Recent Advances in Twisted-Fiber Artificial Muscles

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An artificial muscle is a type of actuator that can contract, extend, or rotate when exposed to external stimuli (e.g., electrochemical, temperature, pressure, humidity, light, etc.). Twisted fibers can be used in powerful artificial muscles and can convert volume expansion upon stimuli into torsional rotation or axial contraction due to their spiral structure. Upon twist insertion, torsional stress is produced in the fiber, and fiber volume expansion increases the torsional stress, resulting in fiber untwisting. By inserting twist to form a self-coiled fiber, fiber volume expansion causes the contraction of this self-coiled fiber if the fiber is torsionally tethered. Fiber-based artificial muscles have potential applications in a variety of fields such as temperature-regulating clothing, soft robots, prosthetics, and exoskeletons. Herein, the recent progress in twisted-fiber artificial muscles with different actuation stimuli, such as thermal, photo, solvent adsorption or infiltration, and electrochemical, is reviewed. The opportunities and challenges for twisted-fiber artificial muscles are also discussed. Therefore, this review provides an insight for designing high-performance and multi-functional twisted-fiber artificial muscles and motivates the development and applications of fiber-based artificial muscle in future research.

1. Introduction

The development of artificial muscles is an interdisciplinary field of science involving materials science, mechanical engineering, chemical biology, and chemistry. The artificial muscle is a type of actuator composed of a single-component device that can generate external work by producing deformations (such as reversible expansion, rotation, and tensile actuation) under various external stimuli, including heat, humidity, electric current, pressure, light, etc. Similar to human muscles, artificial muscle is expected to work as the muscle of soft robotics for lifting things, for walking or locomotion, and even for sensing and medical applications. Such a single-component design shows a high volume-specific or weight-specific energy density and work output, when compared to the traditional electric motor. Moreover, it provides high flexibility and simplifies the design of soft robotics. Inspired by natural smart systems, numerous responsive materials have emerged that can transfer dynamic and reversible shape changes into mechanical motions under various external stimuli. Based on the basic motions of expansion, rotation, and contraction, other actions of artificial muscles, such as bending, can be realized using an anisotropic double-layer structure where the expansion of one side is greater than the other. Table 1 summarizes the comparison of different types of artificial muscles. Among them, fiber-based artificial muscle can transform volume expansion into radial rotation and axial contraction of the fiber through its spiral structure and more complex movements can be achieved through weaving. In addition, the energy conversion efficiency, power density, and work of artificial muscle fiber are much higher than those of existing membrane actuators. It also has excellent mechanical properties, good flexibility, and is closer to natural biological muscle in form. Therefore, we focused on twisted-fiber artificial muscle, which is designed to show torsional rotation, tensile contraction, or extension.

Twisted-fiber artificial muscles have been developed and have received widespread attention from scientists since the 1990s. A variety of materials have been used for twisted-fiber artificial muscles, including carbon nanotube (CNT) yarns, graphene fiber, fishing line and sewing thread, shape memory polymer, metal alloys, elastomers, and their composites. These fibers can be fabricated to be artificial muscles simply by twist insertion and coil formation, which is an ancient technique used to make yarns or ropes. During the twisting process, torque is generated in fibers or yarns, the morphology of the polymer chains becomes twisted and forms a spiral configuration, and the fibers in the yarn become more compact. Therefore, twisting of the fibers produce novel mechanical,
Table 1. Overall comparison of different types of artificial muscles and skeletal muscles.

| Types of materials | Efficiency [%] | Stress [MPa] | Types of deformation | Power density [W kg⁻¹] | Pros | Cons | Ref |
|--------------------|----------------|--------------|----------------------|------------------------|------|------|-----|
| Crystal piezoelectric | 90             | 110          | Bend                 | 172                    | High speed, high stress, high energy efficiency, and high positioning precision | Need high voltage | [43] |
| Shape memory polymers | –               | 1–3          | Bend                 | –                      | Programmable, and high recoverable strains | Low recovery stress | [44] |
| Shape memory alloys | 1.3             | 200          | Bend                 | 50 000                 | High power density and high stress | Narrow bandwidth of SMA materials | [32] |
| Ionic polymer–metal composites | 30             | 0.3          | Bend                 | 20                     | Low working voltage, high working frequency | Electrolyte needed | [45] |
| Dielectric elastomer actuator | 80–90          | –            | Bend                 | 200                    | Large strain, high efficiency, reasonably high bandwidth, and good power density. | Require high voltage | [46] |
| Pneumatic          | 90             | 0.7          | Extending, clamping | –                      | High force-to-weight ratio, variable installation possibilities, no mechanical parts, lower compressed air consumption, and low cost | Bulk size | [47] |
| Twisted fiber      | 90             | 32           | Tensile, torsional   | 500                    | Muscle-like structure, the mechanically simple, high power density, weave | Suitable for fiber shape materials | [48] |
| Natural skeletal muscles | 39             | –            | Bend, tensile, torsional, etc. | 50                     | Flexible, diversity of actuation mode | – | [49] |

