ModiFiber: Two-Way Morphing Soft Thread Actuators for Tangible Interaction

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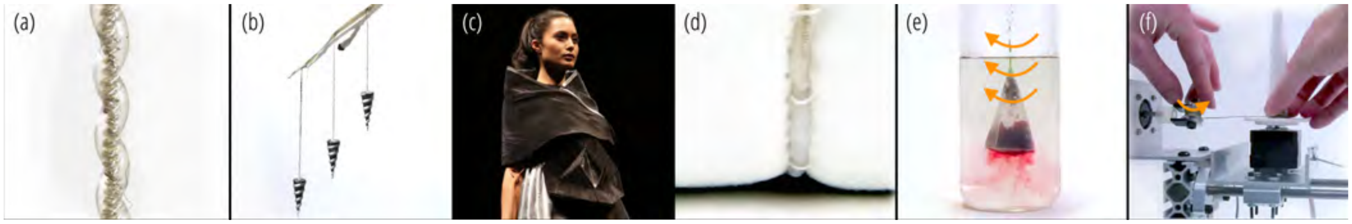

Figure 1: ModiFiber as a twisting actuator (A), spinning tassels as fashion style piece (B), clothing that engages an origami structure for tunable porosity (C), non-invasive haptic feedback actuator that heats and squeezes the user as a notification reminder (D), smart packaging for a self-stirring tea bag (E), the semi-automated machine used to fabricate such actuators (F).

ABSTRACT

Despite thin-line actuators becoming widely adopted in different Human-Computer Interaction (HCI) contexts, including integration into fabrics, paper art, hinges, soft robotics, and human hair, accessible line-based actuators are very limited beyond shape memory alloy (SMA) wire and motor-driven passive tendons. In this paper, we introduce a novel, yet simple and accessible, line-based actuator. ModiFiber is a twisted-then-coiled nylon thread actuator with a silicone coating. This composite thread actuator exhibits unique two-way reversible shrinking or twisting behaviors triggered by heat or electrical current (i.e., Joule heating). ModiFiber is soft, flexible, safe to operate and easily woven or sewn, hence it has a great potential as an embedded line-based actuator for HCI purposes. In this paper, we explain the material mechanisms and manufacturing approaches, followed by some performance tests and application demonstrations.

CCS CONCEPTS

• **Human-centered computing → User interface toolkits**; *Human computer interaction (HCI).*

KEYWORDS

Thread actuators, Coiled thread actuators, Reversibility, Shrinking actuator, Linear actuator, Soft actuator, Torsional actuator, Twisting actuator, Artificial muscles.

ACM Reference Format:
Jack Forman, Taylor Tabb, Youngwook Do, Meng-Han Yeh, Adrian Galvin, and Lining Yao. 2019. ModiFiber: Two-Way Morphing Soft Thread Actuators for Tangible Interaction. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May*

CHI 2019, May 4–9, 2019, Glasgow, Scotland Uk

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300890

4–9, 2019, Glasgow, Scotland Uk. ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3290605.3300890

1 INTRODUCTION

Soft and embedded actuation is a growing interest in HCI. Among many existing actuator options, including pneumatic actuators [33], hydraulic actuators [9, 32, 34], and pH driven actuators [13], string actuators stand alone for their unique properties. For example, SMA wires are a well-adopted string actuator for HCI research and have been used to actuate human hair [6], adaptive window shutters [5], smart clothing [7], paper sculptures [21] and robotic artifacts [23]. Analyzing the reason that researchers adopt SMA wires and other thin line-based actuators, we found that they are silent, lightweight, flexible, easily integrated into other soft substrates and visually unobtrusive. However, SMA wires are relatively expensive, tricky to control, and easily burnt. Moreover, thicker SMA wires are generally very stiff, while thinner ones can be quite fragile. In addition, SMA does not have its own internal restorative force so the reversible actuation depends on an external counter-balancing weight. While SMA can be trained to have a two-way shape memory effect, two-way SMA is not readily accessible and the training process is arduous [10]. Besides SMA wires, passive tendon threads driven by motors are widely used in HCI as well; however, these threads require dedicated motor control systems.

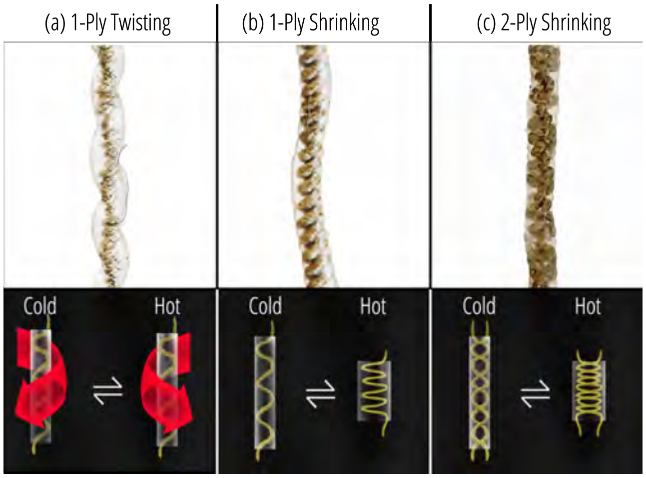

Figure 2: Actuation types and coiling shapes

Alternative string actuators are emerging in materials science and engineering. Nylon thread and fishing line based actuators have gained increasing attention since Science reported research on artificial muscles from such materials in 2014 [11, 18]. These readily available and high energy density thermoplastic threads exhibit greater controllability than shape memory alloys, lower cost than carbon nanotube (CNT) composite fibers [16], and greater repeatability than organic conductive polymer fibers [4, 29, 30]. *However, similar to SMA wires, this nylon actuator is only passively reversible. That is, if one end of the actuator is not attached to an external restorative force, such as a dead weight or a spring, the actuation is non-reversible.*

