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1-1-2016

### New twist on artificial muscles

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Haines, Carter S.; Li, Na; Spinks, Geoffrey M.; Aliev, Ali E.; Di, Jiangtao; and Baughman, Ray H., "New twist on artificial muscles" (2016). *Faculty of Engineering and Information Sciences - Papers: Part A*. 6167. <https://ro.uow.edu.au/eispapers/6167>

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## New twist on artificial muscles

### Abstract

Lightweight artificial muscle fibers that can match the large tensile stroke of natural muscles have been elusive. In particular, low stroke, limited cycle life, and inefficient energy conversion have combined with high cost and hysteretic performance to restrict practical use. In recent years, a new class of artificial muscles, based on highly twisted fibers, has emerged that can deliver more than 2,000 J/kg of specific work during muscle contraction, compared with just 40 J/kg for natural muscle. Thermally actuated muscles made from ordinary polymer fibers can deliver long-life, hysteresis-free tensile strokes of more than 30% and torsional actuation capable of spinning a paddle at speeds of more than 100,000 rpm. In this perspective, we explore the mechanisms and potential applications of present twisted fiber muscles and the future opportunities and challenges for developing twisted muscles having improved cycle rates, efficiencies, and functionality. We also demonstrate artificial muscle sewing threads and textiles and coiled structures that exhibit nearly unlimited actuation strokes. In addition to robotics and prosthetics, future applications include smart textiles that change breathability in response to temperature and moisture and window shutters that automatically open and close to conserve energy.

### Keywords

twist, artificial, muscles

### Disciplines

Engineering | Science and Technology Studies

### Publication Details

Haines, C. S., Li, N., Spinks, G. M., Aliev, A. E., Di, J. & Baughman, R. H. (2016). New twist on artificial muscles. *Proceedings of the National Academy of Sciences of USA*, 113 (42), 11709-11716.

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## **A New Twist on Artificial Muscles**

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## **Abstract**

Light-weight artificial muscle fibers that can match the large tensile stroke of natural muscles have been elusive. In particular, low stroke, limited cycle life and inefficient energy conversion have combined with high cost and hysteretic performance to restrict practical use. In recent years, a new class of artificial muscles, based on highly twisted fibers, has emerged that can deliver over 2,000 J/kg of specific work during muscle contraction, compared to just 40 J/kg for natural muscle. Thermally-actuated muscles made from ordinary polymer fibers can deliver long-life, hysteresis-free tensile strokes of over 30% and torsional actuation capable of spinning a paddle at speeds of over 100,000 revolutions per minute. In this perspective, we explore the mechanisms and potential applications of present twisted fiber muscles, and the future opportunities and challenges for developing twisted muscles having improved cycle rates, efficiencies, and functionality. We also demonstrate artificial muscle sewing threads and textiles, and coiled structures that exhibit nearly unlimited actuation strokes. In addition to robotics and prosthetics, future applications include smart textiles that change breathability in response to temperature and moisture, and window shutters that automatically open and close to conserve energy.

## **Keywords**

artificial muscles | actuators | carbon nanotubes | yarns | textiles

## **The Need for Better Artificial Muscles**

Electromagnetic motors and actuators have enabled an impressive array of robotic and prosthetic devices. Unfortunately, these actuators are heavy, and cannot provide the large contractile strokes in the small footprint that natural muscles do. This has led to robotics that can greatly overpower natural organisms in terms of raw force generation, but which have difficulty achieving the fine motion and soft actuation required for complex tasks, like recreating human-like facial gestures or catching a ball. Additionally, nature tends to achieve high dexterity across large working envelopes by using kinematic chains of actuators. The human arm is a good example, beginning at the shoulder, and ultimately supporting over 7 degrees of freedom in the arm and up to 27 additional degrees of freedom in the hand (1, 2). This arrangement is a compounding issue for robotics using heavy actuators and motors, which must rely on increasingly larger actuators towards their base in order to support actuator mass at the extremities.

Numerous types of ‘artificial muscles’ have been developed to try to bridge this gap. Since our goal is to consider light-weight artificial muscles that offer similar shape and functionality as natural muscle, we here restrict discussion to artificial muscle fibers. While some types of artificial muscle fibers can generate 53 times higher maximum contractile work per cycle, 85 times higher typical contractile power density, and much larger strokes than can natural muscle (3, 4, 5, 6), no artificial muscle fiber can yet provide the high energy conversion efficiencies, self-reparability, and billions of reversible actuation cycles of natural muscles (3, 7).

Wires made from shape memory alloys have seen use as artificial muscles since their popularization in the 1970’s. When heated thermally or electrothermally by Joule heating, these muscles can provide large specific work per cycle, exceeding that of natural muscle by over 20 times (~930 J/kg vs. 40 J/kg). However, these wires normally provide less than 8% contraction, with 4-5% being typical, and their response is relatively binary and hysteretic (8, 9), making it hard to controllably achieve intermediate contraction states. Coiling these shape-memory alloy wires increases stroke to as much as twice their initial coil length (10), but these springs are difficult to fabricate into tight coils, leading to muscles with low force generation. Shape memory polymers may also be used as artificial muscle fibers, but they typically provide low

work capacity, and, like shape memory alloys, their contraction is difficult to control precisely (11, 12).

A host of other remarkable actuating materials and actuation processes have been extensively investigated. These include, for example, piezoelectric ceramics and polymers (13, 14, 15), electrostatic actuators based on deformable capacitors (16, 17), electrochemically-doped conducting polymers (18), and cantilever-based ionic-polymer metal composites (19, 20). However, since it is challenging to employ these alternative actuator materials and processes in small-diameter artificial muscle fibers, we will restrict present discussion to recently discovered high-performance artificial muscle fibers whose remarkable properties depend upon inserted twist.