This review summarizes the recent research advances on twisted-fiber artificial muscles including the actuation mechanism, fabrication, properties, and applications (Figure 1). The twisted-fiber artificial muscles are discussed with respect to different actuation stimuli, including thermal, electrochemical, and photo responses, as well as solvent absorption or permeation. The advantages and disadvantages of the four types of fiber-based artificial muscles are summarized in Table 2. The possible applications for each type are also summarized according to the different stimuli and muscle structures. Finally, this review provides a discussion on the remaining challenges of twisted-fiber artificial muscles, along with a perspective. Overall, this review aims to help readers understand the working mechanism and actuation methods of twisted-fiber artificial muscles and provides an outlook for the development of efficient and powerful artificial muscles for multifunctional applications.

2. The Working Mechanism of Twisted-Fiber Artificial Muscles

In general, the actuation strain of a fiber produces a small reversible strain without twist insertion upon volume expansion. In 2011, the pioneer work of Spinks and co-workers found that twist insertion can further amplify the actuation performance.
metrics of artificial muscle fibers.\[9\] In recent years, much research progress has been made in the field of twisted-fiber artificial muscles based on fibrous materials, including torsional and tensile actuations, using twisting and coiling structures (Figure 2A). Upon volume expansion in response to environmental stimuli (including temperature, humidity, light, electricity, pH, etc.), these twisted-fiber artificial muscles generate a large-angle torsional actuation and a large stroke tensile actuation. By inserting twist into the fiber, torsional stress is generated in the fiber and a bias angle is observed on the fiber surface. In general, twist is inserted into a fiber loaded with a constant weight (isobaric), which is torsionally tethered and not allowed to rotate freely. If the torsional tethering is removed after twist insertion, the inserted twist tends to be released partially or completely, depending on whether plastic deformation occurs, causing irreversible torsional rotation of the load. This is analogous to the rotation of the twisted rubber band used as the engine in an airplane toy. To obtain a reversible torsional actuation, two fibers are serially connected, isobarically loaded with a weight, and twist is inserted into the fiber with the weight torsionally tethered. For such a configuration, as volume expansion occurs for one fiber working as the actuating part, twist will transfer from this fiber to the other fiber serving as an inert balance spring (Figure 2Bii). Reversible torsional rotation occurs at the interconnection of the two fibers.\[22\]

Table 2. Summary of the pros and cons for various types of muscles.

| Types                     | Work capacity [J kg\(^{-1}\)] | Power density [W kg\(^{-1}\)] | Actuation Speed [rpm] | Pros                                                                                     | Cons                                      | Ref.          |
|---------------------------|-------------------------------|-------------------------------|-----------------------|------------------------------------------------------------------------------------------|-------------------------------------------|--------------|
| Thermally responsive      | <2766                         | <27 900                       | <11 500               | Abundance of material choice, fast response, higher work capacity.                        | Low efficiency                            | [11,16,17,22]|
| artificial muscle         |                               |                               |                       |                                                                                          |                                           |              |
| Solvent responsive        | <73                           | <1980                         | <6500                 | Environmental stimuli, fast response, high volume expansion.                              | Difficult control of solvent and vapor    | [26,35,50]   |
| artificial muscle         |                               |                               |                       |                                                                                          |                                           |              |
| Electrochemical           | <41.2                         | <920                          | <10 500               | High efficiency, low electric voltage.                                                    | Electrolyte needed                        | [9,14,20]    |
| artificial muscle         |                               |                               |                       |                                                                                          |                                           |              |
| Photoresponsive           | –                             | <17.5                         | 6                     | Abundance of light source, nonelectromagnetic interference, remote control.              | Low energy density                        | [41,42]      |
| artificial muscle         |                               |                               |                       |                                                                                          |                                           |              |

