Designing Muscle-powered Robotics with Super Coiled Polymers

Jun Zhang and Michael C. Yip

I. SCP Muscle: A New High Performance Muscle

When designing robotic systems, we heavily rely on motors, pneumatic actuators, hydraulic actuators, artificial muscles such as shape memory alloys (SMAs) to achieve actuation [1]. Cost, volume, mass, inertia, friction, among others, often need to be carefully considered, and it is not rare to end up with very few choices of actuation that are suitable for the application that we have in mind.

"Super-coiled" polymer (SCP) actuators are a recently-discovered, low-cost, lightweight, and accessible actuation technology. These SCP muscles are constructed from twisting sewing threads or fishing lines until coils are formed, and can achieve large contraction in length when they are heated [2]–[5]. With different thread materials, muscle thicknesses, and operation conditions, SCP muscles can generate varying performances and can be adapted or scaled to different applications. Their unique properties show strong promise as a transformative artificial muscle technology for robotic applications. Yet, due to the relative novelty of these actuators, there has been sparse information regarding how to design these actuators for use in robotic applications.

This paper's primary goal is to describe SCP actuators for robot makers. In particular, it discusses the muscle construction approaches and design considerations, and presents preliminary design examples of robots that use SCP actuators. Future prospects of this new technology are considered.

II. Construction Principles of SCP Muscles

A normal piece of conductive sewing thread (e.g., nylon thread as shown in Figure 1(a)) can only produce 2% contraction in length and about 4% expansion in diameter when joule heated. SCP actuators work when the thread is coiled, as shown in Figure 1(b), which can produce much larger contraction because of thermal expansion and helical structure [3].

While many different materials have been tested in [3] and nylon, polyvinylidene fluoride and polyethylene have shown good contractile properties, the most accessible SCP actuator material comes from conductive sewing thread. Sewing threads also come in different materials, yet a substantial variety of threads are composed of Nylon 6,6 which has the best performance capabilities. Fishing line is also an accessible nylon material that you can find in plentiful quantities, yet there are no manufacturers that offer conductive fishing lines. Thus, to electrically control muscle activation using Joule heating, painting the lines with conductive paint is required, thereby diminishing the "accessibility" of fishing line-based actuation.

Jun Zhang and Michael C. Yip are with the Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla, CA 92093, USA. Email: {j5zhang,yip}@ucsd.edu.

(a) (b)

Fig. 1. (a). A conductive nylon thread (V Technical Textiles, 117/17 dtex). (b). A super-coiled polymer (SCP) muscle constructed from coiling the nylon thread in Fig. 1(a).

Conductive threads and conductive yarns are commercially available at a low price (V Technical Textiles), while fishing lines (Berkley Trilene) can be made conductive by applying expensive conductive paint (Silver paint, SPI Supplies, 05002-AB) at a higher cost.

A. Coiling

Coiling can be achieved by attaching a weight to one end of the thread and spinning the weight to insert twists until coils are formed [4]. We found the most efficient way is to use a constant speed motor for inserting twists while constraining the thread from untwisting. As the motor spins, the mass is not allowed to rotate, resulting in twists to the thread. The coiling thread shortens in length during the twisting process. When the thread is completely coiled (as shown in Figure 1(b)), it will have a desire to untwist. This is avoided by double-backing the length of the coiled thread on itself to create a two-ply configuration, as shown in Fig. 2(a) [4]. When a single nylon thread (V Technical Textiles, 117/17 dtex) is used, fully coiled muscle is formed at 390±15 rotations/cm.

Two aspects of the coiling procedure are worth mentioning. The first is the number of threads to use. When a single thread is used, the coiled muscle will only generate enough force to lift a hundred to a few hundred grams, and

(a) (b) (c)

Fig. 2. SCP muscle samples formed from twisting (a) 1, (b) 2, and (c) 3 conductive threads (V Technical Textiles, 117/17 dtex) until forming coils. These muscles have different diameters and different values of stiffness.

furthermore can snap easily under the load of the weight. Muscle with greater strength can be attained by twisting multiple threads together, which increases the diameter of the thread, can generate larger force and lift heavier weights. Fig. 2 shows the SCP muscles that are constructed from coiling different number of threads. The other aspect is the weight used to keep the thread taut while being twisted, and that during coil-forming process the thread does not snap. When the weight is too small, the produced coils will be non-uniform; when the weight is too large, the thread will snap before coils are formed. While determining the weight often requires some trials, we found a good choice of the weight can be obtained by multiplying 50g and the number of nylon threads (V Technical Textiles) used. It is expected that this choice of weight may not be ideal for threads with other materials. It is found that uniformly coiled muscles are easier to make when the number of threads being coiled increases, perhaps because fewer twists are required.

