QUICK STUDY

How twisted fibers could help robots move nimbly

Fibrous materials that can reversibly twist and coil can be coaxed to contract and elongate as part of lightweight exoskeletons and other bioinspired structures.

By Caterina Lamuta

Because of recent advances in AI, today's robots appear to think like humans in certain ways. But why do robots still struggle to move like humans? Despite remarkable progress in robotics over the past few decades, robots still tend to move in a segmented, stop-and-go manner. Rather than in seamless flows, their motions unfold in noticeable steps, much like the choppy gestures that inspired the robot dance made famous by Michael Jackson in the 1970s.

The root of the problem is that most robotic motion systems bear little resemblance to biological muscles. Many robots move with the use of actuators, such as electric motors and pneumatic and hydraulic systems. Those devices rely on rotors, stators, pistons, valves, and other rigid, bulky, and mechanically complex parts.

To replace conventional actuators, researchers are developing materials that mimic the soft, adaptable, and distributed nature of muscle tissue. One class of materials is the biologically inspired artificial muscle.

Artificial muscles are materials that can contract, expand, and twist in response to an external stimulus before returning to their original shape once the stimulus is removed. Unlike conventional actuators, artificial muscles operate with an actuation mechanism that is embedded in one continuous structure, whether it is composed of a single material or a composite of several materials. In that sense, artificial muscles share a conceptual similarity with skeletal muscles, which also function as a single component despite being composed of fibers, proteins, and connective tissues.

The overarching goal of researchers is to have artificial muscles replicate the low weight, high flexibility, and exceptional power-to-weight ratio of their biological counterparts. Among the various types of artificial muscles being explored, one category has recently drawn significant attention: twisted and coiled artificial muscles, usually known as TCAMs. First demonstrated in 2011, they stand out because of their low cost, simple manufacturing

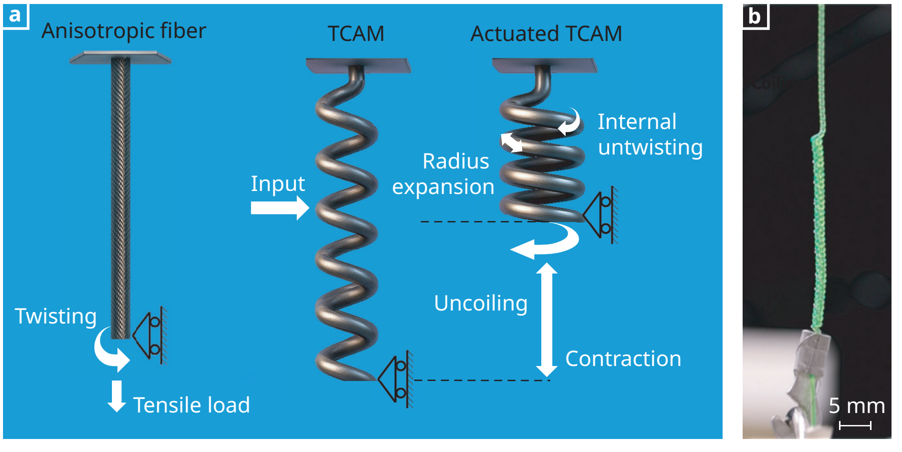

Figure 1. How twisted and coiled artificial muscles (TCAMs) work. **(a)** When an anisotropic fiber, such as a nylon fishing line, is twisted under tension, it will spontaneously coil. When the fiber retains the twisted and coiled shape, it forms a TCAM. When the TCAM heats up or swells in response to external stimuli, its radius expands, it untwists and uncoils, and it contracts linearly. **(b)** A nylon TCAM has its lower portion coiled and twisted, and its upper portion is only twisted.

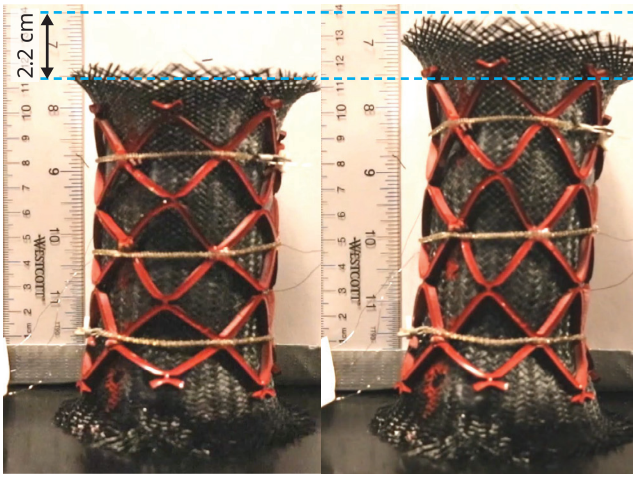

Figure 2. When an octopus-inspired sleeve is squeezed, it elongates by almost 20%. The motion is initiated by three twisted and coiled artificial muscles (brown) that are wrapped horizontally around the soft structure. In response to external stimuli, such as heat, the muscles contract and squeeze the composite sleeve. The red elastomer mesh distributes the load over the sleeve. (Image adapted from P. Kotak et al., *Soft Robot*. **11**, 432, 2024.)

process, and impressive performance. Although more research is needed before TCAMs can be used widely, they're a promising path forward in the quest for lifelike robotic motion.