Our work is motivated by the potential of adapting and improving such fishing line actuators for HCI and to add ModiFiber to the library of string actuators commonly used in HCI. ModiFiber presents the following contributions:

- A novel composite structure to achieve reversibility on top of existing nylon-thread actuators.
- A proposal and quantification of two actuation types. From 1-ply ModiFiber actuators: shrinking actuation and twisting actuation (Figure 2A and 2B). From 2-ply ModiFiber actuators, shrinking actuation in which the shrinking is inherently restricted only to linear movement (Figure 2C).
- Use cases for the two actuation types, and summarization of the design space including applications in performative garments, fashion, interactivity, and packaging (Figure 1).

2 RELATED WORK

Polymer Coils for Actuation

Nylon coil based muscles are a relatively recent discovery made by Haines et al. and are a significant contribution in the search for better artificial muscles [11]. Due to their tendency to untwist when heated, twisted-then-coiled polymer (TCP) muscles also act as powerful torsional actuators when allowed to rotate [3, 28]. Since TCP actuators maintain their heated position when cooled (one-way shape memory), in order to achieve reversible they are usually attached to a spring which acts as an external torsional restorative force in order to achieve reversible behavior. This technique is also used for SMA torsional actuators [1]. The practicality of such an easily manipulatable actuator has been exemplified by many follow up works on robotics, wearables [12], assistive devices and knitted fabrics [17].

Compared to the literature, ModiFiber proposes a novel TCP silicone composite structure with internal restorative force to allow for *reversible* shrinking or twisting actuation, without the need for a dead weight or a spring. This means the restorative force is an intrinsic property of the material, making it a two-way actuator. Relevant literature to this includes a robotic artificial skin [2]. In this work, although the coiled thread is not coated with silicone, a group of actuators is embedded in an elastomeric surface. Undulatory and bending reversible movement types are produced from silicone sheet structures. The difference is that ModiFiber is still considered a thread actuator and can be weaved or sewed into other substrates if needed, while the robotic skin is an integrated sheet-like material.

For fabricating coiled thread actuators, researchers have previously developed a desktop coiling machine with a heating wire [27] to standardize and quicken the fabrication process. However, it only produces short coils (up to 7 cm of working length). We developed our own machine that can produce 2-3 meter-long coiled threads.

Novel Materials for Actuation in HCI

The HCI community has a growing interest in novel materials for actuation. Shape-changing interfaces have been piquing research interests [20, 22] in recent years, with HCI researchers exploring chemical materials [13], biological materials [34], and other materials in the interest of material-driven actuation. For the options of actuation for shape-changing interfaces, HCI researchers have introduced multiple actuator types, including pneumatic actuators introduced in *PneUI, AeroMorph and Printflatable* [19, 25, 33], hydraulic actuators including *bioLogic, Transformative Appetite and Jamming UI* [9, 32, 34], SMA wires- *Morphees* [23]) and pH driven actuators in *Organic Primitives* [13].

Among all the aforementioned soft and flexible actuators, string actuators stand alone for their unique properties. They are often lightweight, visually unobtrusive, and easily embedded or weaved into other hard or soft substrates. ModiFiber thread actuators are developed to enrich the existing library of thread-based actuators. Compared to the widely adopted SMA wires in various interactive systems [5, 6, 8, 21, 26], the ModiFiber thread actuator is inherently reversible without requiring external restorative force; additionally, it is cheaper and more compliant. Additionally, for some use cases (e.g., on the skin), ModiFiber is a more user considerate option because the contact surface is made of soft silicone rather than heated metal wire.

3 OVERVIEW OF MODIFIBER

ModiFiber and Similar Actuators

Table 1 compares ModiFiber with the uncoated TCP muscles and Nitinol (NiTi), the most commercially relevant shape memory alloy. While NiTi and ModiFiber both have a 5% actuation rate[15], ModiFiber has a two-way shape memory behavior while NiTi does not. NiTi can be trained to have a two-way shape memory effect; however, two-way NiTi is not readily available and the complex training process can require up to 14 cycles of heating/cooling. NiTi and TCP can also be used as high-speed torsional actuators, but without an external restorative force (like a spring), it is in only a one-way transformation. Unlike NiTi [10], ModiFiber is well suited for textiles as its flexibility means it can be knit, weaved, and sewn. Additionally, ModiFiber's silicone coating provides electrical and thermal insulation improving compatibility for wearables. Finally, ModiFiber is considerably cheaper that NiTi[15].