B. Heat Treatment

The coiled threads need to be thermally set before being utilized as muscles. The heat treatment can be realized by placing the coiled threads in an oven [3], or by applying current to generate heat, which is usually an easier method to adopt because current (and therefore Joule heat) can be controlled much more accurately. Because material setting of the coils happens on the "seconds" scale, even Joule heating can vary and be difficult to control if a constant voltage is held for an extended period of time. Thus, square voltage pulses heat the threads and then provide adequate cooling time before treating with heat again [4]. Under appropriate voltage pulses (1.5V/cm of coil length), the coiled threads undergo plastic elongation of 20% – 50% of their initial lengths. After multiple voltage pulses are applied, the lengths of the coiled threads converge and the muscles are ready for use. Note that because the muscle contraction converges to a steady state range, the maximum strain achieved during the heat-treating process sets the upper limit of the thread, where any Joule heating beyond the prescribed amount in application will cause irreversible plastic deformation (thus shifting the steady state range).

The coiled threads with different values of stiffness require different on and off times of the voltage pulses. It is found that as the diameter of the muscle increases, the on and off times of the voltage pulses also increase (e.g., 1s on, 9s off when a single thread is used for the muscle; and 5s on, 50s off when 4 threads are adopted for the muscle). This can be explained as the thermal dynamics of the thicker muscle is slower than that of the thinner ones, thus longer heating and cooling times are needed.

III. Design Considerations for Muscle Actuation

It's important to design SCP muscles to fit specific application needs. Two design specifications and considerations are provided, namely, the actuation speed and the largest strain output.

A. Actuation Speed

So far, we have found that SCP muscle has a time constant of approximately one second under steady state input voltage. The speed of the muscle actuation depends on the thermal mass of the muscle and the absolute thermal conductivity of the muscle in the ambient environment. The actuation speed can be quantified by the time constants of the actuation or the stress transient under constant strain during heating and cooling cycles.

Two aspects will affect the actuation speed. First is the operation condition. Previous work [4] found that while the time constant of the thermal dynamics was around 3s in standing air, the time constant decreased to 1s and less than 1s in forced air and water environments, respectively. The forced air and water can promote heat transfer and dissipation, thus increasing the actuation speed. The forced air is the best choice considering its ease of operation and tunable actuation speed when adjusting the speed and amount of the air-flow in the environment. The other aspect is the diameter of the muscle. It is found that the thermodynamics is faster with thinner muscle. This can be explained – muscle with a larger diameter has slower heating dynamics due to the thicker threads to heat, and slower cooling dynamics due to the heat being trapped in the muscle.

B. Maximum Strain

So far, we have found that SCP muscle has a maximum contraction of approximately 20% with the presented construction approach, using off-the-shelf conductive sewing thread. The largest strain of the SCP muscle depends on the material used to construct the muscle and the diameter of the muscle.

Previous work [4] has demonstrated that the muscle constructed from a single 117/17 conductive Nylon 6,6 thread can produce up to 8-10% strain. It is verified that the SCP muscles constructed from Nylon 6,6 generate considerable amount of strain. In our recent studies, conductive yarns (V Technical Textiles, 110/34 dtex) were adopted for muscle construction. We found that 5-7% strain can be repeatedly obtained when a single yarn is adopted; When two yarns are utilized, the resulting SCP muscle could produce 9-11% strain; Furthermore, 17-20% strain could be achieved when 3 or 4 yarns are adopted.

Different conductive threads and conductive yarns, as well as fishing lines can be used, as shown in Table I. When conductive fishing lines are constructed to muscles, similar amount of strain can be produced when the muscles based on the conductive thread and fishing lines have comparable diameters.

IV. Control

Controlling these muscles requires a voltage differential across the length of the muscle, which will be converted into Joule heating. Achieving the voltage differential can be done easily using a N-channel MOSFET circuit, that takes in pulse-width-modulated signals at its gate and supplies a switching current to the muscle through the drain channel of the MOSFET. Here, the gate can be driven by an embedded solution such as the Arduino microcontroller board.

A variety of control options exist. “Bang-bang” control presents an adequate control option for many applications, where little needs to be known about the dynamics of your system. To use linear control design (such as lead compensation, pole-zero placement, etc.), a thermo-electrical-mechanical dynamics model needs to be used to describe the actuator. This model can be expressed as

$$F = k(x - x_0) + b\dot{x} + \lambda(T - T_0) \tag{1}$$

and

$$C_{th}\frac{dT(t)}{dt} = P(t) - \lambda(T(t) - T_{amb}), \tag{2}$$

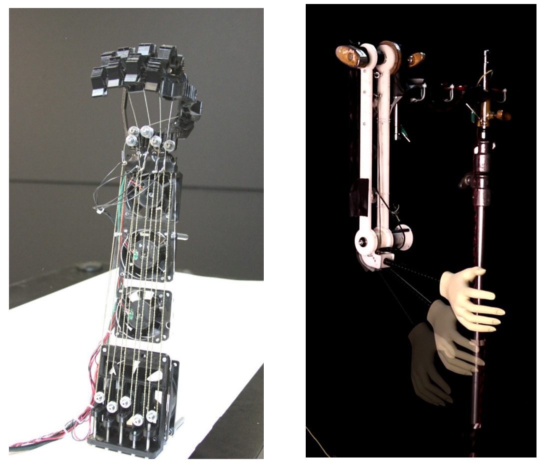
where x and x_0 are the current and the neutral length of the muscle, $T(t)$ is the actuator temperature, T_{amb} is the ambient temperature of the environment, k and b are the mean stiffness and damping of the actuator, C_{th} is thermal mass of the actuator (Ws/°C), $P(t)$ is the heat applied to the actuator, λ is the absolute thermal conductivity of the actuator in the ambient environment (W/°C), $P(t)$ is controlled using voltage $V = \sqrt{PR}$, and R is the mean resistance of the actuator. Because this requires a more in-depth analysis involving dynamics modeling, model identification, and linear control theory, we refer readers to [4] for further details.