### **The Path to Twisted Artificial Muscles**

In recent years, a new class of muscles has emerged based on highly twisted fibers. These muscles can provide powerful strokes at over 30% reversible contraction (4), torsional actuation that can spin rotors at over 100,000 revolutions per minute (rpm) (21), and specific work during contraction of 2.48 kJ/kg, which is over 50 times that of natural skeletal muscle. In the following sections, we explore the mechanisms that underlie these muscles and the opportunities they bring forth.

The first demonstration of a highly-twisted artificial muscle was the 2011 discovery of torsional actuation from carbon nanotube (CNT) yarns (22). When twisted and immersed in an electrolyte, a 12- $\mu\text{m}$ -diameter yarn provided 250°/mm of rotation at speeds up to 590 rpm when charged electrochemically. In 2012, CNT yarns were further shown to provide tensile actuation after twisting to such an extreme degree that the fiber spontaneously formed coils (5). These coils mechanically behave like tight springs and can provide tensile contraction of ~7.3% when pristine coiled CNT yarns are heated to incandescent temperatures in an inert environment. More practically, by infiltrating CNT yarns with a guest material having a large coefficient of thermal expansion, these hybrid CNT yarns could provide torsional and tensile actuation in lower temperature ranges. For instance, a coiled CNT yarn infiltrated with paraffin wax delivered over 5% contractile stroke when heated to 200°C (5). More recently a coiled, silicone-rubber-infiltrated CNT yarn has provided a tensile stroke of over 34% when heated electrothermally, and 50% when actuated by solvent absorption (31).

Twisted and coiled CNT yarns have provided unprecedented torsional and tensile work capacities, but the high cost of fabricating these CNT fibers has limited their application. In this area, a key breakthrough came in 2014 with the development of polymer-based twisted fiber muscles. These artificial muscle fibers could be easily fabricated by simply twisting widely-available, low-cost materials like fishing line and sewing thread. When twisted to form coils, these muscles provided over 30% tensile stroke when heated, operated without hysteresis, and provided millions of cycles of stroke without significant degradation (4Error! Bookmark not defined.).

### Twisted Muscle Mechanisms

The process of making a twisted artificial muscle begins with a precursor fiber which has at least some degree of internal alignment. In the case of carbon nanotube yarns, this alignment comes from the bundles of nanotubes which are oriented along the fiber direction during fabrication to provide strength to the yarn. Polymer muscles similarly employ high strength fibers, such as those used for fishing line or sewing thread, which have been stretched along their fiber direction to align the constituent macromolecules.

This alignment gives muscle precursor fibers a key property: fiber anisotropy. In particular, for thermally-actuated muscles, the precursor fiber's length-direction thermal expansion differs from its radial thermal expansion. This effect is most dramatic in certain aligned polymer fibers like nylon, which, as-received and without any inserted twist, expand in diameter but contract in length when heated (23). This strange property derives from the molecular structure of the fiber, wherein entropic forces cause the fiber to contract in length when heated, despite increasing in overall volume (24, 25). In the case of nylon 6/6, this process can result in a 4% decrease in fiber length when heated to 240°C (4).

By inserting twist into an anisotropic fiber, the fiber's constituent elements (polymer chains or CNTs) are reoriented into helices. This twist is most dramatic at the fiber's surface, where alignment shifts away from the fiber axis by an angle  $\alpha_f$ , referred to as the fiber bias angle:

$$\alpha_f = \tan^{-1}(\pi DT) \quad [1]$$

where  $D$  is the fiber diameter, and  $T$  is the twist inserted into the fiber per fiber length (typically in units of turns/m). By drawing a straight ink line along the fiber, we can visualize this

transformation from linearly oriented polymer chains in the original fiber to helically oriented chains in the twisted fiber (Fig. 1A).

Twisting fibers of anisotropically-expanding materials gives rise to a new phenomenon: the thermal torsion effect. In the case of most aligned fibers, which experience a greater radial thermal expansion than axial thermal expansion, this causes a reversible untwisting of the fiber as temperature increases. This process can be understood by considering a string, representing a single contracting polymer chain, that is wrapped around a rod of fixed diameter, and attached to both rod ends. If the string contracts, then the rod must untwist if the rod length does not change. Similarly, a string of fixed length, wrapped around a rod of fixed length, also causes the rod to untwist when the rod's diameter increases. For fibers like nylon, both length contraction and radial expansion additively contribute to untwisting. More generally, any oriented fiber that expands in radius more than it expands in length (before twisting) can generate untwist to form a torsional actuator simply by inserting twist into the fiber.

Hybrid carbon nanotube yarns represent a special case of this effect. Although pure carbon nanotube yarns also provide anisotropic thermal expansion, since nanotube length contracts and yarn diameter expands during heating, like for the in-plane and inter-plane expansions in graphite (26), this dimensional change is small and can only generate useful actuation when the yarn is heated across extreme temperature ranges. However, by infiltrating a volume expanding guest within the confines of a twisted CNT yarn, a large, initially isotropic guest expansion can be transformed into an anisotropic yarn expansion by the helically aligned, high-stiffness CNTs, thereby producing torsional actuation.

### **Coiled Muscle Mechanisms**

Highly over-twisted yarns and fibers spontaneously form coils in order to minimize strain energy (27). These coiled structures provide remarkable tensile actuation, such as the over 30% tensile stroke delivered by heating a twisted coil made from nylon sewing thread, that is prevented from untwisting at its ends (4). At first, it may seem that this effect is a simple lever-arm amplification of the tensile contraction seen from non-coiled nylon filament. This is, however, not the case.