Table 1: Summary of the primary precursor fibers used, their cooling parameters, and the names used to reference the resulting actuators.

Actuator	Shrinkage	Two-Way Reversibility	Hysterysis	Cost (per meter)	Insulation	Textile Compatibility
ModiFiber	5%	Yes	Low	$1.08	Electrical $ Thermal	High
TCP	20%	No	Low	$0.80	None	High
NiTi	2%-5%	Yes	High	4.5–10	None	Low

Design Space

ModiFiber is a cheap, reversible, flexible, electrically insulating actuator that has good compatibility with conventional textile manipulation, allowing unique potential for interfacing with humans; however, limitations do come from relatively low energy density and actuation speed. ModiFiber is intended as an enrichment to the soft actuator toolbox for interaction designers and the e-textile community.

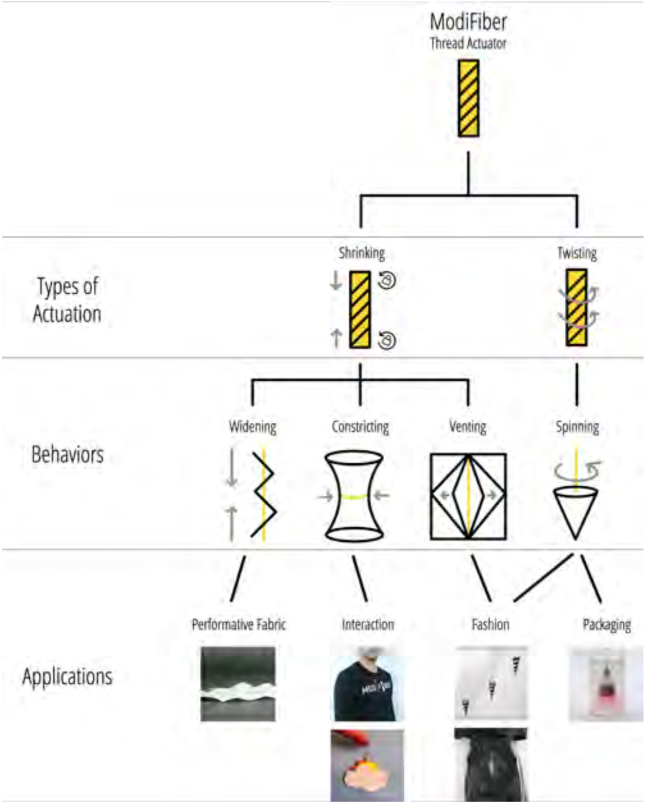

Figure 3: Design Space of ModiFiber.

ModiFiber thread actuators can provide two reversible actuation types: shrinking actuation and twisting actuation

(Figure 3a). For the same 1-ply ModiFiber thread actuator, if both ends are prevented from rotating during heating, it generates reversible linear actuation (repeatable shrinking and recovering); if one end is free to rotate, then it tends to generate reversible torsional actuation (repeatable untwisting and twisting). By using short duration and high power electrical pulses, considerable twisting, untwisting, and retwisting is observed. By timing the heating and cooling cycle properly, momentum in the twisting actuator is built up, allowing for an increase in speed and number of reversible rotations. Generally, twisting motions are driven by motors, which can be noisy and have geometric constraints; ModiFiber actuators allow for driving twist in noise-sensitive or geometrically challenging contexts.

In order to restrain the actuation to only shrinking, we developed a 2-ply ModiFiber thread actuator. This is due to the nature of the torque-balanced structure of 2-ply thread actuators. This would be particularly useful in on-body applications, or any application where the environment could make tethering difficult. We will detail the 1-ply and 2-ply manufacturing techniques in later sections.

The two actuation types, while relatively slow, can be leveraged to design higher level structural behaviors, including widening, constricting, venting, and spinning. We envision a wide spectrum of applications by integrating these behaviors. ModiFiber can be adapted to performative fabric, haptic interactions, fashion, and decorative arts and packaging.

ModiFiber Mechanisms

ModiFiber is a nylon TCP thread coated with an elastomeric coating (e.g. silicone coating). Figure 4A shows the nylon thread coated with silicone (Figure 4C). For the purpose of using resistive heating to trigger the actuation, we can use a commercial nylon thread with a silver coating (Figure 4B). Figure 4D and 4E show the two states of the polymer chain alignment before and after the thread actuator is heated.

Twisting Structure. While the novelty of ModiFiber lies in its reversibility, the twisted structure is fundamental to each actuation type. When the fiber is made, the polymer chains of the thread become extended in the fiber direction (Figure 4D), causing anisotropy (directionally dependent properties). When heated, the extended polymer chains contract to a lower energy state (Figure 4E), resulting in a reduction in fiber length and expansion in fiber diameter. This thermal shrinkage in response to heat, which is a common trait for polymers, is the driving force behind actuation. If twisted, the fiber untwists when heated as it shrinks along the twisted direction. Alone, these twisted fibers function as twisting actuators but continued twisting causes the fiber to form a coiled spring-like structure. These muscles are considered homochiral (twist direction and coil direction are the same), and provide significant shrinking and twisting actuation. This is because writhe (in-plane loop) and twist can be freely converted as long as the linking number (the sum of twist and writhe) is conserved.

