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Review

Stimuli-responsive fiber/fabric actuators for intelligent soft robots: From current progress to future opportunities

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A R T I C L E I N F O

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A B S T R A C T

Bioinspired soft actuators with adaptive, reconfigurable, and multifunctional features have gained increasing attention in soft-robotic applications of intelligent responsive devices. Fueled by the development of wearable electronics, fiber/fabric actuators are of particular interest owing to their unique characteristics of mechanical flexibility/stretchability, high degree-of-freedom morphing, body-compatible shape factor, and mature industrial producing. In this review, the state-of-arts of fiber/fabric-based actuators and soft-robotic systems including preparations, structures, stimulating mechanisms, and functional applications are comprehensively investigated. The analysis of advantages and disadvantages in practical actuation scenarios is highlighted, starting from the introduction of the fabrication routes and typical structural designs. Furthermore, the actuating mechanisms of fiber/fabric-based robots are examined in terms of the key stimulus types (single/multiple stimulating schemes), and the wide spectrum of application fields are illustrated: namely, smart clothing, artificial muscles, intelligent devices, and flexible electronics. Finally, the challenges and opportunities for next-generation fiber/fabric-based actuators/robots are discussed in terms of manufacturing scalability for pervasive use, multifunctionality for enhanced adaptability, and self-healability/degradability for recyclable design.

1. Introduction

There are many amazing plants or animals in nature, such as wheat, pine scales, storks, and pea pods, that can respond to changes in their surroundings [1,2]. Inspired by creatures in nature, many smart materials have been prepared [3,4]. The so-called smart materials are able to respond to the surrounding environmental conditions (such as humidity, heat, light, electricity, magnetism, etc.), thus causing deformation of the material (such as shrinkage, expansion, bending, rotation, etc.) [5–7]. These smart materials are also known as stimulus-responsive materials. Recently, with the rapid development of stimulus-responsive materials, they have been widely used in artificial muscles [8,9], soft robots [10], smart clothing [11–13], and other applications that benefit from stimuli-responsive actuators.

Fiber is the basic unit of textile materials, usually referring to a soft fine body at micron or nanometer, whose length-to-diameter ratio is more than 10^3 times. The fiber can be further processed into yarn or fabric, and this kind of textile material has been widely used in people's daily lives [14,15]. In the past, these textiles were mainly used as clothing fabrics with the function of maintaining warmth. In addition, textiles have significant adaptability as a material for daily usage because of their comfort, toughness, and other desirable characteristics [16,17]. In the current era, as society and science and technology advance, researchers have begun to explore the potential of fiber materials to be multifunctional and intelligent, in order to meet the basic requirements of humans [18–20]. Fiber/fabric intelligent responsive materials, by combining the properties of intelligent response with fiber or fabric, can respond to different stimuli, manifested as the contraction, rotation, and bending of fibers, changes in inter-yarn spacing, and so on. At the same time, fibrous materials have a variety of weavability and structural response from one-dimensional (1D) to three-dimensional (3D), for example, fiber/yarn-based actuators show rapid drive advantages in 1D directions, and have important potential in artificial muscles, implantable medical robots, and other fields. Among them, micro-nano-fiber membrane is highly designed in terms of structure, function and mechanics, which is expected to realize the coordinated

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response and efficient actuation of the actuators to multiple environmental stimuli (humidity, light, heat, electricity, magnetic field) [21]. Therefore, these emerging stimuli-responsive fiber/fabric materials can play an important role in actuation, sensing, and smart clothing and are expected to achieve remote control, health detection, and other functions [22].

Considering the lack of a systematic and detailed review of the structure of fiber/fabric actuators in the previous literature and their promising application prospects, this review provides a comprehensive overview of the latest research developments in this field. It mainly includes four core contents: preparation method, structural design, stimulus response type, and related application, as displayed in Fig. 1. To be more specific, we introduce the current methods of preparing fiber/fabric-based actuators from two aspects of the fiber forming method (such as twist, mold forming, electrospinning, 3D printing, wet spinning, etc.) and fabric weaving and post-finishing. Different from the past, the typical structural designs of fiber-based actuators, including helical, core-shell, side-by-side, woven, knit, nonwoven, and so on, are also emphasized in detail. Then, we highlight the different stimulus types (single/multiple stimulating schemes) of fiber/fabric actuators and discuss the characteristics of the different types of actuators. Next, we discuss several emerging applications in the intelligent gripper, artificial muscle, smart clothing, and other fields to demonstrate the great application potential for intelligent responsive materials. Finally, we share our perspective on the future directions from the perspective of the application field, and the potential for practical use in production.

2. Preparation method of stimuli-responsive fiber/fabric actuators

1D fiber-based stimuli responsive actuators are typically associated with a number of significant advantages, such as enhanced stability, flexibility for further processing, and cost-effectiveness. Here, we describe the various methods that have been employed in recent years to prepare fiber-based stimuli responsive actuators, including twisting, electrospinning, wet spinning, melting spinning, 3D printing, and others (such as microfluidic spinning, gel spinning, and so on).

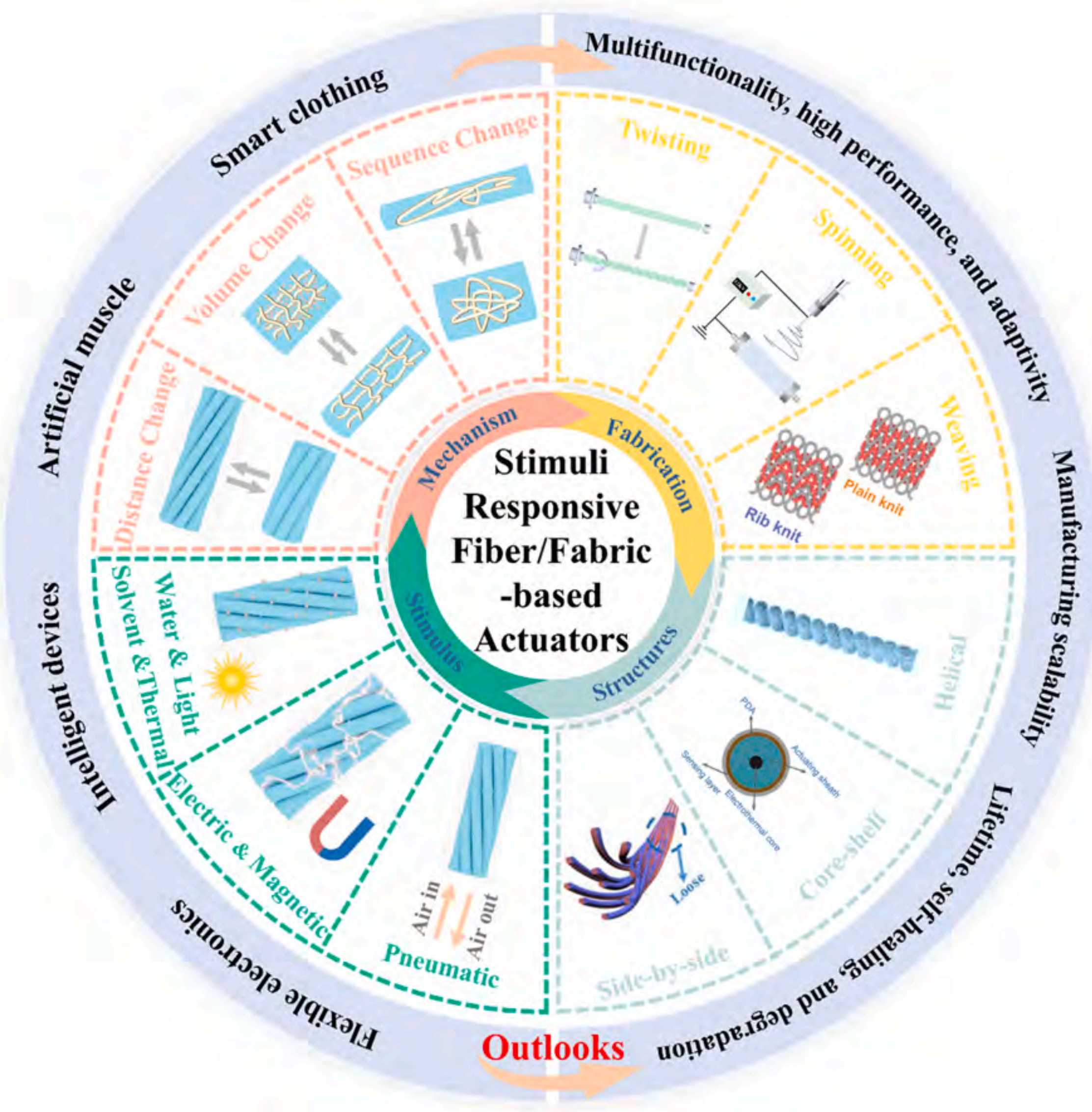

Fig. 1. Overview of the fiber/fabric-based actuators. Weaving. Reproduced with permission [23]. Copyright 2023, Wiley-VCH. Helical structure. Reproduced with permission [24]. Copyright 2021, Wiley-VCH. Core-shell structure. Reproduced with permission [25]. Copyright 2021, The Royal Society of Chemistry. Side-by-side structure. Reproduced with permission [26]. Copyright 2023, Elsevier.

2.1. Twist

The most prevalent and straightforward approach to preparing fiber-based actuators with a helical structure is twist. Among them, the general method is (stretching), twisting, (plying) these steps to obtain the helical structure of the fiber. The preparation of this fiber is inspired by the helical structure in plants. In the early days, some low-cost and high-strength fibers, such as polyethylene (PE) and nylon, were widely used as precursors for artificial muscles because they had some advantages with reversible fiber-direction thermal contraction, large volumetric thermal expansion, and large anisotropy in thermally induced dimension changes [27]. In addition, natural fibers (such as spider silk, silk, cotton, and wool) and regenerated cellulose obtained are widely used because of their eco-friendly and biocompatible characteristics (Fig. 2(a)) [28]. The fiber-based actuators can be prepared by a combination of top-down and bottom-up approaches, which involve hot drawing-induced enhanced alignment of the fiber microstructures, followed by twisting and plying to form a double-helical yarn structure (Fig. 2(b)). The twist deformation of twisted yarn is determined by the change in fiber shape, when the fibers are stimulated by water, the twist of the fibers is reduced, and the twist stroke of the twisted yarn is also reduced [29]. It should be pointed out that the driving form of the actuator prepared by twisting is limited by the structure, so it has certain limitations in practical application.

2.2. 3D printing

Since Charles Hull invented the first 3D printer in the mid-1980s, various 3D printing processes have been developed [32]. With the rapid development of 3D printing technology, its products are gradually being used in the field of intelligent devices, such as in the area of soft robotics rapidly developing. Schaffner et al. [30]. proposed a multi-material 3D printing technology for the preparation of silicone actuators (Fig. 2(c)). This study simplifies the manufacturing process of soft robots, thereby reducing the risk of layering the interface while further expanding the freedom of deformation. Furthermore, Kotikian et al. [31]. created LCE actuators with spatially programmed nematic order in arbitrary form factors, which contrast with soft actuators based on shape memory polymers (SMP), exhibit massive, reversible, and repeatable contraction with high specific work capacity (Fig. 2(d)). There is no doubt that 3D printing technology has facilitated the mass production of flexible actuators.

2.3. Mold forming

In addition to fiber twisting, it is also a relatively simple and convenient method to prepare fiber actuators that are responsive to external stimuli by using specific molds. Inspired by the spiral tendrils of plants, the fiber actuator that can realize the deformation behavior of high degrees of freedom has a wide application prospect. For example, we can use a helical mold to shape liquid crystal elastomer oligomers into helical precursors (soft springs) with a length difference between the outer and inner perimeters, and then decamped and stretched to obtain helical fibers with an asymmetric distribution of strain/stress on the cross-section (Fig. 3(a)) [33]. This is a simple and scalable preparation method that eliminates the need for precise design of double-layer structures and avoids complex material design and preparation. For example, Hu et al. [34]. used a similar method to prepare LCE fibers

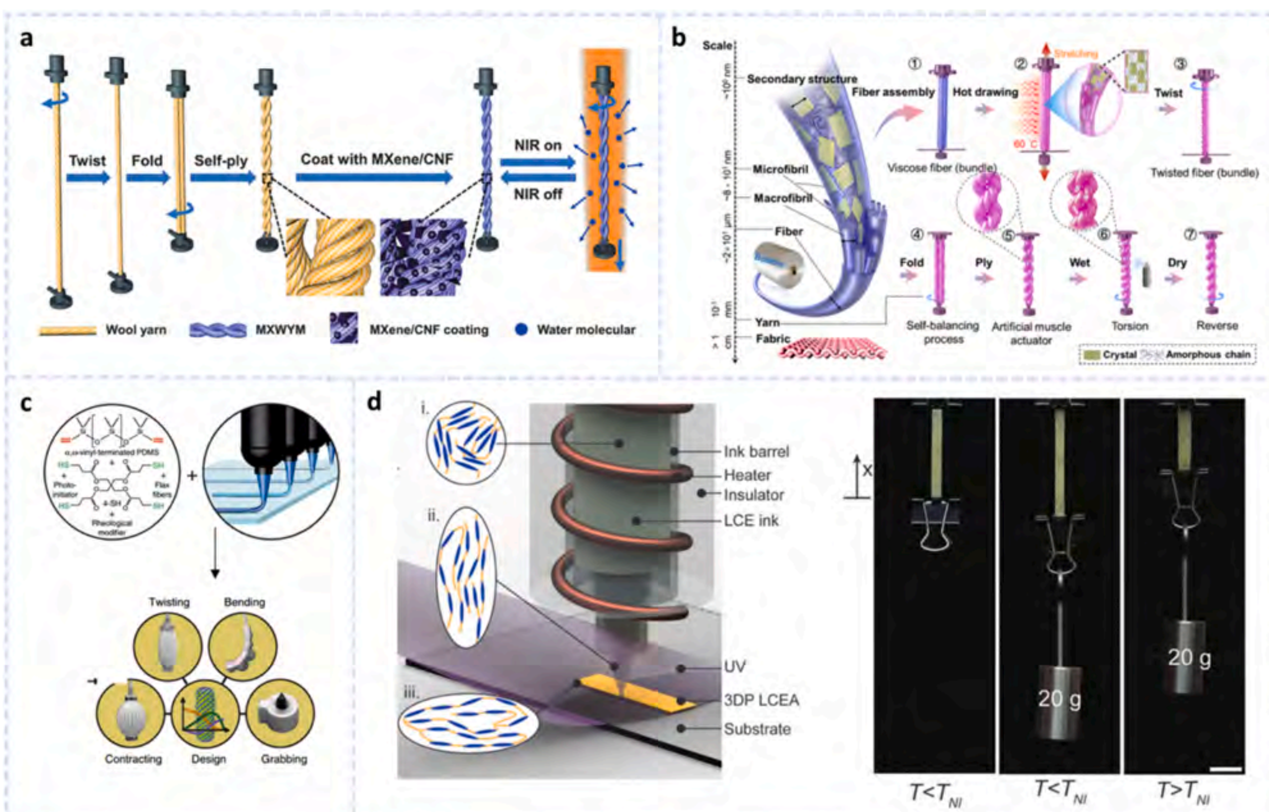

Fig. 2. Schematic illustration of the twisting method to fabricate the fiber-based actuators. (a) Schematic illustration of the fabrication of wool fiber actuator. Reproduced with permission [27]. Copyright 2024, Wiley-VCH. (b) Fabrication of viscose fiber actuator. Reproduced with permission [29]. Copyright 2021, American Chemical Society. Schematic illustration of the 3D printing method to fabricate the fiber-based actuators. (c) 3D printed programmable pneumatic actuator. Reproduced with permission [30]. Copyright 2018, Springer Nature. (d) 3D printed liquid crystalline elastomer (LCE) fiber actuator. Reproduced with permission [31]. Copyright 2018, Wiley-VCH.

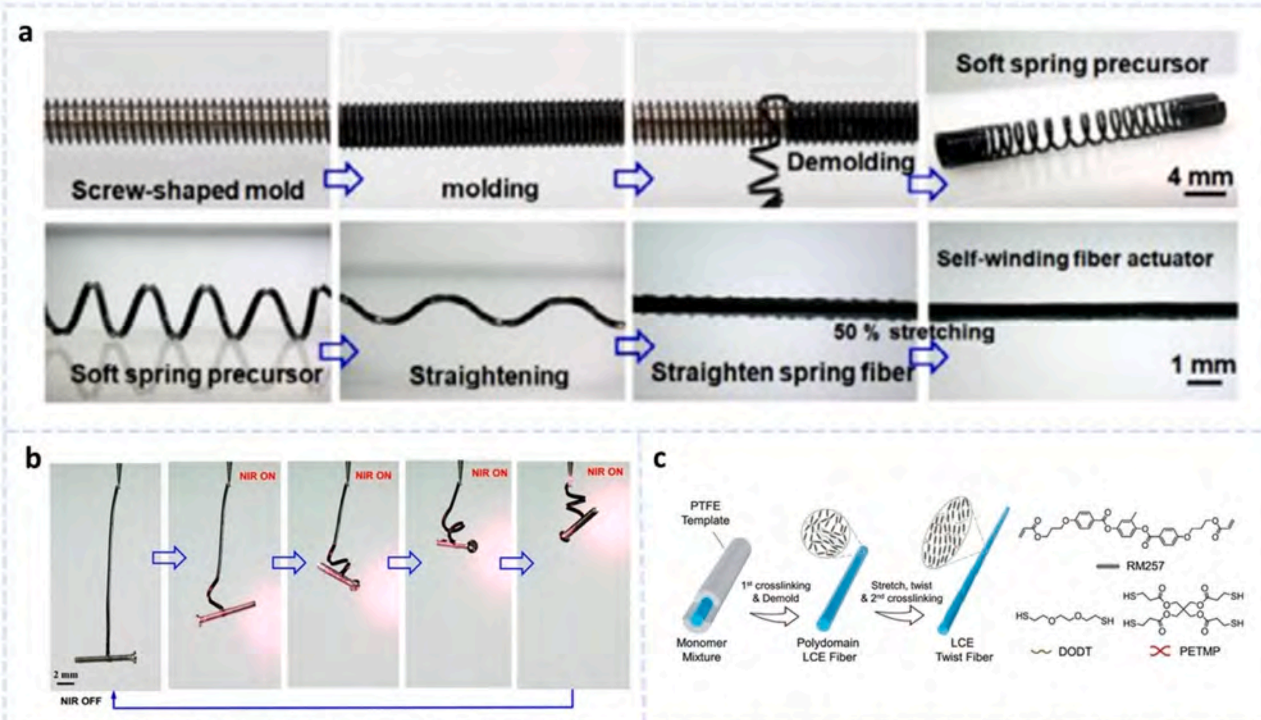

Fig. 3. Schematic illustration of the mold forming method to fabricate the fiber-based actuators. (a) Experimental photo of self-winding fiber actuator using spiral mold. Reproduced with permission [33]. Copyright 2022, Elsevier. (b) Actuating behavior of spiral coiled fibers under near infrared irradiation. Reproduced with permission [34]. Copyright 2021, Springer Nature. (c) Template fabrication of LCE fiber actuator. Reproduced with permission [35]. Copyright 2022, Wiley-VCH.

under near-infrared (NIR) irradiation and showed a variety of deformation behaviors such as twisting, bending, curling, and so on (Fig. 3(b)). The shape of the mold determines the shape of the smart responsive material to a certain extent. Wang et al. [35]. used the template method of a two-step crosslinking strategy to manufacture LCE torsion fiber. Firstly, a hollow polytetrafluoroethylene (PTFE) template was used to prepare LCE fiber, and then helically twisted fiber was obtained by the chemical crosslinking method (Fig. 3(c)). Although this method avoids the necessity for complex material and structural design, the deformation of the actuator will be affected by the mold shape.