Much insight about the actuation mechanism of these coiled fibers can be derived from the humble coil spring. Although a wire made from spring steel can extend by no more than a



few percent, coiled extension springs made from the same material can be stretched to several times their initial length. Although this phenomenon has been employed for centuries, one of the best analytical explanations appears in AE Love's 1892 mathematical treatise on elasticity (28). Herein, Love explains how tensile stretch of a coil spring can be shown to primarily derive from torsional rotation of its constituent filament. Rearranging Love's equations into a more suggestive form, a change in coil length can be related to a change of twist within its constituent filament by the equation:

$$\Delta L = l^2 \Delta T / N, \quad [2]$$

where  $\Delta T$  is the change in filament twist,  $N$  is the number of coils,  $l$  is the length of the filament making up the coil, and  $\Delta L$  is the change in coil length. In this case, an untwist in the filament that makes up a coiled muscle can be seen as pulling adjacent coils closer together, shortening the coiled muscle (Fig 1B).

This torsional origin for coiled muscle stroke provides remarkable agreement between the torsional stroke measured from twisted fibers and the corresponding tensile stroke of coils made from these fibers (**Error! Bookmark not defined.**). Perhaps even more importantly, it indicates two key parameters for making coiled muscles. First, the relative diameter of a coil can play a critical role in determining the tensile stroke and stress of a coiled muscle. By further borrowing from spring mechanics, we can define a scale-independent quantity,  $C$ , the coil spring index, as the average coil diameter divided by the filament diameter. By making coiled muscles with a low spring index, tight, high-stiffness coils can provide large actuation forces. However, since there is little space between adjacent coils, these muscles provide limited contractile stroke. Alternatively, giant-stroke muscles can be fabricated from large spring index coils, but at the cost of decreased force generation.

The second lesson learned by considering torsion as the origin of coil actuation is the significance of the twist insertion and coiling directions. Ordinarily, overtwisted fibers form 'homochiral' coiled structures, wherein a coil spontaneously forms in the same chirality as the fiber's twist, so as to minimize strain energy. When a homochiral coil of nylon monofilament is heated, fiber untwist pulls coils together, causing contraction along the coil axis. However, by wrapping a twisted fiber around a mandrel so as to reverse the relative chiralities, a 'heterochiral' muscle is formed. By switching these twist and coil chiralities, the same thermal untwist of the fiber now drives length expansion of the coiled muscle during heating. Such coils made from

nylon can reversibly expand by over 60% of their original length when heated, providing coefficients of thermal expansion which are well over an order of magnitude larger than for bulk nylon (**Error! Bookmark not defined.**).

### **Understanding Coiled Muscles with Knot Theory**

While Eq. 2 can be derived from coil geometry, it is interesting to note that knot theory provides an equivalent explanation. When two ends of a fiber are tethered to prevent twisting, it at first seems intuitive that the fiber's twist cannot change. However, as with the supercoiling of DNA strands, knot theory explains that in fact only a quantity known as the linking number must be conserved. Linking number is defined as the sum of two values, twist and writhe, wherein one unit of twist is a net rotation of the ends of a straight fiber, and one unit of writhe is an in-plane loop of fiber. Consequently, twist and writhe can be converted between each other even when fiber ends are tethered to fix the linking number. This effect can be seen by wrapping a string around a rod, removing the rod, and pulling the string straight. The fiber will become twisted, even though no twist was directly added to the fiber during wrapping, because the writhe introduced during wrapping is converted into twist during stretching.

In a coiled muscle, each coil represents writhe. However, since each coil extends out of the plane along the fiber axis, a coil amounts to less than a full unit of writhe. The writhe of a single coil is therefore represented as  $1 - \sin(\alpha_c)$ , where  $\alpha_c$  is the coil angle, defined as the inclination of the coil relative to the plane orthogonal to the coil axis (Fig 1B). For a coil which is tethered at both ends to prevent rotation, when the fiber within a coil untwists, this untwist must be accompanied by an increase in writhe to accommodate a constant linking number. This simple conversion between twist and writhe can be used to derive Love's original equation, and provides a succinct description of the mechanism of coiled muscle actuation.

### **Emerging Types of Twisted Muscles**

As explored above, CNT yarn hosts can be used to convert any shape or volume changing guest material into torsional and tensile muscles. At present, thermally-driven muscles,

especially those made from polymer fibers, are among the simplest to demonstrate. In the two years since their discovery, robotic hands (29), self-healing composites (30), and muscle textiles (**Error! Bookmark not defined.**) have emerged. However, these thermal muscles provide limited efficiency, and muscles made from large-diameter fibers can suffer from slow cooling rates. The guest-host twisted muscle platform opens up broader possibilities to design smart materials and muscles which respond to heat, light, electricity, liquid absorption, or other stimuli.

Several exciting guest materials have already been demonstrated within CNT scaffolds. Some of the most promising examples are muscles driven by liquid sorption and by electrochemical charge injection, since both mechanisms have the potential to surpass the Carnot efficiency limit of thermally-powered muscles. For instance, silicone-rubber-infiltrated CNT yarn muscles have been demonstrated to provide over 50% stroke and 1.2 kJ/kg during contraction while absorbing solvents such as hexane and ether (31). Water-driven muscles have also been demonstrated by infiltration with water-absorbing polymers, such as poly(diallyldimethylammonium chloride) (PDDA). Such coiled PDDA/CNT hybrid muscles have delivered over 40% stroke and a contractile work of 2.17 kJ/kg when exposed between 10 and 99% relative humidity (32). Even without additional guest materials, the large surface area provided by a CNT scaffold can be used to drive actuation. For instance, Chen et al. have shown fast 340%/s actuation from pristine coils which absorb ethanol (33). By using a tension-annealing process to stabilize twisted and coiled CNT yarns against irreversible untwist, Di et al. have further used ethanol and acetone absorption to rotate heavy rotors without the need to tether yarn ends against irreversible rotation (34). Additionally, by plasma etching CNTs to convert yarns from hydrophobic to hydrophilic, He et al. have shown that CNT yarn can be directly used to make water-sorptive actuators (35).

