Design, Characterization, Modeling, and Comparison of Helically Wrapped Super-Coiled Polymer Artificial Muscles

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ABSTRACT

Super-coiled polymer (SCP) artificial muscles demonstrate a number of desirable properties, like high power density, inherent compliance, light weight, and low cost. However, the realization of their full potential in achieving appreciable robot motion is hindered by their limited strain or force generation capabilities. Fabricated with multi-thread nylon filament, non-mandrel-coiled SCP actuators can only generate up to 10–20% strain, and mandrel-coiled SCP actuators are often fragile and fail to produce large force consistently. This paper presents the design, characterization, and modeling of helically-wrapped SCP (HW-SCP) actuators. HW-SCP actuators exhibit the advantages of mandrel-coiled and non-mandrel-coiled SCP actuators simultaneously—they can produce 15–55% strain, and consistently lift more than 90 g of weight. The design parameters of HW-SCP actuators can be conveniently adjusted to tune the actuator’s performance. Furthermore, this work presents the first comprehensive comparative study of non-mandrel-coiled, mandrel-coiled, and HW-SCP actuators based on conductive multi-thread nylon filament. The correlations between strain and constant voltage were accurately captured by Preisach hysteresis models. The correlations between force and constant voltage were modeled by three low-order polynomial models. This work contributes to the development of high-performance artificial muscles and may facilitate optimal selection of SCP actuators under scenario-specific future studies.

1. Introduction

Robots are playing significant roles in our everyday uses, such as performing pick and place tasks at manufacturing sites, being social companions at homes, and helping with patient rehabilitation in hospitals. With robots becoming more ubiquitous, the demand for new materials that are lightweight and actuators that are cheaper and safer than hydraulic systems and conventional motors has increased dramatically [1]. High costs will make robots inaccessible to the general population. Since these robots are no longer operating behind locked cages, safety becomes even more important. Future robots will be driven by artificial muscles, which are defined as materials and systems that can alter their shapes when a physical or chemical external stimuli is applied [2, 3, 4]. The shifts in robot uses and the way consumers interact with robots have significantly increased the need for new artificial muscles. Miniature robots that will allow for minimally invasive operations are becoming possible with the application of shape memory alloy based actuation [5]. Pneumatic-based actuation has been widely explored due to their high force and strain appeal [6, 7]. For example, an intimate compression device based on fabric soft actuators demonstrate just how the human–robot interaction space is changing [8]. The requirement of an external pressure source limits the application of pneumatic-based actuators. Highly adaptive biomimetic soft robots driven by artificial muscles have shown a lot of promise [9, 3, 4].

As a recent artificial muscle, super-coiled polymer (SCP) actuators, or twisted and coiled actuators, produce repeat-
approaches, non-mandrel-coiling and mandrel-coiling, have been predominantly adopted.

Non-mandrel-coiled SCP actuators, as shown in Fig. 1(a), can be efficiently manufactured through twist-insertion and heat-treatment [10, 11]. They can be fabricated using nylon 6 mono-filament [23] or conductive silver-plated multi-thread nylon 66 filament [20]. The activation can be achieved by either Joule heating, as shown in Table 1, or direct temperature control using a heat gun, an oven or hydrothermal heat-treatment [10, 13]. Nylon 6 mono-filament is not conductive, a resistive wire is often used as a heater [27, 19]. The need for the heating element can complicate the fabrication process and require extra considerations in the process. This heating element needs to be compact enough that it does not significantly affect the size and dynamics of the actuator while being powerful enough to heat the actuator efficiently. Nevertheless, actuators made with nylon mono-filament have shown larger strain and force than that with nylon multi-filament, mainly due to their increased stiffness [23, 24]. Using the conductive multi-thread nylon filaments eliminate the need for additional heating element while allowing for Joule heating. Performing experiments using Joule heating is often convenient to ensure the ease in translation to practical SCP actuator-driven robots. It is easier for roboticists to control and carry electrical power and therefore better simulates the real world robotics application. Non-mandrel-coiled SCP actuators do not perform well at low tension conditions when the adjacent coils are not pulled apart [10, 28]. For better performance, the minimum load needs to be known in advance. The pre-tension requirement of non-mandrel-coiled SCP actuators reduce the applications that they can be leveraged in—the pre-tension from the actuators is often transferred into the system [28]. For applications in assistive robots, for example, the need for pre-tension reduces the level of comfort for the wearer [29]. In addition, non-mandrel-coiled SCP actuators can often generate strains no more than 10–20% [11, 20], limiting the possible motion of the SCP-driven robots. It is believed that the close distance between adjacent coils is partially the reason for small strain of the non-mandrel-coiled SCP actuators [11]. Nonetheless, non-mandrel-coiled SCP actuators often generate a considerable amount of force—a 1 mm diameter actuator could produce force of over 1 N [30, 31]. Non-mandrel-coiled actuators have also been fabricated out of other materials like polydimethylsiloxane (PDMS) and Spandex to further enhance their performance [32, 33, 34]. These materials are also not conductive and require an external heater.

Mandrel-coiled SCP actuators, as shown in Fig. 1(b), can be manufactured by wrapping twisted polymer threads around a mandrel to form coils [10, 13]. Nylon 6 mono-filament and nylon 66 conductive silver-plated multi-filament are widely adopted, as shown in Table 1. The performance of the actuation is partially dependent on the heating method and the duration of the actuation. For example, the mandrel-coiled actuators in [22] are activated using Joule heat for an actuation duration of 2 seconds. These actuators can generate strain levels of up to 49%, and operate without pre-tension [10, 35]. Unlike the non-mandrel-coiled actuators, the manufacturing method for mandrel-coiled actuators allow for the adjustment of the space between adjacent coils. It has been demonstrated that the highly coiled polymer threads can provide incredible increase in the strain performance but suffer from low force outputs [10]. The low forces mean that mandrel-coiled SCP actuators cannot support substantial loads, and form fragile coil structures, limiting their potential for practical applications where sufficient force is needed. The low stiffness of the polymer threads is partially attributed to the mandrel-coiled SCP actuators being weak [10]. Even though the mandrel-coiled SCP actuators can be embedded in soft robot media without residual tensions transferred to the media, the low force generation will result in poor capability to generate appreciable robot motion. While large achievable strain is attractive, the low force of mandrel-coiled SCP actuators may significantly challenge their uses in real-world scenarios like soft robotics.