Figure 2. Schematic diagram of several types of twisted-fiber artificial muscles. A) SEM images of twisting (left) and coiling structures (right) for fiber-based artificial muscles; Left: Reproduced with permission.\[9\] Copyright 2011, American Association for the Advancement of Science.; Right: Reproduced with permission.\[22\] Copyright 2012, American Association for the Advancement of Science. B) Schematic illustration of the carbon nanotube (i) and silk fiber artificial muscle (ii); (i): Reproduced with permission.\[22\] Copyright 2012, American Association for the Advancement of Science; (ii): Reproduced with permission.\[26\] Copyright 2019, Wiley-VCH. C) Actuation mechanism of the artificial muscle, which is based on water adsorption-induced swelling and untwisting of the helical yarns; Reproduced with permission.\[27\] Copyright 2016, Royal Society of Chemistry. D) Schematic illustration of the twisted graphene oxide (GO) artificial muscle. Reproduced with permission.\[10\] Copyright 2014, Wiley-VCH.
Such torsional artificial muscles can also be realized using other configurations. For example, the twisted fiber may be folded in the middle to allow it to ply together to form a self-balanced structure (Figure 2Bii). In this case, the fiber plying serves as the torsional balance spring to avoid twist release of the individual fibers. Volume expansion in individual fibers causes reversible untwisting of the individual fiber and twisting of fiber plying. Such torsional balancing may also be realized by a sheath-core structure (Figure 2C) or during the formation of a twisted fiber by twisting a gel-spinning fiber (Figure 2D).

By twist insertion, the fiber surface forms a bias angle with the fiber length direction, which is denoted by $\alpha$. This angle shows that the fiber orientation is off the center axis, which can be calculated using the following formula: $\alpha = \tan^{-1}(2\pi r T)$, where $r$ is the radius of the fiber and $T$ is the twist density (insert twist divided by the length of fiber, typically measured in units of turns per m). The volume expansion-induced torsional actuation stroke can be explained by

$$\frac{n}{n_0} = \left(\frac{V_0 L_0 I_2^2 - \lambda L_0^2}{V I_0 L_2 - I_0^2}\right)^{1/2}$$

where $V_0$, $I_0$, and $n_0$ are the fiber volume, fiber length, and number of inserted twists in the initial state, respectively; $V$, $L$, and $n$ are the fiber volume, fiber length, and number of inserted twists for the actuated state, and $\lambda = L/L_0$.

By inserting twist into the fiber until the fiber self-coils on itself, a tensile artificial muscle can be prepared. The self-coiled fiber that is isobarically loaded with a torsionally tethered weight will contract by volume expansion upon external stimuli. Such a coil configuration converts the twist release of the twisted fiber into tensile contraction. Similarly, if a twisted fiber with S chirality was wrapped around a mandrel to form a coil with Z chirality, a heterochiral-coiled-fiber artificial muscle is prepared. To avoid cancellation of the fiber twist with the fiber coating, the coated fiber needs to be treated to set the coil shape, using methods such as thermal annealing for polymer fibers. Such a heterochiral coated muscle showed extension upon volume expansion-induced fiber twist release, which is different from the homochiral coated muscle (e.g., self-coiled muscle).

Different types of fibrous materials (such as multi-walled CNTs, nanowires, graphene, polymer fibers such as polyethylene (PE) and nylon, silk, cotton, and their composites) have been used to prepare twisted-fiber artificial muscles because of their inherent attribute of volume expansion upon external stimuli. As different stimuli result in different actuation methods and actuation performances, in the following sections we summarize the twisted-fiber artificial muscles by different stimuli, including thermal, electrochemical, and photo responses as well as solvent absorption or permeation, and discuss the possible applications in soft robotics, sensors, and other fields.

3. Twisted-Fiber Artificial Muscles by Different Stimuli

3.1. Thermally Responsive Artificial Muscle Fibers

Thermal expansion of a material is used to actuate a twisted-fiber artificial muscle, and can be realized by Joule heating, convective heating, or photothermal response. A typical example is polymer fiber materials such as nylon and PE fishing lines, which have a semi-crystalline structure. Thermally responsive actuation can also be realized by incorporating guest materials in a yarn; for example, CNT yarns infiltrated with wax or elastomers. Owing to the high electrical conductivity and high photothermal response, electrothermal and photothermal actuation can be realized for CNT yarn composite fibers.

The Baughman and co-workers developed a twisted-fiber artificial muscle by inserting twist in PE and nylon fibers to obtain a coiled structure (Figure 3A). When the temperature was between 25 and 95°C, the two polymer fibers exhibited a reversible volume change of ≈2%. Twist insertion technology efficiently amplified the tensile stroke, resulting in contraction of coiled-fiber artificial muscles of up to 49%. Moreover, the coiled nylon 6.6 artificial muscle fiber showed negligible performance decay over 1 million cycles of actuation at 1 Hz. This fishing line-based twisted-fiber artificial muscle has many advantages, such as excellent work capacity and high durability. The low price and high availability of these materials open a new door for many bionic applications of artificial muscle fibers. For example, inspired by human hand anatomy, the coiled-nylon-fiber artificial muscle can be used to construct artificial fingers.