The large accessible surface area of CNT yarns can be usefully employed for non-thermal, electrically-activated artificial muscles. By electrochemically charging in an electrolyte, CNT yarns can actuate by adsorbing ions and their associated solvating species into the pores within the CNT yarn. The key disadvantage of this technique has been the complication of having a counter electrode, and the need to immerse the system in an electrolyte. Lee et al. have shown that this problem can be overcome by using CNT yarns as both working and counter electrodes encapsulated within a gel electrolyte (36). By plying these twisted yarns into a single

muscle fiber, electrically-activated torsional strokes of 52°/mm were generated by two 29- $\mu$ m-diameter yarns.

Electromagnetic motors commonly achieve conversion efficiencies above 90%, having benefited from nearly 200 years of research and improvement. This impressive performance inspires the use of electromagnetism and magnetic materials to make efficient artificial muscles. Peng's group have reported twisted CNT yarn actuators which they propose are driven by electromagnetic attraction between CNTs caused by Ampere's force law (37,38,39). However, we find this mechanism improbable. The relatively low conductivity of CNTs compared to metals leads to significant heating at even moderate levels of current, and the actuation described by Peng exhibits the characteristic exponential dependence versus time expected for thermal actuation. To confirm this suspicion, we conducted an experiment where a coiled CNT yarn was actuated in air, and compared to its actuation while immersed in transformer oil. In both cases, the same 100 mA of current was applied through the yarn, generating essentially the same magnetic field. However, while the yarn in air was able to heat up to several hundred degrees Celsius, consequently delivering 3.8% tensile contraction, immersion in transformer oil kept the muscle cool, limiting actuation to below 0.1%. We also compared the actuation of a coiled CNT yarn when electrically heated by passing a current through the yarn, to the actuation of the same coiled yarn when heated in an environmental chamber, and found that the temperature-dependence of actuation was the same in both cases. These observations are consistent with our opinion that a simpler Joule heating explanation applies to the presently demonstrated actuators.

Twisted fiber muscles can also perform as remote sensors, which do not require external power to operate. For example, Lee et al. have demonstrated the use of hydrogels as guests within twisted CNT yarns to sense glucose (40). By conjugating the hydrogel with boronic acid, the infiltrated gel swells and deswells in response to the surrounding glucose concentration causing torsional actuation, and rotating an indicator paddle attached to the middle of the yarn. Such sensors may be used to monitor the levels of substances in vivo, where electrical power is unavailable, and can form the basis of active sieves and filters that adjust permeability to increase efficacy.

Guest materials can also modify the actuation of a muscle fiber and provide additional functionality. By adding viscoelastic polystyrene-poly(ethylene-butylene)-polystyrene (SEBS) polymer to paraffin wax, Chun et al. were able to tune a CNT muscle's damping coefficient to

suppress unwanted torsional oscillations during high speed actuation (41). Once damped, arrays of these muscles could reposition miniature mirrors with settling times of roughly 100 ms. For thermally-driven muscles, the use of chemical fuel can increase energy storage density and runtime by over 20 times that of lithium-ion batteries. Methanol and hydrogen powered shape memory muscles have been enabled by adding catalyst nanoparticles to the surface of solid shape-memory wires (42). By incorporating catalytic particles within twisted muscle fibers, autonomous actuation and robotics may become practical for twisted and coiled fiber actuators.

Ultimately, the ability to amplify the small strain of otherwise promising actuator materials such as piezoelectric, electrostrictive, magnetostrictive, and photoisomeric materials may be one of the key benefits of twisted fiber muscles. For instance, photoresponsive molecules have been shown to change their conformation in response to light with switching times faster than 2.1 ps (43, 44). Unfortunately, the small strain delivered by these molecules makes them impractical for actuation. The typical strategy has been to graft photoisomeric molecules into large liquid crystalline polymers in order to generate large strains, but such polymers do so at greatly reduced rates, and their work density is limited by the relatively small fraction of the molecule that is photo-active (45, 46). Future twisted fiber muscles may be able to employ small-strain, but high-rate photoisomeric guests to deliver useable strokes at unprecedented cycle rates.

While CNT yarns are often an ideal fiber host, any fiber which confines a guest to an anisotropic volume expansion can produce a twisted artificial muscle. For instance, large-diameter, wax-filled yarns made from niobium nanowires have been demonstrated to torsionally actuate by up to 12°/mm when electrically heated (47). Similar to water-absorbing CNT yarns, Cheng et al. have used twisted graphene oxide fibers to absorb water, delivering up to 5,190 rpm during torsional actuation (48). More recently, Cruz-Silva et al. have demonstrated graphene-oxide fibers which can be twisted, knotted and coiled (49), potentially opening the path to tensile actuation from graphene fibers. In the future, electrospun polymer nanofiber yarns may enable a wide range of muscle hosts owing to their lower cost, high internal surface area, and large availability of functional polymers. For instance, electrospun fibers of piezoelectric poly(vinylidene fluoride trifluoroethylene) (PVDF-TrFE) have been demonstrated that can be twisted and coiled (50).

