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REVIEW

Advanced Design of Fibrous Flexible Actuators for Smart Wearable Applications

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Abstract

Smart wearables equipped with integrated flexible actuators possess the ability to autonomously respond and adapt to changes in the environment. Fibrous textiles have been recognised as promising platforms for integrating flexible actuators and wearables owing to their superior body compliance, lightweight nature, and programmable architectures. Various studies related to textile actuators in smart wearables have been recently reported. However, the review focusing on the advanced design of these textile actuator technologies for smart wearables is lacking. Herein, a timely and thorough review of the progress achieved in this field over the past five years is presented. This review focuses on the advanced design concepts for textile actuators in smart wearables, covering functional materials, innovative architecture configurations, external stimuli, and their applications in smart wearables. The primary aspects focus on actuating materials, formation techniques of textile architecture, actuating behaviour and performance metrics of textile actuators, various applications in smart wearables, and the design challenges for next-generation smart wearables. Ultimately, conclusive perspectives are highlighted.

Keywords Flexible textile actuators · Advanced design · Smart wearables · Actuating behaviours · Actuating materials

Introduction

Over the past decade, there has been growing interest and demand for wearable technology [1]. Most commercial wearables, such as glasses, watches, and wristbands, are composed entirely or partially of rigid microelectronics that detect or monitor the wearer's environmental or human physiological data [2–4]. However, the rapid development of wearables has promoted the emergence of smart wearables, which can sense external stimuli, react, and adapt to their surroundings by incorporating actuators. Actuators are known for their capacity to reversibly translate a physical domain into mechanical motion in response to an external stimulus, which can be categorised into different categories depending on various features. According to external stimuli, actuators are primarily grouped into electrical, thermal, humidity, light, bladder, and magnetic actuators [5–8]. Based on their actuating motion characteristics, actuators are categorised into linear, bending, and rotating actuators; in accordance with their flexibility, actuators are classified into two categories, namely, hard and soft actuators [9, 10]. Hard actuators built using rigid materials can be divided into several well-established domains, including electric motors, springs, hydraulics, and pneumatics. Compared with hard actuators, soft actuators composed of soft materials exhibit superior characteristics, including but not limited to softness, lightness, flexibility, compliance, air permeability, and close fitting, which enables the wearer to feel more comfortable, demonstrating their great potential for smart wearable applications.

As two representative soft materials, polymer films and textiles show great flexibility, good biocompatibility with human skin, lightweight, and high mechanical strength, making them favourable platforms for soft actuators [11, 12]. Compared with film-based actuators, textile actuators exhibit better breathability owing to their richer porous structures [13, 14]. These pore features enable the transportation and evaporation of steam or heat from human skin, thereby improving the comfort of wearables. Furthermore, film-based actuators often need to be bonded with other fibrous materials to form multilayered wearables. In contrast, textile actuators can be assembled with other fibrous materials

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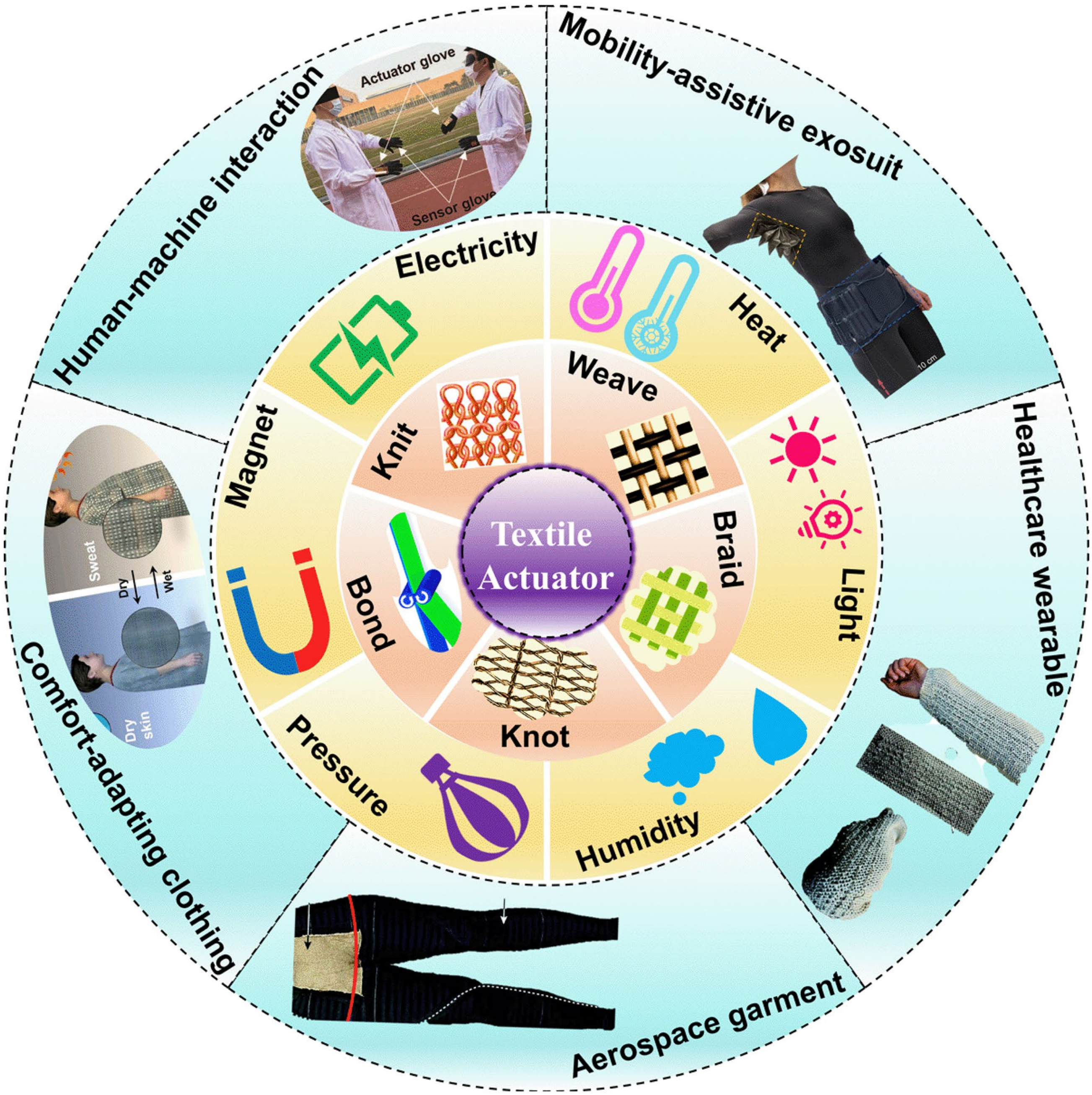