Figure 3B shows a fabric woven of nylon fibers, conductive silver-plated fibers, polyester fibers, and cotton fibers. Twelve parallel 102µm-diameter coiled-nylon-fiber muscles can lift up to 3 kg of weight. Compared with a single muscle fiber with a large diameter, this structure shows a large specific thermal dissipation area and a low response time. Thermally induced expansion of coiled-fiber muscle can be used for smart clothing to increase the wearer’s comfort by opening the material pores, and thermally induced contraction of the coiled-fiber muscle can be used to protect emergency responders from intense heat by decreasing the porosity of their protective clothing.

The Anikeeva and co-workers presented a scalable strategy to produce twisted-fiber artificial muscles with lateral dimensions ranging from millimeters to micrometers, and with arbitrary lengths. As shown in Figure 3C, cold-drawn bimorph fibers composed of PE and cycloalkane elastic copolymer (COCe) were used to prepare coiled double-layer artificial muscles. The reversible and repeatable thermal actuation of this artificial muscle arose from the mismatch in the thermomechanical properties between the PE and COCe layers. With a rate temperature increase of $130.3 \pm 16.9 ^\circ C s^{-1}$, an actuation rate of $6.33 \pm 0.72 N s^{-1}$ and a power-to-mass ratio of $90 W kg^{-1}$ were obtained, which exceeded the average power-to-mass ratio of human natural muscle (50 W kg$^{-1}$). Thus, this coiled-fiber artificial muscle can be potentially applied in prosthetic limb technologies and soft robotics (Figure 3D).

Composite yarn is one of the main raw materials for the preparation of thermally actuated twisted-fiber artificial muscles, where the guest materials in the yarn enhance the volume expansion and improve the actuation performance. Paraffin and silica gel are used as typical guest materials, which have the advantages of high thermal stability, temperature tunability, large volume-expansion coefficient, and the ability to wet CNT yarns. Electrolyte-free CNT composite yarns consisted of variable-volume guest materials in CNT yarns, which can be actuated in various ways with excellent actuation performance. The guest
materials are bisrolled between the CNT fibers. Thermal actuation led to volume change in these guest materials and enlarged the distance between the individual CNTs so that the fibers can achieve torsional and tensile actuation. The Baughman and co-workers developed a tensile artificial muscle by impregnating paraffin wax into CNT yarns (Figure 4A). The wax penetration greatly enhanced the tensile actuation of the yarn (Figure 4B). Electro-heating a dual-Archimedean CNT yarn produced a contractile stroke of 7.3% at 2560°C (Figure 4C). The performance was enhanced by optimizing the applied voltage and load. The maximum work density was 0.836 kJ kg⁻¹ and the power density was 27.9 kW kg⁻¹, which is 85 times higher than that of mammalian skeletal muscles. However, the cycle life was reduced due to excessive heating and paraffin evaporation in the case of excessively high applied electrical voltage.

For the CNT/wax fiber torsional muscle, paraffin wax was transferred from the solid to liquid phase upon Joule heating, causing the volume expansion of the yarn of approximately 30%. Because the artificial muscle yarn was tethered at both ends, and every individual fiber did not show elongation, the volume expansion of the wax-infiltrated section resulted in untwisting in the CNT/wax section (actuator) and twisting in the CNT section of the yarn (return spring). Nickel–titanium alloy (including NiTi, NiTiCu, NiTiFe, etc.) is a type of shape memory metal that can recover its original shape under the stimulus of heat for a predeformed material. This prominent character has made Nickel–titanium alloy very prevalent in studies of smart materials and has attracted continuous development since its discovery in the 1960s in the US Naval Ordnance Laboratory. In 2017, Mirvakili and Hunter developed a reversible torsional artificial muscle via twisting pairs of NiTi micro-wires. As shown in Figure 4D, the torsional fiber artificial muscle consisted of a twisted NiTi yarn with half its length gold-coated. When a constant current was applied to both ends of the fiber-based artificial muscle, an utterly reversible torsional actuation was achieved, and a torsional stroke of up to 16°/mm with a torsional speed of 10 500 rpm and a gravimetric torque of
8 N m kg⁻¹ was obtained (Figure 4E). The working mechanism of this NiTi torsional fiber artificial muscle is similar to that of the wax-infiltrated CNT yarn, and the primary difference is that a length change was observed during actuation. In addition to the untwisting of the microwire induced by its shape memory effect, this twisted NiTi fiber can shrink up to 4.5% in length and expand by up to 1.5% in diameter with a Poisson’s ratio of 0.33 under heating.