2.4. Fiber spinning

2.4.1. Electrospinning

Since its development in the early 20th century, electrospinning has been used as a straightforward and efficacious methodology for the fabrication of nanofibers from a range of polymers [36]. The stimuli-responsive actuators prepared by electrospinning has two forms, nanofiber yarn and nanofiber film. Electrospinning nanofiber films is the first step in the process. The other is to secure one end of the nanofiber film that has been prepared and the other end by twisting and rotating to obtain the nanofiber yarn. Yin et al. [37]. prepared oriented silk nanofiber films by directional electrospinning and then twisted the films into yarns (Fig. 4(a)). The main components of natural silk fibers are fibroin proteins rich in hydrophilic groups. This property is an important reason for its use as a smart responsive material. Similarly, Meng et al. [38]. used the same method to prepare oriented polyurethane (PU) nanofiber films, and then twisted them into yarns, as shown in Fig. 4(b). The distinction lies in the fact that the incorporation of certain functional materials into the precursor solution during electrospinning can impart additional properties to the nanofiber yarn. In addition to yarns composed of oriented nanofiber films, yarns composed of randomly arranged nanofiber films can also exhibit a response to external environmental stimuli following torsion (Fig. 4(c and d) [39,40].

In conclusion, electrospinning is an effective strategy to fabricate nanofiber nonwoven mats, which exhibit a high surface area and porosity [41]. Generally, the nanofiber film prepared by electrospinning is composed of double- or multi-layer nanofiber nonwoven mats at the same time [42,43]. Wang et al. [44]. and Jiang et al. [42]. prepared a double-layer nanofiber membrane actuator by electrospinning (Fig. 4(e and f)). The actuator prepared by this simple and programmable electrospinning method exhibits satisfactory deformation response performance.

2.4.2. Melt spinning

Nowadays, melt spinning is widely used in various fields due to its simple production line, high spinning speed, low production cost, and environmentally friendly preparation method [45]. Among them, two-component melt spinning is a kind of melt spinning that is often used to prepare intelligent responsive fiber materials. The cross-sectional structure of the filament can vary depending on the spinneret (e.g., core-sheath, side-by-side, segmented pie, and islands-in-the-sea). Fig. 5(a) shows the general preparation process for melt spinning. Firstly, poly (L-lactic acid)/poly (D-lactic acid) (PLLA/PDLA) blends were prepared by melt blending, and then PLLA/PDLA fibers were prepared by melt spinning. In order to further promote the crystallisation of fibers, fibers with a relatively perfect crystal structure and polymer orientation were obtained by tensile orientation and annealing process [46]. The fact that twisted and coiled fiber-based actuators can respond mechanically to external thermal stimulation has attracted a lot of interest. As shown in Fig. 5(b and c), the fiber produced by melt spinning should generally be combined with the twisting process to create fiber-based actuators [47,48], which have the advantages of high efficiency, quick response, scalability, and low cost, among others, and have a wide range of application possibilities in the fields of intelligent clothing, sensing, and other fields.

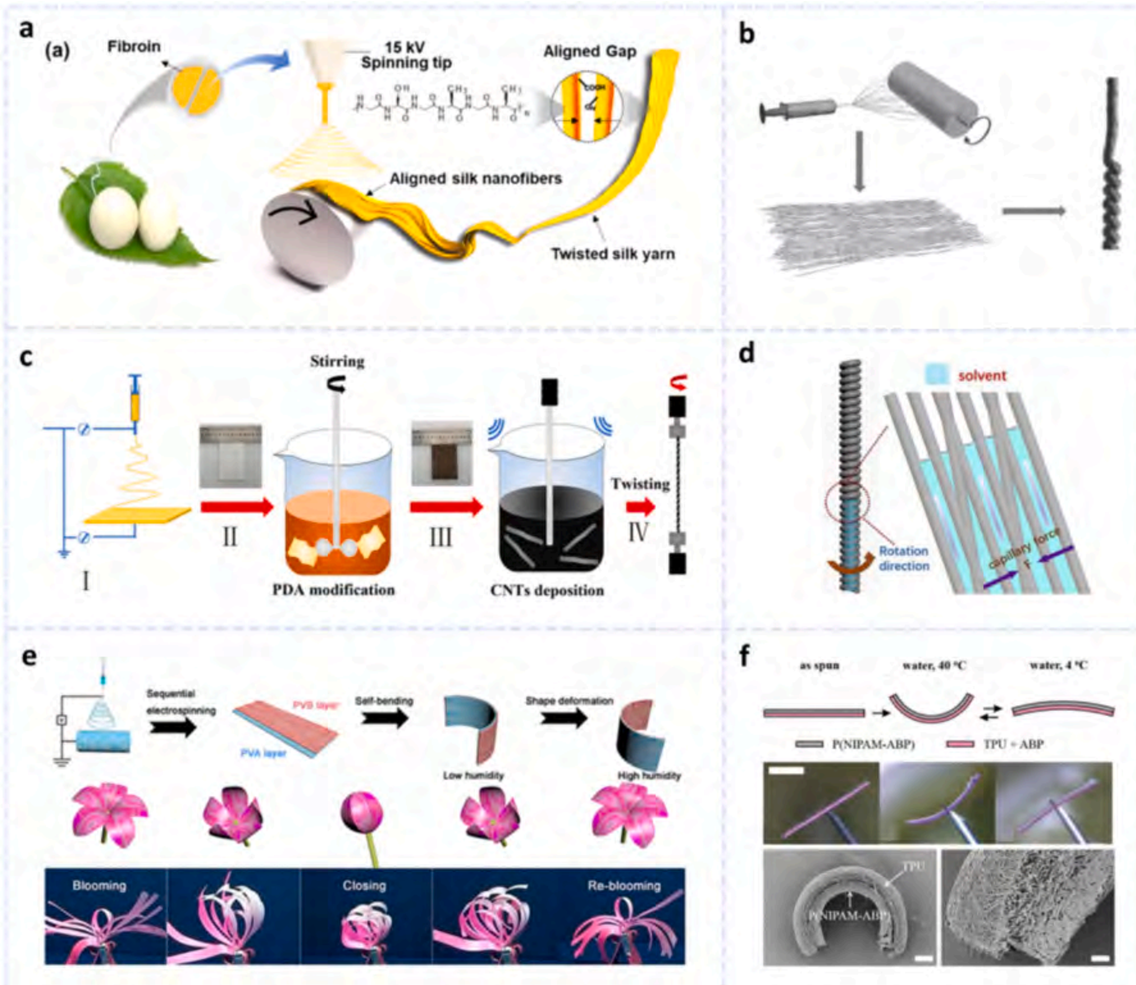

Fig. 4. Schematic illustration of the electrospinning to fabricate the fiber-based actuators. (a) The fabrication process of the silk-yarn actuator. Reproduced with permission [37]. Copyright 2019, Springer Nature. (b) The fabrication process of PU-based actuator. Reproduced with permission [38]. Copyright 2019, Springer Nature. (c) The fabrication process of yarns made of randomly arranged nanofiber films. Reproduced with permission [39]. Copyright 2023, Elsevier. (d) The schematic illustration of the capillary force induced shrinkage and twisting of coiled polyamide-6 (PA6) yarn. Reproduced with permission [40]. Copyright 2020, Elsevier. (e) The fabrication of double-layered polyvinyl alcohol (PVA)/polyvinyl butyral (PVB) nanofibrous actuator by electrospinning. Reproduced with permission [44]. Copyright 2021, Elsevier. (f) The schematic diagram of a double-layer nanofiber membrane. Reproduced with permission [42]. Copyright 2015, Wiley-VCH.

2.4.3. Wet spinning

Wet spinning is a low-cost and flexible method to controlling the mechanical properties of fibers in the preparation of intelligent responsive materials. It mainly includes four steps: the dissolution of the spinning stock solution, the extrusion of the solution, the solidification of the solidified material, and the collection of fibers (Fig. 6(a)) [49–51]. Wang et al. [52]. creatively twisted a single gel-state alginate fiber fabricated by a wet spinning process to obtain a twisted fiber-based actuator for the first time (Fig. 6(b)). It has become an effective method for manufacturing new natural fiber actuators with excellent actuating properties, rapid preparation, and cost-effective processing technology. Afterward, in order to solve the problem that a single stimulus response or multiple stimulus environments cannot drive the response collaboratively, Zheng et al. [53]. tried to prepare a fiber-based actuator that can perform a collaborative drive response under the coexistence of light and humidity stimuli by introducing two components in the fiber preparation process. The specific preparation process is shown in Fig. 6(c). To summarize, wet spinning represents an optimal approach for the fabrication of fiber-based actuators. However, it also has the disadvantages of slow production speed and environmental pollution caused by solvent volatilization.

2.4.4. Other methods

As the field of stimuli-responsive fiber-based actuators to evolve, an increasing number of preparation methods are being developed. Besides the above-mentioned preparation methods, there are also some other methods, such as gel spinning and microfluidic spinning.

Gel spinning, a specific spinning method, is a subcategory of solution spinning. The polymer solution or plasticized gel (solid content up to 35~55 %) is extruded from the fine hole of the spinet head into a gas medium, and the fiber is obtained by thin flow cooling, solvent evaporation, and polymer solidification (Fig. 6(d)). The spinning equipment is the same as for the melt spinning method, so it can also be called semi-melt spinning. Ultrahigh molecular weight polyethylene (UHMWPE) fibers prepared by gel spinning exhibit excellent reversible shape memory properties, enabling them to deform in response to external stimuli. These fibers have a wide range of potential applications, including in smart textiles, polymer fillers, and the medical field [54].

Stimulation-responsive hydrogels have many excellent properties in smart responsive materials, such as ionic permeability and flexibility, which will facilitate complex movements of the material under external stimuli. Many efforts have been made to devise various effective strategies for the construction of 1D hydrogel fiber for potential

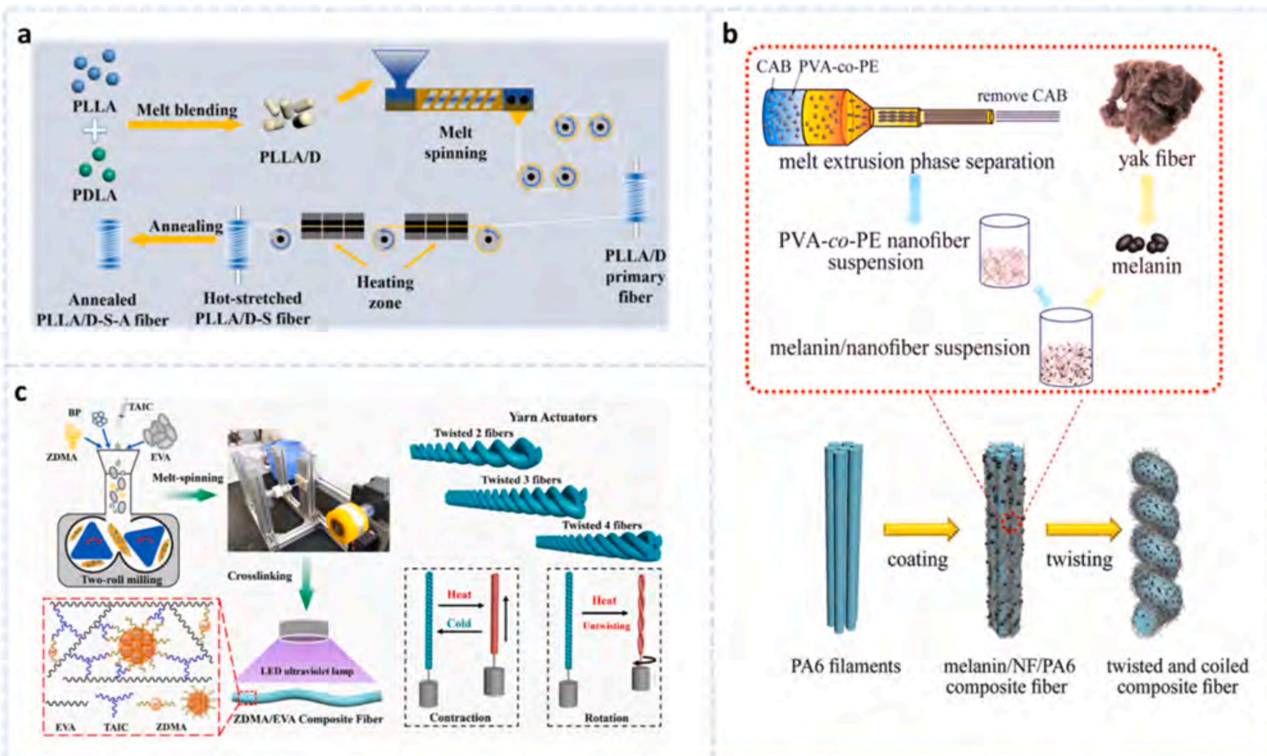

Fig. 5. Schematic illustration of the melt-spinning to fabricate the fiber-based actuators. (a) The melt-spinning process of PLLA precursor fibers. Reproduced with permission [46]. Copyright 2022, American Chemical Society. (b) and (c) The preparation process of melt spinning combined with twisting. Reproduced with permission [47,48]. Copyright 2022, Elsevier. Copyright 2020, Springer.

applications. Duan et al. [55]. demonstrate an effective approach toward the fabrication of hydrogel fiber by using the self-lubricated spinning (SLS) strategy (Fig. 6(e)). This approach solves inherent problems in hydrogel fibers, such as vulnerable mechanical properties, poor processability, and so on. In addition, the microfluidic spinning technology proposed in the early 2000s can also be used to prepare hydrogel-responsive fibers [56]. In the microfluidic spinning process, a second solution sheathes the continuous fluid of the pre-gel solution in the microchannel, which subsequently produces continuous fibers through crosslinking or solidification (Fig. 6(f)). In order to give hydrogel fibers more comprehensive function and excellent mechanical properties, Peng et al. [58]. used the method of microfluidic spinning to prepare polyacrylamide-based hydrogel microfibers using alginate as a template and, at the same time added graphene oxide (GO) to improve the electrical response and mechanical properties of the hydrogel fibers. Although stimulus-responsive hydrogel fibers possess numerous advantages, they also present certain limitations. One such limitation is the difficulty in achieving a satisfactory interface combination with commercial fibers. Additionally, the manufacturing process is not continuous. Sun et al. [57]. solved these problems through the construction of a solvent exchange and covalent anchoring network, successfully coated the hydrogel skin uniformly on various commercial fibers, such as glass fiber, aramid fiber, and metal wire, and realized large-scale continuous manufacturing of thermoresponsive hydrogel fibers (Fig. 6(g)).

The preparation method of stimuli-responsive actuators is presented in Table 1, which also outlines the advantages and disadvantages of these methods. The preparation method of intelligent responsive actuators and the explanation of its principle point out the direction for the development of actuators in the future. At the same time, an understanding of the advantages and disadvantages of each preparation method has become the basis for further enhancements to the actuator.

2.5. Weaving

Components made from textiles are lightweight, breathable and robust to failure modes such as tearing. These beneficial properties contribute to the application of textiles in clothing and enable researchers to use these materials to create soft robotic textiles with structures and properties similar to clothing [67]. However, manufacturing remains a challenge in the development of fabric-based soft robots.

2.5.1. Woven

Weaving, as one of the main textile processing methods, can weave yarn with actuating properties into fabric. Zhao et al. [13]. studied the textile actuator prepared by the weaving method. Firstly, using the yarn with actuating performance as the warp, a plain fabric is designed for making self-crimping curtain. When simulated sunlight (100 mW cm^{-2}) shines in from outside the house, the curtain begins to bend under the drive of the warp yarns and finally rolls to the top of the window within 50 seconds (Fig. 7(a)). Secondly, inspired by the stomata of plant leaves, this yarn is used as a weft to weave a smart "breathable" thermoregulatory fabric based on textile actuators. The cut piles are designed to be air holes. When the ambient temperature rises, the weft yarns at the stomata bend to the left and right sides, allowing more air to flow between the skin and the outside. This work provides a novel approach to the rational design and scalable construction of wearable fabric-based actuators, but its performance is limited by the actuating performance of the yarn itself.