What makes artificial muscles work?

Only fibers with the property of anisotropic volume expansion are suitable for TCAMs. That means that the fiber expands primarily in the radial direction without getting any longer.

When exposed to heat, a twisted and coiled anisotropic fiber untwists and becomes stiffer as its radius expands. As shown in figure 1(a), that untwisting leads to uncoiling, which in turn results in contraction—just like a muscle. Importantly, the actuation is reversible: When the heat source is removed and the fiber cools, the TCAM returns to its initial length, ready for the next actuation cycle.

TCAMs are relatively simple to construct. They can even be made at home with a fishing line and a hand drill. First, fix the upper end of a fishing line to a drill chuck. To keep the line under tension, hang a small weight from the lower end. Then, once the fiber is taut, start twisting it with the drill; be sure to constrain the torsion or the fiber will simply unwind. As the fiber twists, it will self-coil and form tight spirals, which can be seen in figure 1(b). Once the fiber is fully coiled, place it in an oven at 175 °C for an hour. (Make sure the fiber is still constrained to prevent it from untwisting.)

After it cools, the fishing line will hold its spring-like, coiled shape—it's now a TCAM. To see it in action, hang a small weight from the muscle to keep it under tension, then point a hair dryer or a heat gun at it. As it warms, the fiber will contract and behave like a linear actuator and mimic the function of a biological muscle.

Most fishing lines—made from materials such as nylon or polyvinylidene fluoride—exhibit anisotropic volume expansion because of the way they're manufactured. During the extrusion and drawing processes, the molecular polymer chains become aligned along the length of the fiber. That structural orientation allows the fiber to expand radially and for its length to stay nearly the same.

Researchers studying TCAMs have explored such materials as carbon fibers, carbon nanotubes, and natural fibers like silk and bamboo because they also exhibit anisotropic volume expansion. In some cases, such as with carbon fiber, the material doesn't expand enough. To boost the effect, fibers are embedded in a matrix material with a high thermal-expansion coefficient. Silicone rubber is a common choice.

Direct heating is not the only way to induce volume expansion in such materials. Actuation can be triggered either electrically by applying a voltage that generates internal heating or chemically through swelling, such as when a fiber absorbs a solvent. Certain silicone rubbers, for example, swell considerably when exposed to hexane. Swelling-driven actuation can be more energy efficient than heat-driven actuation because it does not require an external heat source. The actuation response in swelling-driven materials, however, is typically slower than in heat-driven materials because of the time it takes for the solvent to diffuse through the material.

Applications of bioinspired robotics

When it comes to performance, TCAMs deliver. With a low input voltage and just a few watts of power, they can lift more than 10 000 times their own weight. The strength of TCAMs originates from their fibers being twisted. Unlike a straight fiber, a twisted one redistributes an applied load more uniformly along it, which reduces stress concentrations and allows the material to withstand significant forces without failing. The principle is similar to the properties of ropes and load-bearing bridge cables: Twisting multiple strands together greatly increases the fiber's overall strength and structural integrity.

TCAMs mimic many of the properties and behaviors of skeletal muscles. They are compact and lightweight, and they can be embedded in soft tissue and passively stretched. Individual TCAM fibers can be arranged in parallel in a bundle, and specific fibers can be selected to perform a particular motion or exercise.

Researchers have already applied TCAMs in various bioinspired technologies, including lightweight exoskeletons for upper and lower limbs and smart fabrics made from TCAM fibers that adapt to changes in humidity. Inspired by the muscle architecture of octopus limbs, which are capable of bending, contracting, elongating, and twisting, researchers have demonstrated that TCAMs can be embedded into soft materials to replicate that architecture. Figure 2 shows TCAMs that elongate a soft robotic arm.

The full potential of TCAMs remains to be seen—researchers have achieved results in the lab, but no commercial technology using TCAMs exists yet. More work is needed to develop scalable, repeatable, and mass-produced manufacturing processes. In addition, researchers still need to improve the software algorithms that control the motion of TCAMs. With further development, TCAMs could become essential to the creation of lifelike robots whose muscle structures are capable of smooth, precise, and humanlike movement. PT

Additional resources

- S. M. Mirvakili, I. W. Hunter, "Artificial muscles: Mechanisms, applications, and challenges," *Adv. Mater.* **30**, 1704407 (2018).
- C. Lamuta, "Perspective on highly twisted artificial muscles," *Appl. Phys. Lett.* **122**, 040502 (2023).
- P. Kotak et al., "Octopus-inspired muscular hydrostats powered by twisted and coiled artificial muscles," *Soft Robot.* **11**, 432 (2024).
- T. Jia et al., "Moisture sensitive smart yarns and textiles from self-balanced silk fiber muscles," *Adv. Funct. Mater.* **29**, 1808241 (2019).

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