Fig. 1 Overview of flexible textile actuators in smart wearables. Mobility-assistive exosuit; Reproduced with permission from ref [15], Copyright 2022, Amer Assoc Advancement Science. Healthcare wearable; Reproduced with permission from ref [16], Copyright 2023, Wiley–VCH Verlag Gmbh. Aerospace garment; Reproduced with permission from Ref. [17], Copyright 2022, Wiley. Comfort-adapting clothing; Reproduced with permission from Ref. [18], Copyright 2023, Springer Nature. Human–computer interaction; Reproduced with permission from Ref. [19], Copyright 2022, Wiley–VCH Verlag Gmbh

through preprogrammed technology to form smart wearables with unique patterns and structures, thanks to their intrinsic hierarchical structure. With these benefits, the adoption of textiles as actuating carriers for soft actuators is a good choice for smart wearables. Conventional textiles are closely related to our daily lives in the form of garments, bedding, bags, shoes, or interior furnishings. With the advancement of interdisciplinary technology integration, many actuating materials go hand in hand with textile-forming technologies to develop flexible textile actuators. As demonstrated in Fig. 1, through traditional textile-forming techniques as well as bonding methods, actuating materials can be structurally expanded into textile actuators [15–19]. These flexible textile actuators demonstrate great potential for meeting

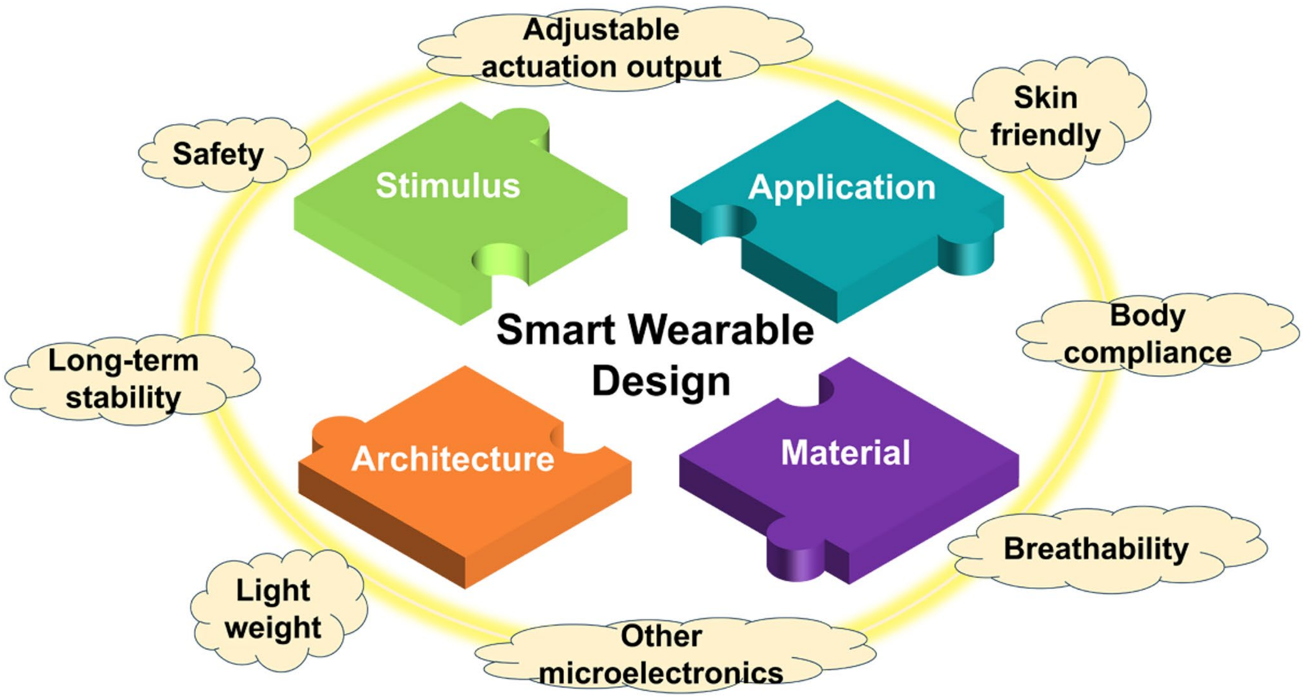

Fig. 2 Design of smart wearables using textile actuators in aspects of materials, architectures, stimuli, and applications

the intelligent requirements for smart wearables, which are able to automatically sense and respond to environmental changes.