2.5.2. Knitted

Knitting technology is a waste free additive manufacturing method with unique advantages in the preparation of soft robots. Knitted fabrics can utilize geometrically compliant interwoven or cross-stitched structures to form a variety of flexible and stretchable bulk materials, even if

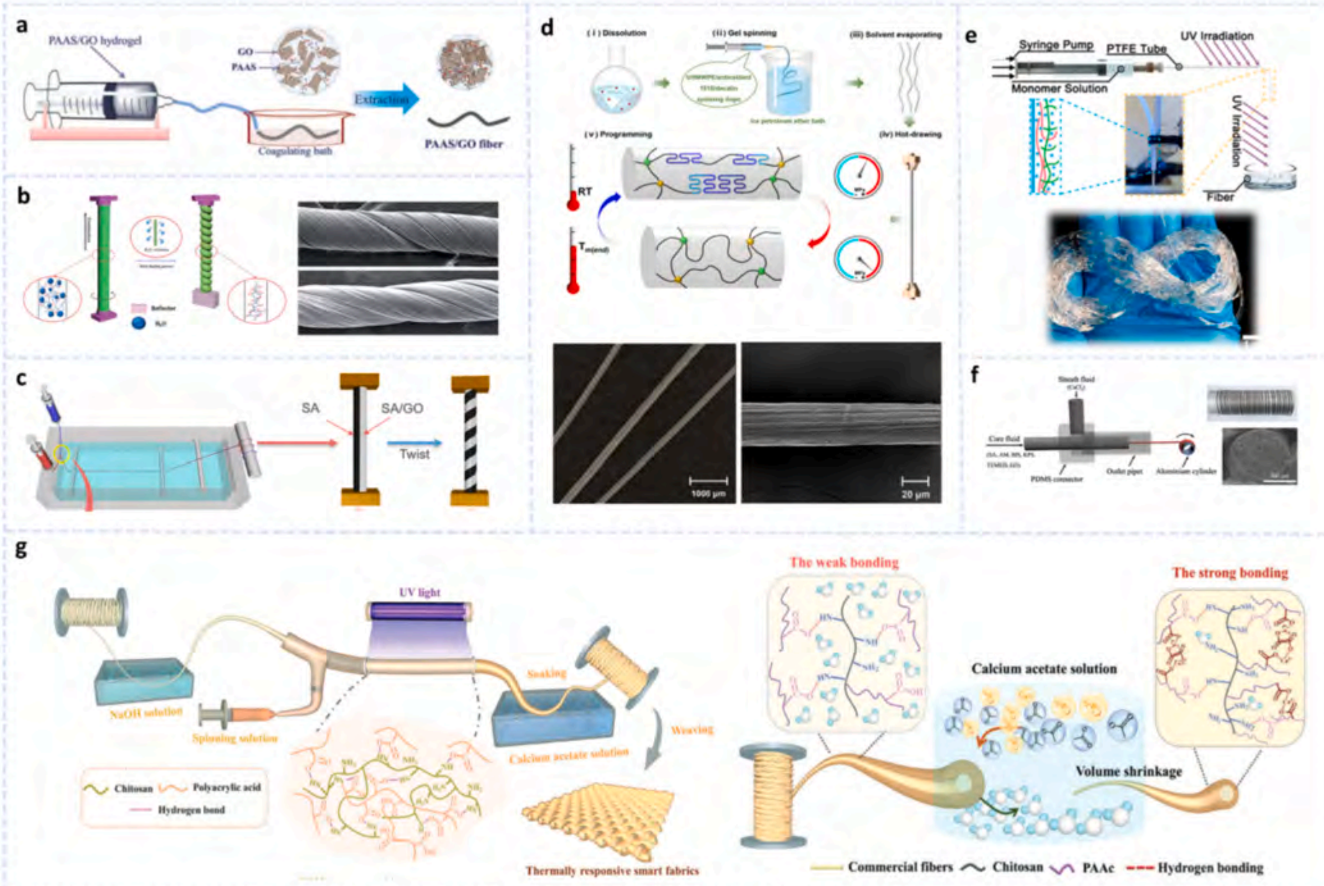

Fig. 6. Schematic illustration of the wet-spinning and other methods to fabricate the fiber-based actuators. (a) The diagram of wet spinning. Reproduced with permission [49]. Copyright 2020, American Chemical Society. (b) The photograph of Scanning electron microscope (SEM) of the sodium alginate (SA) fiber twisting. Reproduced with permission [52]. Copyright 2018, The Royal Society of Chemistry. (c) The diagram of side-by-side wet spinning. Reproduced with permission [53]. Copyright 2021, American Chemical Society. (d) The preparation process of gel spinning. Reproduced with permission [54]. Copyright 2022, Elsevier. (e) The diagram of SLS and the photograph of hydrogel fibers. Reproduced with permission [55]. Copyright 2020, American Chemical Society. (f) Schematic of the coaxial microfluidic spinning. Reproduced with permission [56]. Copyright 2004, The Royal Society of Chemistry. (g) Schematic diagram of continuous large-scale fabrication of thermally responsive hydrogel fiber. Reproduced with permission [57]. Copyright 2023, Wiley-VCH.

Table 1
Comparison of different intelligent responsive fiber actuators.

Method	Materials	Structure	Mechanism	Advantage	Disadvantage	Refs.
Twist	Fiber or yarn	Helical	Distance change	Mature technology	Unitary structure	[27–29, 59–63]
3D printing	SMP, LCE	Linear	Sequence change	Scale preparation	Complex equipment and limited materials	[6,30,31]
Mold forming	LCE, hydrogel	Helical	Sequence change	Simple preparation	Performance is limited by the mold	[33–35]
Electrospinning	Polymer solution	Helical, double/multi-layer	Volume change, Distance change	Simple preparation, wide range of suitable materials	Limited scale production	[37–40,64, 65]
Melt spinning	Polymer melt	Side-by-side, core-shell	Volume change	Continuous, mass production	Complex equipment	[45,48]
Wet spinning	Polymer solution	Side-by-side	Volume change	Continuous preparation	Slow production speed and environmental pollution	[49,51,52, 66]

the constituent yarns are non-stretchable. Based on this, Sanchez et al. [68]. built a three-dimensional knitted soft actuator for stretching, contracting, and bending (Fig. 7(b)). By combining these actuator primitives (Jersey and Garter), soft grippers and robots for a variety of applications can be manufactured as a whole in a one-step rapid prototyping manufacturing process.

2.6. Fabric post-finishing

Post-finishing strategy is an important method for endowing fabric with functionality. Wang et al. [69]. designed a Janus textile featuring adaptive thermal management by post-finishing both sides of the fabric, respectively. Specifically, two kinds of responsive polymers, one with a lower critical solution temperature (LCST) and another with a higher critical solution temperature (UCST), were sprayed onto different sides of the pre-treated cotton fabric and then polymerized in situ and

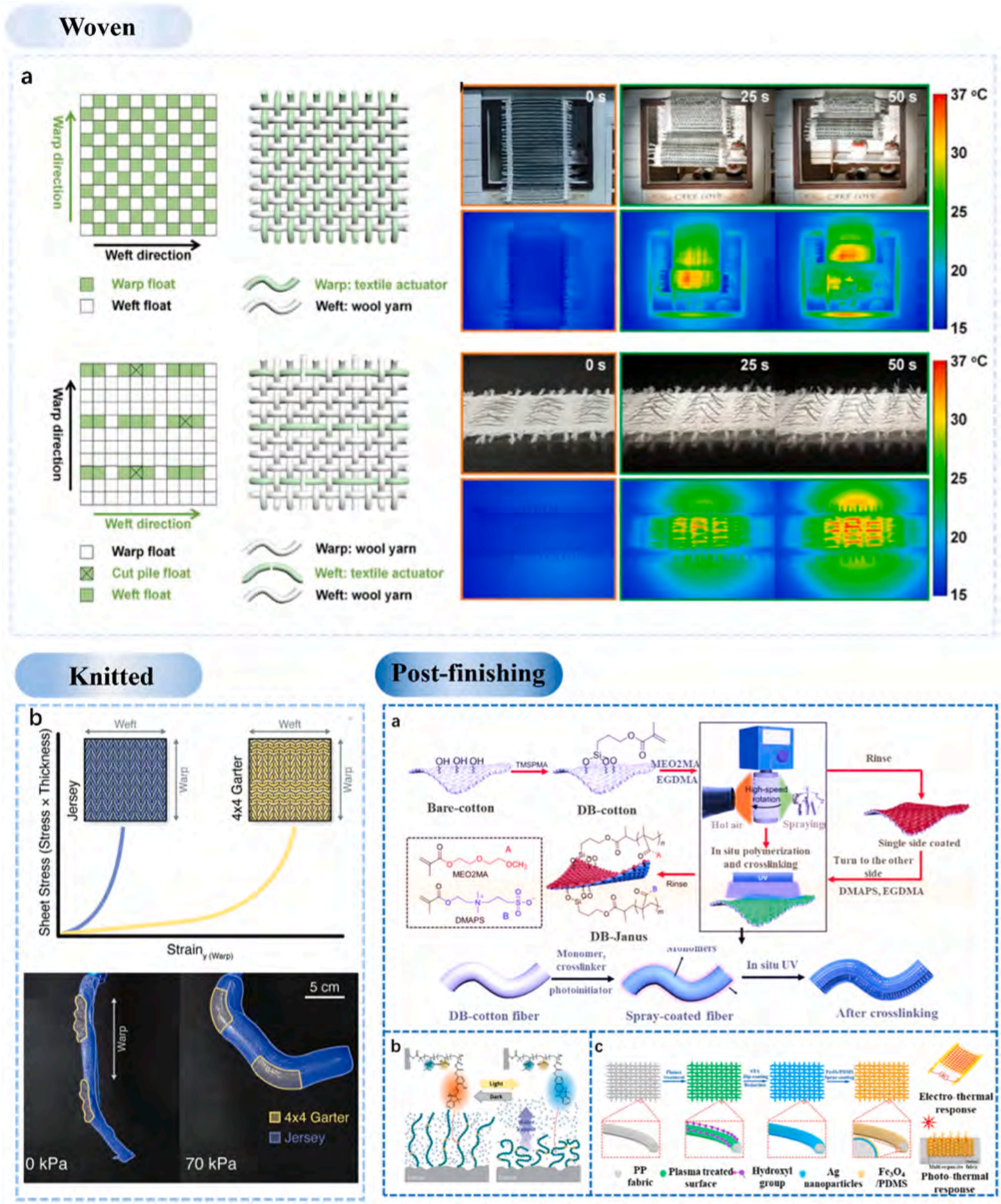

Fig. 7. Schematic illustration of fabricating fabric actuator. (a) Applications of woven fabric actuator-based smart textiles. Reproduced with permission [13]. Copyright 2021, American Chemical Society. (b) Structures and actuation performance of knitted fabric-based actuator. Reproduced with permission [68]. Copyright 2023, Wiely-VCH. (c) The process of cotton fabric post-finishing. Reproduced with permission [69]. Copyright 2020, Wiley-VCH. (d) Schematic representation of the polymer-grafted cotton fibers. Reproduced with permission [70]. Copyright 2016, The Royal Society of Chemistry. (e) The fabrication process of multi-responsive fabric. Reproduced with permission [71]. Copyright 2020, Elsevier.

cross-linked under ultraviolet light (Fig. 7(c)). The local expansion and contraction of each cross-linked polymer network causes surface energy transformation and pore size change to achieve adaptive moisture and heat management. This strategy achieves the dual effect of rapidly evaporating sweat to cool the skin in hot weather and preserving heat to avoid sudden chilling in cold weather. Similarly, Schiphorst et al. [70]. achieved reversible changes in volume and shape by grafting double-response hydrogels on the surface of cotton fabric through surface-initiated polymerization (Fig. 7(d)). In addition, multi-stimulus response fabric actuators can be obtained by simply spraying or coating some material with photothermal and/or electromagnetic effects on the fabric surface, as shown in Fig. 7(e) [71].

3. Structure design of stimuli-responsive fiber/fabric actuators

The structure of fiber/fabric-based actuators is affected by the preparation method to a certain extent. At the same time, the structural configuration of the actuator will affect the response performance of the material, which means fiber/fabric actuators with varied hierarchical structures display distinct deformations. For instance, yarns with the ability to contract under external stimuli can accomplish bending deformation when processed into fabrics. Accordingly, in this part, we summarized the structural design strategies of the common stimuli-responsive fiber/fabric actuators [72].

3.1. Structure design of fiber actuators

3.1.1. Helical structure

The helical structure is the most common structure of fiber-based intelligent responsive actuators, this structure is mainly formed by the twisting fibers or yarns, or through the use of a specific mold preparation. When subjected to external stimulation, the helical structure's rapid expansion and contraction capabilities enable it to generate a specific form of response [73].

Fiber twisting is an extremely common way of preparing stimuli-responsive actuators with helical structure. The twisting form includes single fiber twisting, two fiber twisting, and multiple fiber twisting to obtain a graded arrangement of spiral structural fibers (as shown in Fig. 8(a)) [74]. Natural cellulose fibers, such as cotton, linen, and silk, are used in actuators, sensors, and energy harvesting devices because of their inherent moisture response to mildly stimulating conditions (such as water and humidity), which is superior to that of polymer fibers (Fig. 8(b)) [75]. Wool, as a natural protein fiber, was one of the earliest fibers used by humans. A water-driven single spiral yarn artificial muscle was constructed through simple twisting, coupled with environmentally friendly ultraviolet irradiation and oxygen plasma treatment, as shown in Fig. 8(c) [76]. In order to improve the response speed of water-driven intelligent responsive actuators, it is usually necessary to chemically treat natural cellulose fibers. Viscose fiber, as a kind of regenerated cellulose fiber, is widely used in clothing fabrics. Similarly to natural cellulose, viscose fibers are capable of absorbing significant quantities of water and exhibiting anisotropic expansion, whereby they

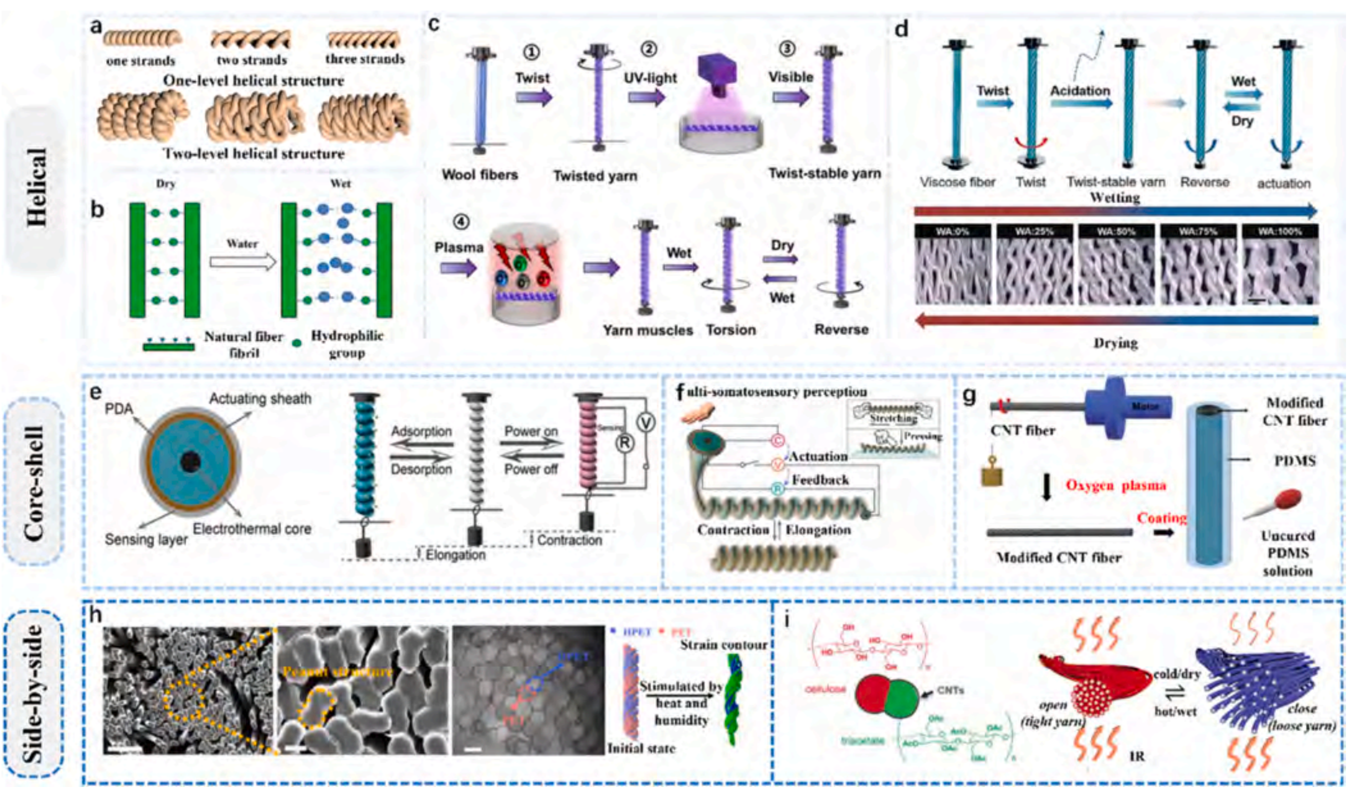

Fig. 8. Structure design of fiber actuators. (a) The hierarchical helical structures of hydrogel fibers. Reproduced with permission [74]. Copyright 2020, American Chemical Society. (b) Mechanism of natural fiber actuation with twist structure. Reproduced with permission [75]. Copyright 2018, American Chemical Society. (c) The schematic illustration of the woolen yarn-based actuation. Reproduced with permission [76]. Copyright 2022, IOP Publishing. (d) The diagram of viscose yarns and its fabric before and after water stimulation. Reproduced with permission [59]. Copyright 2024, Wiley-VCH. (e) Schematic illustration of the cross-section and the actuating mechanism of the MXene/SWCNTs-coated CNT@PDMS coaxial muscle fiber. Reproduced with permission [25]. Copyright 2021, The Royal Society of Chemistry. (f) The structure and the working mechanism of coaxial artificial muscle. Reproduced with permission [77]. Copyright 2022, American Association for the Advancement of Science (AAAS). (g) Preparation and structure of CNT fiber@PDMS coaxial fiber. Reproduced with permission [78]. Copyright 2023, Springer Nature. (h) The SEM and the working mechanism of bi-component PET fiber. Reproduced with permission [26]. Copyright 2023, Elsevier. (h) Design principle of infrared adaptive functional textiles. Reproduced with permission [79]. Copyright 2019, American Association for the Advancement of Science (AAAS).

exhibit a preferential radial expansion (Fig. 8(d)). Based on this anisotropic water expansion, commercial viscose fibers can be converted into high-performance artificial muscles without the need for chemical modification, which has broad application prospects in smart clothing [59].

3.1.2. Core-shell structure

Artificial muscle is an important application area for intelligent responsive materials. The recently prepared sheath-run artificial muscles demonstrate the importance of the core-shell structure for attaining excellent actuation performance [80,81]. As shown in Fig. 8(e), researchers presented a multifunctional $Ti_3C_2T_x$ MXene/single-walled carbon nanotubes (SWCNTs) coated-PA6@polydimethylsiloxane (PDMS) coaxial muscle fiber that is capable of both elongation and contraction on the same fiber thanks to the significant expansion coefficient difference of PDMS in response to heat and solvent [25]. In addition, the coaxial artificial muscle fibers studied by Dong et al. [77]. were obtained by sequentially wrapping a carbon nanotube (CNT) fiber core with an elastomer layer, a nanofiber network, and an MXene/CNT thin sheath, and the actuation was driven by the CNT/elastomer components (Fig. 8(f)). However, when a weak current is applied, the Joule heat generated by the CNT fibers in the core layer is not enough to heat the sheath sufficiently, so the internal torsion energy cannot be released. The sheath-core actuator prepared by Zhao et al. [78]. with pre-twisted CNTs as the core layer and PDMS as the shell layer, enabling the release of internal torsional energy stored under a weak current. The preparation method and structure are shown in Fig. 8(g).