In our recent work, initial performance of the helically wrapped (HW)-SCP actuators was presented [36]. This conference paper was presented at the 2020 IEEE International Conference on Robotics and Automation. However, the study focused on the design and testing of HW-SCP actuators, but not detailed analysis of the obtained measurements. Furthermore, the performance of the HW-SCP actuators was not compared with other SCP actuators with similar sizes and configurations. The HW-SCP actuator, as shown in Fig. 1(c),
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is designed and manufactured such that it exhibit the advantageous characteristics of the non-mandrel-coiled and mandrel-coiled SCP actuators. Non-mandrel-coiled SCP actuators produce high forces but limited strains due self-coiling. Self-coiling allows for the formation of a structure with coils in contact with adjacent coils which limits strain production. Mandrel-coiled SCP actuators produce limited force but large contractions due to controllable separation of adjacent coils. The HW-SCP actuator is manufactured by wrapping a non-mandrel-coiled SCP actuator around a mandrel to form a helically coiled structure. In this way, the HW-SCP actuator has a large stiffness and a controllable distance between adjacent coils. Using non-mandrel-coiled SCP actuator as the precursor fiber provides three benefits: Firstly, it increases the strain of the HW-SCP actuator — the non-mandrel-coiled SCP actuator can generate 10–20% contractions while the nylon threads can only produce 2–5% contractions at the most [10, 37]; Secondly, it increases the structural stability of the HW-SCP actuator. The non-mandrel-coiled SCP actuator has a much more stable structure than the precursor fiber of the mandrel-coiled SCP actuators (a bundle of nylon multi-filament); Lastly, it increases the stiffness of HW-SCP actuators. Our study confirms thatHW-SCP actuators have three design parameters, namelyHW-SCP actuators, and the demonstration that they can generate large forces and large contractions; 2. The comprehensive performance characterization, and comparison, and analysis of non-mandrel-coiled, mandrel-coiled, and HW-SCP actuators made from multi-thread nylon filaments with different design parameters.

The contribution of this work is two-fold:

1. The design of a new configuration of SCP actuators, namely HW-SCP actuators, and the demonstration that they can generate large forces and large contractions;
2. The comprehensive performance characterization, and comparison, and analysis of non-mandrel-coiled, mandrel-coiled, and HW-SCP actuators made from multi-thread nylon filaments with different design parameters.

The comprehensive characterization and comparisons in this work may facilitate optimal selection of SCP actuators for different applications. This is effectively the development of a datasheet with essential information on the performance of the actuators with different design configurations and parameters. To our knowledge, this is the first comprehensive study to perform comparative analysis of SCP actuators with different configurations using Joule heating.

The rest of the paper is organized as follows: Section 2 presents the design and fabrication procedures. Section 3 provides the comparison metrics. Section 4 proposes the modeling approaches. Section 5 details the experimental setup. Section 6 presents the experimental results of the study. Finally, Section 8 concludes the findings of this work.

2. Design and Fabrication

2.1. Design

The non-mandrel-coiled SCP actuators have only one design parameter, the fiber diameter, \( d \), as shown in Fig. 2(a). The diameter can be modified by changing the number of filament threads (the ply number) of the precursor material. For this study, the twisting speed, twist density and the load were kept constant for all actuators.

Mandrel-coiled SCP actuators have three design parameters that are shown in Fig. 2(b), namely, the inner diameter, \( s \), the pitch, \( p \), and the fiber diameter, \( d \). The inner diameter, \( s \), is the diameter of the mandrel used during fabrication. It is expected that reducing the sizes of the mandrel will increment the stiffness of mandrel-coiled actuators. The pitch, \( p \), is the separation between two adjacent coils. The fabrication process allowed for the modification of the pitch. The pitch can also be modified under different loads. It is expected that the force and strain performance of the actuators will be influenced by the change in the pitch. When the pitch is very large, the mandrel-coiled actuators resemble nylon fibers.

HW-SCP actuators have three design parameters, similar to the mandrel-coiled actuators. These parameters are inner diameter, \( s \), the pitch, \( p \), and the diameter of the non-mandrel-coiled SCP actuator used for wrapping, \( d \), as shown in Fig. 2(c). The inner diameter, \( s \), and the pitch, \( p \), are defined in the same manner as for the mandrel-coiled actuators. For HW-SCP actuators, the actuator looks like a non-mandrel-coiled SCP actuator when the pitch is very large and will generate a small contraction. Fig. 2(d) shows HW-SCP actuators with different pitch values.

2.2. Fabrication Procedure

2.2.1. Non-mandrel-coiled SCP actuator

Non-mandrel-coiled actuators are manufactured through twist insertion of conductive silver-coated nylon fibers until coiling. First, a load of 18.75 g per thread was suspended on

![Fig. 2: The design parameters of the SCP actuators: (a) non-mandrel-coiled, (b) mandrel-coiled, and (c) HW-SCP actuators. (d) Samples of fabricated HW-SCP actuators with different configurations.](image-url)
the distal end, with a motor attached on the proximal end. Accordingly, the 4 ply actuator was suspended with 75 g. The ideal load ensures that the fibers are taut but do not rupture [10]. Heat treatment is then concluded when the actuator can consistently achieve 8–10% of strain. A stable structure can be conveniently achieved by double backing the coiled fiber [11, 38]. Similar methods have been used in other studies [30, 39]. It is important to note that the definition of ply is different from work in [21, 40]. 1-ply was not used in this work – it would be too thin to generate appreciable forces and strains. The diameter of 1-ply was approximately 0.06 mm. Thicker threads could also be used.

2.2.2. Mandrel-coiled SCP actuator

These actuators are fabricated through 4 steps [10], detailed as follows:

- **Step 1: Twist Insertion**: A load is suspended by nylon fibers as twist insertion takes place. Twist insertion is stopped at the onset of coiling. This procedure is useful because it has been shown that twisting fibers increase the strain performance of the actuator [10]. The load is chosen such that it is large enough to keep the thread taut but not too high that it leads to breakage.