In the last five years, flexible textile actuators with applications in smart wearables have undergone rapid development. Great progress has been made in the development of actuating materials for textile actuators. Shape memory alloys (SMAs), a preferred class of thermally or electrothermally responsive materials, have been shown to be powerful and extensively utilised in the development of textile actuators for aerospace suits, mobility-assistive exosuits, and healthcare wearables [20]. Recently, a variety of synthetic polymers, natural materials, and micro- or nanoparticles have been demonstrated to exhibit high actuation capabilities for textile actuators for comfort-adapting clothing. For instance, nanostructured block copolymer hydrogels composed of hydrophilic poly(ethylene oxide) (PEO) and hydrophobic polystyrene (PS) demonstrate an actuation strain of 80% over 100 actuation cycles [21]; natural silk yarn actuated by artificial sweat within 80 s is a viable option for developing textile actuators that effectively regulate the humidity and temperature levels of human skin [22]; and nylon/Ag/PS heterostructure-based nanocomposite films with rectangular holes can be adhered to garments to expand the thermal comfort zone by 30.7% compared to that of normal static textiles when exposed to human perspiration vapour [23]. Along with the development of actuating materials, textile-forming methods have also been rapidly developed to form desirable structures for textile actuators. To overcome large volume changes in unforeseen dimensions during actuation and reduce time consumption during manufacturing processes, complex textile structures from fibres or yarns to textile levels can be achieved through multilayer knitting and three-dimensional (3D) knitting [24]. To develop high-performance SMA textile actuators, a unique knotting strategy using multiple-unit knots has been proposed to create a novel textile architecture that increases the actuation force and strain [25]. However, the combination of these newly reported actuating materials and textile-forming technologies has not yet been reviewed for use in textile actuators for smart wearables.

Several comprehensive reviews on actuating materials for smart textiles, as well as actuating fibres and textiles for soft robots, have been reported. In 2019, Kongahage et al. outlined a mini-review for actuating materials for smart textiles [26]. In 2020, Sanchez et al. and Xiong et al. reviewed textile and fibre technology surveys for soft robots, respectively [27, 28]. In 2022, Fu et al. summarised the progress of functional textiles as soft actuators in soft robots [29]. However, there is a notable lack of timely and comprehensive reviews on the advanced design of textile actuators for smart wearables. Herein, this review focuses on the advanced design concepts of flexible textile actuators in smart wearables over the past five years. It covers actuating materials, textile architecture configurations, external stimuli, and their applications in smart wearables, as schemed in Fig. 2. Furthermore, the design challenges of next-generation smart wearables are elucidated based on actuation performance, human body fit, integrated microelectronic systems, safety, etc. Finally, we propose our perspectives on the future development of flexible textile actuators in smart wearables.

Actuating Materials

Actuating materials represent a class of stimulus-responsive materials that possess the ability to convert external stimuli, such as electrical, thermal, light, humidity, pressure, and magnetic stimuli, into mechanical energy. The combination of actuating materials and fibrous substances has effectively promoted the development of flexible textile actuators. Fibrous actuating materials in the form of fibres, wires, or yarns have been demonstrated to be well suited for designing textile actuators. However, some actuating materials, such as micro- or nanoparticle-actuating materials, are difficult to directly spin into fibrous forms due to their limited stretchability and discontinuous structure. These actuating materials can first be dispersed in solvents to form homogeneous suspensions. Then, the suspensions are incorporated inside or coated onto fibrous substrates before or after spinning.

Fibrous Materials

SMA Wires

SMAs are a category of order-change materials that can change back and forth between the austenitic thermoelasticity phase at high temperature and the martensitic phase at low temperature [20]. As a result, SMAs are able to undergo a phase transition from martensite to austenite during heating and afterwards revert back to their original form during cooling. This unique behaviour enables SMAs to effectively