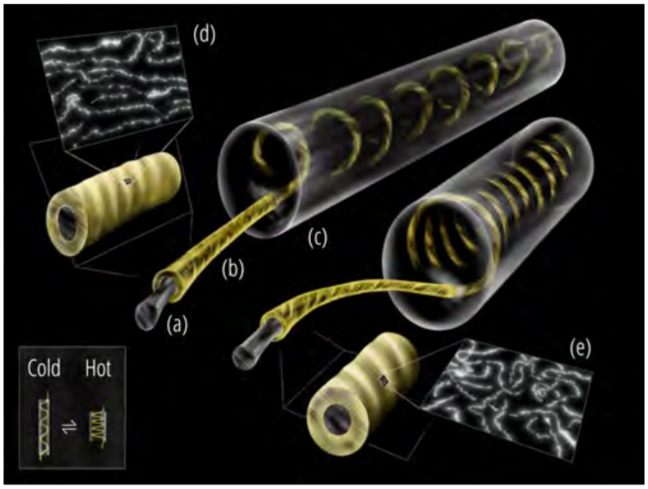

Figure 4: ModiFiber structure. (A) depicts a twisted nylon thread with (B) a silver coating. The coiled muscle is then coated in silicone C. (D) depicts the elongated polymer chains before heating and (E) depicts the contracted polymer chains after heating

Reversibility. Reversibility is achieved by coating the TCP muscles in silicone, where the contraction of the coil is countered by the silicone's stress response to compression. When the heat source is removed, the silicone elongates the muscle to become uncompressed. This principle also applies to twist actuators, where when heated, the coils untwist, putting torsional stress on the silicone. When the heat is removed, the silicone untwists to restore the coils to a twisted state. Throughout all testing and morphing types, no hysteresis (progressive loss of actuation during cycling) was observed in the actuators.

4 FABRICATION

Making Short Coils

Short actuators for experiments were fabricated using the method reported by Tadesse et al [24]. Throughout the paper, we utilized three types of precursory nylon threads to create our actuators; we will refer to them as "thin actuator" "thick actuator" and "fishing line actuator." The first two types are a silver-coated thread, thus conductive for electrical-current driven resistive heating

Table 2: Summary of the primary precursor fibers used, their cooling parameters, and the names used to reference the resulting actuators.

Name	Precursor Fiber	Source	Coiling Weight
Thin Actuator	Nylon 6,6 Sewing 2-Stranded Multifilament (Silver-Plated)	Shieldex #260151011717H	30g
Thick Actuator	Nylon 6,6 Sewing 4-Stranded Multifilament (Silver-Plated)	Shieldex #260151023534H	150g
Fishing Line Actuator	Nylon Fishing Line	South Bend Monofilament 30 Pounds M1430	300g

Making Long Coils

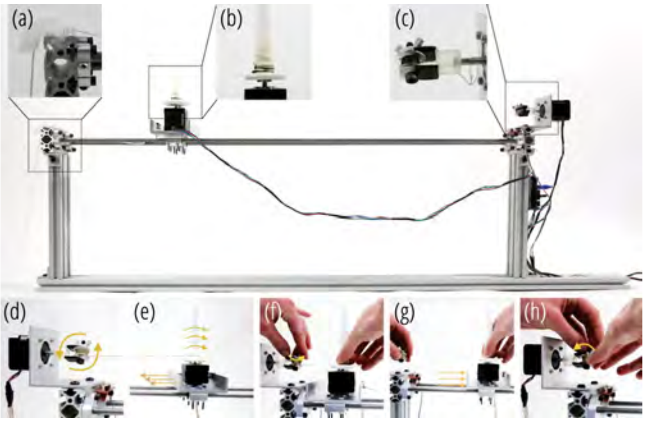

Figure 5: The process of making longer coils.

While the previous method is suitable for producing short coils, it is not well suited to make the longer coils that are necessary for our applications. To address this, we designed a semi-automated machine implementing a two-phase process of coiling and collecting, which we have used to obtain working lengths of approximately 2-3 meters.

To set up the machine, a bobbin is loaded into our custom bobbin clamp (Figure 5C). The coiling weight is attached to the carriage, then allowed to hang freely over a low friction surface (Figure 5A), creating a horizontal tension of the desired magnitude. Then, the thread is fixed to the collecting spool (Figure 5B), finalizing the machine set-up.

To begin, the operator uses a computer interface to activate the spinner seen in figure 5D. Once the desired twist density is achieved, the operator activates the collecting spool, which rotates to collect the finished segment (Figure 5E). The bobbin is then loosened (Figure 5F), and the carriage is pulled back to the original position, revealing uncoiled thread (Figure 5G). Finally, the bobbin is re-tightened (Figure 5H), and spinning can begin again. After the desired length is achieved, it can be lifted off the spool and cut away from the bobbin. After this, the actuators are annealed, plied (optional), coated, and trained as normal.

Plying, Annealing, Coating, and Training

There are four steps following the thread coiling process.