3.1.3. Side-by-side structure

The cross-section of the intelligent responsive actuator with a side-by-side structure contains both active and inert materials. The corresponding principle is mainly that when subjected to external stimulation, the active material and the inert material have different expansion properties in response to this stimulus, resulting in actuation [82].

Chen et al. [26]. studied the preparation of bi-component asymmetric structure polyester (PET) fiber by the melt spinning method and then woven this fiber as the structural unit into metafabric (Fig. 8(h)). The response principle is to use the differential response of the two components to heat and humidity to intelligently control the aperture of the metafabric so as to realize the intelligent regulation of the heat and humidity microclimate. Specifically, each yarn consists of a bundle of fibers that respond directly to changes in heat and/or humidity around them via a drive mechanism. When the environment is cold and/or dry, the fibers in the yarn are in a loose state and the porosity of the metafabric is low, thus preventing heat exchange and moisture output. When the environment becomes hot and/or wet, the torsional deformation of the fibers in the yarn reduces the interfiber spacing, resulting in an increase in the porosity of the metafabric, which enhances heat exchange and moisture output. This low-cost manufacturing technology offers great potential for addressing the comfort of individuals working in harsh environments, including medical workers, athletes, and astronauts. Similarly, a textile with an infrared adaptive function was prepared by taking cellulose and triacetate as two components of the side-by-side fiber [79]. When high temperatures and/or humidity occur, yarn collapse brings adjacent fibers closer together, generating resonant electromagnetic coupling that changes the emissivity of the textile, effectively enhancing heat exchange while increasing the porosity of the textile to facilitate human heat dissipation. In the case of cold and/or dry conditions, the yarn responds in an opposite manner in order to reduce heat dissipation and achieve warmth (Fig. 8(i)).

3.2. Structure design of fabric actuators

Textiles are a type of traditional soft material that can be divided into woven fabric, knitted fabric, nonwoven fabric, and so on according to the classification of fabric structure. These traditional textile processes have consistently proven to be an effective method for preparing fabric-based actuators, due to their inherent advantages and suitability for diverse applications [72].

The fabric structure is an important factor in determining the intelligent response performance of the fabric. Weaving and knitting are the basic structures of traditional textiles, and reasonable structural design can play an important role in the field of actuators. At the woven fabric level, Furuse et al. [83]. prepared a simple plain fabric using fibers that are active and inert to stimulation as the warp and weft of the fabric, respectively, to achieve changes in yarn spacing and fabric deformation under stimulation conditions (Fig. 9(a)). At present, the structure design of knitted fabrics is the research hotspot of fabric actuators. Researchers designed a double-structure knitted fabric, which consists of yarn with moisture response on the outside and PET yarn with poor moisture absorption on the inside (Fig. 9(b)) [84]. When wet, the outer yarn changes from loose to dense, and the expanded coil structure can release more heat and moisture while allowing more air to flow through the fabric, further cooling the skin. However, this traditional textile actuator tends to expand in all directions when pressurized, resulting in a lower response strain. Starting from the fabric structure design, Yang et al. [85]. prepared a pneumatic actuator with a three-layer knitting structure by combining the design principles of weaving and knitting with a structured controllable fancy yarn (as shown in Fig. 9(c)). The caterpillar-like actuator enables fast response and multi-modal deformation of the fabric. Similarly, it is also possible to design different knitting patterns as actuator modules to achieve controllable in-plane contraction and out-of-plane bending in different directions (Fig. 9(d)) [23]. So far, the actuator of traditional textile structures is still used, so there is little research on the actuator of new fabric structures. Zhang et al. [22]. extended the interlocking knots formed by functional fibers to single-column actuators and studied the effect of knot patterns on the performance of the actuators. The use of multiple unit knots that can be interlocked and extended in a two-dimensional direction allows for the design of a fabric actuator with a special structure (Fig. 9(e)).

A double-layer or multilayer structure is the most common structural form of intelligent responsive fabric actuators. Similar to the response mechanism of side-by-side fibers, it is formed by the self-assembly of active materials and inert materials in response to stimuli. At present, this material is widely used in the field of fiber/fabric-based actuators.

Influenced by some plant seeds with directional fiber structure in nature, Shin et al. [86]. used directional electrospinning to deposit hygroscopic polyethylene oxide (PEO) with poor hygroscopic properties on polyimide (PI) tape. The resulting double-layer actuator could bend at a high speed and amplitude according to changes in ambient humidity (Fig. 10(a)). Although this material has a simple structure and can be connected to the actuator to achieve autonomous directional motion, this actuator cannot achieve multi-direction, multi-mode, multi-dimensional, or large bending deformation. To address this problem, the researchers used a structural bionic strategy to design and fabricate a novel water/moisture response nanofiber actuator with an alignment gradient [87]. The gradient of nanofibers along the thickness direction can cause the actuator to produce non-uniform contraction and further rapid shape deformation under the stimulation of water/-moisture. At the same time, the highly arranged structure can also control the direction of shape deformation. Therefore, the nanofiber actuator has an ultra-high response speed (less than 150 ms), controllable deformation direction, multi-actuation model, large bending curvature (25.3 cm^{-1}), and excellent shape deformation performance with a repetition rate of at least 1000 times (Fig. 10(b)). However, these two actuators can only respond to a single stimulus response, and there are limitations in performance and controllability.

For this reason, many researchers have designed double- or multilayer fiber-based intelligent responsive materials with multi-stimulus response functions. Similar to common double-layer actuators, Cho et al. [88]. prepared a multi-response fiber matrix composed of active and passive layers by continuous electrospinning. Through lithography,

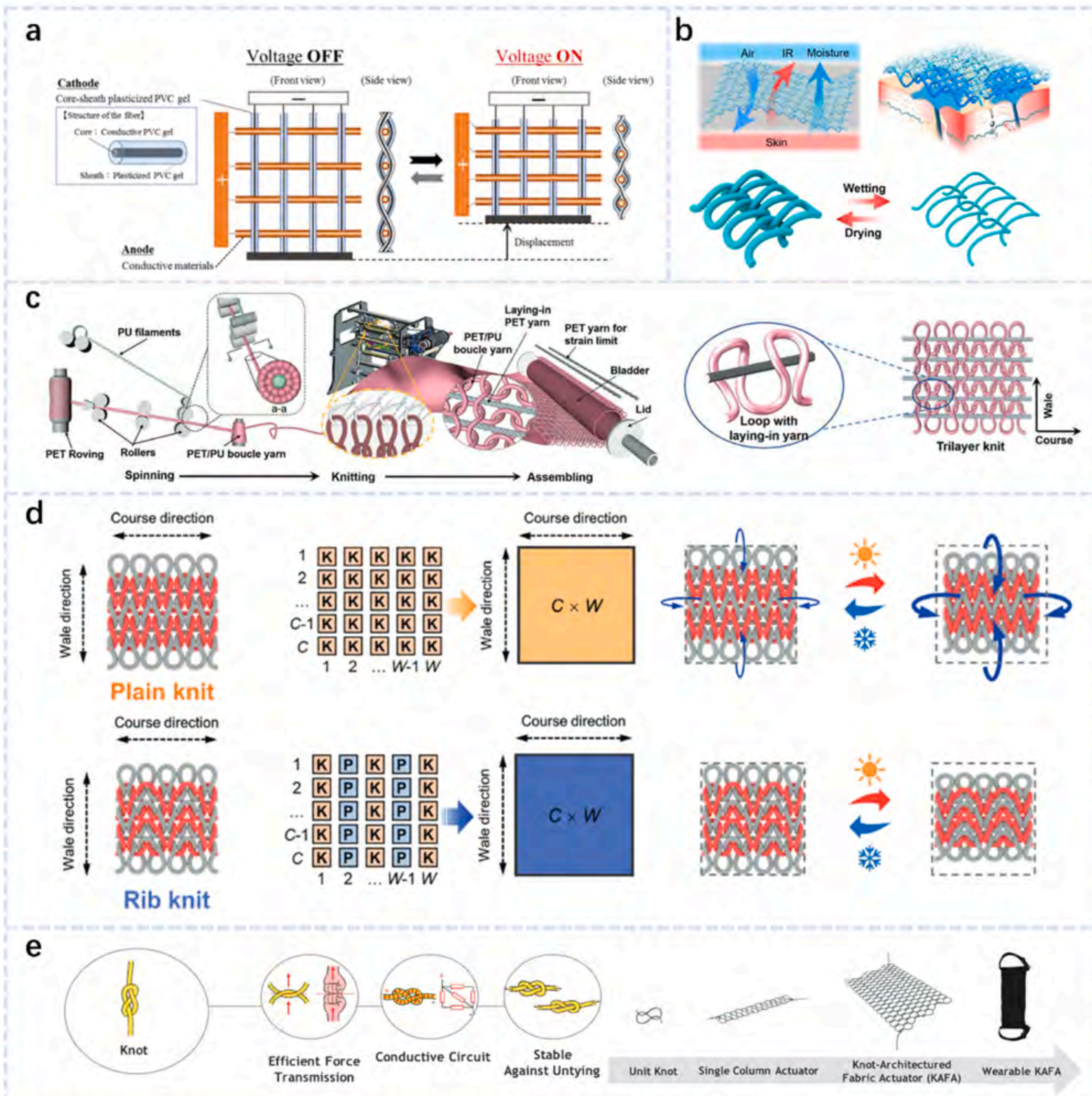

Fig. 9. Schematic diagram of fabric actuator structure design. (a) Deformation of the woven actuator by applying a voltage. Reproduced with permission [83]. Copyright 2017, Biophotonics Discovery. (b) The schematic diagram of knitted fabric with double layer design. Reproduced with permission [84]. Copyright 2019, Springer Nature. (c) The fabrication and diagram of the tri-layer knit architecture. Reproduced with permission [85]. Copyright 2023, Wiley-VCH. (d) Deformation of actuators with plain knit pattern and rib knit pattern under thermal trigger. Reproduced with permission [23]. Copyright 2023, Wiley-VCH. (e) Diagram of knot-architectured fabric actuators. Reproduced with permission [22]. Copyright 2022, Wiley-VCH.

different types of fiber substrates are stacked and integrated into polyethylene glycol (PEG) hydrogel micropatterns. The actuator consists of a stimulus-responsive active layer, a non-responsive passive layer, and a micropattern-coupled hydrogel layer. In order to achieve the function of multi-stimulus response, pH and temperature response layers can be simultaneously superimposed with PEG hydrogel micropatterns. This multi-response drive is achieved by adding another active fiber layer without modification (Fig. 10(c)). Compared to this method, simpler multi-stimulus response materials can be designed and manufactured using conductive fabric (CF) and biaxially oriented polypropylene (BOPP) composite film lamination methods (Fig. 10(d)). The electrothermal and optical properties of conductive copper or nickel-coated fabrics, along with the different thermal expansion coefficient between the film and the fabric, are exploited through proper structural design to achieve large and fast wireless actuation under various stimuli [89].

4. Responsive mechanism and types of stimuli-responsive fiber/fabric actuators

4.1. Response mechanism

Stimulus-responsive material is a kind of intelligent material that has emerged in recent years. By integrating this kind of intelligent response property into textiles, it can provide more novel functions for textiles [90,91]. In general, fiber-based actuators possess high flexibility and

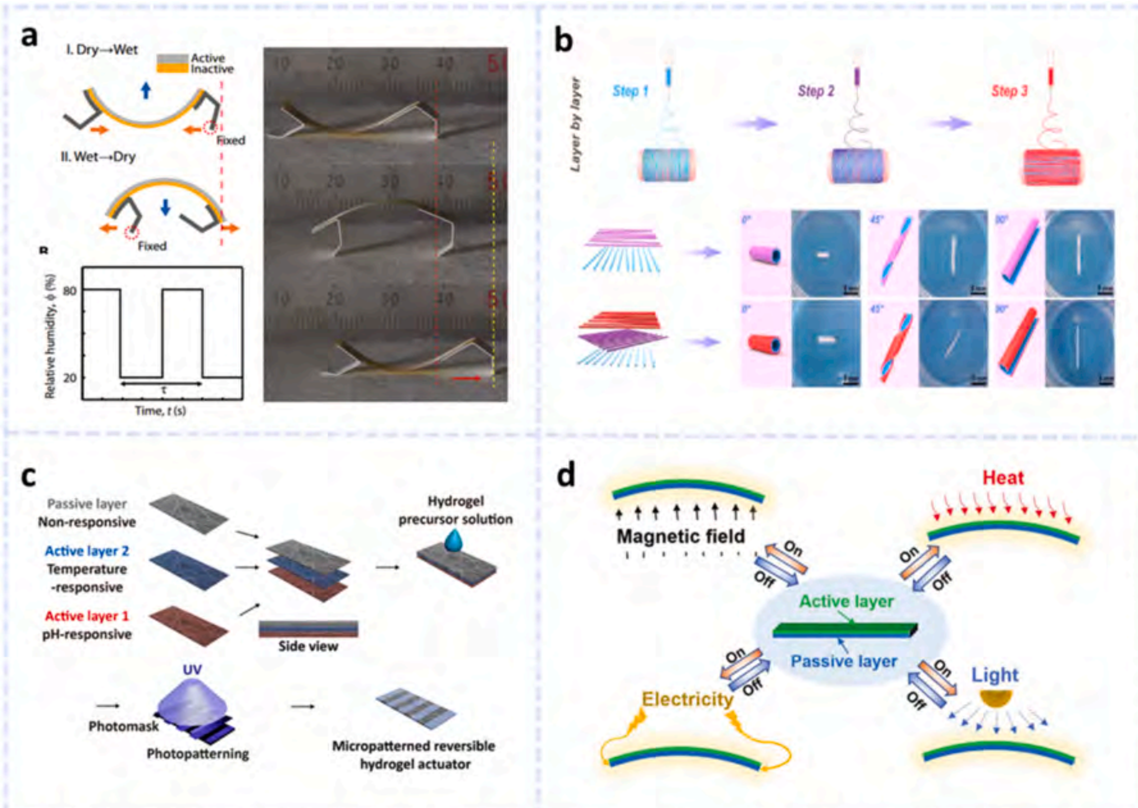

Fig. 10. The diagrams of double/multi-layer structure. (a) Ratcheted locomotion of PEO/PI actuator. Reproduced with permission [86]. Copyright 2018, American Association for the Advancement of Science (AAAS). (b) Illustration of fabrication process and actuating behavior of layer-by-layer nanofibrous actuators. Reproduced with permission [87]. Copyright 2020, American Chemical Society. (c) Fabrication procedure to prepare multi-responsive actuator. Reproduced with permission [88]. Copyright 2022, Elsevier. (d) A soft fabric-based bimorph actuator responds to multi-stimuli, including magnetic, heat, light, and electricity. Reproduced with permission [89]. Copyright 2020, Wiley-VCH.

durability and can be further processed into yarn or fabric intelligent responsive actuators by twisting, weaving, and other processes [92]. The stimuli-responsive fiber/fabric-based actuator is mainly manifested in three forms after being stimulated by the external environment: fiber contraction and elongation, interyarn or fiber space change, and flap opening and closing (that is, fiber bending and rotation, fabric bending) [93]. According to these three response forms, the response principle of fiber/fabric-based actuators can be summarized. In fiber-based actuators, there are three principles of stimuli-response: (1) changes in the sequence of molecular chains, (2) the volume change of the fiber due to expansion, and (3) the change of distance between fibers or yarns.

There are two main types of actuators that respond to changes in the molecular chain: one is the molecular chain changes caused by the stress dependence on the temperature of the stretched amorphous polymer network. This method involves the mechanical alteration of the polymer chain at elevated temperatures, resulting in the formation of a conformation distinct from the original. This conformation is then stabilized under cooling conditions. The resulting actuator can be stimulated by temperature to produce a change in the molecular chain, resulting in a change in shape [94,95]. The other is a non-conductive elastic polymer between two electrodes, also known as a dielectric elastomer [96]. The application and removal of an electric field will lead to the relaxation and restoration of the elastomer to its initial shape. Therefore, this is called the actuator of the electrical stimulus response [97,98]. The second response mechanism is the change in fiber volume. The mass transfer between the fiber and its surrounding environment, the change in expansion coefficient caused by light, heat, humidity, and other stimuli, or the phase transition caused by crystallization will lead to a change in fiber volume [99,100]. The mechanism for changing the distance between fibers is specific to yarns. A change in the distance between fibers will result in a shrinkage or rotation of the yarn. Because yarns are made up of multiple fibers, changes in the order of the molecular chains in the fibers and in the volume of the fibers can also lead to changes in the distance between the fibers, resulting in shrinkage or rotation of the yarn [101–104].

In general, a single fiber or yarn and its fabric may exhibit limitations in terms of response speed and the range of responses that can be triggered. In order to enhance the performance of the intelligent responsive actuator, a method combining inert and active materials is proposed. The combination of these materials allows for the production of different expansion coefficients, which in turn enables the actuator to bend, twist, and perform other functions in response to external stimuli. In general, the greater the difference in properties between the two materials, the better the response. When two kinds of materials with disparate volumetric expansion properties are combined by simple stack configuration, the actuator produces a bending response after receiving certain stimulation. If two materials are stacked on top of each other in the form of inclined sections, when one layer expands asymmetrically under a specific stimulus, the material will bend along and twist around the axis, forming a deformation that can be described as a peptide-type response. If you add another layer on top of this to form a slanted sandwich structure, a DNA spiral drive occurs [105–107].

In short, the response mechanism of fiber-based actuators is mainly determined by the properties of the material itself, including molecular order, fiber volume, and the distance between the fibers. The influence of different stimulus types on actuator deformation should be considered in material selection and structural design. In addition, in order to meet the demands of practical applications, it is also necessary to improve the response speed of the actuator and prepare a multi-stimulus response actuator to cope with complex environmental changes.

4.2. Stimuli types

Fiber/fabric-based actuators, also referred to as smart materials, find alternative strategies for the driving of reconfigurable systems. These intelligent responsive materials do not require motors or external actuators, can be remotely controlled when stimulated by the external environment (such as moisture, light, heat, and so on), and are capable of being selectively or distributedly actuated [108]. According to the mode of operation, fiber-based actuators can be divided into single stimulus response actuators and multi-stimulus response actuators. The single stimulus response encompasses a range of stimuli, including moisture or liquid water response, thermal response, light response, and electric response, among others. The multi-stimulus response actuator is a combination of single stimulus responses.

4.2.1. Humidity/solvent response

Moisture is a non-polluting energy source that is renewable, easily available, and convenient. Water-driven materials are well-known in nature, and the researchers believe that moisture driving is a promising actuation method [109,110]. The behavior of moisture response is mainly manifested by flaps opening and closing and yarn/fiber deformation. The deformation of fibers is a consequence of volume changes caused by mass exchange, such as swelling and contraction, when small molecules enter and exit.