- **Step 2: Oven Annealing**: The twisted nylon fibers from Step 1 are attached to an annealing fixture and heat-treated in the oven. In this work, the twisted fibers were heat-treated at 180 °C for a duration of 1 hour. Joule heating can also be used. Oven annealing was chosen for this study—it allowed for the simultaneous annealing of multiple actuators.

- **Step 3: Mandrel Coiling**: The heat-treated nylon fibers are then coiled around a mandrel using a mandrel fabricator. The mandrel diameter and pitch can be modified by changing the mandrel size and manufacturing parameters, respectively.

- **Step 4: Oven Annealing**: The coil structure of the mandrel-wrapped nylon fibers are heated in an oven for stabilization. The same temperature and duration used in Step 2 is again used in this step. It is noted that Joule heating can also be used.

2.2.3. HW-SCP actuator

The HW-SCP fabrication process is depicted in Fig. 3(a):

- **Step 1: Twist Insertion to Coiling**: Nylon threads are affixed to a motor and a weight is suspended to insert twist on the threads until the threads are fully coiled [30, 39]. Similarly, the load is chosen to keep the thread under high tension but not lead to breaking of the fibers during twisting.

- **Step 2: Joule Annealing**: The coiled structure from Step 1 is heat-treated through Joule heating. A load is suspended to keep structure taut while Voltage is applied across the thread [10, 11]. During this process, the coiled thread first elongates plastically. The process is complete once around 10% strain is achieved consistently. It was observed that HW-SCP actuators fabricated without performing this step showed poor performance.

- **Step 3: Mandrel Coiling**: HW-SCP actuators are manufactured by helically wrapping around a mandrel the actuator from Step 2, using a customized fabricator depicted in Fig. 3(b). The inner diameter and the pitch of the created HW-SCP actuator can be adjusted. The fabricator consists of three stepper motors: \(M_1\), \(M_2\), and \(M_3\). Motors \(M_1\) and \(M_2\) spin simultaneously in opposite directions, resulting in the mandrel to spin in one specified direction at a constant speed. \(M_3\) drives the carriage left or right by rotating the lead-screw which attaches to the carriage. The carriage consist of a compressed spring pusher and a pulley for routing SCP actuators into the mandrel. The pulley minimizes the friction the SCP actuator experiences when it is being wound. The pitch can be controlled by adjusting the speed of \(M_3\).

- **Step 4: Oven Annealing**: The mandrel-wrapped SCP structure is set in a temperature-controlled oven to form a stable coil structure. The temperature and duration for annealing are determined empirically. The idealized annealing temperature is higher than the operating temperature of the actuator, but lower than the
melting temperature of nylon. Annealing was performed at 180 °C for a duration of 1 hour in this study. Note that without step 2, the structure is not stable and performing further steps becomes difficult.

Both contracting and elongating motions can be attained by modifying the coil’s chirality [10]. In the current study, we focus on the contraction performance of HW-SCP actuators.

2.3. Fabrication Results
Non-mandrel-coiled SCP actuators with varying diameters were manufactured. Actuators of diameters 0.90 mm, 1.11 mm, and 1.34 mm, were manufactured.

Mandrel-coiled actuators with different inner diameters (s), and fiber diameter, (d) were created. Mandrel-coiled actuators with three different inner diameters of 0.13 mm, 0.25 mm, and 0.51 mm, were fabricated. The fiber diameters were 0.40 mm, 0.48 mm, and 0.56 mm, respectively.

HW-SCP actuators with varying inner diameters, and fiber diameters were fabricated. Similar to mandrel-coiled actuators, actuators with inner diameters of 0.13 mm, 0.25 mm, and 0.51 mm, were manufactured. The fiber diameters of the HW-SCP actuators used were 0.90 mm, 1.11 mm, and 1.34 mm, respectively.

As seen, for each type of SCP actuators, either their actuator diameters or inner diameters are the same, thus are appropriate for fair comparisons conducted in this work. All actuators were fabricated using silver plated conductive multi-thread nylon 66 filaments (110/34 dtex Z turns High Conductive Yarn, V Technical Textiles). It is noted that other materials can be used to construct SCP actuators that exhibit different performances [23, 24]. More discussions can be found in Section 8.

3. Performance Metrics of Interest
The actuators are compared based on the following properties: stroke, stiffness, pre-tension, force, and thermo-electric dynamics.

**Stroke** is defined as the maximum strain performance as given by the relation

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

where \( \Delta x_u \) is the strain, \( x \) is the actual length of the actuator when fully activated, and \( x_f \) is the actuator length when under a constant load with no electric power applied. Adopting this definition implies that the stroke of the actuator will always be less than 100% when the actuator is contracted. A number of existing works have adopted the actuator resting length for strain computations [11, 30, 10].

The **stiffness** is computed using the helical spring model given by [41]:

\[ k = \frac{4GJ}{\pi n D^3}, \text{ with } J = \frac{\pi d^4}{32}, \]  

where \( G \) is the shear modulus, \( J \) is the second moment of area, \( d \) is the diameter of the fiber, \( n \) is the number of coils, and \( D \) is the mean diameter of the coils. The force–strain behavior is hysteretic, and as a result, the stiffness–strain relationship also exhibit hysteresis [42]. Therefore, the average stiffness is used. From now on, average stiffness and stiffness will be used interchangeably.

**Pre-tension** is defined as the force of the actuator when no voltage is applied. Pre-tension provides a measure of the dependence of the actuator performance on initial load and this pre-tension requirement can significantly alter the performance of SCP actuators, as well as SCP actuators-driven robots.

**Force** is a measure of the amount of pull the actuator generates as it contracts.

The speed of the **thermo-electric dynamics** can be approximately measured using heating and cooling time constants of the force–voltage measurements of the actuator [11, 30]. The time constant for a first-order system is the time it takes for the output to reach 63.2% of the steady-state in a step response. The thermo-mechanical properties of the SCP actuators can be estimated as

\[ F = b_1(x - x_f) + b_2x + b_3(T - T_0), \]  

with \( F \) denoting the force output, \( x \) and \( x_f \) represent the current and resting actuator length, respectively, \( b_1 \) is the stiffness, \( b_2 \) is a damping term, \( T \) is the actual actuator temperature, \( T_0 \) is the surrounding temperature, and \( b_3 \) is the change of force per unit temperature [11]. Note when the length is fixed (\( \dot{x} = 0 \)), \( F = b_1(x - x_f) + b_3(T - T_0) \), where the force can be obtained based on temperature. We can thus estimate the cooling and heating time constants by measuring the transient response of the force measurements under voltage steps.