## **Muscle Scaling**

Because twisted and coiled fiber muscles fundamentally actuate by torsion, and these torsional actuation mechanisms are intrinsically scalable, these muscles can be used for actuation from the nanoscale on up to the macroscale. For instance, consider a twisted nylon fiber muscle. As long as the fiber diameter is appreciably greater than the scale of the constituent molecules themselves (0.4-0.5 nm) (51), the process of twisting a fiber of a given aspect ratio is essentially scale invariant. In-depth mathematical analysis can be found in the work of Aziz et al. (52) and the supplementary materials of our 2014 paper on polymer muscles (**Error! Bookmark not defined.**), so we will limit our discussion below to the key consequences of this scaling.

The defining parameter for a twisted fiber is its fiber bias angle, which defines the degree of helical rearrangement of the fiber's constituent elements at the surface of the fiber. From Eq. 1, the bias angle depends on the product of diameter and twist per length. This can be restated as the required twist scaling with the fiber's aspect ratio,  $L/D$ . Alternatively, when normalized to fiber length, the twist insertion required to obtain a given bias angle decreases linearly with increasing fiber diameter. Since it has recently been demonstrated that torsional stroke depends only on the inserted twist per fiber length (46), it is also concluded that torsional actuation decreases linearly with increasing fiber diameters, where fiber bias angles are constant. Scaling implies that muscle work must be proportional to muscle volume. Since work is the product of torsional stroke and torque, the generated torque must scale with the cube of diameter. This can be understood by considering that the cross-sectional area, and thus amount of material causing torsional force, increases with the square of diameter, and this is multiplied by the effective lever arm of this torsion, which also increases with diameter.

Since coiled muscles derive their tensile stroke from torsion, these relationships extend to the fabrication of coiled muscles. In an analysis by A.L. Ross (53), the twist-induced coiling of a cable occurs beyond a critical torque,  $\tau_c$ , defined as:

$$\tau_c = \sqrt{2EIF} \quad , \quad [3]$$

where  $E$  is the material's Young's modulus,  $I$  is the second moment of area, which is  $\pi D^4/16$  for a fiber of circular cross-section and diameter  $D$ , and  $F$  is the tensile force applied to the fiber. For coils made under the same stress,  $\sigma$ , the force is  $F = \sigma A = 4\pi\sigma D^2$ . The critical twist to coil in turns per meter,  $T_c$ , is therefore:

$$T_c = \frac{\tau_c}{2\pi JG} \quad , \quad [4]$$

where  $J$  is the polar moment of inertia, defined as  $\pi D^4/32$  for a cylindrical fiber, and  $G$  is the fiber's shear modulus. Combining Eqs. 5 and 6 yields the twist required to coil a cylindrical fiber:

$$T_c = \frac{8\sqrt{2\sigma E}}{\pi D G} \quad , \quad [5]$$

This equation shows that the critical twist to cause coiling is inversely proportional to fiber diameter when twist insertion is performed at constant tensile stress. This analysis is consistent with previous observations that coiled muscles provide essentially the same tensile stroke when made from 150- $\mu\text{m}$ -diameter fibers as they do with 2450- $\mu\text{m}$ -diameter fibers, as long as the applied tensile stress during twist insertion is kept constant (**Error! Bookmark not defined.**).

### What Limits Muscle Stroke?

In regular coiled structures, two factors can limit the maximum tensile stroke of a muscle. On one hand, the twisted fiber within a coiled muscle provides a limited amount of torsional actuation. If this torsional actuation is exhausted, tensile contraction stops. On the other hand, tensile actuation can also be limited when adjacent coils come into contact, even if further torsional actuation is available. We believe the latter coil-coil contact is typically what limits tensile stroke for most coiled nylon muscles. For instance, the inset of Fig. 2B plots the torsional stroke of a twisted, 300- $\mu\text{m}$ -diameter nylon fiber. After annealing this twisted fiber around a mandrel, the coiled muscle contracts when heated up to 140°C. Beyond this point, strain flat-lines at around -46% as adjacent coils come into contact. Calculating the tensile stroke using Eq. 2 allows us to predict the expected tensile stroke (Fig. 2B), which agrees with the actual muscle stroke up to the point of coil contact. However, while tensile contraction halts because of coil interference, further stroke would be possible if this coil-coil contact were avoided, for example by applying an increased tensile load.

By making coils of large spring index, this restriction can be minimized. Producing large diameter coils leads to greater twist per coil to drive actuation, and greater inter-coil spacing for actuation to occur. Defining actuation stroke as the change in length during actuation, divided by the non-actuated length,  $(L_{\text{initial}} - L_{\text{final}})/L_{\text{initial}}$ , this limits contraction to a theoretical maximum of just below 100%.

However, even this contraction by the entire muscle length is not a fundamental limitation. Fig. 3 depicts a coil formed by annealing a highly-twisted nylon 6 fishing line in a

spiral mold. As opposed to traditional coils, the spiral structure allows adjacent coils to pass through each other during contraction. Fig. 3A plots the muscle length, measured between the tip and tail of the coil, versus temperature, when heated and cooled in an oven. When heated, the muscle not only contracts to its minimum possible length, where it is essentially a flat spiral with the thickness of the constituent fiber (around 860  $\mu\text{m}$ ), but inverts through itself to extend in the opposite direction. In this case the tensile stroke, as normalized to the initial coil length, exceeds 100% and actually increases to near 200%. However, in many reports, especially for expanding actuators, stroke is reported normalized to the shortest actuator length as:  $(L_{\text{max}} - L_{\text{min}})/L_{\text{min}}$ . In this case, this metric for stroke breaks down, since the minimum length is restricted only by the fiber diameter. By considering that the actuator in Fig. 3 can shrink down to around 860  $\mu\text{m}$ , and extend to 75 mm in length, the result is an astonishing 8,600% stroke. Defining stroke is even more confusing when considering that the coil reaches negative length after the coil inverts, and both positive and negative displacements occur during a single heating cycle. The explanation for this switching is that a homochiral muscle converts into a heterochiral muscle during heating. This demonstration shows that torsional actuation can be used to achieve practically limitless muscle stroke, which may be useful for providing intelligent insulation that responds to temperature change by increasing thickness, thereby controlling thermal transport. To accomplish this effect, the spiral muscle can be thermally annealed while elongated in either a homochiral or heterochiral state, such as being annealed around a conical mandrel, so that heating causes the insulation to either reversibly increase or decrease. This giant actuation could also be used for deployable structures, such as folding solar panels for possible use in outer space.