The first (optional) step is *plying*. 2-ply linear actuators are formed by folding the muscles in half under twice the original coiling load. The two halves are then allowed to twist freely around each other to form a torque-balanced structure. This means that when heated, the actuator will only shrink, even if untethered. All muscles are 1-ply unless otherwise specified.

Annealing refers to heating the coiled or plied thread a load larger than its coiling weight. This allows for shrinking actuation, as it separates the coils, creating space for contraction when reheated, and allows the silicone to penetrate into the coil. Linear actuators require annealing, while torsional actuators do not. Silver-plated actuators, thin actuator and thick actuator, go through three cycles of annealing, with 5 minutes of Joule heating with their specific actuation current and 5 minutes of cooling. Fishing line actuators go through the same three annealing cycles but are instead heated to 65°C with a heat gun.

For the *coating*, a thin (.2 mm) coating of silicone is applied in two stages with a sponge to the coils, which are still held under their annealing weight. The excess silicone is wiped away to attain relatively constant thickness. After curing, a second layer of silicone is applied to obtain suitable thickness required for reversibility while minimizing actuation impediment.

For *training*, the load is removed from the actuator and heated with the same method and cycles used for annealing. The shrinking or twisting actuator will shrink or spin until it reaches a force equilibrium with the silicone. At that point, reversible actuation can be observed.

Cost and Timing of Fabrication

In full, the fabrication time for 100 cm of precursor thread is 20 minutes plus curing time: 5 minutes to coil, 10 minutes to train, and 5 minutes to coat. Cure time depends on the type of silicone; with the use of Dragon Skin 10, 20, 30, and MoldStar 20T. At 23°C, cure times are 45 min, 4 h, 16 h, and 30 min, respectively. The cost of an actuator from 100 cm of precursor thread thread would be, in bulk, $0.27. This is comprised of $0.20 for thread and $0.07 for silicone. In small batches, pricing aligns closer to $0.35 for thread and $0.37 for silicone. The resulting actuator is 25 cm long.

5 ELECTROTHERMAL PERFORMANCE ANALYSIS

It is known that a higher activation temperature is correlated to an increase actuation [14]. The temperature must at least be above Tg (glass transition temperature) for actuation to occur, with higher temperatures resulting in greater sample performance. However, heating the sample above its melting temperature can damage the actuator. The optimal power will yield the largest actuation without damaging the sample's actuation effect.

Assuming the change in resistance of the actuator with regard to temperature is negligible, we consider constant voltage and current as the sample is heated. We tested several different current options (Figure 6) for a 195mm-long thin actuator and a 270mm-long thick actuator, coated with two types of silicone with different stiffness (Dragon Skin 10A and Dragon Skin 20A), respectively. Figure 7 shows our thicker sample before and after heating under a thermal camera. To keep the testing samples straight, we hung test loads - the same as the samples' annealing loads - on each sample: 60g for the thin actuator, and 300g for the thick actuator.

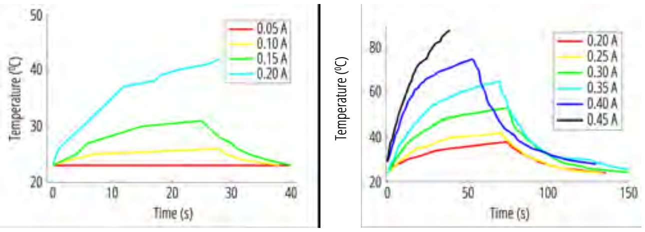

Figure 6: Temperature changes of thin actuator (left) and thick actuator (right) according to different currents.

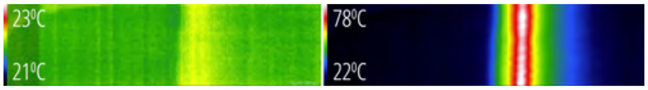

Figure 7: Thermal images of the thick actuator sample before being heated (left) and after it reaches its maximum temperature (right).

Figure 6 represents temperature changes of the thin actuator as it is heated by the current options in the aforementioned list. Figure 6 shows that actuation is faster at higher current, but a current that is too high melts the thread (.20A for thin actuator and .45A for thick actuator). From this, we selected our optimal activation currents with a safe margin(.15A for thin actuator, .40A for thick actuator).

Considering the thin actuator sample has 109.5Ω resistance and the thick actuator sample has 36Ω resistance, we can derive for each sample ***the minimum normalized power per unit length*** P_n to be $9.13 * 10^{-3}$ W/mm and $2.95 * 10^{-2}$ W/mm respectively. Using these derived P_n values, we can calculate the ideal driving power for samples of any arbitrary length.

6 SHRINKING ACTUATOR PERFORMANCE

To study the effect of *annealing weight* on shrinking actuation reversibility, 9 thick actuators were prepared, but before being coated they were divided into 3 groups of 2 actuators. Groups 1, 2, and 3 were annealed using .40A and a weight of 300g, 450g, and 600g, respectively. Additionally, in order to assess the effects of *silicone stiffness* on actuator performance, one actuator from each group was coated using Dragon Skin 10A, and the other was coated using Dragon Skin 20A (a stiffer silicone).