In 2019, Poulin and co-workers studied polyvinyl alcohol (PVA) polymer fibers by combining twist insertion with the principle of “shape memory effect.” The mechanical properties and actuation performance were significantly improved by mixing CNTs and graphene into the polymer fiber (Figure 4F). This study showed that the output torque of the twisted PVA fiber was dependent on the actuation temperature. When the PVA fiber is heated to the programming temperature (higher than its glass transition temperature, e.g., 100 °C), the inserted twist can be fixed in the PVA fiber after cooling back to room temperature. Then, the stress of the twisted PVA fiber can be released by raising the temperature again to the programming temperature. In Poulin’s study, the PVA–graphene oxide (GO) fiber artificial muscle was heated to 200 °C after the programming treatment at 100 °C, which generated ≈21 N m kg⁻¹ of torque. This is higher than the value previously reported for rotational artificial muscle fibers. Moreover, when the two ends of the PVA–GO artificial muscle fiber were fixed and then heated to 210 °C after removing torsional tethering, the fiber-based artificial muscle produced a torque of 0.27 mN m, which was higher than the torque generated by the PVA-single-walled carbon nanotube (SWCNT) fiber (0.12 mN m) and the torque of the pure PVA fiber (0.11 mN m). Twist retention was also achieved by a self-balanced structure, which can increase the energy density. For example, the energy density of the self-balanced PVA–GO fiber artificial muscle was 2766 J kg⁻¹, which was 966 J kg⁻¹ higher than that of the non-self-balanced artificial muscle.

### 3.2. Solvent Adsorption- or Permeation-Actuated Artificial Muscle Fibers

Some fiber materials can absorb solvent, resulting in volume expansion. For example, cotton yarn, silk fiber, or cellulose nanofibers can absorb water, and the CNT yarn can swell when absorbing organic solvents. Compared with the volume thermal
expansion of paraffin, the volume expansion by solvent adsorption or permeation of some cross-linked fibers is larger than 30%, and can even approach 400% in some cases. Many solvent-responsive fiber artificial muscles have been realized to show tensile and torsional actuation.

In 2014, the Qu and co-workers developed a torsional artificial muscle fiber using twisted graphene fibers, which can produce rapid rotation upon exposure to high humidity. By removing the moisture, the artificial muscle fiber quickly rotated back to its initial state (Figure 5A). The maximum rotational speed of the torsional artificial muscle fiber reached 5190 rpm, the angle of maximum torsion reached 117°, and after 500 cycles, it still showed excellent actuation performance. In 2015, Peng and co-workers developed a novel hierarchically helical CNT-fiber artificial muscle that exhibited some nanoscale and microscale channels, which had excellent mechanical actuation strokes in response to moisture. The twisted CNT yarns exhibited hierarchically helical channels and hydrophilic surfaces, resulting in reversible, fast, and large shrinkage and rotation driven by moisture. To obtain hydrophilic helical CNT fibers with hierarchical structures, the pristine CNT fibers were treated with oxygen plasma (Figure 5B). After such plasma treatment, water molecules quickly transported via the microscale pores and then permeated into the interconnected capillary nanoscale channels, which is similar to the blood flow in the human body. Moreover, compared to the traditional modifying methods, plasma treatment has a nonobserved effect on the aligned structure of CNTs. Thus, the reversible artificial muscle fiber could achieve rapid and high rotation and contraction. This artificial muscle fiber exhibited promising applications in intelligent switches, soft robots, and biomimetic devices.

Although twist-based CNT hybrid yarn artificial muscles (HYAM) have been developed recently, it is still a challenge to develop a fundamentally new host–guest structure to improve the actuation performance compared to the traditional CNT composite yarns with uniformly dispersed fillers. In 2019, Baughman and co-workers developed a new sheath-run artificial muscle (SRAM), where the guest material was coated as a yarn sheath instead of being infiltrated into yarns for volume change. This study found that the SRAM showed clearer advantages actuated by vapor absorption when compared with the conventional CNT hybrid yarn muscle. In Figure 5C, the researchers compared the time dependence of paddle rotation and speed for sulfonated poly(ethylene oxide)@CNT-SRAM (PEO-SO$_3$@CNT SRAM), CNT HYAM, and pristine CNT muscle that were undergoing one complete reversible cycle of ethanol vapor.