### **Metrics for Artificial Muscles**

It is often difficult to compare the published performance of various types of artificial muscles because of the lack of appropriately normalized metrics. For instance, consider the popular statement that an actuator can lift “X times its own weight”. While it may lead to impressive sounding numbers, this metric conveys little useful information since it neglects both muscle length and stroke. By cutting such a muscle in half, it would weight half as much, but still be able to lift the same weight, thus arbitrarily doubling the metric.



Such pitfalls are also common when characterizing torsional muscles, and we here offer fairer metrics for comparing torsional fiber muscles. A simple, but flawed, metric to report is the torsional stroke normalized to muscle length, in turns/m or °/mm. Initially, this metric seems fair since rotation scales proportionally with fiber length. However, as described above, fiber diameter also critically affects fiber twist and torsional actuation. Since large diameter fibers accept less twist to reach the maximum achievable bias angle, they intrinsically provide smaller torsional stroke, albeit while generating a higher torque. Guided by the scaling laws described above, we suggest a more appropriate metric, which, for a given fiber bias angle, scales proportionally with fiber length and inversely with fiber diameter. The corresponding units are in turns·m/m, or, more simply, degrees normalized to aspect ratio,  $L/D$ . Alternatively, both the torsional stroke per length and muscle diameter should be reported. Using this approach, the 300- $\mu\text{m}$ -diameter torsional nylon actuator of Fig 2B, provides ~11 degrees of normalized actuation by rotating 103 turns/m between 20 and 190°C. For torsional muscles not twisted to the same bias angle, a more general metric is to report the torsional actuation as a percentage of inserted twist.

Metrics for coiled muscles are further complicated by the issue of spring index. While a large tensile stroke may, in itself, seem impressive, such actuation could result from an otherwise poorly performing muscle formed into a large spring index coil. It is, therefore, important to compare coils of similar spring index, or to take into account both the percent stroke and stress capabilities of coiled muscles to realize a meaningful comparison. It is more useful for most applications to report percent stroke as a function of applied tensile stress.

## **Future Outlook**

The opportunity to combine functional guest and host materials provides a platform to meet the needs of a wide range of potential applications. Given the emphasis on artificial muscles, the most straightforward uses are for improved robotics, prosthetics and orthotics. However, further opportunities exist in smart materials which respond to their environment, such as fibers that harvest or help conserve energy. For instance, by coupling torsional and tensile muscles to electromagnetic generators, Kim et al. have demonstrated harvesting low-grade waste heat to recover over 124 Watts of energy per kilogram of muscle weight (21). Louvers and vents which passively adjust to regulate building temperature are also anticipated.

In the near term, the ability to easily mass-produce muscles from low-cost polymer fibers, like nylon and polyethylene, may enable smart textiles for clothing that change porosity in response to temperature and moisture to regulate breathability, or for curtains that adjust their transparency in response to ambient light levels. Fig 4 shows examples of present capabilities to continuously process sewing thread into thermally and electrically activated muscle fibers, and the ability to use conventional sewing, knitting and weaving techniques to fabricate and modify textiles with such muscle fibers.

Future applications are also likely to benefit from the wide ranging scalability of this technology, from nanoscale robots propelled by twisted muscle flagella, to dynamic architecture and buildings that morph based on changes in the surrounding environment.

### **Acknowledgements**

We thank Michael Dinh, Joyce Chemplanikal, Dawood Albarq, Alexander Atkins, Brian Buckenham and Christopher Cormier for assistance with sample preparation and measurements. Support was provided by Air Force Office of Scientific Research grants FA9550-15-1-0089, AOARD-FA2386-13-1-4119, and FA9550-12-1-0035; and Robert A. Welch Foundation grant AT-0029; and the Australian Research Council Discovery Grant DP11 0101073.

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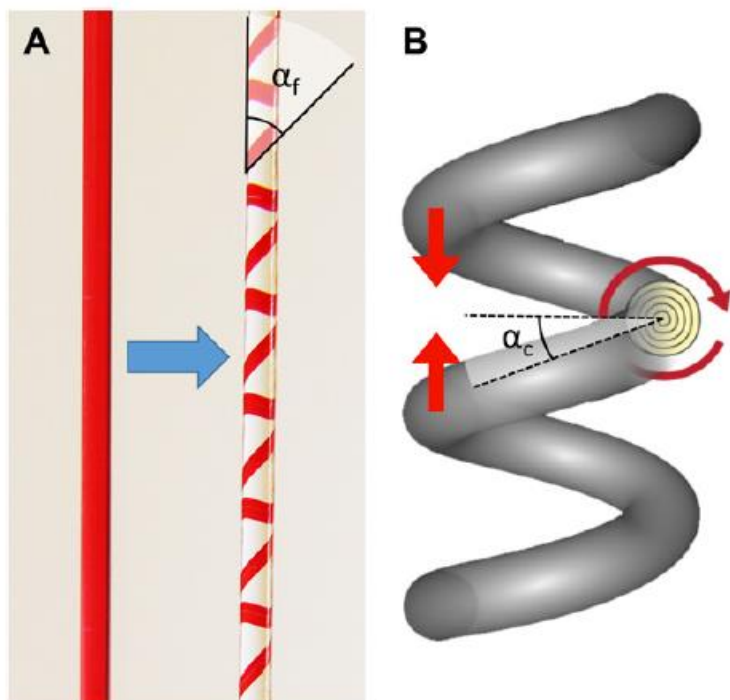