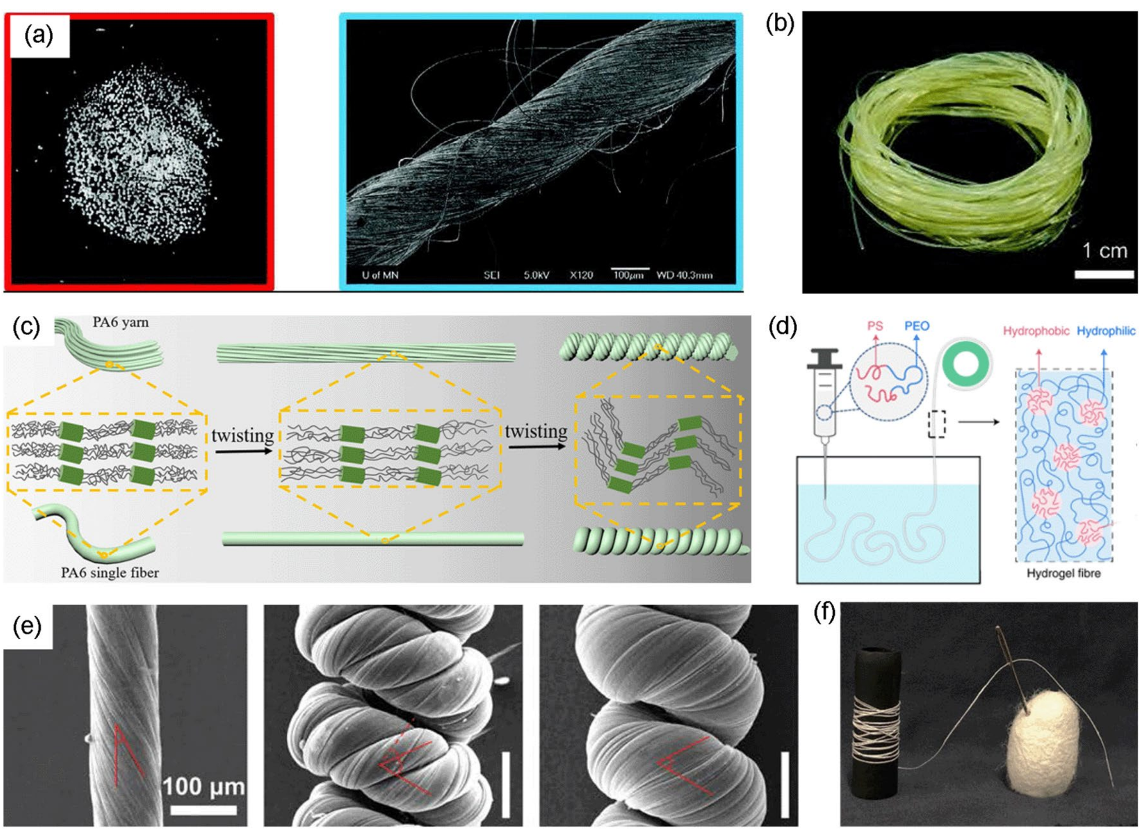

Fig. 3 Fibrous actuating materials. **a** Cross-sectional optical and SEM images of SMA yarns; Reproduced with permission from Ref. [31], Copyright 2020, Wiley. **b** LCE fibres; Reproduced with permission from Ref. [24], Copyright 2023, Wiley–VCH Verlag Gmbh. **c** PA6 fibres or yarns before and after twisting and coiling insertion; Reproduced with permission from Ref. [32], Copyright 2022, Elsevier Science SA. (d) Hydrogel fibre; Reproduced with permission from Ref. [21], Copyright 2022, Nature Portfolio. **e** Twisted and coiled CNT yarns; Reproduced with permission from Ref. [33], Copyright 2020, Royal Soc Chemistry. **f** Silk yarns; Reproduced with permission from Ref. [22], Copyright 2019, Springer Nature

convert thermal energy into mechanical motion. Typically, SMAs are composed of two or more metallic elements with unique characteristics, including nickel–titanium (Ni–Ti), iron (Fe), and copper (Cu) SMAs [30]. Among them, NiTi-based SMAs like Ni–Ti–Cu and Ni–Ti–Fe are frequently preferred for textile actuators owing to their exceptional stability and practicability. Thanks to their high mechanic strength, large thermal actuation strain, and good compatibility with the human body, SMAs in the form of fibres or wires have been considered promising actuating materials integrated with textile-forming methods (Fig. 3a) [31].

Actuating Polymer Fibres or Yarns

As listed in Fig. 3b–d [21, 24, 32], actuating polymers in the form of fibres or yarns are excellent candidates for textile actuators thanks to their high compatibility with fabric processing. Classic actuating polymers include highly oriented semicrystalline polymers, shape-memory polymers (SMPs), dielectric elastomers (DEs), hydrogels, and azobenzene-based polymers [34]. By inserting twists and coils, the actuation performance of these polymer fibres or yarns can be greatly improved. In general, highly oriented semicrystalline polymers and SMPs are thermally active, DEs are electroactive, hydrogels are hydrophilic, and azobenzene-based polymers are optically active. Recently, some of these polymers have been discovered to possess multi-stimulus–response properties. Notable examples are liquid crystal elastomers (LCEs), a class of typical DEs that demonstrate thermal and photosensitivity, and hydrogels that exhibit electrical, thermal, and moisture sensitivity [35].

Highly oriented semicrystalline polymers are a class of cost-effective polymers with repeating semicrystalline structures that have been utilised in the manufacture of flexible textile actuators in the form of twisted and coiled fibres or yarns [36]. Examples of highly oriented semicrystalline polymers commonly include polyamide 6/66 (PA 6/66, Nylon 6/66), polyethylene (PE), polyethylene terephthalate (PET), and polypropylene (PP). SMPs are a category of polymers with shape-memory capabilities, enabling them to transition from pre-determined shapes to their original shapes when exposed to external stimuli [37]. SMPs include a range of polymers, such as LCE, polyurethane (PU), thermoplastic polyurethane (TPU), PET, and PS. DEs have emerged as prominent electronic electroactive polymers for textile actuators owing to their inherent softness, rapid response, and ability to induce substantial deformation in response to high voltage [38]. Common types of DEs include silicone-based, PU-based, acrylic-based, and polyvinyl chloride (PVC)-based elastomers.

Hydrogels with abundant 3D polymer networks are able to absorb and retain large amounts of water, up to 90% of their weight [39]. The network cross-link density and the interaction between polymer and solvent have an impact on the amount of water uptake. When exposed to water, most natural and synthetic hydrogels with a hydroexpansive nature undergo substantial swelling and deformation. Polyethylene glycol (PEG), PEO, polyacrylamide (PAM), polyvinyl alcohol (PVA), polyacrylic acid (PAA), polydimethylsiloxane (PDMS), viscose, and Nafion are the common hydrogels. Azobenzenes are typical molecules of photo-responsive polymers [35]. They can translate light energy into various deformation strains through the photoisomerization of photochromic molecules. Apart from azobenzenes, spiropyrans, and spirooxazines are further examples of photo-responsive molecules that can be incorporated into polymers.