Silk has excellent physical and mechanical properties, biocompatibility, and biodegradability. Most importantly, they can achieve good wearing comfort and show sensitive response characteristics to moisture. Jia et al. [111]. demonstrate the moisture-driven torsional and shrinkage actuation of degummed silk fibers and the application of this fiber-based actuator in smart textiles. The torsion silk has a fully reversible torsion stroke of 547 $^\circ$ mm^{-1} when exposed to a moist environment. The excellent actuation behavior observed is the result of water absorption-induced breakdown of hydrogen bonds and resulting structural changes within silk proteins. Upon absorption of water molecules, each individual fiber segment with an S-twist is untwisted due to the expansion of the fiber volume, generating torque. This results in an increase in the entanglement of the two fibers in the Z direction, as the entanglement direction is opposite to that of the fiber. In addition, the desorption of water reverses these processes. Due to the deformation reaction of the silk fiber to the wet environment, the prepared smart sleeve will shrink when exposed to the wet environment, and the gap between the smart clothing yarns will increase (Fig. 11(a)). A water/humidity responsive actuator was created using a combination of wet-spinning and twisting techniques. The actuator is made of multi-strand carboxyl methyl cellulose (CMC) fibers with helical shapes

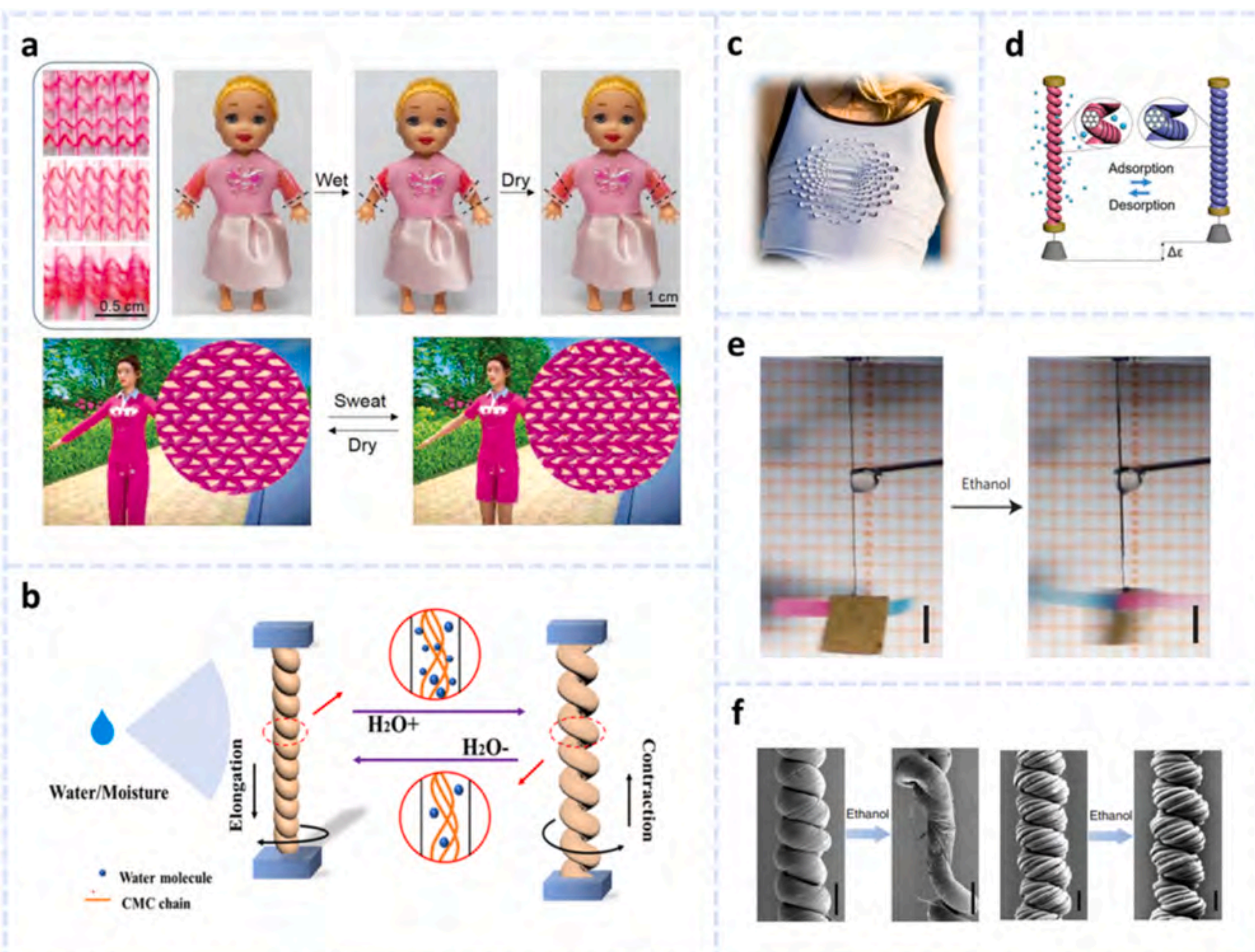

Fig. 11. Humidity/solvent actuators. (a) The schematic diagrams of moisture actuation of degummed silk fibers for smart textiles. Reproduced with permission [111]. Copyright 2019, Wiley-VCH. (b) The mechanism diagram of actuating performance of multi-strand helical CMC fibers actuator. Reproduced with permission [112]. Copyright 2023, American Chemical Society. (c) Wet actuator with flap opening and closing under wet stimulation. Reproduced with permission [113]. Copyright 2020, MDPI. (d), (e), and (f) The actuating performance of CNT actuator under solvent stimulation. Reproduced with permission [117–119]. Copyright 2018, The Royal Society of Chemistry. Copyright 2015, Springer Nature. Copyright 2017, Springer Nature.

(Fig. 11(b)). Similarly, the driving behavior of this actuator is also the deformation of fibers, which can spontaneously lift or move heavy objects like human muscles under wet stimulation [112]. In addition, the actuating behavior under wet stimulation is also manifested by flaps opening and closing. A double-layer textile consisting of a hydrophobic PET yarn and a hydrophilic polyamide (PA) yarn. When stimulated by sweat or moisture, the PA fibers expand, causing the phenomenon of flaps to open and close (Fig. 11(c)) [113]. As green and environmentally friendly moisture/water responsive materials, silk fiber and cellulose fiber are expected to be widely used in the field of moisture/water responsive actuators to replace inorganic synthetic materials such as GO, MXene, and CNTs due to their advantages of low cost, easy access, and excellent mechanical properties. In addition, the moisture/water responsive actuator also provides a new approach to the preparation and application of natural fiber materials in the field of smart textiles.

In addition to actuation by moisture, some response materials are actuated by absorbed and desorbed guests, like solvents. CNT yarns are one of the commonly used actuator materials, which have the ability to be strong, lightweight, flexible, conductive, and capable of hosting functional guest materials, so they have recently been used to fabricate fibrous artificial muscles [114–116]. Jin et al. [117]. showed a CNT yarn muscle that is fabricated by allowing the self-plying of a coiled CNT yarn, which has the characteristic of being twist-stable. The working mechanism of CNT yarn muscle decoupling driven by acetone solvent adsorption is shown in Fig. 11(d). The properties of torsional stability can facilitate the practical application of this yarn muscle. The research of Chen et al. [118]. and Deng et al. [119]. also proved that CNT yarns can produce actuation in response to solvent stimulation, with a high response speed and travel (Fig. 11(e and f)). A large number of nanoscale gaps between CNTs and a large number of micron-scale gaps between fibrils ensure a large volume change and fast reaction when solvents and vapors infiltrate through capillary action, which is an important reason for the fast response and large drive travel of the fibers. Moreover, these fibers are lightweight and flexible, which makes them suitable for a variety of applications, including energy-harvesting generators, deformable sensing springs, and smart textiles.

Fiber/fabric-based actuators that respond to moisture and solvent have received considerable attention from researchers due to their advantageous properties, including the absence of pollution, the simplicity of the stimulus, the programmability of the actuation behavior, and so forth. However, it should be noted that moisture-responsive actuators also have certain disadvantages. These include the high frequency and rapid change of environmental humidity, as well as the difficulty of obtaining a material that is sensitive to humidity stimulation. This is an area that we will strive to overcome in the future.

4.2.2. *Thermal response*

In addition to the fiber deformation caused by humidity stimulation, the change in temperature will also cause a change in fiber volume to achieve the purpose of driving. The mechanism of thermal response is mainly the ordered change of the molecular chain. A thermal response actuator can be actuated by a number of different mechanisms, including thermal radiation, infrared (IR) radiation, electrical Joule heating, and the photothermal effect. Moreover, they can be remotely activated by heating techniques. For particular applications, such as biomedical applications, thermal stimulation also offers a safer strategy than UV light or electric fields [120].

In thermal actuators, poly(N-isopropyl acrylamide) (PNIPAM) is a common heat-responsive polymer that expands and contracts below and above the LCST [121,122]. In order to control the direction of motion of the actuator, Liu et al. [43]. fabricated a fibrous bilayer material by electrospinning, which is composed of thermoplastic polyurethane (TPU) and cross-linked PNIPAM fibers and oriented at different angles as passive and active layers. When the temperature is 40℃ (> LCST), the PNIPAM layer, acting as the active layer, shrinks and curls in the direction of fiber orientation. Conversely, when the temperature drops to 4℃ (< LCST), the curls open in the direction perpendicular to the fiber orientation (Fig. 12(a)).

Shape memory alloys (SMA) are another material commonly used in thermal responsive actuators, which can be divided into amorphous polymers, semi-crystalline polymers, and LCE. The shape memory effect of SMA is due to the thermoelastic martensitic transformation in the material during deformation [123]. When the temperature of the material rises above a certain threshold through Joule heating, the material becomes an austenitic crystal state and returns to the original shape of the "memory" before deformation [124]. The advantages of using SMA in textile production include its lightweight nature, simple production process and low manufacturing costs. Consequently, numerous researchers have begun to develop textile actuators with SMA [125]. A soft morphing actuator based on loop-linked structures with SMA fibers was fabricated by Shin et al. [126]. Active fibers are SMA, wrapped with PET fibers, while inactive fibers are conventional knitting yarn. The driver source of the actuator is the SMA yarn, and due to the shape-memory effect, the SMA yarn is deformed under heating (Fig. 12(b)). Except for SMA, SMP is also a good smart material for preparing heat-responsive actuators, which can be programmed to retain temporary shapes and return to a permanent shape when thermal stimulation is applied [127,128]. Inspired by the nature of tendrils anatomy and the mechanism by which phased behavior translates into macroscopic motion, Farhan et al. [129]. designed a multi-material fiber (MMF) with a shape memory fiber as the core material and an elastic deformable matrix as the shell layer. The shape memory effect of the core fiber can be realized by the strain mismatch in MMF by physical means, and it can carry out reversible movement under thermal stimulation (Fig. 12(c)).

The field of fiber/fabric-based flexible thermal responsive actuators has witnessed considerable advancement over the past decade. However, limited by the mechanical strength of flexible materials, commercial applications and long-term use in robots and intelligent devices are still a big challenge.

4.2.3. *Light response*

Light is a clean and safe energy source used in intelligent responsive actuators that can be controlled remotely and contactlessly, and has easy-to-adjust characteristics [130]. The essence of photoresponsive is a photochemical or photothermal drive, where photochemistry drives and controls mechanical motion through chemical reactions, while the photothermal effect uses the conversion of light to heat to achieve heat-drive mechanical motion [131].

(1) Photochemical response

The basic mechanism of the photochemical drive is that under the action of light, the unsaturated chemical bond in the photosensitive material is destroyed and reconFig.d, which leads to the deformation of the photoresponsive actuator. As the intensity of light changes, the deformation of the photosensitive material also changes [73].

Liquid crystal polymers (LCP) are good materials for the preparation of photoresponsive actuators. The principle of light-driven is based on the photoinduced molecular rearrangement of polymer networks [132]. Xu et al. [133]. fabricated a photocontrollable flexible microtube with a bilayer structure comprising a flexible support layer and a photodeformable linear LCP layer. The hollow fiber was filled with a variety of light-propelled liquid slugs. The LC molecules were reoriented when illumination was supplied, and their deformation led to a shift in capillary force, which assisted the liquid slugs in moving (Fig. 13(a)). Moreover, azo-benzene and spiropyran, two popular photochemical materials, are often used in conjunction with LCE or hydrogels to realize a faster light responsiveness effect [134,135].

(2) Photothermal response

The photothermal conversion actuation is primarily driven by

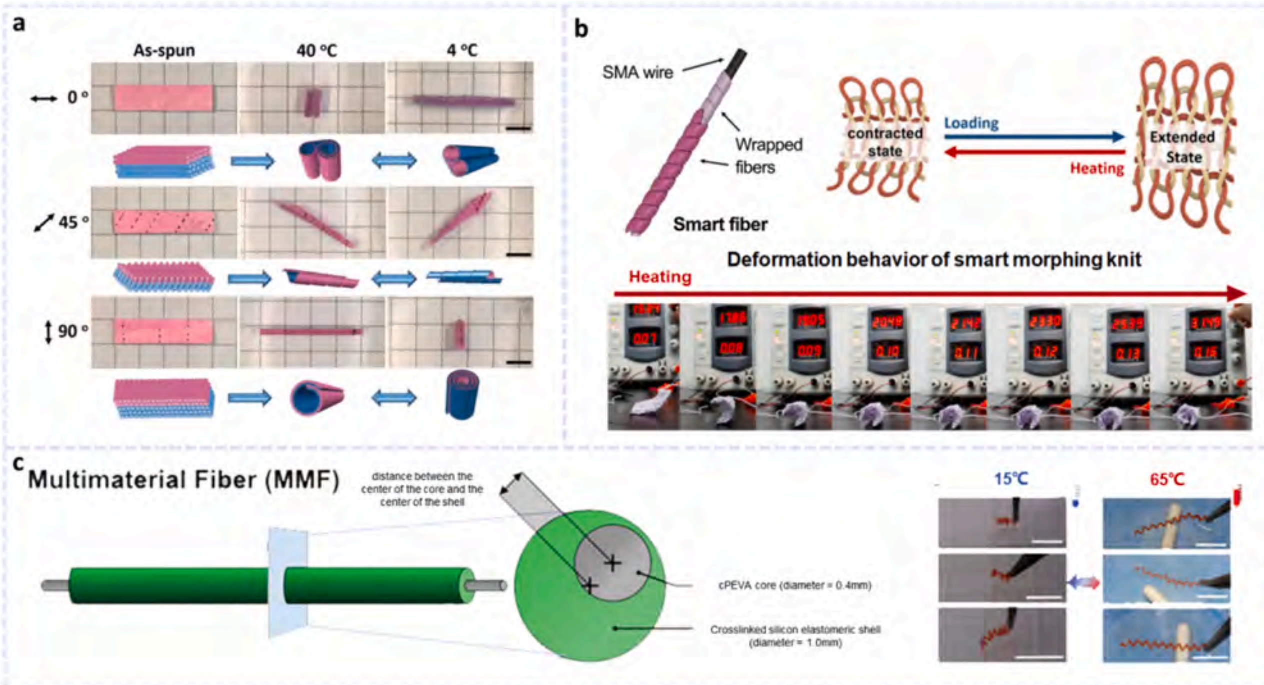

Fig. 12. Thermal actuators. (a) Fiber actuation behavior of bilayer TPU/P(NIPAM) fibrous membranes at different temperatures. Reproduced with permission [43]. Copyright 2016, Wiley-VCH. (b) The diagram of the actuation performance of the SMA actuator. Reproduced with permission [126]. Copyright 2023, MDPI. (c) The actuation performance of MMF-based thermal response actuator. Reproduced with permission [129]. Copyright 2023, Wiley-VCH.

an external light source, which converts light energy into heat energy, thereby altering the temperature of the device. This, in turn, enables the actuator to deform in response to the heat generated. Photothermal conversion actuation can be divided into photothermal expansion deformation, photothermal guest molecule deformation, and photothermal phase transition deformation [136].

The principle of photothermal expansion deformation is based on the two materials with high thermal expansion coefficients and low thermal expansion coefficients produce different deformation amplitudes under light. Chen et al. [137]. modeled a supramolecular system formed by the hierarchical self-assembly of amphiphilic molecular motors based on the motion characteristics of certain substances in living systems and induced macroscopic muscle contraction motion by light stimulation. The molecular motors were first assembled into nanofibers, which were further assembled into neatly arranged bundles. Light causes the rotational motion of the molecular motors, and the propagation and accumulation of this motion cause the fibers to contract towards the light source (Fig. 13(b)). In addition, a sandwich photoresponsive actuator with low cost, simple preparation, and excellent performance was prepared by Huang et al. [138]. The Fig.s show the bending and non-bending motion of the PI-PDMS-potassium bromide (KB)/PDMS sandwich driver under 395 nm ultraviolet light. It is visible that the KB-based photothermal sandwich actuator exhibits an obvious bending deformation when exposed to light (Fig. 13(c)).

At present, GO as a stimulus-deforming material has been used to prepare fiber-shaped stimulus-response actuators [139]. Shi et al. [50]. prepared sodium polyacrylate (PAAS)/GO fibers by wet spinning and further axial spiral twisting. Low-power near-infrared light (50 mW cm^{-2}) induces drive in torsionally pre-deformed PAAS/GO fibers (Fig. 13(d)). The photoresponse mechanism of the fiber is that the surface water adsorbed on the PAAS/GO fiber evaporates as a result of the photothermal effect of GO, which causes the spiral channel of the PAAS/GO fiber to constrict. This volume deformation of hydrophilic molecules caused by light is called photothermal guest molecular deformation.

In addition to the photothermal actuating mechanism mentioned above, in recent years, Wu et al. [65]., inspired by the structure and function of spider webs, combined with electrospinning technology and subsequent photocrosslinking strategies, prepared a new biomimetic gold nanorods (AuNRs) @LCE yarn with super actuating ability and stable driving characteristics (Fig. 13(e)). First, similar to the contraction of individual fibers in a spider web, many dielectric units in each micro/nanofiber polymer network contract and deform due to phase transitions stimulated by external temperatures. Secondly, the electrospinning AuNRs@LCE yarn contains many strong fiber networks composed of different micro and nano fibers, similar to the elastic fiber interwoven web formed by spider spinning. At the same time, due to the reversible deformation of a single micro-nano fiber, the above strong fiber network formed inside the electrospun yarn will undergo stable shape deformation, which further improves the actuating performance of the yarn. This work provides new ideas for the integration and development of soft actuators and smart wearables based on LCE active yarns (Fig. 13(f)).