4. Modeling
In this section, the modeling techniques employed in this work are provided. We demonstrate why the voltage of the SCP actuators can be used as a surrogate from the thermo-electric model. In addition, the approach for the implementation of the polynomial model and Preisach hysteresis model are described and show their application to SCP actuators. The reader is referred to [11, 30, 39, 43, 44, 45, 46, 47] for more details of the adopted approaches.

4.1. Steady-state Voltage as Temperature Surrogate
The dynamics of Joule heating of SCP actuators can be approximated by a first-order linear equation:

\[ C_{th} \frac{dT}{dt} = P(t) - \kappa(T - T_0), \]  

where \( C_{th} \) is thermal mass, \( \kappa \) is the absolute thermal conductivity, and \( P(t) \) is the input electrical power at time \( t \) [11, 30]. The time constant of the system is \( \tau = \frac{C_{th}}{\kappa} \).
In this work, constant voltage will be used as a temperature surrogate, similar to other studies [42]. It is challenging to directly measure the temperature of the SCP actuators using tools like thermocouples or laser thermometers due to the actuator’s small form factor. From Eq. (4), the electrical power can be expressed as

\[ P(t) = \frac{V^2}{R} \]  \hspace{1cm} (5)

where \( V \) is voltage and \( R \) is resistance. Under a steady-state temperature, it can be shown that

\[ V = \sqrt{k R (T - T_0)} = f(T). \]  \hspace{1cm} (6)

Evidently, \( f(T) \) is a function of a single variable and can be used as a surrogate of \( T \). Note that the goal of using voltage is to obtain a steady-state temperature which is responsible for the activation of the actuators. However, this approach has inherent limitations when the resistance of the actuators potentially vary. A variation in actuator resistance could mean that the constant voltage vs strain performance of the actuator may be different to the temperature vs strain performance of the actuator. In future studies, the electrical power could be used as an input.

4.2. Polynomial Model

A polynomial model can be implemented as

\[ O_{linear}(V) = a_m V^m + \cdots + a_2 V^2 + a_1 V + a_0, \]  \hspace{1cm} (7)

where \( O_{linear} \) is the actuator output, \( a_m, \cdots, a_1, a_0 \) are constants, \( V \) is the input voltage to the actuator, and \( m \) is the order of the polynomial. The output (\( O_{linear} \)) is the force or the strain in this work. It has been demonstrated that the force-power input relation of SCP actuators only show mild hysteresis [42, 30]. Further, this model can be realized in MATLAB by using the command \texttt{polyfit}, with a low computational cost.

4.3. Preisach Hysteresis Model

Hysteresis is a common type of nonlinearity in artificial muscles [3, 48, 49]. Hysteresis is the tendency of the output to lag behind, leading to the output to not only depend on the current input but also its history [50]. Understanding the hysteresis behavior is critical in ensuring that the output can be predicted to allow for accurate control. Without accurate models to capture hysteresis, the realization of designed motions becomes a challenge. For instance, SCP actuators can exhibit as much as 30% error if a hysteresis model is not used [39]. Recently, there has been a number of studies that confirmed and analyzed the hysteresis in SCP actuators [51, 39, 52, 53]. It is thus expected that HW-SCP actuators will also exhibit hysteretic behavior.

The Preisach model has been predominantly adopted to capture hysteresis behaviors in different fields [54]. The model is defined as

\[ O_{\text{Preisach}}(V) = s_0 + \int_{P_0} w(\beta, \alpha) \gamma_{\beta,\alpha}(V; \zeta_0(\beta, \alpha))(t) \, d\beta \, d\alpha, \]  \hspace{1cm} (8)

where \( s_0 \) is a constant shift or offset, \( P_0 := \{(\beta, \alpha) : V_{\min} \leq \beta \leq \alpha \leq V_{\max}\} \), \( w(\beta, \alpha) \) is the weight function, \( \gamma_{\beta,\alpha} \) is a representation of the hysteretic unit and \( V(\cdot) \) represents the voltage history. The reader is referred to [55, 47] for more information. The output of the discretized Preisach model, \( O_{\text{Preisach}} \), can be expressed as follows:

\[ O_{\text{Preisach}}(V) = \sum_{i=1}^{M} \sum_{j=1}^{M+1-i} w_{ij} \gamma_{ij}(V) + s_0. \]  \hspace{1cm} (9)

where \( w_{ij} \) is the Preisach weight – a model parameter, \( \gamma_{ij}(V) \) is determined by the input voltage history, \( M \) is the level of discretization, and \( s_0 \) is a constant shift or offset. The output (\( O_{\text{Preisach}} \)) is the strain of the SCP actuator. The model can be efficiently identified using the MATLAB command \texttt{lsqnonneg} as a linear least-squares approach can be used [39].

5. Experimental Setup

5.1. Experimental Apparatus

5.1.1. Strain versus Voltage

The setup for strain measurement is shown in Fig. 4(a). The position sensor (Honeywell SPS-L225-HALS) is used to measure the displacement of the actuators, which is used to compute strain. This sensor can measure up to 225 mm with a resolution of 0.14 mm. This resolution corresponds to 0.116% strain for the non-mandrel-coiled, 0.186% for the mandrel coiled and 0.175% for the HW-SCP actuators. It uses magnetostrictive arrays to determine the position of a magnet that is affixed to a translating object. A magnet assembly, consisting of a holder and a magnet, is attached to the end of the actuator. The magnet holder is designed to ensure quick changing of the loads applied to the actuators.
and to minimize induced friction. A blower fan (Mechatronics MD4028V12B-RSR) is installed and operated at 3.2 V to provide even airflow, similar to our previous study [39]. The voltage increments are controlled using an Arduino-regulated P-Channel MOSFET with the sensor positions acquired with ADS1115 16-Bit ADC through the Arduino as well. With every voltage step, a displacement reading was obtained after 90 seconds. This time duration for each step was chosen to guarantee that steady-state was achieved for the actuators.