![Figure 5](image-url)

**Figure 5.** Twisted-fiber artificial muscles triggered by solvent adsorption and its applications. A) Schematic demonstration of the rotational behavior of twisted GO fiber when exposed to moisture. Reproduced with permission. Copyright 2014, Wiley-VCH. B) Preparation of hydrophilic secondary fiber (HSFs) with hierarchically helical channels. Reproduced with permission. Copyright 2015, Wiley-VCH. C) Torsional actuation of twisted sulfonated poly(ethylene oxide) (PEO-SO$_3$) SRAMs and HYAMs driven by ethanol vapor. D) Illustration of vapor delivery to a fiber artificial muscle and the time dependence of torsional stroke and rotation speed for a PEO-SO$_3$@CNT SRAM, a CNT HYAM, and a pristine CNT yarn. (C,D) Reproduced with permission. Copyright 2019, American Association for the Advancement of Science. E) Sequential photos showing sleeves of smart clothing contracted when exposed to moisture and recovered to its original length when exposed to dry air. Reproduced with permission. Copyright 2019, Wiley-VCH. F) Sequential photos of a smart window using cotton artificial muscle fibers. Reproduced with permission. Copyright 2020, Chinese Academy of Sciences.
powered actuation. The peak stroke and peak rotation speed for the SRAMs were approximately twice that for the pristine CNT yarn (Figure 5D). Moreover, the SRAMs can generate 1.98 W g⁻¹ of average shrinkable power, which was 40 times higher than that of the human muscle and 9.0 times higher than that of the electrochemical muscle with the highest power. Thus, SRAMs have various applications, such as smart clothing, powerful muscles for humanoid robots, and drug-delivery systems.

In general, the reversible actuation of twisted-fiber artificial muscles requires torsional tethering to avoid twist release, which can obtain a large contractile or rotational stroke, but at the same time increases the device complexity. To solve this problem, a torque-balanced two-ply structure was developed using silk fibers. First, twisted silk fibers were obtained by twist insertion. However, they were mechanically unstable and tended to untwist when the torsional tethering was removed. Thus, the twisted silk fiber was folded in the middle, and the two sections of the fiber were plied together under a load to form a torque-balanced torsional silk muscle. The torsional silk fiber achieved a completely reversible torsional stroke of 547° mm⁻¹ when exposed to water fog. The self-balanced silk fiber can also be wrapped around a mandrel to form a coil and thermostet to form a tether-free tensile silk muscle, which produced a 70% shrinkage when the relative humidity changed from 20% to 80%. The silk artificial muscle fibers open up additional possibilities of twisted natural fibers using smart textiles (Figure 5E).

In addition to silk fiber, cotton and flax are significant materials for the textile industry. They also exhibit good biocompatibility and admirable hygroscopic properties, which are good candidates for the development of humidity-responsive artificial muscle fibers. The Liu and co-workers developed cotton artificial muscle fibers actuated by moisture and used it for smart fabrics. The humidity-responsive cotton artificial muscle fibers were constructed from twisted and plied cotton fibers, which used torque-balanced fiber structures to avoid the need for torsional tethering. The cotton artificial muscle fiber produced a completely reversible torsional stroke of 42.55° mm⁻¹, which was at the same level as that of the water-actuated coiled CNT fiber (61.30° mm⁻¹). This humidity-responsive torsional artificial muscle using natural textile fibers offers a novel application for natural fibers in the area of intelligent windows and other smart textiles (Figure 5F).

### 3.3. Electrochemically Actuated Twisted-Fiber Artificial Muscles

Electrochemically actuated twisted-fiber artificial muscles can directly convert electrical energy into mechanical energy, which is of great significance for the development of artificial muscles driven at low electric voltages. Energy efficiency is an important factor in electrochemically actuated artificial muscle fibers. Compared with artificial muscles driven by thermal expansion, electrochemically powered artificial muscles have two advantages: their efficiency is not limited by the Carnot efficiency, and the stroke can be maintained without the input of substantial electrical energy.