Despite the extensive exploration and application of photoresponsive actuators in recent years due to their rapid response speed and straightforward preparation process, there remain some challenges. Firstly, most of the current photoresponsive intelligent response actuators are driven by artificial optical, which presents an urgent need to develop photoresponsive actuators driven by natural light [73]. Secondly, the majority of photoresponsive actuator applications are currently only carried out in the theoretical stage of the laboratory, resulting in a lack of practical applications in daily life. In addition, it is necessary to overcome the limitations of materials and design, and to solve the contradiction between the larger driving force and other necessary performance of the actuator.

4.2.4. Electrical response

Electrical stimulation, as a kind of stimulus-response form, has the advantages of convenient application and controllable intensity (voltage size, frequency, and waveform), which has led to its widespread interest

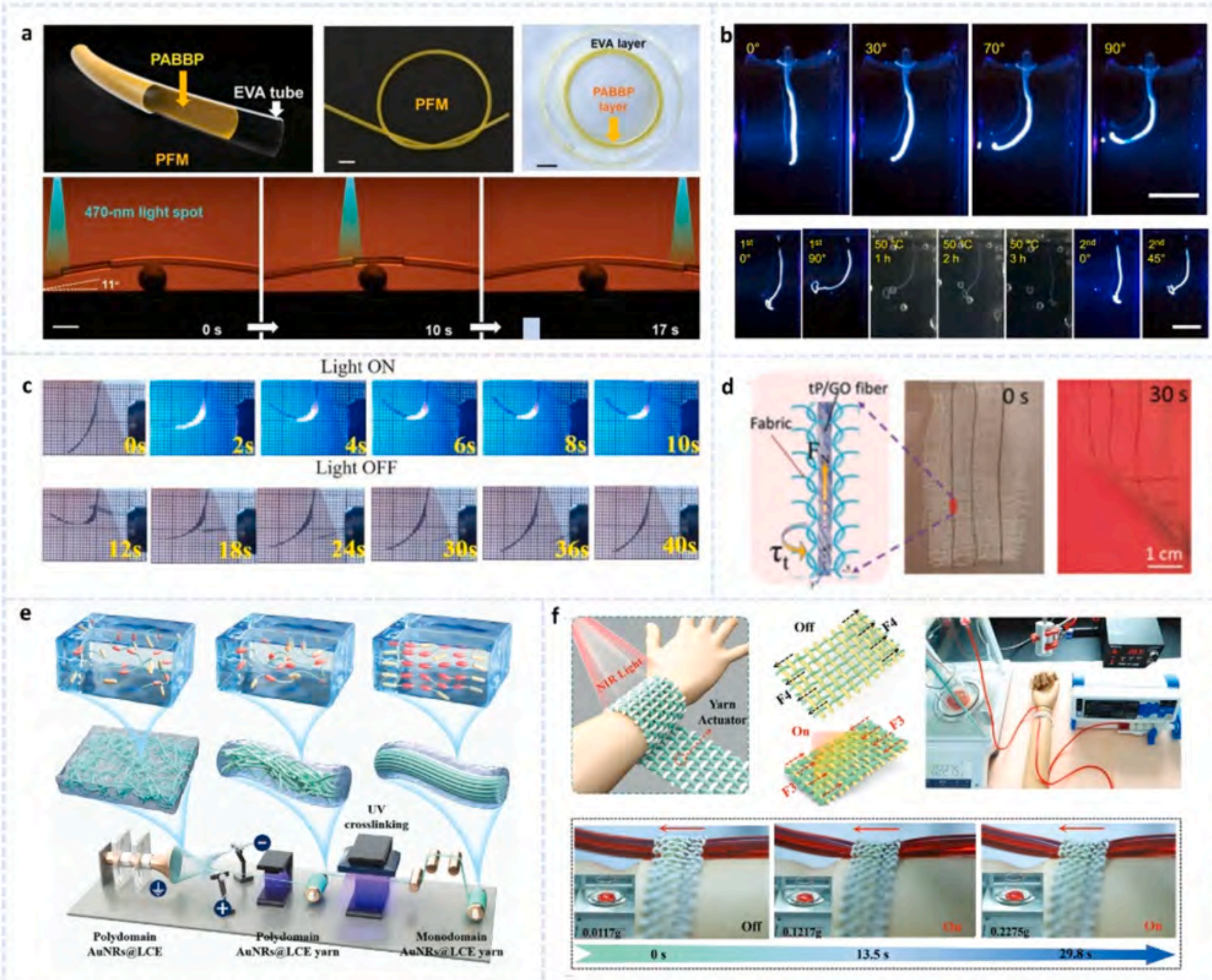

Fig. 13. Light actuators. (a) The diagram of photocontrollable flexible microtube and actuating behavior. Reproduced with permission [133]. Copyright 2019, Wiley-VCH. (b) Fiber actuator fabricated by hierarchical self-assembly of supramolecular motors. Reproduced with permission [137]. Copyright 2018, Springer Nature. (c) The bending and unbending behavior of a sandwich photoresponsive actuator under 395 nm UV light irradiation. Reproduced with permission [138]. Copyright 2022, Elsevier. (d) PAAS/GO fiber-based light response actuator. Reproduced with permission [50]. Copyright 2017, The Royal Society of Chemistry. (e) The diagram of the fabrication process of the AuNRs@LCE active yarn. (f) Application of AuNRs@LCE active yarn in medical bandages. Reproduced with permission [65]. Copyright 2024, Wiley-VCH.

among researchers. Herein, we describe the common types of electric stimulus-response actuators and explore the current driving principles of electrical stimulus-response.

In the drive behavior of the electrically stimulated intelligent responsive actuator, the electric current can directly drive the conductive yarn to change the distance between the fibers. According to Ampere's law, the electromagnetic interaction between CNTs changes the distance between fibers when an electric current flows through helically arranged CNT fibers, so helical and layered assembled macroscopically multi-walled carbon nanotube (MWCNT) fibers prepared by a simple dry spinning process show both contraction and torsional drives under the stimulation of an electric current (Fig. 14(a)) [140]. Chen et al. fabricated electromechanical actuators by sewing together elastic and mechanically robust, spring-like CNT fibers. Electromechanical motion can be triggered by a linear current, with the current applied, the fiber produces contraction, and the contraction stress increases with the increase of the current. In addition, the contraction and elongation of the fibers are determined by the chirality of the spiral fibers (Fig. 14(b)) [141].

In addition to the direct current drive, the electroactive polymer (EAP) also has a rapid response to electrical stimulation. Its driving behavior is dependent on the electrostatic pressure generated by a local electric field formed by a high voltage [142]. An excellent candidate material for the construction of a soft actuator for a wearable robot is a plasticized polyvinyl chloride (PVC) gel with high driving stability in the atmosphere and the capacity to deform when subjected to a relatively low voltage (400 V). Furuse et al. [83]. fabricated a yarn-based actuator consisting of a core plasticized PVC gel fiber and a conductive stretch fiber connected to a cathode and an anode, respectively. Upon application of a voltage, the cathode gel is positioned in close proximity to the anode, resulting in the actuator being elongated along the axis (Fig. 14 (c)).

Except for the aforementioned actuators that produce driving behavior due to electrostatic pressure, electrochemical and electrothermal actuators also exist in electrically stimulated intelligent responsive actuators [143,144]. Among these, electrochemically driven actuators are fiber contraction/elongation caused by ion migration under an electric field [145]. However, the practical use of the aforementioned electrochemical yarn muscles is significantly constrained by the use of liquid working systems. To address this challenge, solid-state electrolytes have been utilized to replace liquid electrolytes [146]. Wang et al. [147]. twisted a set of s-CNT yarns with a layered internal

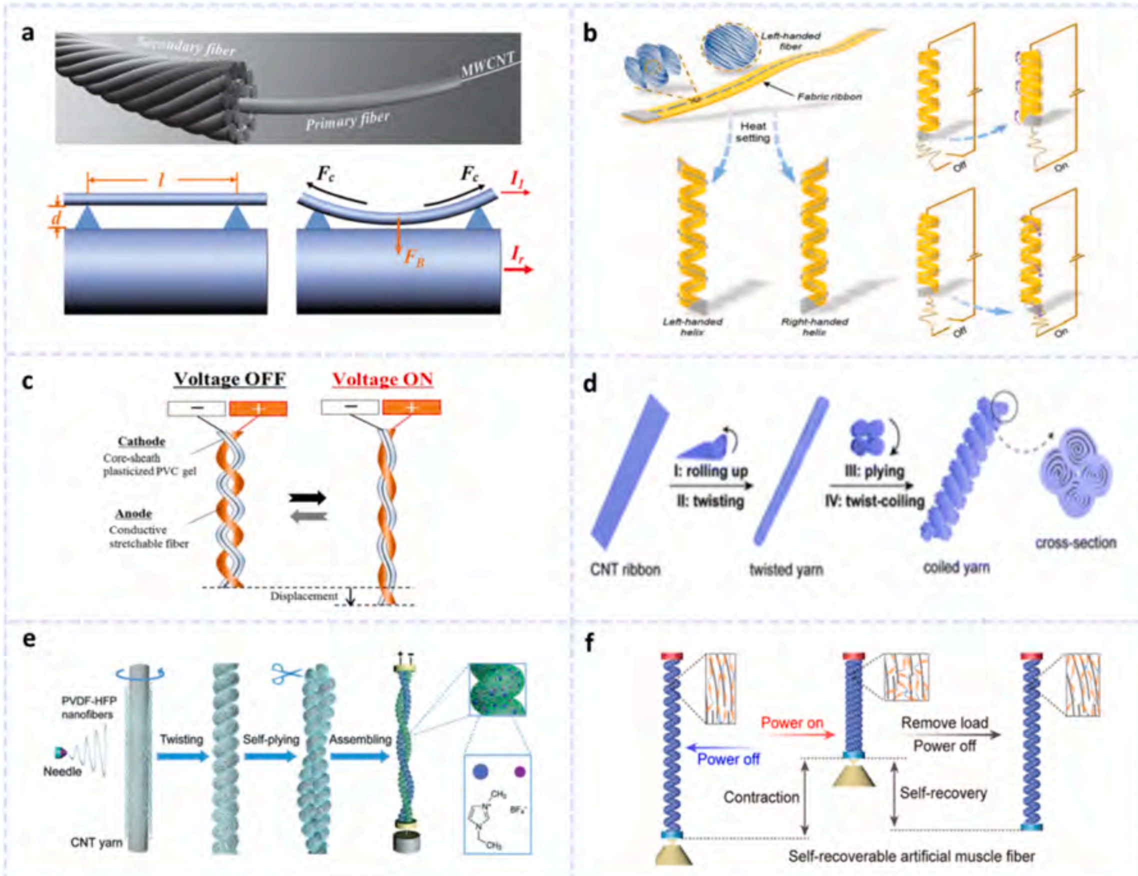

Fig. 14. Electric actuators. (a) Current-actuated MWCNT. Reproduced with permission [140]. Copyright 2015, Wiley-VCH. (b) Electromechanical motions generated by helical Kapton fabric actuator. Reproduced with permission [141]. Copyright 2015, Wiley-VCH. (c) Deformation mechanism of a PVC-based actuator. Reproduced with permission [83]. Copyright 2017, Biophotonics Discovery. (d) Schematic diagram of the hierarchical spinning of an electrochemical yarn muscle. Reproduced with permission [147]. Copyright 2020, The Royal Society of Chemistry. (e) Schematic illustration of the solid-state electrochemical yarn muscle. Reproduced with permission [24]. Copyright 2021, Wiley-VCH. (f) Joule heating-actuated LCE/CNT composite fiber. Reproduced with permission [149]. Copyright 2023, American Chemical Society.

structure to prepare a high-twist penetration electrochemical yarn muscle with an extremely large rapid contraction drive, in which CNT was obtained by floating catalytic chemical vapor deposition (Fig. 14(d)). In fact, the twisted yarn muscle can untwist due to volume expansion brought on by the electrochemical injection of ions, and the unwinding can further bring the coils towards producing strong contraction. Therefore, the yarn muscle prepared by this method is superior to those ordinary yarn and electrochemical yarn muscle with the same amount of CNTs. At the same time, Ren et al. [24]. also prepared a kind of CNT yarn muscle coated with ionic liquid in nanofibers, which solved the problem of the lack of suitable electrolyte for the stable operation of electrochemical yarn muscle in the air, and this solid electrochemical yarn muscle also solved the problem of solvent volatilization and poor stability of liquid electrolyte or wet gel electrolyte for electrochemical yarn muscle (Fig. 14(e)). The electrothermally driven actuator is driven by phase change under the action of Joule heating or expands or contracts due to the difference in the coefficient of thermal expansion [148]. Cui et al. [149]. coated CNT fibers with an extremely thin LCE sheath. Due to the helical nematic phase arrangement of the LCE chains, the phase transition caused by Joule heating drives the actuation process. The resulting fiber exhibits excellent drive performance, including a contraction stroke of 56.9 %, a shrinkage rate of 1522 % s^{-1}, and a power density of 7.03 kW kg^{-1} (Fig. 14(f)).

In summary, electrical actuators have been subjected to the most research due to their superior controllability and higher energy conversion efficiency [150]. For electrostatically driven actuators, extremely high drive voltages are required. For electrothermal and electrochemical driven actuators, response delays and poor cycle life are common. The effect of the electrolytic medium on electrochemical actuators is limited. These are some of the challenges faced by electric actuators.

4.2.5. Magnetic response

Magnetic fields have the advantages of being easy to control and non-contact, so they have been a concern for the majority of researchers. Magnetic response properties are achieved by adding magnetic response substances to the polymer [151–154]. Under the action of an external magnetic field, the effective magnetic force of the magnetic-responsive flexible actuator is distributed along the direction of the magnetic field and then shows the characteristics of variable size, adjustable direction, and recyclable use.

In the presence of a variable magnetic field, the shape and size of the magnetically responsive material can change reversibly, usually because the inorganic magnetic material is covalently fixed or physically trapped within the 3D cross-linked network. To develop magnetically responsive fibers, Kim et al. [155]. used 3D printing methods to print magnetic fibers from elastomer composites doped with ferromagnetic particles. By applying a magnetic field to the dispensing nozzle during printing, the magnetic particles are oriented in a directional manner under the control of the magnetic field direction, thus giving the magnetic polarity of the fiber pattern (Fig. 15(a)). This ferromagnetic domain printing method can be further extended to complex 3D structures, enabling fast

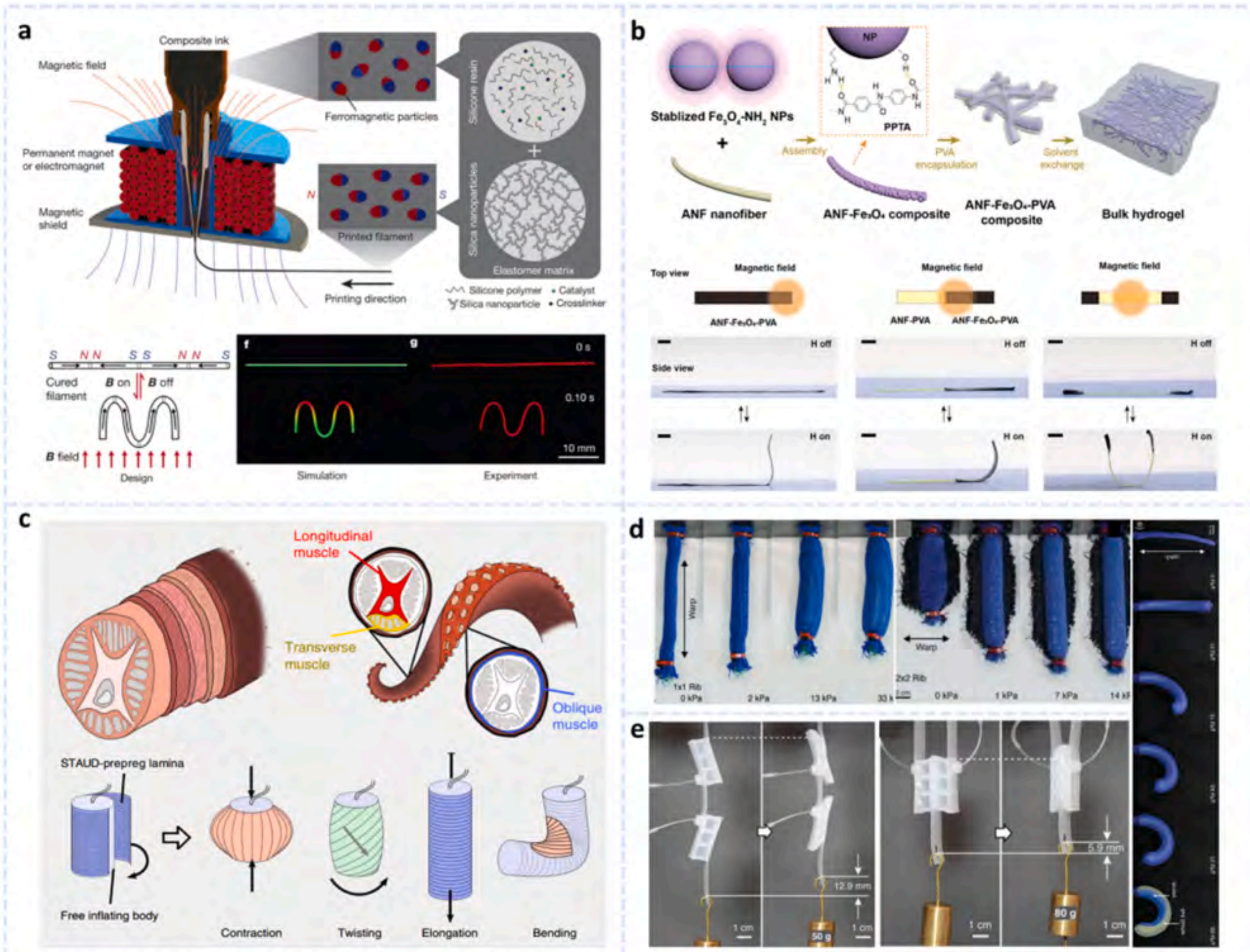

Fig. 15. Magnetic and pneumatic actuators. (a) 3D printing magnetic actuator. Reproduced with permission [155]. Copyright 2018, Springer Nature. (b) Magnetic Fe_3O_4 nanoparticles-based actuator. Reproduced with permission [156]. Copyright 2023, American Chemical Society. (c) 3D printed reprogrammable pneumatic actuator. Reproduced with permission [161]. Copyright 2019, Springer Nature. (d) The Pneumatic actuation of 3D Knitting fabric. Reproduced with permission [68]. Copyright 2023, Wiley-VCH. (e) Shear vacuum linear actuator. Reproduced with permission [166]. Copyright 2017, Wiley-VCH.

transitions between complex 3D shapes when driven by magnetic responses. The soft actuator with a complex magnetic drive mode designed by Wang et al. [156]. was also obtained by incorporating magnetic ferroferric oxide (Fe_3O_4) nanoparticles into other polymer solutions, providing opportunities for further applications of implantable soft robotics, human-computer interaction, drug delivery systems, and other technologies (Fig. 15(b)).