5.2. Force versus Voltage

One end of an SCP actuator was attached below the fan. A load cell (LSP-2, Transducer Techniques) was attached to the distal end of the actuator as shown in Fig. 4(b). The force signal is recorded using the same ADS1115 16-Bit ADC used for the strain–voltage setup. At the beginning of each run, the position of the load cell can be adjusted — allowing for the flexibility to modify the pre-tension. The input voltage was applied and controlled using an Arduino circuit.

6. Experimental Results

6.1. General Procedure

The number of coils for mandrel-coiled actuators and HW-SCP actuators were recorded. In addition, for each loading condition, the length of the actuator was measured when the load was applied without any electrical power. Three loading conditions were used for strain–voltage characterizations and three pre-tensions were used for force–voltage measurements. Non-mandrel-coiled actuators and HW-SCP actuators were used for all loading conditions.

The strain–voltage and force–voltage experiments were conducted through application of a series of increasing and decreasing voltage steps. The steps were monotonically increased from zero to maximum and then sequentially decreased to zero, with each step held constant for 90 seconds to ensure the actuator attained steady-state. Similar inputs have been used to measure the behaviors of SCP actuators [39, 30].

For each actuator, the maximum burnout power was determined for each loading condition. During the experiments, each actuator was activated from zero voltage to an adjusted maximum voltage that ensures that the actuator did not burn out. For non-mandrel-coiled and HW-SCP actuators, the adjusted maximum voltage was 0.2 V smaller than the burnout voltage. For mandrel-coiled SCP actuators, the adjusted maximum voltage was 0.1 V less than the burnout voltage. The current limit was fixed at 1.5 A for all experiments. Each monotonic increase and decrease cycle was repeated 4 times for each experiment.

6.2. Actuator Stiffness

The average stiffness of the SCP actuators is shown in Table 2, where $d$ is the fiber diameter, $s$ is the inner diameter and $x_0$ is the length of the SCP actuator when no load is applied. For the same fiber diameter of the mandrel-coiled and HW-SCP actuators, the stiffness decreased as the inner diameter was increased. As shown in Table 2, HW-SCP actuators have the largest stiffness, mandrel-coiled SCP actuators have medium stiffness with non-mandrel-coiled SCP actuators having the lowest stiffness. The stiffness of the non-mandrel-coiled actuators was small, partially because the number of coils, $n$, was much bigger compared to the HW-SCP actuators and the mandrel-coiled SCP actuators. As seen in Fig. 2, the coil structure of non-mandrel-coiled SCP actuators is more dense. Another possible reason is that the resting length of non-mandrel-coiled SCP actuator is the largest. The average stiffness of the actuator is inversely proportional to its length.

### Table 2

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<th>Ply</th>
<th>$s$ [mm]</th>
<th>$x_0$ [mm]</th>
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6.3. Strain Versus Voltage

6.3.1. Non-mandrel-coiled SCP actuator

Actuators of different fiber diameters were used in conducting the experiments. As shown in Fig. 5(a)–(c), the actuators were tested for three constant loading conditions: 0.343 N, 0.637 N, and 0.931 N. The loads were achieved by suspending 35 g, 65 g, 95 g weights on the actuator, respectively. For a fixed fiber diameter, the actuators exhibited increasing strain performance as the load was increased. Changing the loading conditions for the same diameter changed the adjacent coil separation.

In addition, plateaus can be observed as the voltage was increased for all loading conditions and this phenomenon is more prominent in Fig. 5(c). This is likely due to the adjacent coils touching and the actuators not contracting further. This phenomenon is also reported in Li et al. [23], where it is coined “saturated contraction”. Saturated contraction occurs when thermal contraction is achieved before the actuator reaches the maximum working temperature [23]. For actuators with the same stiffness, the actuator continues to contract until the burnout voltage is achieved, therefore, only non-saturated contraction is realized. Conversely, for the same actuator, a lower loading condition leads to saturated
A fourth-order polynomial model was adopted. It was found that a third-order polynomial model did not accurately capture the measurements. Additionally, a Preisach model was also employed. As an example, Fig. 6(a) shows the graphical representation of the performance of the two models applied to a 4 ply non-mandrel-coiled SCP actuator with $d = 0.90$ mm and load = 0.637 N. The Preisach operator can accurately capture the hysteresis behavior of the non-mandrel-coiled SCP actuators. The average error of the Preisach model was 0.0185 ± 0.0396%. The average error of the polynomial model was 0.6672 ± 0.4339%. The Preisach discretization level, $M$, was fixed at 16, and $s_0 = 4.47\%$. This discretization level is picked to be 16 such that it is not too high for high computation cost, but maintain a sufficiently accurate modeling performance. The typical value of the discretization level of the Preisach model is between 10 and 20 [44, 47, 48]. The Preisach model weights are shown in Fig. 6(d). These weights demonstrate the contribution of the cells to the output. From Eq. (9), $\gamma_{ij}$ is the result of the hysteresis over the area of cell $(i,j)$. Since the strain is the output of the Preisach operator, $w$ has units of $\% V^{-2}$. It is important to note that $\alpha$ and $\beta$ is in the range $V_{\text{min}} \leq \beta \leq \alpha \leq V_{\text{max}}$. More details of the Preisach model can be found in [55, 47].

6.3.2. Mandrel-coiled SCP actuator

Mandrel-coiled actuators with inner diameters 0.13 mm, 0.25 mm, and 0.51 mm were used in the experiments. The fiber diameter was kept the same at 0.56 mm. Three constant loading conditions were used for these actuators, namely, 0.063 N, 0.160 N, and 0.258 N. Lower loading conditions were used for these actuators mainly because they could not...
actuate effectively under larger loads. The steady-state strains increased as the inner diameter, $s$, was increased, as shown in Fig. 5(d)–(f). For example, when the load was 0.063 N and $s = 0.13$ mm, the maximum strain was 9.4%; when $s = 0.25$ mm, the maximum strain was 16%; and when $s = 0.51$ mm, the maximum strain was 21.1%. This trend is likely due to coils stretching farther apart under larger loads, thus providing more distance for coils to contract.