Table 3 represents the actuation shrinkage rate according to different fabrication parameters: silicone types and annealing weights. Generally, the result shows a trend that the heavier the annealing load for an actuator's fabrication, the larger the shrinkage rate the actuator can achieve. In addition, the actuator coated in a less stiff silicone has a smaller shrinkage rate than the sample coated in a stiffer silicone. This is likely because the less stiff silicone did not provide enough force to prevent intercoil contact. Once the coils are in contact, they are unable to shrink further and instead stiffen.

Table 3: Thick actuator shrinkage rate according to different annealing weight parameters.

Annealing Weight	Shrinkage Rate (Dragon Skin 10A)	Shrinkage Rate (Dragon Skin 20A)
300g	1.7%	3.4%
450g	2.9%	3.3%
600g	5.0%	5.0%

7 TWISTING ACTUATOR PERFORMANCE

Period Test

In order for an actuator to possess stable, fast, and repeatable reversibility, it is important to accelerate the twisting actuation rapidly while ensuring overheating does not damage to the sample (as observed in *Electrothermal performance analysis*). For this experiment, we used a 215mm-long thin actuator coated in MoldStar 20T silicone, under a test weight of 30g, as a small amount of tension is needed to hold the actuator straight. We then applied different current options to the actuator and measure the time taken to reach the maximum numbers of rotations.

In general, twisting behavior becomes more rapid at higher currents (Figure 8). While currents above 0.15A are shown in *Temperature test* to damage the sample, we find that at 0.20A, for up to 6 seconds, the sample exhibits the maximum number of rotations, before beginning to fail shortly after.

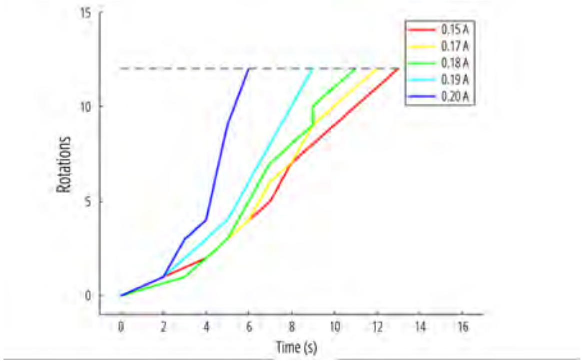

Figure 8: Time is taken to achieve the maximum number of rotations according to different currents.

Accumulated Momentum Test

Based on the *Period test*, we chose to drive 0.20A current into a 180mm-long thin actuator sample coated in MoldStar 20T silicone for 6 seconds of twisting actuation, by hanging a test weight of 30g at the free end of the threaded actuator. To best accumulate torsional momentum, it is essential to time the heating a cooling cycle properly. We chose different combinations of actuation times and break durations for the test. Figure 9 shows that the optimal reversible accumulated torsional performance is achieved in a thin actuator using a 30g load, a driving current of 0.20A, and the combination of 6-sec of actuation and either 14-sec or 16-sec of break time.

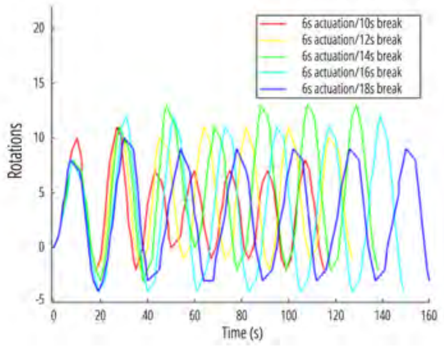

Figure 9: The number of rotations achieved by accumulated momentum according to different sets of actuation and break periods

8 STRUCTURAL EXAMPLES AND APPLICATIONS

In order to demonstrate how our thread actuators can be utilized in a variety of interaction contexts, we developed four demonstrations greatly ranging in style and scope.

Fabric-Embedded Non-Invasive Haptic Feedback

We embedded the ModiFiber shrinking actuator into the sleeves of a shirt for on-body haptic feedback. The sleeve can react to a variety of conditions- ranging from text message notification to barometric pressure drops– to activate the garment. When triggered, the actuator begins to warm and constrict around the user's arm. Once deactivated, the actuator relaxes and the shirt loosens. For this application, actuation takes 5 min, and recovery takes 6 min.

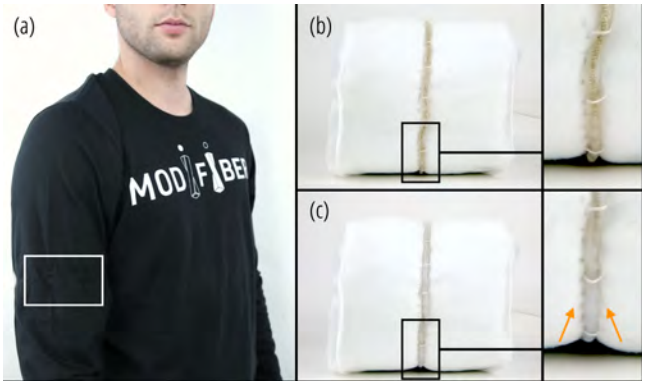

Figure 10: ModiFiber embedded in a shirt (A), foram surrounded by a sample shirt-actuator before activation (B), and during activation (C).