Carbon Nanotube (CNT) Fibres or Yarns

CNT fibres or yarns have one-dimensional tubular structure, large specific surface area, superb electrical conductivity, intrinsic thermal nature, and high flexibility, which have attracted great interest in the application of textile actuators, as shown in Fig. 3e [33]. After inserting twists and coils, the CNT fibres or yarns are capable of generating large torsional and tensile actuations. Baughman et al. first investigated CNT forest actuators that directly convert electrical energy into mechanical motion through an electrochemical process. Subsequently, thermal, electrothermal, or optical stimulation has also been discovered to cause the actuation of CNTs.

Natural Fibres or Yarns

Natural fibres or yarns with hydrophilic and hydrophobic domains are highly sensitive to moisture and heat, making them ideal actuating materials for smart wearables. The hydrophilic domain can achieve water absorption or dehydration by forming or destroying hydrogen bonds, thus leading to deformation during humidity changes. After twisting and coil insertion, the highly oriented natural fibres or yarns demonstrate enhanced actuation capabilities. Currently, alginate, cellulose, cotton, wool, and silk fibres or yarns have been developed for textile actuators owing to their high stretchability and good body compatibility (Fig. 3f) [22].

Micro- or Nano-particle-Based Materials

Carbon Micro- or Nano-particles

Carbon micro- or nanoparticles, such as CNTs, graphene, and carbon blacks, have been proven to be outstanding candidates for incorporation into fibrous substrates to develop flexible textile actuators, thanks to their micro- or nanoscale size, high electrical conductivity, strong charge transfer capability, outstanding mechanical strength, and unique optical and thermal properties [40]. Graphene with a two-dimensional (2D) carbon structure has become an important actuating material owing to its astonished properties, such as exceptional electrical conductivity, high thermal conductivity, broad-spectrum optical absorption, and a unique porous structure for ion adsorption/desorption or insertion/extraction. Recently, graphene nanosheets have been successfully assembled into fibrous substrates to form graphene fibres, which are regarded as a promising actuating material by inserting high twists and coils. After irradiation or oxidation treatment, derivatives of carbon micro- or nanoparticles can even exhibit hydrophilic characteristics, such as graphene oxide (GO). GO with rich oxygen-containing functional groups shows excellent hydrophilicity and good humidity sensitivity, demonstrating powerful potential in humidity textile actuators.

Conducting Polymers (CPs)

CPs are ionic electroactive polymers normally paired with electrolytes which utilise the injection of charges or ions into the polymer backbone to induce deformation [41]. Common micro- or nano-scale CPs coated on fibrous substrates are polypyrrole (PPy), polyaniline (PANi), and poly(3,4-ethylenedioxythiophene)/poly(styrene sulfonate) (PEDOT/PSS). During the driving process of CPs, electrochemical energy is usually converted into mechanical motion through the synergistic effect of pseudocapacitance and electrochemical double-layer processes at low voltages.

MXenes

MXenes, as a member of emerging 2D materials, are composed of transition metal carbides, nitrides, or carbonitrides and polar surface functional groups. Owing to their favourable hydrophilic surface, high electrical and thermal conductivity, excellent ion insertion performance, and unique photothermal conversion ability, MXenes are expected to be a new actuating material for doping into fibrous substrates to develop textile actuators [42]. For example, MXene nanosheets coated on silk textiles can effectively improve the photothermal conversion efficiency as well as actuation power, thereby resulting in biomimetic deformation and movement of “claw,” “snake,” and even “octopus” [43].

Metal and Metal Compound Micro- or Nano-particles

Metal and metal compound micro- or nano-particles typically exhibit excellent electrical and thermal conductivity, high mechanical performance, and unique magnetic properties. Therefore, these micro- or nano-particles are beneficial for electrothermal, photothermal, and magnetic actuation of fibrous substrates. For example, silver nanoparticles (AgNPs) or nanowires (AgNWs) and gold nanoparticles (AuNPs) have been coated on fibrous substrates to enhance thermal conversion efficiency. In addition, the use of magnetic micro- or nanoparticles composed of metal compounds has been considered an effective strategy for endowing fibrous substrates with magnetic actuation characteristics.

Polymer Membranes

Some polymer materials can also be prepared as membranes instead of fibres or yarns and then combined with existing fabric substrates to form textile actuators, such as rubbers, elastomers, ion gels, etc. For instance, cuttable silicon-based rubber or PU-based elastomer soft membranes are often used to fabricate bladder chambers [29]. These chambers can be inflated or deflated upon pressure stimulation and then covered with existing fabrics to form pneumatic textile actuators. Additionally, since the stretchable strength of ion gels is not high enough, ion gel films are easier to manufacture from raw materials and then bonded to fabric substrates to create textile actuators.

Architectural Designs

Textile-forming technologies with a long history of use have shown remarkable efficacy in facilitating seamless integration of textile units and actuating materials in smart wearable applications. Typically, actuating materials in the form of fibres or yarns as textile units can be applied to construct textile actuators through traditional textile-forming technologies. Nonfibrous actuating materials can function as actuation layers with existing fabric substrates to form textile actuators through bonding methods.

Surface Modification

Most textiles made from conventional fibres or yarns lack or do not have adequate actuation functionality. To achieve or enhance their actuation abilities, actuating materials are usually assembled with conventional fibrous substrates. However, some actuating materials cannot be directly spun into fibres due to their inability to withstand the deformation required for stable stretching operations, such as micro- or nano-particle-based actuating materials. These actuating materials may be incorporated into the precursors of conventional fibre substrates prior to spinning or coated on the surface of conventional fibrous substrates after spinning. Consequently, the immobilisation of actuating material on the surface of the fibrous substrate is critical. To improve the interfacial bonding between the actuating material and fibrous substrate, surface modification of the fibrous substrate is required. Plasma technology and chemical oxidation are two effective surface modification strategies used in textile actuators. These surface treatments may introduce sufficient oxygen-containing functional groups to facilitate the loading of actuating materials onto the surface of existing fibrous substrates [44]. For example, Wu et al. employ plasma technology to activate and modify the surface of LCE fibres to improve the adhesion between coated MXene nanosheets and LCE fibres, thereby endowing the as-prepared textile actuator with good photothermal and long-term electrothermal properties [45]. Additionally, HNO_3 oxidation promotes the affinity between CNTs and PVA fibres to achieve a more homogeneous and densified composite structure, weaving a textile actuator with high curl deformation when sprayed [46].