The maximum repeatable strain performance of 21% for the mandrel-coiled SCP actuators was lower than the 49% reported in Haines et al. [10, 22]. This high strain performance was also reported in other studies [23, 22]. These studies were predominantly performed using nylon monofilament (fishing line) as the precursor and were performed under direct temperature controlled chambers. Our results are comparable to the studies in Wu et al. and Semochkin [26, 19].

Notably, even though the actuators can generate high strain ranges, it was found that the large actuation had low repeatability. The actuator would contract such that the adjacent coils were touching and could remain welded together after the end of the cycle. This meant that the actuator became shorter than its original length at the beginning of the cycle. Fig. 7(a) shows the strain behavior for a load of 0.063 N. The first cycle only produced 12.82% maximum strain. At this voltage level, the coils were not touching and there was room for more movement. In Cycle 2, the voltage level was increased by 0.1 V and could achieve about 10% more contraction to produce 25% maximum strain. This small increase in voltage increased the contraction quite considerably, showing the sensitivity of the mandrel-coiled actuator to voltage changes. Pushing the actuator to the limit, meant that the coils came in contact. We observed that at the onset of intercoil contact, the current increased drastically. This
meant the temperature increased as well, leading to the intercoils attaching almost permanently to each other. Hence, when no electrical power was applied, the actuator did not return to the starting length. This was likely the reason there was a negative offset in the strains in the decreasing half cycle. At the extreme voltage, the actuator burns out. When this occurred, actuators achieved up to 60% strain for a load of 0.0254 N, as shown in Fig. 7(b). In Fig. 7(b), it can be observed that there was a drastic change in the rate of increase of the strain as the voltage increases from 4.5 V to 5.8 V. The adjacent coils start contacting when the voltage level was increased to 5.25 V. A failure of the actuator was observed when the maximum voltage level of 5.8 V was set. At higher loads, it was observed that the mandrel-coiled actuators tended to slightly elongate, as shown in Fig. 7(c).

A third-order polynomial and Preisach models were utilized to successfully capture the behavior of the strain–voltage measurements. The visual representation of the performance of the two models is shown in Fig. 6(b), for an actuator with \( s = 0.13 \text{ mm} \) and a load of 0.063 N. The Preisach modeling error was 0.0368 ± 0.1038% and the polynomial modeling error was 0.3680 ± 0.1746%. The results shown are for the mandrel-coiled actuator with \( d = 0.4 \text{ mm} \), \( s = 0.13 \text{ mm} \) under a load of 0.063 N. The Preisach discretization level, \( M \), was fixed at 16, \( s_0 = 4.84 \% \), with the Preisach model weights shown in Fig. 6(e).

### 6.3.3. HW-SCP actuator

HW-SCP actuators with inner diameters of 0.13 mm, 0.25 mm, and 0.51 mm with the fiber diameter fixed at 1.34 mm were tested. For each inner diameter, the actuators were tested for three constant loading conditions: 0.343 N, 0.637 N, and 0.931 N — the same loading conditions used for non-mandrel-coiled SCP actuators. The maximum voltage increased as the load increased. This was a result of the increased resistance of the HW-SCP actuator as it was stretched. It was also noted that the strain decreased as the load was increased.

The strain of HW-SCP increased as the inner diameter, \( s \), was increased from 0.13 mm to 0.51 mm, as shown in Fig. 5(g)–(i). The actuator exhibited large contraction at low loading conditions. For instance, when the inside diameter was 0.51 mm and the load was 0.343 N, the actuator contracted by 55.3%. The strain–voltage results showed apparent hysteresis, especially under low loading conditions. The observed hysteresis behavior in this work was consistent with the existing studies [51, 39].

A Preisach model and a third-order polynomial model were employed to capture the strain–voltage measurements for HW-SCP actuators. Fig. 6(c) shows the modeling performances for both models for an HW-SCP actuator (\( s = 0.13 \text{ mm} \), loading = 0.343 N). As shown, the pronounced hysteresis behavior of the HW-SCP actuator could be accurately captured by the Preisach operator. The modeling error of the Preisach model was 0.0254 ± 0.0670% and the modeling error for the polynomial model was 6.5987 ± 5.7468%. The level of discretization, \( M \), of the Preisach model was picked to be 16, \( s_0 = 23.43 \% \), and the Preisach model weights are shown in Fig. 6(f). Evidently, the Preisach model outperforms the polynomial model, with considerably small modeling errors.

The overall performance of the polynomial model and the Preisach model under all loading conditions and for the three SCP actuators is shown in Fig. 6(g) and (h), respectively. The average error was 1.325%, 1.5667%, and 11.729% for non-mandrel-coiled, mandrel-coiled, and HW-SCP actuators, respectively. The Preisach average error was 0.034%, 0.168%, and 0.105% for non-mandrel-coiled, mandrel-coiled, and HW-SCP actuators, respectively. The polynomial model demonstrated a much larger modeling error for the HW-SCP actuator. This is mainly attributed to the wide hysteresis loop and large strain that the HW-SCP actuator demonstrated. The Preisach model showed the largest average error for the mandrel-coiled SCP actuators. This may be attributed to the coils of the actuators either wielding together resulting in the actuator being shorter than the initial starting length or elongating such that the coils deform.

### 6.4. Force Versus Voltage

#### 6.4.1. Non-mandrel-coiled SCP actuator

For this study, three non-mandrel-coiled actuators with fiber diameters, \( d = 0.90 \text{ mm}, 1.11 \text{ mm}, 1.34 \text{ mm} \), were...
Fig. 8: Steady-state force versus voltage measurements and modeling for different SCP actuator configurations for varying fiber diameters. (a)–(c) are the force production of non-mandrel-coiled SCP actuators; (d)–(f) depict the force generation of mandrel-coiled SCP actuators; (g)–(i) show the force production of HW-SCP actuators. All actuators are tested under three increasing pre-tensions (force values when $V=0$).