Fig 1. Twisted and coiled artificial muscles. (A) Optical image of a nylon monofilament before (left) and after (right) twist insertion. The ink line represents the alignment direction of the fiber's constituent molecular chains before and after twisting, which reorient to a bias angle  $\alpha_f$  (approximately  $45^\circ$  in this example). Note that the bias angle is constant along the surface of fiber, but nearly-horizontal lines appear as artifacts from the back side due to cylindrical lensing through the transparent fiber. (B) Schematic of a 'homochiral' coil where the fiber twist and coil share the same 'Z' chirality. When heated, the fiber untwists, drawing coils closer together to cause tensile contraction, thereby decreasing the coil bias angle ( $\alpha_c$ ).

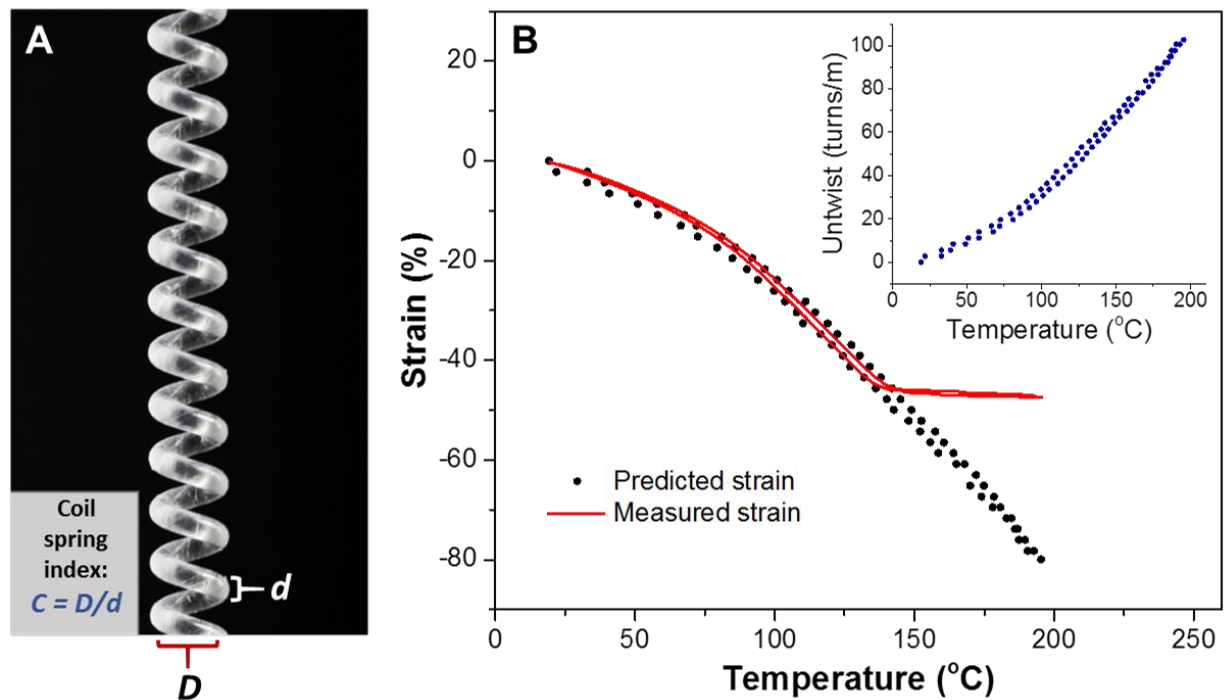


Fig 2. Tensile stroke of a coiled nylon muscle. (A) Optical picture of a homochiral coil prepared by twisting a 300- $\mu\text{m}$ -diameter nylon 6/6 monofilament sewing thread to just before the point of coiling, and then annealing the fiber around a mandrel. The coil spring index,  $C$ , is depicted as the ratio of  $D$ , the average coil diameter (typically the average of the outer and inner coil diameter) and  $d$ , the filament diameter. (B) Plot of the tensile actuation measured for the coil in A, versus temperature (red line), and the theoretical actuation predicted for this coil (black circles). The predicted actuation was calculated from Eq. 2 by considering the coil's geometry, and data measured for the torsional stroke of the precursor, highly-twisted fiber shown in the inset. The theoretical and experimental results agree at low temperature, but diverge when adjacent coils come into contact above 140°C.