Actuation is achieved through the implementation of two 2-ply shrinking thick actuator into the sleeves of a long sleeve shirt, as highlighted in Figure 10A. The 2-ply shrinking thick actuators were annealed with 1.2 kg with a current of .60A, coated with Dragon Skin 30A, then stitched into the bicep area of the shirt.

The actuator is driven by an Arduino embedded in the shirt, powered by an array of small rechargeable 9v batteries. A 1Sheeld Arduino Shield is used to allow environmental data, and other web-based information, to be shared with the Arduino through Bluetooth from a mobile phone, allowing data to trigger the actuation, and the actuation to subside after a set duration or change in data.

Performative Pleats

We developed a prototype for a temperature responsive self-pleating fabric. We foresee these materials being useful in temperature-regulating garments. For example, a self-pleating fabric could be a mid-layer for a firefighter jacket, so that it can quickly increase in thickness to create an air insulation layer. This would maximize mobility while still providing proper heat protection when needed.

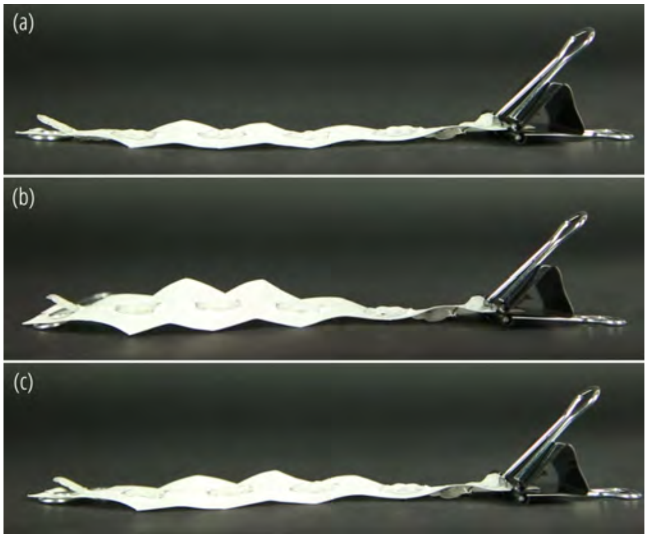

Figure 11: Thermoresponsive pleats before heat is applied (A), while heat is applied (B), and after heat has been removed (C).

To do this, a 1-ply shrinking actuator was stitched through a pre-creased piece of paper. The actuator starts flat (Figure 11A). When heated with a heat gun, the actuator contracts causing the paper to pleat (Figure 11B), and becomes flat again when cooled (Figure 11C).

Active Fashion - ”Homeostasis”

We implemented actuators into two garments to demonstrate the potential for these applications in transformative fashion. The actuators are well-suited to these applications, as external restorative forces, like weights or a spring, are not feasible for wearables.

Figure 12: Active garments triggered by spinning actuators (top), and the power and control system used to drive motion (bottom).

The first garment engages an origami structure allowing the porosity of the garment to be tuned (Figure 12). This garment uses a 57.75 cm long shrinking 2-ply thick actuator that is annealed with 1.2 kg at a .60A current and coated in Dragon Skin 30A. The garment is powered by two 9 volt Li-ion batteries. For this application, actuation takes 5 min, and recovery takes 5 min.

Figure 13: Active garments triggered by 2-ply shrinking thread actuators.

The second garment has spinning tassels (each weighing 8.58g) as style pieces (Figure 13). This is achieved by using six twisting thin actuators, coated with MoldStar 20T. Each tassel is powered by a single 9 volt NiMH battery (6 total), allowing for over an hour of continuous use. For this application, actuation takes 4 s, and recovery takes 4 s.

We embedded an electronic circuit within each garment to control each transformation. The circuit for actuation is mainly comprised of three parts: actuators, batteries, and a switch. Each actuator is connected with the switch and the batteries in parallel. Models can press the switch to trigger the actuation when they pose at the end of a runway. Additionally, we integrated the relay control for the garment with tassels to achieve accumulated momentum via a pulsing power supply.

Self-Stirring Tea Bag

In addition to resistive heating via electrical current, the thread actuators can react to environmental heat sources as well. In this case, the spinning thin actuator functions as the string of the tea bag and respond to hot water (Figure 14).

To help tea steep faster, we utilize a twisting actuator as the string to hold the tea bag. When the bag and string enter the water, they automatically start to spin and stir; when the tea bag is temporarily pulled out of the water, it will spin the opposite direction to release the torsional stress. This motion can be repeated.

The tea bag is also an exploration of Modifiber in the space of material driven responses to environmental stimuli (e.g. water temperature, human sweat, weather.) [31, 29]. Though on the fringe of classic interaction scenarios, the tea-bag illustrates ModiFiber as a part of the vision for human-material interaction.

To implement the tea bag, a twisting thin actuator coated in MoldStar 20T is used. Actuation takes 64 s, and recovery takes 16 s.