The force output for the non-mandrel-coiled SCP actuators exhibited mild nonlinear behavior at high pre-tensions, as seen in Fig. 8(a)–(c). At low and medium pre-tensions and low voltages, the force production was very low. This is because at low pre-tensions, the coils were mostly touching and the force production was due to the negative thermal expansion. As the voltage increased, the contraction slightly increased, which in turn increased the separation of coils and increased the force generation.

The force–voltage behavior can be captured with a third-order polynomial. While the force–voltage behavior exhibited linearity at high pre-tensions, a third-order polynomial was chosen to keep the model working consistently for all loading conditions. A summary of the parameters and the modeling errors that were identified are shown in Table 3. The models show good performance. For example, the error for the non-mandrel-coiled actuator with $d = 1.34$ mm, under high pre-tension was $0.0343 \pm 0.0365$ N, while the range of the force output was as large as 3.83 N.

6.4.2. Mandrel-coiled SCP actuator

Mandrel-coiled actuators of fixed inner diameter, $s = 0.13$ mm, with three different fiber diameters, $d = 0.40$ mm, 0.48 mm, 0.56 mm, were used for experimentation. The steady-state force–voltage results are shown in Fig. 8(d)–(f). The force generation of mandrel-coiled SCP actuators was also nonlinear with respect to constant voltage input. This nonlinearity persisted even at higher pre-tension, unlike the non-mandrel-coiled SCP actuators where at higher pre-tensions, the force generation was linear. There was a plateau in the force generation at low voltages. This nonlinear behavior will be further investigated in the future. This behavior is potentially complex — force is related to stiffness, contraction, and temperature. While our study used constant voltage as the input to infer temperature, in future temperature vs force will be studied. The force generation behavior was captured with a third-order polynomial. The parameters of the polynomials for the different actuator diameters under the three pre-tensions are shown in Table 3.
The polynomial model shows high accuracy for actuator diameters. For instance, the biggest error occurred when \( d = 0.48 \) mm, medium pre-tension and was \( 0.0095 \pm 0.0076 \) N for a range of \( 0.548 \) N. The average error for was \( 0.0047 \) N for all the other cases.

### 6.4.3. HW-SCP actuator

The experiment for the HW-SCP actuator was performed with three fiber diameters (\( d = 0.90 \) mm, 1.11 mm, and 1.34 mm) and a fixed inner diameter, \( s = 0.13 \) mm. The pitch for actuator increased under higher pre-tensions. Fig. 8(g)–(i) shows the steady-state force generation under different voltage inputs. The force–voltage measurements showed great linearity. The force–voltage was linear for all pre-tensions. This was unlike the non-mandrel-coiled and mandrel-coiled SCP actuators, which exhibited evident nonlinearity. The non-mandrel-coiled SCP actuators exhibited nonlinear behavior at low pre-tensions and the nonlinearity vanished as the pre-tension was increased. This phenomenon evidently highlights the dependence of the force generation on pre-tension. Mandrel-coiled SCP actuators exhibited persistent nonlinear behavior that was not dependent on pre-tension.

First-order polynomials were implemented to accurately capture the correlations, and the resulting modeling performance and the realized model parameters are summarized in Table 3. Both non-mandrel-coiled and mandrel-coiled SCP actuators required third-order polynomial models compared to a first-order polynomial model for the HW-SCP actuator. This good linearity of the HW-SCP actuators presents an advantageous characteristic. The polynomial model presents...
Table 3
Model identification results of the force–voltage correlation of SCP actuators.

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6.5. Dynamics

The actuation speed was measured using the heating and cooling time constants based on the transient force measurements under voltage step inputs. The time constants for all the actuators are shown in Fig. 9. Non-mandrel-coiled SCP actuators showed increasing time constants as the fiber diameter was increased. The average time constant was 10.65 ± 2.94 seconds, 12.69 ± 3.85 seconds, 13.31 ± 3.35 seconds for actuators with \(d = 0.90\) mm, 1.11 mm, and 1.34 mm, respectively. The mandrel-coiled SCP actuators showed the same increasing behavior as non-mandrel-coiled SCP actuators. The average time constant was 4.98 ± 1.71 seconds when \(d = 0.40\) mm; was 6.55 ± 2.06 seconds when \(d = 0.48\) mm; and was 7.56 ± 2.26 seconds when \(d = 0.56\) mm. The HW-SCP actuator had average time constants that were 5.22 ± 1.15 seconds, 5.61 ± 1.23 seconds, and 6.85 ± 1.74 seconds for \(d = 0.90\) mm, 1.11 mm, and 1.34 mm, respectively.

The overall average time constant for non-mandrel-coiled SCP actuators was 12.22 seconds, mandrel-coiled actuators was 6.36 seconds and HW-SCP actuators was 5.89 seconds. The HW-SCP actuator and the mandrel-coiled SCP actuator exhibited comparable time constants while the non-mandrel-coiled SCP actuators showed much larger time constants. The time constants for all actuators showed a moderate increase as the diameter was increased.

6.6. Effects of Actuator Configuration

1) Strain: The non-mandrel-coiled SCP actuators exhibited limited strain, as shown in Fig. 10(a). When the load was increased, the strain performance increased. This is likely due to the increase in intercoil separation, which in turn increased the amount of travel possible before saturated contraction was achieved. Increasing the diameter of the actuator produced similar strain at higher loads. For example, the maximum strain was 9.29%, 9.37%, and 9.10% when \(d = 0.90\) mm, 1.11 mm, and 1.34 mm, respectively. Additionally, these actuators exhibited slightly higher contractions at lower loads for the same diameter. The decreasing contraction led to a decrease in the stiffness. For the same load, decreasing the stiffness means that the intercoil separation was increased.

Mandrel-coiled SCP actuators showed an increase in contraction as the inner diameter was increased, as shown in Fig. 10(b). This was consistent with other studies [10]. Increasing the inner diameter decreased the stiffness of mandrel-coiled SCP actuators. The lower stiffness allows for an increase in the pitch of the actuator for the same loading conditions, consequently leading to larger actuation. Furthermore, for the same inner diameter, the strain performance decreased as the load was increased. The lower stiffness likely cannot support the higher loads and the contraction tends towards the contraction of the uncoiled fibers. As shown in Fig. 7(b), the actuators started to lengthen at higher loads.