Fig. 4 **a** Three basic knitting patterns (i); Reproduced with permission from Ref. [48], Copyright 2023, Wiley–VCH Verlag Gmbh. Textile actuators with double- and triple-layer knitting techniques (ii); Reproduced with permission from Ref. [49], Copyright 2023, Wiley–VCH Verlag Gmbh. **b** Four basic weaving patterns (i); Reproduced with permission from Ref. [50], Copyright 2023, Taylor & Francis Ltd. Weaving technique of a textile actuator with SMA wires, nylon, and glass fibres on a weaving machine (ii); Reproduced with permission from Ref. [51], Copyright 2020, Elsevier Sci Ltd

Architectural Formation

Knitting

Knitting, as one of the oldest textile-forming techniques, has been increasingly leveraged for fabricating textile actuators, in which yarn loops are consecutively interconnected in rows to form potentially highly elastic structures [47]. The process of knitting encompasses two automated methods, namely, weft and warp knitting. In both strategies, rows and columns of yarn loops are also known as courses and wales. In weft knitting, the yarn loops of courses are interconnected in horizontal rows, resulting in the growth of knitted textiles in the wale direction as the number of courses increases. In warp knitting, the stitches run in the wale direction, whereas the growth of knitted fabric in the course direction is attributed to the individual yarn stitches. In contrast to weft-knitted fabrics, warp-knitted textiles typically present less flexibility and stretchability as a result of their more rigid structure.

On a computerised knitting machine, three fundamental knitting patterns with varied stitch combinations can be structured using knitting and purl as two basic loop types, namely jersey, rib, and garter (purl) patterns, resulting in diverse actuation motion diversity in knitted textile actuators. Specifically, the jersey pattern consists of an individual knitting or purl yarn loop, a rib pattern is formed via alternating courses of knitting and purl yarn loops, and a garter pattern is constructed by linking knitting and purl yarn loops alternately in the wale direction. As demonstrated in Fig. 4a(i), the knitted fabrics with three knitting patterns achieve diverse engineering strains under the same number of stitches [48]. Furthermore, modern knitting techniques enable the manufacture of complex knitted textiles with hierarchical and 3D structures to accommodate the mechanical properties and diversity of knitted fabrics in all directions. Knitted textiles can be further multiplied by knitting or inlay knitting to construct multilayer knitted architectures.

Figure 4a(ii) outlines a rib structure with yarn loops and a trilayer knitted architecture with rib fabric and inlaid PET yarns for the fabrication of caterpillar-like pneumatic actuators [49]. The rib-knitted textile actuator generates similar strains in the course and wale directions. Although the trilayer knitted textile actuator exhibits almost unchanged strain in the wale direction, it produces extremely high anisotropy with significantly enhanced strain in the course direction. This is expected to effectively balance the actuation performance of existing textile actuators. However, due to unavoidable sliding and kinetic friction, the force produced by knitted textile actuators is still restricted by inadequate force transmission at interlacing points. Additionally, the knitted structure is unstable when unravelled.

Weaving

Weaving, as a traditional textile-forming technology, has been increasingly used in the integrated design of textile actuators [52]. The interlacing of yarns affects the diversity of woven textiles, resulting in different weaving patterns like plain, twill, satin, and sateen patterns, as depicted in Fig. 4b(i) [50]. In plain weaving, the warp and weft yarns are alternately interlaced with a warp-to-weft ratio of 1:1, forming a highly stable and dense structure characterised by the largest number of interlacing points and the shortest length of floating threads. Twill weaving is characterised by a recognisable diagonal line on the surface of fabric and is composed of a three-harness repeating pattern with a warp-to-weft ratio of 2:1. Due to fewer interlacing points and longer floating threads, satin weaving with a five-harness repeating pattern and a warp-to-weft ratio of 4:1 showcases relatively low stability and sparse structure.

Longitudinal strands (also known as warp yarns) and horizontal strands (also known as weft yarns) are interlaced vertically with each other within weaving machines, as exampled in Fig. 4b(ii) [51]. SMA wires with an average diameter of 0.2 mm are used as actuating materials for bonding with nylon fibres. The hybrid fibres as warp threads and the glass fibres as weft threads are interlaced on a loom to form a woven fabric with multi-mode actuating behaviours. In general, plain weaving, the most fundamental woven textile structure, has been extensively employed as the preferred strategy for building woven textile actuators. Nevertheless, the application of plain-woven textile actuators in highly elastic wearable systems is limited due to their inherently stable structure. To enhance the conformity of plain-woven fabrics to human body, the incorporation of highly elastic yarns has been empirically proven to be feasible. Furthermore, twill and satin weaving techniques with lower interlacing densities are recommended to improve the flexibility of future woven textile actuators.