CNT yarn is one of the most frequently used electrode materials in electrochemically driven fiber artificial muscles. In 2011, a research team led by Baughman and Spinks used electrolyte-filled twist-spun CNT yarn to develop a torsional artificial muscle fiber in an ordinary three-electrode electrochemical system, as shown in Figure 6A–C. This torsional artificial muscle fiber produced a 15 000° reversible rotation at a speed of 590 rpm. It is suitable for ultrasensitive electrochemoanalysis and shows the possibility of use in ordinary motors. Torsional muscles can also transfer mechanical energy to electrical energy using the electromagnetic effect, and can be used as electric generators to generate electrical signals or used as sensors to detect rotations using electric signals. Compared with the above three-electrode electrochemical system, Kim and co-workers reported an all-solid-state artificial muscle fiber, which avoids the need to use the complex three-electrode electromechanical setup, liquid electrolyte, or packaging (Figure 6D–E). In a low applied voltage (5 V), it can produce a large torsional stroke (53° mm⁻¹). An electrothermally powered, coiled tensile artificial muscle fiber can lift loads 25 times heavier than can human skeletal muscle with the same diameter. These all-solid-state torsional and tensile artificial muscle fibers show promising applications in micromechanical devices which perform such functions as controlling valves and stirring liquids in microfluidic circuits and in medical catheters. Subsequently, coiled electrochemically powered CNT artificial muscle fibers were developed, which can be used for an all-solid-state parallel muscle or braided muscle without the need for liquid electrolyte. These electrochemical artificial muscle fibers produced a 5.4% contractile energy conversion efficiency, which was 4.1 times higher than that of the electrochemically driven CNT artificial muscle in a three-electrode system.

Organic electrolytes have the advantages of high decomposition potentials and very large ion sizes, which enable good performance for artificial muscle fibers. However, organic electrolytes are usually flammable, poisonous, expensive, and have low ionic conductivities. Instead, an inorganic aqueous electrolyte is a better choice because of its biocompatibility, low cost, and high ionic conductivity. Li and co-workers developed a hybrid artificial muscle fiber that can operate in an aqueous electrolyte, with reduced graphene oxide (rGO) bisrolled in a CNT yarn (Figure 6F–G). When actuated in aqueous electrolytes, the coiled CNT/rGO artificial muscle fiber can contract by up to 8.1%.

### 3.4. Photoresponsive Twisted-Fiber Artificial Muscles

In recent years, photoresponsive fiber artificial muscles have attracted tremendous interest due to their merits of abundant light sources, nonelectromagnetic interference, and feasibility of remote control. They can produce reversible mechanical deformation under light stimuli, which shows promise for applications in soft robots, sensors, and biomimetic devices.

Wang and co-workers fabricated a sodium polyacrylate (PAAS)/GO-twisted-fiber artificial muscle by wet spinning and twist insertion, which can rotate at an actuation temperature of ≈25 °C under near infrared irradiation (Figure 7A). The actuation originated from the photothermal effect of GO, resulting in shrinkage of the twisted fiber by evaporation of the
absorbed water from the GO surface, as shown in Figure 7B. Wang and co-workers also designed a sodium alginate (SA)/GO torsional fiber artificial muscle using a similar technique (Figure 7C). The torsional fiber artificial muscle generated rapid and reversible rotational and elongation/contraction under infrared light stimuli (Figure 7D). Artificial muscle fibers powered by photostimulus can also be fabricated by the spinning and twist-insertion technique using other photo-responsive composite materials and by twisting CNT films into fibers.

4. Conclusion and Perspectives

Twisted-fiber artificial muscles, as a new type of intelligent material, can mimic the biological muscle in its form and function. It can be prepared using a variety of materials and can be powered by various stimuli, which can play a significant role in such applications as soft robotics, prosthetics, exoskeletons, comfort-regulated clothing, and micro motors. This review summarizes the recent advances in the fabrication, properties, and applications of twisted-fiber artificial muscles, including actuation mechanisms, different stimuli (thermal, electrochemical, photo-actuation, and solvent adsorption or permeation), and actuation properties. The materials and performance of different fiber artificial muscles are summarized in Table 3. Moreover, we try to determine the current research status and future development trends of artificial muscle fibers to provide more ideas for follow-up research.

First, various materials, including natural and synthetic fiber materials, can be used for developing twisted-fiber artificial muscles, and they can be used with different actuation stimuli. Second, the design of the fiber material structure can help to improve the performance of artificial muscles. For twist-insertion-based artificial muscles, the self-balanced two-ply muscle can be used to avoid the need for torsional balancing.
and sheath-run muscle can achieve a higher work output compared to the biscrolled yarn muscles with uniformly dispersed guest material. Third, twisted-fiber artificial muscles usually have the advantages of good flexibility, so they can be woven into textiles to further improve the actuation stroke and form, and expand their applications.