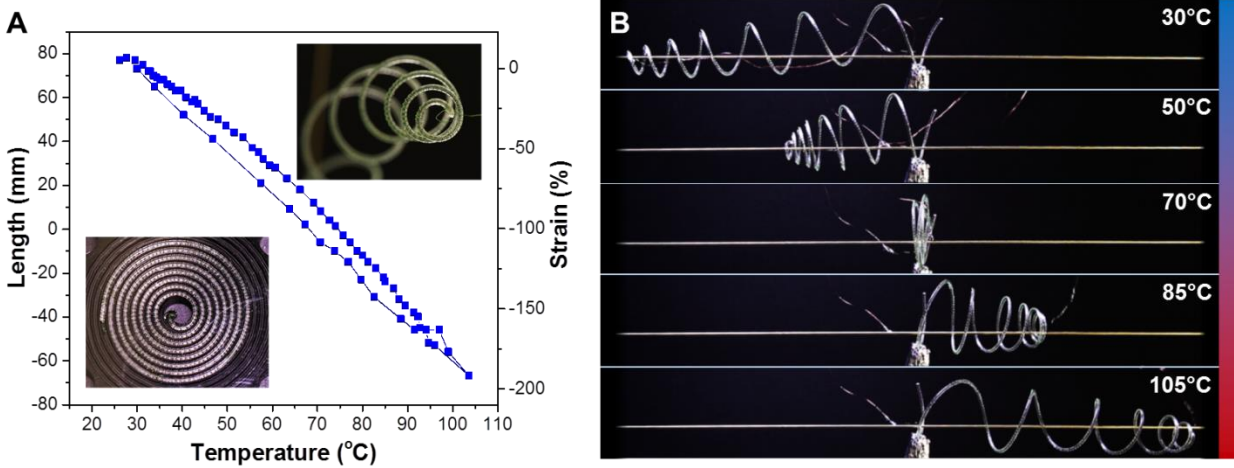


Fig 3. Giant-stroke actuation of a spiral coil muscle in which coil-coil interference is eliminated. (A) The length of the coil versus temperature, and corresponding strain when normalized to the initial muscle length. The picture inset on the bottom-left shows the spiral mold used to anneal the coil, and the picture inset on the top-right shows the coil after fabrication. (B) Optical pictures of the spiral coil when heated electrically, showing the progression of actuation during heating. A brass rod is inserted through the muscle to guide actuation horizontally.

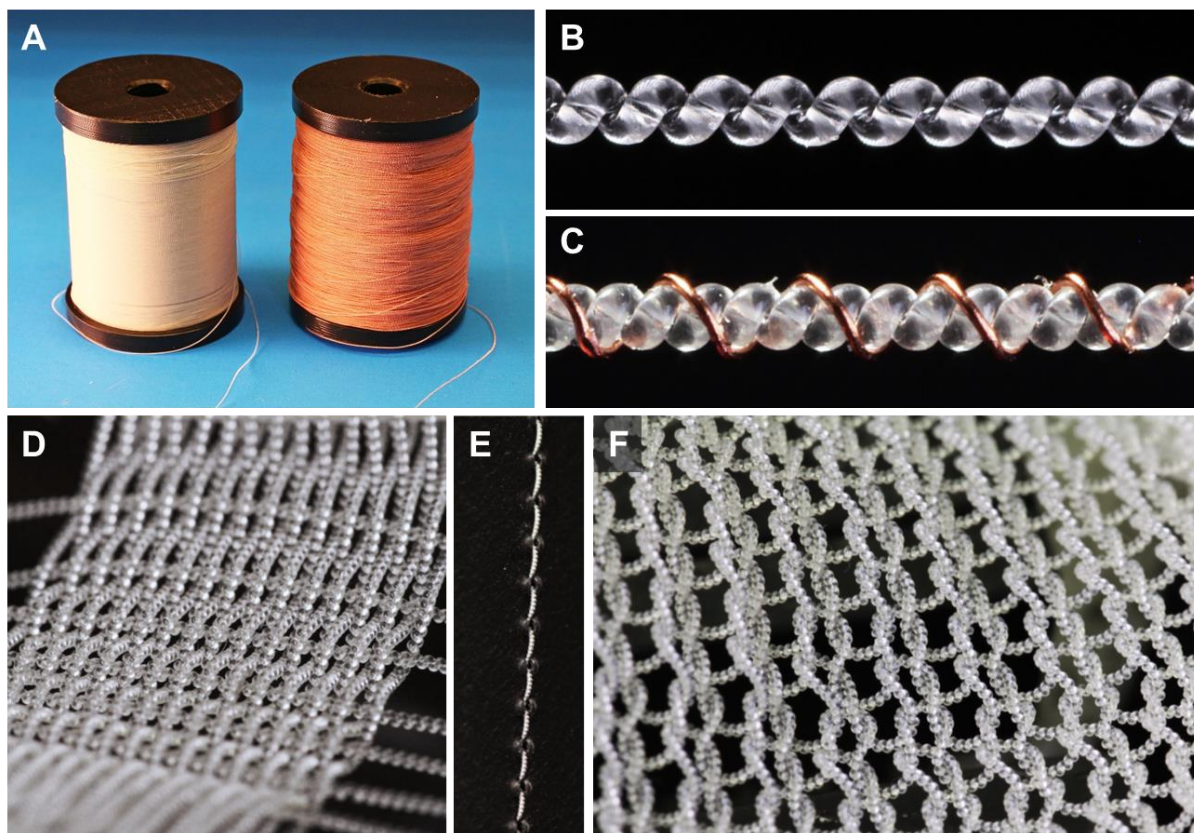


Fig 4. Coiled polymer muscle threads and textiles. (A) A spool of 320 denier, coiled muscle (235  $\mu\text{m}$  outer coil diameter) made from 125- $\mu\text{m}$ -diameter nylon 6/6 monofilament sewing thread by a continuous process, which has been pre-stretched to provide space between coils for actuation, and the same fiber with an insulated copper wire wrap for electrothermal actuation, without pre-stretch, pictured on the left and right, respectively. (B, C) Close-up photographs of the fibers in A. (D) Woven fabric made from coiled, 225- $\mu\text{m}$ -diameter nylon sewing thread muscle. (E) Stitches made by sewing the coiled fiber in A into a polymer sheet using a conventional sewing machine. (F) Machine-knitted textile made from a coiled 225- $\mu\text{m}$ -diameter nylon sewing thread muscle.