In addition, advances in 3D technology have enabled the manufacture of textile actuators with complex seamless geometries like conical, plate-shaped, and tubular structures to achieve 3D deformations during actuation [53]. Silva et al. developed a 3D-woven textile actuator by combining linen yarns, nylon yarns, and LCE yarns into a radial circular weaving pattern [54]. The textile actuator reversibly shrinks and protrudes into a cone shape upon heat. Also, Pan et al. designed a 3D-woven textile actuator using SMA wires, basalt yarns, and Kevlar yarns to achieve variable stiffness of plate-shaped structures at driving temperature [55].

Braiding

Braiding, similar to weaving, is a textile-forming technology that involves interweaving a set of yarns at an angle

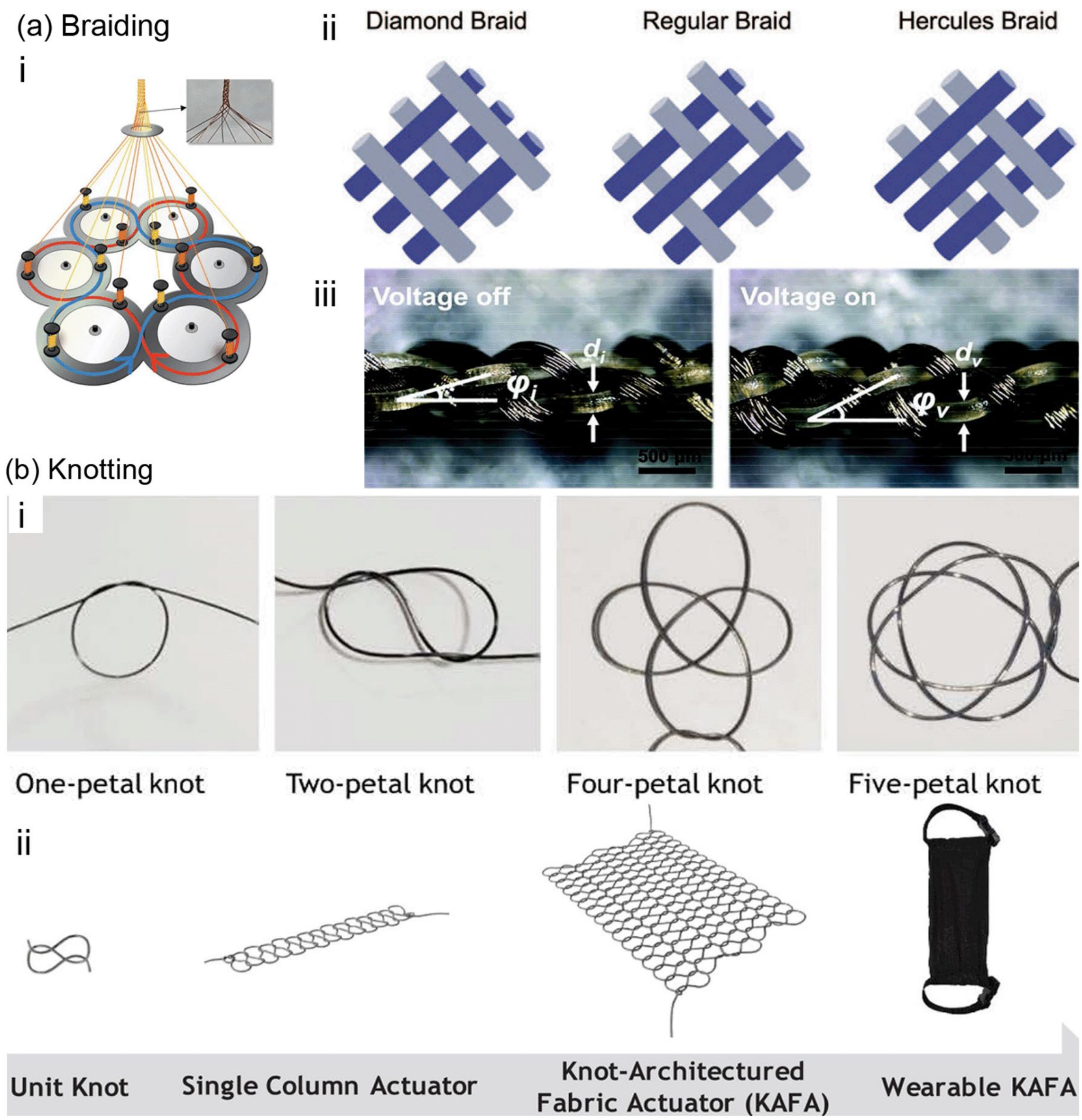

Fig. 5 **a** Braiding technique with metal wires (i); Reproduced with permission from Ref. [57], Copyright 2021, Nature Portfolio. Three common braiding patterns (ii); Reproduced with permission from Ref. [58], Copyright 2022, Wiley. A braided actuator (iii); Reproduced with permission from Ref. [59], Copyright 2023, Wiley. **b** Four potential patterns of knotting unit (i), knotting technique of textile actuators with two-petal units (ii); Reproduced with permission from Ref. [25], Copyright 2022, Wiley–VCH Verlag Gmbh

to form a strand or tubular structure [56]. Commonly, the braiding process interwinds three or more strands at an angle ranging from 0° to 90°, forming a highly flexible structure. Figure 5a(i) depicts the braiding technique used to form a cylindrical metal fabric, in which one set of clockwise metal wires intersects with another set of anticlockwise fibres along the central axis [57]. As drawn in Fig. 5a(ii), three different 2D-braided structure patterns are created through machine settings, namely, diamond, regular, and Hercules braiding patterns [58].