Table 3. Summary of properties for current twisted-fiber artificial muscles.

| Types of stimuli   | Materials          | Types of actuation | Rotation speed [rpm] | Strain [%] | Work capacity [J kg⁻¹] | Power density [W kg⁻¹] | Ref   |
|--------------------|--------------------|---------------------|----------------------|------------|------------------------|------------------------|-------|
| Thermal            | Nylon 6,6          | Tensile             | –                    | 49         | 2480                   | 27 100                 | [11]  |
|                    | PVA-GO fiber       | Torsional           | 600                  | –          | 2766                   | –                      | [16]  |
|                    | PE and CCOe        | Tensile             | –                    | 50         | –                      | 90                     | [17]  |
|                    | CNT/wax            | Torsional           | 11 500               | /          | –                      | –                      | [22]  |
|                    | CNT/wax            | Tensile             | –                    | 16.5       | 836                    | 27 900                 | [22]  |
|                    | NITi fibers        | Torsional           | 10 500               | –          | –                      | –                      | [14]  |
| Electro-chemical   | CNT                | Torsional           | 590                  | –          | –                      | 920                    | [9]   |
|                    | All-Solid-State CNT| Tensile             | 2330                 | –          | –                      | –                      | [38]  |
|                    | All-Solid-State CNT| Torsional           | –                    | 1.3        | –                      | –                      | [38]  |
|                    | CNT                | Tensile             | –                    | 16.5       | 2200                   | –                      | [39]  |
|                    | CNT/rGO fiber      | Tensile             | –                    | 8.1        | 236                    | –                      | [40]  |
| Electro-chemical /Solvent | PEO-SO₃@CNT SRAM | Torsional           | 507                  | –          | –                      | –                      | [18]  |
|                    | PEO-SO₃@CNT SRAM  | Tensile             | –                    | 70         | 2350                   | 1980                   | [18]  |
| Solvent            | Graphene fiber     | Torsional           | 5190                 | –          | –                      | 71.9                   | [10]  |
|                    | Silk               | Tensile             | –                    | 47         | 1.9                    | –                      | [26]  |
|                    | Silk               | Torsional           | 975                  | –          | –                      | –                      | [26]  |
|                    | Helically assembling multi-walled CNTs | Torsional | 2050 | / | 26.7 | – | [34] |
|                    | Helically assembling multi-walled CNTs | Tensile | – | 10 | 26.7 | – | [34] |
|                    | Hydrophilic primary fiber | Torsional | 1537.72 | – | – | – | [36] |
| Photo-responsive   | Polyacrylate/GO fiber | Torsional | 6 | – | – | – | [41] |
|                    | GO/SA fiber        | Torsional           | 500                  | –          | –                      | 17.5                   | [42]  |
Recently, researchers have shown that twisted-fiber artificial muscles are gaining good momentum and have bright prospects in the field of soft robotics and smart devices. However, there are still a few issues that must be resolved before they can be used for practical applications. First, although some aspects of the actuation performance of the twisted-fiber artificial muscles, such as actuation stroke, force, work capacity, response time, and actuation stimuli have reached very high values, not all of these performances can be realized at the same time. There is still a large space for improvement to cover more aspects of the muscle performance. This may require a new design of fiber materials, muscle structures, and actuation mechanisms to achieve a compromise between different aspects. Second, different actuation stimuli have inherent advantages and drawbacks. For example, thermal actuation can harvest environmental thermal energy, while it faces the problem of dissipation of generated heat as well as low energy conversion efficiency. Light actuation has the advantage of remote control, while improving the energy density of the light is highly desired. Therefore, different actuation stimuli may be used in different application scenarios. For muscle fibers used in soft robotics, electrical stimuli would be a very easy method of muscle control. Here, optimizing the actuation voltage and efficiency with the muscle stroke, output work, and response time is an important design challenge. For thermal or moisture actuation, artificial muscle fibers may find applications in comfort-adjusting textiles, sensors, or robotics used in special environments. Light-actuated fiber artificial muscles may find applications in remote controls, as light can transverse a very long distance. Moreover, if the muscle can be actuated by natural light, it may find applications in solar energy harvesting and sensing. Third, scalable fabrication and low cost is highly desired for practical applications of fiber artificial muscles. One method for achieving this is to convert cheap, high-strength fiber materials into fiber artificial muscles. At the same time, special design of fiber material compositions or structures is needed to meet the requirement of a suitable actuation stimulus. Finally, as artificial muscle fibers can be used in combination with sensors and signal transmission systems, a high-level, multi-functional system comprising sensing, actuation, and signal transmission would be a new trend for artificial design.

In summary, great progress has been made in twisted-fiber artificial muscles with respect to muscle design, fabrication, and actuation performance. This makes an important contribution to the field of soft robotics, intelligent control, and artificial intelligence. However, there is still a large space for further improvement in artificial muscle fibers, which requires multidisciplinary research that covers chemistry, physics, materials science, intelligent control, etc. Although considerable progress has been made, it is still an emerging field that requires researchers in different fields to work together to accelerate the development of fast, strong, and powerful fiber artificial muscles.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

actuators, artificial muscles, twisted fibers

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