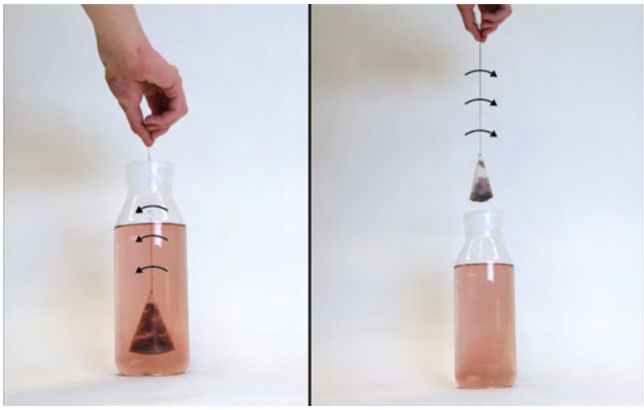

Figure 14: Self stirring tea bag.

Interactive Paper Art

To enrich the interaction modality with our thread actuator, we implemented a capacitive sensing function as a demonstration. A relay is used to combine the sensing circuit and the actuation circuit configuration (Figure 15). This allows modifiber to act as a sensor and an actuator in the same feedback loop. We designed the circuit by modifying the experimentation in [31]. Originally, channel 2 opens the capacitive sensing circuit; once a finger touch is sensed, channel 2 closes and channel 1 opens to allow the heating of the thread actuator and enable the morphing of the thread (Figure 15).

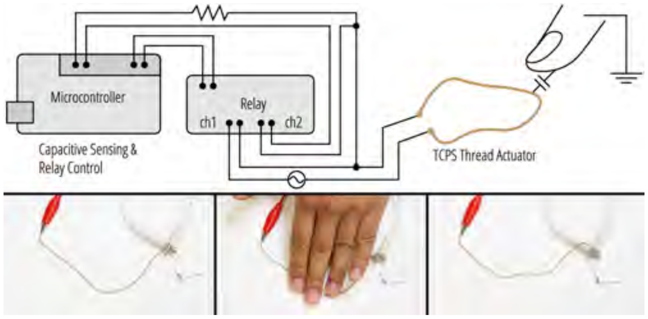

Figure 15: Capacitive sensing and thread actuation.

We use this to add animation to previously static paper art (Figure 16). The thread is touch-sensitive, and triggers the .40A current which shortens the thread and pulls the sun out of the cloud. After a set duration, the power supply turns off, causing the sun to set back into the clouds as the thread extends back to its original length. This uses a thick shrinking actuator, coated in Dragon Skin 20A. Actuation takes 32 s, and recovery takes 32 s.

Figure 16: Touch-sensitive paper art

9 LIMITATIONS AND FUTURE WORK

The two-way thread actuators introduced are subject to limitations. Due to the low thermal-conductivity of silicone, the current activation and recovery times are slow (5 minutes needed for each). Also, the actuators can become quite hot (up to 80°C) necessitating a thermal insulation layer is needed for on-body applications. Additionally, actuators that remain perfectly straight when unattached are difficult to fabricate, as they require a completely uniform silicone coating, although they nonetheless still exhibit reversible behavior.

In the future, we would like to investigate the use of liquid-metal impregnated silicones for the coating. The liquid metal should improve the thermal conductivity of the coating, shortening the activation and recovery time.

We would also like to explore the possibility of knitting our thread actuators and forming higher hierarchical structures. This way, we can achieve more complex motion types and more precise movement.

In order to utilize the thread in either knitting or weaving, we have to manage to produce continuous long fibers in an automated fashion. Not only the coiling process, but also the silicone coating process has to be improved. We think our actuator threads are especially suitable as embedded actuators for wearables, as we have proved that the power supplied by a 9v battery is enough for actuation. We would also like to go beyond commercially available fishing line, and produce coiled actuators with different shapes by 3D printing structures with helically aligned polymer chains. This would allow for a greater variety of actuation types possible, as well as improving the strength of actuation.

Adjacent to the precision that a printed coil actuator would allow, further automation of the fabrication process to yield longer samples without the need for a machine operator would allow for the exploration of actuators on the many many meters length scale. These actuators can then be explored with knitting and weaving techniques to allow for the seamless integration of actuating muscles in textile design.

10 CONCLUSION

In this paper, we introduced ModiFiber, a novel soft thread actuator composite that can achieve reversible actuation without an external restorative force. We developed two basic morphing types - shrinking and twisting. We investigated the control method, and quantified the role of silicone stiffness and annealing weight critical to the performance of shrinking and spinning thread actuators. Through a few applications, we hoped to demonstrate the potential applicability of such actuators in interactive wearables, toys, robots, and daily life. ModiFiber is a thread based actuator with a conformable coating, meaning it is usable by textile manufacturing machines; and, compared to other string actuators, flexible polymers are more skin friendly. We envision great potential for this technology in on-body applications. We hope ModiFiber can enrich HCI's soft and flexible actuator toolbox, and enable researchers to further explore string-based soft actuation.

11 ACKNOWLEDGEMENTS

The authors would also like to thank the College of Engineering TechSpark makerspace, School of Drama Costume Design, Alan Guo for video footage and active fashion, Koya Narumi for the camera ready format support, and Humphrey Yang for helping greatly refresh our figures.

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