Similar to the light stimulus responsive actuator, the magnetic stimulus responsive actuator can achieve non-contact drive and control during the response to the stimulus, but the control distance is limited and can only be realized in a certain local space.

4.2.6. Pneumatic response

The pneumatic soft actuator consists of a series of elastic body cavities, which are deformed by pressurizing the fluid to expand the chambers [143]. According to the type of pressure, pneumatic drives can be divided into two types: positive pressure drives and negative pressure (vacuum) drives [157–160]. These two methods of actuators also play a crucial role in intelligent responsive actuators.

The working principle of the soft pneumatic actuator is essentially a directional expansion or contraction of the elastic cavity under the action of working pressure (positive or negative pressure) and structural constraints in a certain spatial dimension (such as axial, bending, torsion, etc.). When the pressure inside the positive pressure actuator increases, the flexible air cavity can be expanded under the action of the internal pressure, and a certain form of expansion motion can be generated. Inspired by the fiber structure of muscular hydrostats, a super elastic matrix composed of unidirectionally inlaid non-expandable fiber and adhesive substrate is used as a prepreg to control the movement of pneumatic soft robots. By adhering to the prepreg, the actuator can be programmed to achieve different shape changes (Fig. 15(c)) [161]. Textiles, a class of materials that can provide a great deal of flexibility to adjust material properties, have gradually replaced elastomer structures as the core material for soft robot actuation [162–165]. Sanchez et al. [68]. reported the role of knitting structure and yarn material properties in textile mechanics across three mechanisms of unfolding, geometric rearrangement, and yarn stretching, and showed that they are customizable in unique knitting structures and yarn materials. Thus, pneumatic flexible actuators can be prepared by 3D knitting methods for stretching, contracting, and bending (Fig. 15(d)). In addition to the use of compressed air to do work through the directional expansion of the flexible chamber, the pneumatic soft actuator can also be driven by vacuum negative pressure. Yang et al. [166]. prepared a flexible linear actuator called a shear vacuum-actuated machine, which is made of an elastomer, a composite of soft and hard materials, or a rigid structure in which a void inside the elastomer is connected to an external vacuum source and works by reducing the pressure of the void cavity in the elastic structure to below atmospheric pressure (negative pressure or partial vacuum) (Fig. 15(e)).

Pneumatic drive has become the dominant technology for soft robots due to its low cost, fast response time, and ease of implementation [167]. However, the pneumatic actuator requires a pneumatic source, which limits its application in portable applications [168]. And the air compressor or vacuum pump needed to achieve the drive will produce obvious noise when working [169].

4.2.7. Multi-stimuli response

As a novel type of intelligent materials, actuators based on stimulus-responsive materials play an important role in the fields of artificial muscles, soft robots, intelligent grabbers, and so on [170]. However, traditional stimuli response materials are mainly focused on a single stimuli response and are unable to effectively adapt to complex environmental changes [171–173]. Therefore, research into multi-stimuli response actuators is of paramount important.

In the multi-stimuli responsive actuator, the dual-stimuli responsive actuator that driven by light and water stimuli is the most common type [40,174]. Liu et al. [175]. (Fig. 16(a)) and Wang et al. [176]. (Fig. 16 (b)) used wet spinning and twisting methods to prepare fiber actuators comprising GO and natural sodium alginate (SA), which can produce fast reversible rotational motion upon stimulation with light and water. The difference is that Liu et al. used a coaxial needle to wet-spin the GO/SA mixture solution to obtain the hollow hydrogel fiber (RGO@HHF). The hollow fiber can reach the maximum rotation speed in just 40 s, and has a faster response speed compared to ordinary solid fibers.

In addition, dual-stimuli response materials with thermal and electrical responses also broaden the design and manufacturing horizons of multi-functional smart materials. Xu et al. [177]. prepared a fast dual-response fabric with shape memory and reversible color-changing properties under electrical and thermal stimulation. The weft of the fabric was prepared by melt spinning from PET and thermochromic microcapsules (TMC), and the warp was a PET and stainless-steel fiber (SSF) blend yarn. Among them, PET/TMC showed a dual response of shape and color under thermal stimulation, and PET/SSF also showed excellent electrothermal shape memory and discoloration performance under electrical stimulation [178]. These findings indicate that dual-response materials of thermal and electrical stimulation play a pivotal role in the advancement of smart materials (Fig. 16(c)).

In addition to the dual-stimuli response, the research on multi-stimuli intelligent responsive materials has expanded the application field and has greater development potential. Wu et al. [179]. prepared a stretchable fiber actuator with light, electrical, and thermal responsiveness by dry-spinning and coating methods (Fig. 16(d)) [180]. In parallel, the study verifies the synergistic effect of optical drive and energy harvesting and conversion, laying the foundation for the multi-functional application of multi-stimulatory smart materials in soft

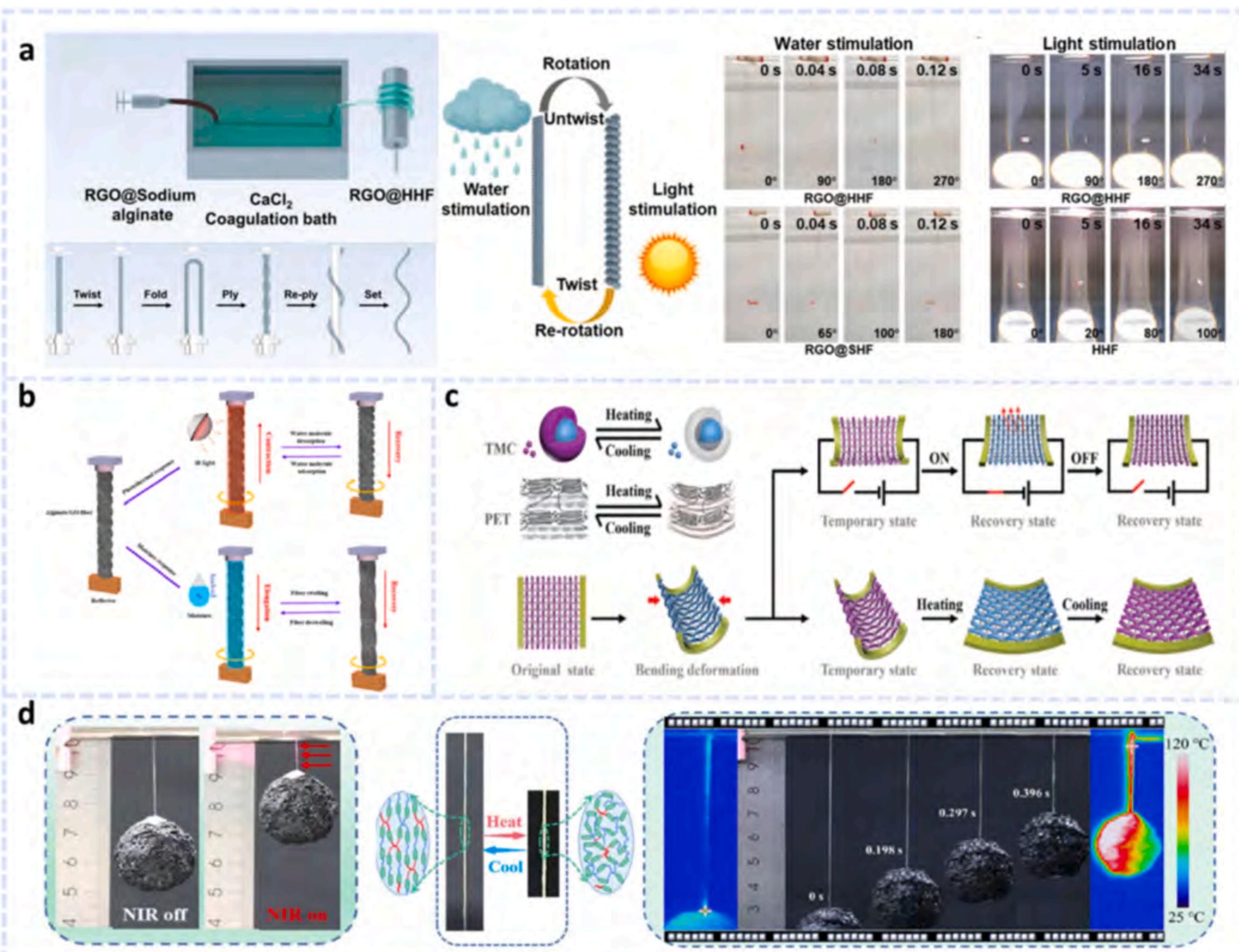

Fig. 16. Multi-stimuli response actuators. (a) and (b) GO/SA fiber actuator. The difference between the two is that (a) obtains hollow fibers. Reproduced with permission [175.176]. Copyright 2023, Wiley-VCH. Copyright 2019, American Chemical Society. (c) The driving behavior diagram of the actuator in response to both electrical and thermal stimuli. Reproduced with permission [177]. Copyright 2023, Wiley-VCH. (d) LCE/MXene fiber-based multi-stimuli response actuator. Reproduced with permission [179]. Copyright 2023, The Royal Society of Chemistry.

robots, artificial muscles, and other fields.

At present, the development goal of intelligent responsive actuators is mostly multi-stimuli responsive actuators, the aim is to expand their application in different fields. However, the current research on multi-stimuli response actuators is still in its infancy, with the majority of studies being proof-of-concept research. Further practical demonstrations are necessary to advance this field [181].

5. Application of stimuli-responsive fiber/fabric actuators

Stimulus-responsive actuators are materials that produce shape changes (shrinkage or expansion) or reversible rotation under an external environment stimulus (water, heat, light, electricity, or magnetism) [182–185]. As an emerging intelligent material, it occupies an important position in the development of artificial muscles [186,187], intelligent clothing [188], soft robots [189,190], and other related fields [191].

5.1. Smart clothing

Thermal and wet comfort are important indicators for evaluating clothing comfort [192], so it is of great significance to study smart textiles that can effectively manage the skin microenvironment, improve human comfort, and reduce energy consumption. Smart clothing, as the name suggests, can dynamically adjust the heating and cooling of the human body according to changes in the environment or metabolic heat rate [93].

Clothing based on flap opening and closing can achieve heat and humidity management of the human body [193]. This intelligent responsive material is mainly based on double- or multi-layer fabric actuators. Wang et al. [194]. designed a wet-responsive material with a sandwich structure consisting of wet-inert, wet-sensitive, and support layer materials. This material is prepared into sportswear with ventilated biological flaps to adjust the exposed area of the skin by changing the fabric shape under wet stimulation, thereby automatically adjusting the moisture transfer and thermal management performance of the fabric by changing the skin exposure percentage (Fig. 17(a)). However, the moisture-responsive material of this flap configuration is much more expensive than conventional textiles, and the tuning mechanism is entirely based on convection, which limits the potential for advancements in temperature management efficacy. Therefore, Li et al. [11]. combined multiple heat transfer mechanisms to prepare a multimodal adaptive humidity response flap composed of nylon/metal heterostructures that can simultaneously regulate convection, sweat evaporation, and mid-infrared emission, achieving large and fast heat transfer regulation of human sweat vapor (Fig. 17(b)).

Another example of smart garment is a moisture-responsive actuator based on yarn/fiber deformation, including yarn/fiber spacing and textile length adjustment. LCE fibers shrink during heating, creating pores in the textile that return to their original state when the temperature drops. Roach et al. [195]. used this property of LCE fibers to create smart clothing (Fig. 17(c)). Yang et al. [196]. obtained a fiber with the same thermal response as LCE fiber on the surface of cotton fabric by grafting a heat-sensitive polymer, which met the requirements of thermal and wet comfort of the fabric through the change of fiber spacing (Fig. 17 (d)). Although LCE fiber and grafted cotton fibers show excellent response performance in smart clothing, the production method is relatively complex. Peng et al. [29]. obtained a high-humidity-sensitive smart yarn by simply twisting the strands. In a humid environment, the twisting energy stored in the fiber is transferred to the smart yarn to produce a twisting stroke. Therefore, the two groups of yarns are assembled into a spiral knot as the basic unit of knitted fabric, which is then woven into fabric. This fabric produces a natural curl when stimulated by moisture, thus meeting the requirements of smart clothing (as shown in Fig. 17(e)). The combination of actuators and traditional textiles lays a solid foundation for the development of smart textiles.

5.2. Artificial muscle

Artificial muscle is one of the most promising applications of fiber actuators [197]. A fibrous actuator similar to a human muscle fiber bundle can contract, rotate, and bend when stimulated by light, heat, electricity, magnetism, moisture, and fluid pressure, making it an ideal candidate for use in artificial muscle applications (as shown in Fig. 18 (a)) [198–200].

Lotus fiber is a natural fiber that is extracted directly from the lotus

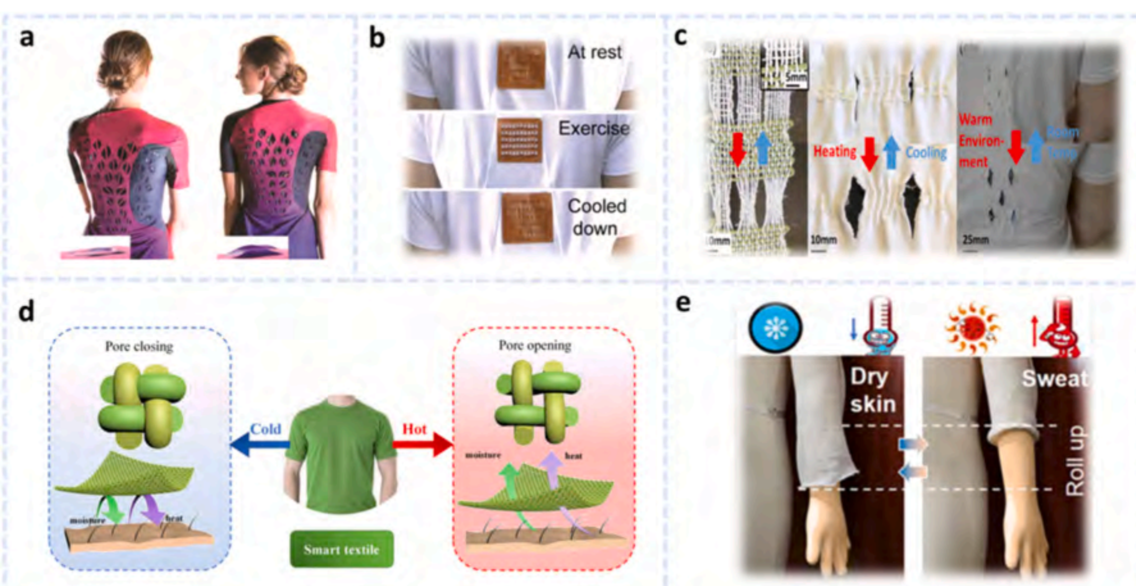

Fig. 17. Fiber-based smart clothing. (a) Sandwich-structured film for sportwear. Reproduced with permission [194]. Copyright 2017, American Association for the Advancement of Science (AAAS). (b) Nylon- silver (Ag) heterostructure moisture-responsive wearable. Reproduced with permission [11]. Copyright 2021, American Association for the Advancement of Science (AAAS). (c) Smart textile using LCE fibers to create pores under heat stimuli. Reproduced with permission [194]. Copyright 2019, American Chemical Society. (d) Cotton fabric based smart response textiles. Reproduced with permission [196]. Copyright 2021, Springer Nature. (e) Application of humidity-responsive actuator to smart clothing. Reproduced with permission [29]. Copyright 2021, American Chemical Society.

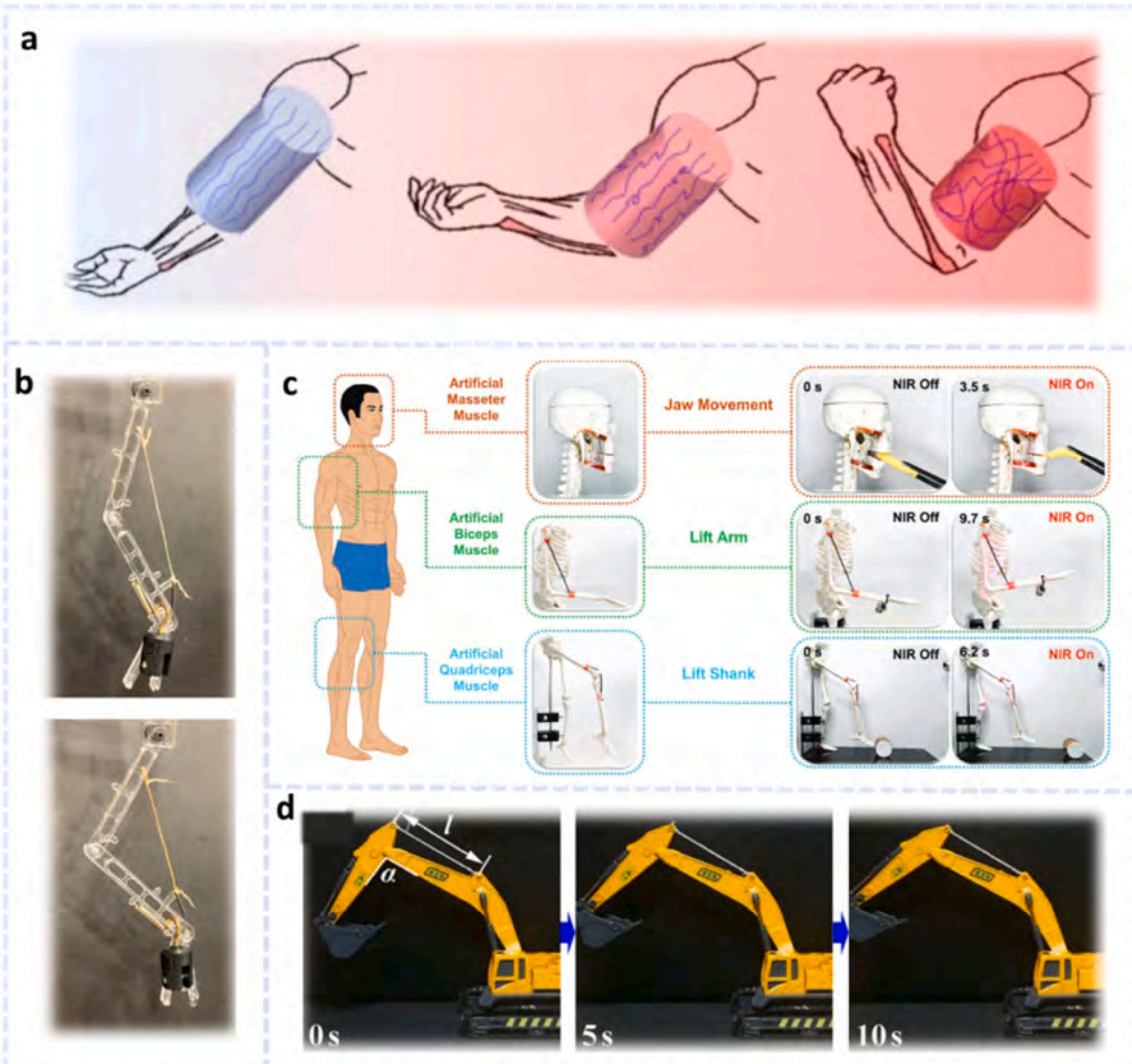

Fig. 18. Fiber-based artificial muscle. (a) The diagram of artificial muscle. Reproduced with permission [198]. Copyright 2019, Springer Nature. (b) The diagram of lotus fiber muscle was driven by water. Reproduced with permission [203]. Copyright 2021, American Chemical Society. (c) Illustration of the LCE microfibers as artificial muscle. Reproduced with permission [204]. Copyright 2023, Wiley-VCH. (d) The images of a moisture-responsive artificial muscle used in a mechanical arm of an excavator. Reproduced with permission [205]. Copyright 2021, IOP Publishing.

