power the proposed TSA, the strain can be generated to the end-effector over a distance. The gripper showcases the benefits of using compliant and large-strain TSAs with promising self-sensing potential during twisting-induced and thermally-induced actuation.

### 7. Discussion and Conclusion

The proposed TSAs show promising potential in soft robotic systems in terms of compliance, large strain, and twisting-induced strain self-sensing. The compliance of the TSA can be tuned by changing the diameters and number of strings. Two modes of actuation, twisting-induced and thermally-induced, lead to large strains compared to either actuation mode by itself. Clear relationships between length and electrical resistance allow for accurate twisting-induced strain self-sensing. Quasi-static actuation and twisting-induced self-sensing properties are both accurately captured by the Preisach operators. The SCP-based TSAs are applied to the gripper with low cost and low manufacturing complexity. There are several limitations which may be overcome through future studies.

Firstly, future SCP-based TSAs may be studied with different diameters or string numbers. This study used relatively thin strings for thermal actuation, with diameters of less than 1.0 mm. In addition, all TSAs were made with two strings each. The compliance, actuation, and self-sensing performance of the TSAs may significantly change if, for example, three strings are twisted instead of two. In addition, the thickness of the strings would affect the time for the actuator to reach its steady-state temperature when heated.

Secondly, more ways of combining the twisting-induced and thermally-induced actuation may be studied. In this study, the actuator was heated only after being fully twisted. The potential challenge of considering the twisting-induced actuation and thermally-induced actuation is their potential coupling. Indeed, when the TSA is twisted at different stages, the heat conduction and convection properties may be different due to the different actuator configurations. Meanwhile, when the TSA contracts under thermal activation, the TSA has different lengths and string diameters, thus the twisting-induced actuation will also be different. To deal with this, the model may consist of three components, namely, twisting-induced actuation, thermally-induced actuation, and a coupling term. In addition, self-sensing using electrical resistance can also be explored during thermal actuation. In this study, self-sensing correlations were found when the TSA was twisted but not heated. The resistance of the TSA may be strongly coupled to temperature as well as length. Because resistance varied with length during twisting, the resistance may vary during thermal actuation as well.

Thirdly, the self-sensing correlations obtained via experiments failed to account for factors that would affect the real application, such as the transient response and potential creep of resistance measurements over many cycles due to inherent nylon material properties. During experiments, resistance readings on the multimeter gradually decreased within the first two minutes after the motor rotated. In a robotic application, the transient response would need to be understood in order to accurately determine the position of the actuator. In addition, perhaps studying relative changes in resistance, instead of absolute resistance, can reveal insight that allows for more useful self-sensing. Also, payload and motor rotation history may have a significant effect on the resistance measurement.

Another limitation is that only a small number of discrete loading conditions are tested and modeled in this study. In practice, the load on the actuator may vary continuously over a range. The payload limits of the TSAs were also not formally tested. In future work, more comprehensive experiments can be conducted that determine the performance of SCPs due to variations in loading. Force-sensing capabilities using resistance measurements can be explored in the future. In this study, separate models were obtained for each experiment, depending on the load and thickness of the actuators. In the future, a robust model should be obtained that accounts for hysteresis, creep, transient resistance change.

In addition, using a robust self-sensing model, position feedback control can be developed in the future without any external sensors. Continuous resistance measurement could allow the length of the TSA to be driven to setpoints quickly and accurately. In a robotic hand, for example, future iterations may possess self-sensing feedback controls for smooth and precise control of each finger’s rotation angle. The controller would need to function without knowing the number of motor rotations or temperature of the actuator. One interesting possible problem may be to compute the individual contribution of the thermally-induced actuation and twisting-induced actuation based on specific scenarios. For example, in areas where compactness and lightweight are important, thermally-driven actuation will be the main actuation method, whereas for applications where the generated heat may be undesirable, the twisting is considered as the major input variable.

Finally, the actuation of SCP-based TSAs through both heating and twisting presents challenges related to its high temperatures, lifetime performance, efficiency, and force output. During human-robot interaction, high temperatures of the SCP strings could harm the user. This issue can be avoided through thermal insulation, rapid cooling between actuation cycles, or motion transmission over a distance. A cooling system between cycles would enable quicker actuation and protect the user from harm. The cooling of SCP actuators has previously been explored with water, standing air, and forced air. When the actuator becomes hot, thermal insulation between the user and actuator could also protect the user. For widely-adopted robotic applications,
the lifetime and repeatability of the SCP strings would also need to be studied. The friction between the strings during twisting and untwisting may make them wear out quickly.

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