However, one thing we can see is that under quasi-static or steady-state conditions, a regression that maps voltage to force can be identified experimentally with only a few sample data points, and can be used for applications not requiring accurate dynamical performance.

TABLE I

Applicable Threads and Fishing Lines for SCP actuators

Material	Unit	Supplier
Fishing line	120, 250, 380 μm	Berkley Trilene
Conductive yarn	117/17, 110/34 dtex	V Technical Textiles
Conductive thread	170, 180, 200 μm	V Technical Textiles



(a) (b)

Fig. 3. (a). A 3-D printed robotic hand based on SCP actuation. (b). A robotic arm composed of SCP actuators [4].

V. Example Designs

To date, SCP muscle technology in the robotics field has been sparse due to the very recent discovery. Some simple systems such as robotic hand and arms, forceps, human assistive devices, and fabric textile woven structures have been explored [3-5]. With our preliminary work [4], we have demonstrated exciting designs with SCP muscles for robotics applications.

In Figure 3(a), a dexterous robotic hand is created using the SCP muscles. The hand is 3D printed, with each finger as a ABS plastic flexure with a steel wire rope routed within. Five SCP muscles are used to mimic human fingers, and are spanned along the length of the forearm. Steel-cable attachments are used to the fingers starting at the wrist location, emulating the physiology of a human hand. The total material and drive electronics cost is less than $10, and no special equipment except a commercial hobbyist MakerBot 3D printer is used. This robotic hand is controlled by an Arduino Nano microcontroller.

In Figure 3(b), we show the use of SCP actuators as bicep muscles in a robot arm. The robotic limb utilizes muscle constructed from a single conductive thread (V Technical Textiles, 234/34 dtex). Three SCP muscles are utilized for the robotic arm. The SCP actuators are approximately 30cm in length, staying within the physical confines of the upper limb. Motion over the entire limbs range, from fully extended to 90° contraction, is demonstrated.

VI. Future Prospects

SCP actuators have the potential to transform artificial muscle technology for robotic applications, considering their ease of manufacturing, low cost, light weight, and compliant nature. Different muscle performances can be obtained to meet application requirements by designing muscles considering the thread materials, muscle thicknesses, and operation conditions. For example, a larger number of threads can be used to obtain thicker muscle and generate larger force.

In order to increase the power output of the SCP muscle, the multiplication of the velocity and the force output of the muscle needs to be increased. The operation condition will affect the actuation speed, thus the velocity of the muscle. For example, the amount of air-flow or the temperature of the air-flow in a force-air environment can affect the thermal dynamics. In order to increase the force output, muscle bundling configurations need to be studied. Although thicker muscles constructed from a greater number of threads can produce larger stiffness, the depth of heat penetration into coil center increases and therefore contraction and relaxation speed decreases. Muscle bundle configurations that reduce penetration depth per thread while recruiting additional threads provide a unique solution that independently increases power output. Muscles that are physically separated through spacers and muscles that are woven together to form a single bundle are two potential approaches. Muscle antagonistic configuration can be studied to achieve bidirectional motion through an active return that increases the dynamic range of the muscle. Another consideration for these muscles are their efficiency. Like any artificial muscle actuated using Joule heating (including SMAs and shape memory polymers), they have efficiencies below 10%. However, one must consider that unlike other muscle-like actuators such as pneumatic McKibbon actuators or hydraulic systems, these actuators can be run off battery power, which can scale to nearly any size. Thus, even though efficiency is low, intelligent power management can enable the adaptation of these muscles for mobile applications with a small volume and with light weight. For immobile applications, power no longer becomes a significant limitation. While SCP muscles have many advantages over commonly used actuators, tradeoffs including contraction and relaxation speed, produced strain and force, and controlled accuracy need to be carefully considered.

SCP muscle technology is particularly promising for human assistive and augmentation applications considering their low-cost, lightweight, and inherent compliance. Recent years have witnessed a rapid increase in the field of robotic exoskeletons, prosthetics, and orthotics for human assistance in rehabilitation therapy and augmentation of their wearers. However, the current technology predominantly utilizes rigid load-bearing structures, and relies on gearmotor, pneumatic, and hydraulic actuation methods, making them unsafe and uncomfortable to use. SCP muscle technology can be used for the robotic assistive and augmentation devices such that these robotic devices are flexible, light, and cheap.

References

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