HW-SCP actuators exhibited superior strain performance compared to non-mandrel-coiled and mandrel-coiled actuators. For the HW-SCP actuator, when the inner diameter was fixed, the actuator produced larger strain under smaller loading, as Fig. 10(c) shows. This is likely because HW-SCP actuators under small loading conditions resemble mandrel-coiled SCP actuators that can produce large contractions. When the load was large, the resulting coils by the mandrel-coiled SCP actuators would become more apart, making them resemble non-mandrel-coiled SCP actuators that can only produce 10–15% strain. It can also be observed that when the inner diameter is increased, the HW-SCP actuator produced more strain under low loading conditions and less strain under high loading conditions, compared to the one with a smaller inner diameter. This is likely due to the inner diameter altering the stiffness. When the inner diameter was large, the stiffness of the actuator decreased, as deduced by Eq. (2) and seen in Table 2. Thus, HW-SCP actuators behave more similar to the non-mandrel-coiled SCP actuators when the inner diameter is larger and are under high loads.

2) Force: The force outputs of the non-mandrel-coiled SCP actuators showed an increase as the fiber diameter and

high accuracy. The error was 0.0587 ± 0.0485 N for the HW-SCP actuator with \(d = 1.34\) mm under the high pre-tension condition. The range for this condition was 1.566 N.
the pre-tension increased, as shown in Fig. 10(d). For a fixed fiber diameter, increasing the pre-tension increased the coil separation, which increased the force the actuator can generate. It can also be observed that increasing the fiber diameter increased the force generation.

Mandrel-coiled SCP actuators’ force generation also exhibited an increasing trend as the pre-tension increased, as shown in Fig. 10(e).

Fig. 10(f) indicates that HW-SCP actuators with larger fiber diameters generated larger force outputs. The diameter and force production of the HW-SCP actuator were positively correlated to the fiber diameter. It was also observed that the actuator could produce a larger range of force outputs under a higher pre-tension.

The error shown in Fig. 10(a)–(c) is indicative of the repeatability of the strain–voltage behavior in Fig. 5. Similarly, the error shown in Fig. 10(d)–(f) is representative of the repeatability of the force–strain behavior in Fig. 8.

7. Discussion

While the design spaces of both HW-SCP and mandrel-coiled SCP actuators are fully controllable, HW-SCP outperforms the mandrel-coiled actuators. At higher loading conditions, HW-SCP actuator behaves like the non-mandrel-coiled actuators. Mandrel-coiled actuators deform their coils at higher loads, making them behave like nylon fibers. The superior performance coupled with the controllable design spaces of HW-SCP actuators are appealing to practical robotics applications. Additionally, the experiments performed consist of long activation times, which shows that the actuators can be applied in cases where persistent force applications are necessary. HW-SCP actuators exhibit a good balance of the advantageous characteristics of non-mandrel-coiled SCP actuator’s large-force output and mandrel-coiled SCP actuator’s large strain and free of pre-tension requirement. Further numerical studies can be performed to understand how to efficiently design HW-SCP actuators and how the design parameters affect the actuator performances. HW-SCP actuators can be directly designed for various applications and scenarios in future studies, showing their versatility and attractiveness.

HW-SCP actuators show a very good linearity with the force production, compared to both mandrel-coiled and non-mandrel-coiled SCP actuators. This makes it appealing for control purposes, with the model being computationally cheap. The nonlinearity in non-mandrel-coiled actuators is likely due to the dependence in pre-tension of the actuator. More modeling work needs to be done to understand the cause of the phenomenon.

SCP actuators have attracted a lot of attention [3] and show strong promise, and more design studies can be conducted to further improve their actuation capability. It is a challenge in soft robotics to obtain large compliant deformations with small pre-tension, all while using artificial muscles that are compact and lightweight. Large deformations allow for higher range of motions to be achieved and small pre-tension allows for actuators to be embedded in soft media without residual stress being transferred to the media. HW-SCP actuators exhibit advantages in both strain and force outputs, as a result demonstrating strong potential as an enabling compliant actuator. In addition, like mandrel-coiled SCP actuators, HW-SCP actuators do not require pre-tension. A large force output can be generated under a high pre-tension, similar to non-mandrel-coiled SCP actuators. These characteristics makes HW-SCP actuator highly desirable for applications that require varying loads and high range of motions, such as soft robots, as well as assistive and rehabilitative devices.

In addition to the promising properties of HW-SCP actuators, this work also provides a systematic method for designing the type and configuration parameters of SCP actuators given specific application requirements. By generating the dataset of key performance properties, the process to select an actuator for a specific task will become simplified. For instance, if a robot with an embedded SCP actuator is desired to produce large force with no strict pre-tension or speed requirements, then non-mandrel-coiled SCP actuator can be chosen, as they will effectively provide high forces. Future work will include optimal design, development, and analysis of soft robot grippers driven by multiple different SCP actuators to achieve complex tasks.

Finally, while this work exclusively focused on SCP actuators based on conductive multi-thread nylon filament, other materials can be used, such as nylon mono-filament, PDMS, and spandex. These different materials may further improve the performance of the SCP actuators. PDMS, for example, was shown to produce non-mandrel-coiled actuators that can generate 25–46% with a stress of 60 MPa [33]. These materials or a hybrid usage by incorporating with the conductive multi-thread nylon filament in this study will be investigated in the future.

8. Conclusion

This work proposed a new HW-SCP actuator and presented a comprehensive characterization, comparison, and analysis of SCP actuators. HW-SCP actuators can simultaneously produce high strain and high force outputs. A number of configurations (e.g., inner diameter, pitch, and the fiber diameter) of the HW-SCP actuators have been designed and manufactured. Non-mandrel-coiled SCP actuators of different fiber diameters were manufactured. Further, mandrel-coiled SCP actuators of multiple configurations (inner diameter, pitch and fiber diameter) were fabricated. The strain and force outputs under voltage steps of varying magnitudes were obtained for all three forms of SCP actuators. The SCP actuators’ time constants were measured experimentally. Additionally, a Preisach hysteresis model and a polynomial model and were successfully utilized to accurately capture the SCP actuators’ behavior.
References


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