stem and can be used without further processing. The cellulose and hemicellulose in lotus fiber can provide large-volume expansion when absorbing water [201,202]. By simply inserting twist into stem-drawn lotus fibers, Wang et al. [203]. were able to create highly twisted and crimped lotus fiber yarns. These lotus fiber artificial muscles can be used to create weight-lifting prostheses that mimic human arms (Fig. 18(b)). One end of the lotus fiber artificial muscle is attached to the upper arm, and the other end is attached to the forearm, and the two parts of the arm are connected by a pivot joint. The absorption and evaporation of water can drive reversible contraction of the prosthesis. During this actuation, it raised an imposed 3 g weight by 7.8 mm in 40 s. In contrast, the LCE, which can show rapid and reversible shape changes when stimulated, has a superior actuating effect through a high-speed extrusion spinning setup to fabricate fiber-based artificial muscles. In addition to being important in human-machine cooperation, such as exoskeletons that assist the disabled, the elderly, and high-strength workers (Fig. 18(c)) [204], it can also be used to drive machine equipment in the robot arm. Wang et al. [205]. prepared a wet-responsive artificial muscle with a spiral structure from flax fibers and used it in the robotic arm of a small excavator. After being stimulated by water, the excavator bucket can move to its maximum height within 10 s (Fig. 18(d)). As a part of soft robots, artificial muscles play an important role in human-machine collaboration [206–208]. Therefore, the artificial muscle prepared by the actuator can be employed to facilitate human rehabilitation movement and achieve bionic functionality.

5.3. Intelligent device

Fiber/fabric-based actuators, attributed to their flexibility and rapid response to external stimuli, are promising for intelligent devices, such as smart on-off switches, smart rain curtains, smart windows [209], and soft grippers [210–212].

Dong et al. [213]. developed a humidity alarm utilizing the superior actuation capability and humidity sensitivity of spider silk yarn. The yarn serves solely as a smart switch in the humidity alarm, controlling the circuit to open or close when applying or removing moisture stimulation. The yarn switch rapidly contracts, the circuit is established, and the alarm is activated when RH > 60 % (Fig. 19(a)).

In order to harness the energy generated by humidity changes caused by weather changes (rain, snow, and sunshine), Wang et al. [52]. prepared a humidity-responsive actuator for smart rain curtains. The rising and lowering of the smart rain curtain are driven by a twisted alginate

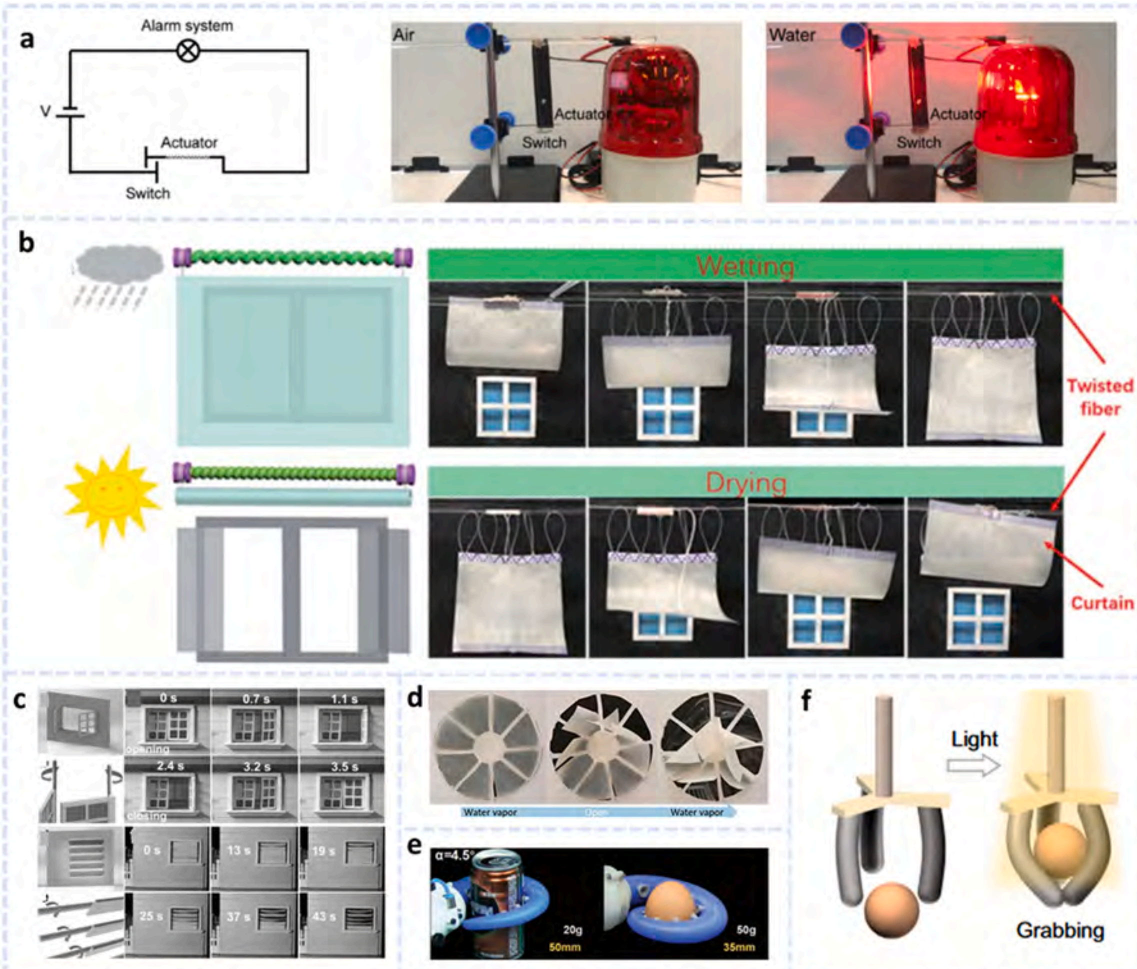

Fig. 19. Fiber-based smart devices. (a) Application of humidity-responsive spider silk yarn actuators in the smart switch. Reproduced with permission [213]. Copyright 2021, American Chemical Society. (b) Schematic diagram of the smart rainy curtain and actuation behavior under water stimulation. Reproduced with permission [52]. Copyright 2018, The Royal Society of Chemistry. (c) and (d) Humidity actuator acting as a smart window. Reproduced with permission [201,214]. Copyright 2019, American Chemical Society. Copyright 2015, Wiley-VCH. (e) Pneumatically actuator acting as a conical gripper. Reproduced with permission [218]. Copyright 2020, Mary Ann Liebert, Inc. (f) The diagram of multi-finger smart gripper. Reproduced with permission [220]. Copyright 2024, Springer nature.

fiber-based actuator (Fig. 19(b)). In the event of precipitation, the rain causes the yarn to rotate, thereby raising the curtain and increasing the brightness of the room. Conversely, in the presence of sunlight, the evaporation of water causes the yarn to rotate in the opposite direction, lowering the curtain and providing shade. Similarly, smart windows are designed on a similar principle, with humidity controlling the opening and closing of the window (Fig. 19(c and d)) [214]. Together, these results show the potential applications of actuation in humidity regulation.

Inspired by the octopus' arm, soft actuators with unique shapes can be designed for smart grabbers [215–217]. Xie et al. [218]. used a pneumatically driven way to prepare a conical gripper, which can easily grip a variety of flat, curved, smooth, and rough objects through the combined action of bending and suction (Fig. 19(e)). However, 1D fibers may not be as adept at grasping objects with the requisite stability. Therefore, in order to increase stability, the gripper should be equipped with multiple fingers to balance the force and maximize the contact area between the gripper and the object [219]. Ai et al. [220]. used three 8-centimeter-long C-shaped muscles to form a gripper, which grabbed the ping-pong ball under the action of light and air heat flow, and released the ping-pong ball when the light ended (Fig. 19(f)). The emergence of intelligent devices has brought convenience to human life, but the current intelligent devices have a common shortcoming, that is, slow response speed.

5.4. Flexible electronics

Soft robotics is a new type of intelligent robot that simulates the physiological structure and movement function of natural soft organisms. Similar to living organisms, with higher degrees of freedom and the ability to continuously deform, it has advantages over hardware robots in adapting to various complex scenarios. Fibers/fabrics has traditional advantages such as comfort, skin friendliness, and washability, therefore, the fiber/fabric-based actuator is expected to build an intelligent interface bridge between the soft robot and the human, facilitating the storage and harvesting of energy, the perception and monitoring of signals [221–223].

The stimuli-responsive actuator is a device that converts energy into mechanical energy, so the researchers began to use the actuating performance of the actuator to achieve energy storage and harvesting. Ren et al. [224]. used intercalation compounds formed during electrochemical reversible insertion reactions to induce a new capture state in the muscles of CNTs yarns, controlling contraction with minimal strain compensation. Furthermore, due to the nature of electrochemical reversible insertion reactions, a large amount of electrical energy stored by artificial muscles can be used to power electronic devices and other muscles (Fig. 20(a)). This energy storage method is highly efficient and reproducible, but further improvements are required in terms of the reaction rate and stability of inserting and extracting ions.

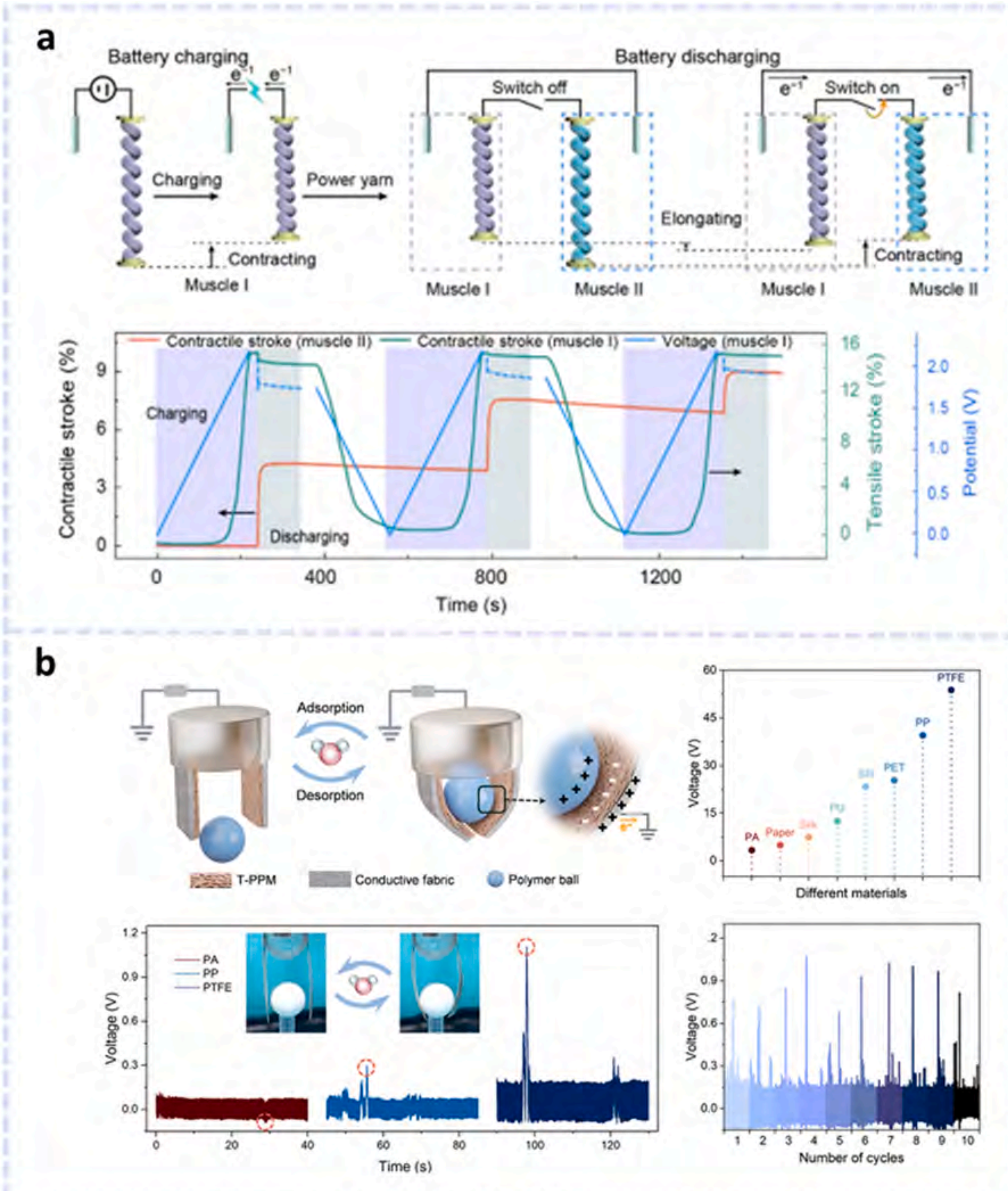

Fig. 20. Fiber-based flexible electronics. (a) Schematic illustration of the contracted artificial muscle serves as a battery to power the other artificial muscle and the results of the contraction stroke [224]. Copyright 2023, American Chemical Society. (b) The intelligent gripper for self-powered perception. Reproduced with permission [64]. Copyright 2023, American Chemical Society.

In the past, the majority of actuators were only capable of manipulating the objects, but lacked the ability to identify their characteristics. Zhou et al. [64]. prepared an actuator with self-powered perception function. The driving behavior of the actuator is a typical mechanical stimulus that can be used to trigger triboelectric effects between objects and generate electrical signals, so as to achieve self-powered sensing of materials and the recognition of different objects information (Fig. 20 (b)). In addition, the research of Xu et al. [225]. and Noh et al. [61]. found that actuators with self-sensing functionality are expected to be successfully used in respiratory monitoring masks, real-time self-driven displacement detectors, and other fields in the future.

6. Challenges and outlooks

Fiber/fabric-based actuators possess inherent advantages of higher freedom, smaller size, and better adaptability to complex structures [226–229], and are expected to revolutionize every aspect of our future lives, such as clothing, human-computer interaction, and healthcare. Although a variety of promising fiber/fabric-based actuator structures and fabrication techniques have been developed, fiber/fabric-based actuators as soft robots still have a long way to go in the real-world application fields. The following provides a summary of the main challenges and possible solutions from the perspective of fiber/fabric-based robotic applications, hoping to provide research ideas for further developments.

(1) Multifunctionality, high performance, and adaptivity

Fiber/fabric-based actuators are excellent devices for converting external stimuli into mechanical energy, but currently lack practicality in wearable electronics. The realization of energy storage and harvesting, sensing, and other functions still requires the combination of the actuator and other devices, and very few fiber/fabric-based actuators can integrate multiple functions in one. Adaptability is also a crucial attribute of fiber/fabric-based actuators, which are inspired by biological systems and require the capacity to adapt passively or actively to diverse tasks and environments. However, there are still some problems for textile-based soft robots to reach the target position through multimodal navigation in the complex and variable physiological environment. In the future, the adaptability of the fiber/fabric-based actuators to different environments can be satisfied through the selection of appropriate materials and the design of an appropriate structure, thus ensuring the safe operation of the soft robot.

It is noted that the actuating properties of fiber/fabric-based actuators, such as actuating stress, actuating strain, response time, and energy conversion efficiency, are relatively weak, which limits their practical application. Single fiber twisting into single aggregate yarn is an effective method to increase the driving stress of aggregate yarn. In addition, methods such as increasing the volume expansion coefficient of the fiber and programmed driving can also be considered. The response time and drive strain can be improved by inserting the appropriate twist into the yarn. While this represents a promising approach to improving the actuation performance of textile actuators, there is also an urgent need to improve the principle of deformation, optimize material synthesis and structural design, and achieve high-performance output.

(2) Large-area and scalable manufacturing

Mass production and scale preparation of fiber/fabric-based actuators are important for commercial development. At present, a lot of work on fiber/fabric-based actuators is still limited to basic research and theoretical design, and cannot be applied to real-life scenarios. Despite the diversity and engineering capabilities of textile yarns, some stimuli-responsive yarns made of soft materials cannot be prepared by knitting machines due to their softness and fragility. Therefore, it is of great significance to develop stable and reliable manufacturing tools and methods for the large-scale production of fiber/fabric-based actuators.

(3) Degradability and self-healing for extended lifetime

The traditional fiber yarn textile lacks self-healing capabilities when subjected to wear and tear during use, and has a limited-service life. Fiber/fabric-based actuators have a wider range of applications and need to consider their application cost and sustainable design. Materials with self-healing functions can extend the service life of damaged actuators, but the effect of healing time needs to be considered in future research. Overcoming these challenges will extend the life of fiber/fabric-based actuators and expand their practical applications in demanding environments. When the fiber/fabric-based actuator is damaged to a certain extent or cannot be repaired, the recycling of materials should be considered. For example, the development of some green and degradable raw materials will ensure that when the actuator reaches the limit its life, it will not produce electronic waste that affects the global environment.

CRediT authorship contribution statement

Yin Cheng: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Wenjing Chen:** Visualization, Conceptualization. **Liming Wang:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Data curation. **Xiaohong Qin:** Supervision, Resources, Funding acquisition. **Maorong Zheng:** Visualization, Methodology, Investigation, Data curation, Conceptualization. **Mingyuan Liu:** Visualization, Methodology, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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