In diamond braiding, yarns continuously pass above one yarn and then below another yarn, with a cross-repetition ratio of 1:1, resulting in a maximum intertwining density. Regular and Hercules braiding involve repeated intercrossing with cross-repetition ratios of 2:2 and 3:3. To achieve variable structures, either floating lines are merged to increase the length of the floating lines or longitudinal yarns are introduced to form triaxial structures. In addition, braiding technology facilitates the construction of 3D structures with notable axial load-bearing capacity, high flexibility, stability, and elasticity against stress and loads from all directions.

To fabricate McKibben textile actuators, tubular fabrics are typically employed to form 3D-braided structures along the cylindrical axis using the maypole braiding technique.

Figure 5a(iii) displays a braided actuator composed of LCE fibres and Ag-coated nylon strands [59]. Thanks to the braided structure, the actuator generates a large reversible contraction of 34% and an actuation force of 18.7 cN upon an electrical stimulation of 0.6 V cm^{-1}, as well as lifting an object 205 times heavier than its weight. During the entire actuation process, the braided actuator only generates radial contraction without axial rotation. This demonstrates that the braided fabric with dense surface structure has the maximum axial strength and radial expansion capability.

Knotting

Knotting, imbued with ancient wisdom, has been verified to be an effective textile-forming technique [60]. Although single-unit knotting is not effective for developing textile actuators, multiple-unit knotting which can interconnect and expand in 2D directions is a promising option for designing textile actuators with novel architectures. Like other textile-forming techniques, the pattern of the knotting unit has a direct impact on the actuation behaviour of the knotted fabric actuator, which must be properly scrutinised. As first summarised by Oh et al., advanced knotting patterns with overly complex intersections may produce random actuation deformation of the knotted textiles during the actuation process [25]. As a consequence, four simple knotting unit patterns are specified from 16 basic knotting unit patterns, including one-petal, two-petal, four-petal, and five-petal knotting patterns (Fig. 5b(i)). Among these knotting unit patterns, two criteria for selecting a possible knotting pattern are introduced, including minimising the number of excessive friction crossovers and the interconnection capability of knotting units in the column direction. Finally, only one-petal and two-petal knotting patterns meet both criteria. Figure 5b(ii) illustrates a schematic diagram of a three-step process to fabricate a knotted textile actuator with a two-petal unit. This can achieve high and reliable actuation through a seamless conductive circuit grid.

Bonding

In addition to the textile-forming technologies mentioned above, actuating materials have been proven to adhere to existing fabric substrates through bonding methods [61]. The bonding methods that utilise physicochemical adhesion or mechanical fixation include coating, pasting, heat sealing,

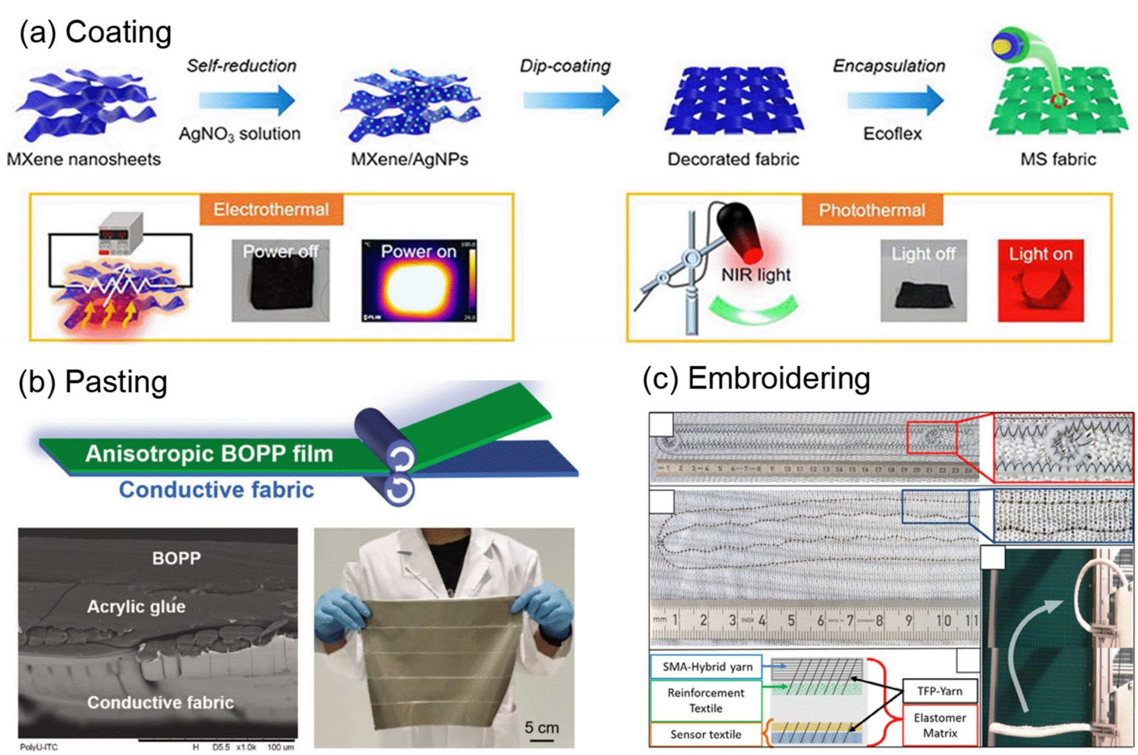

Fig. 6 **a** Coating process of a textile actuator with MXene/AgNPs solution; Reproduced with permission from Ref. [62], Copyright 2022, Springer. **b** Diagram of pasting between a film actuator and a textile substrate; Reproduced with permission from Ref. [63], Copyright 2020, Wiley. **c** Embroidered fabric with SMA wires; Reproduced with permission from Ref. [64], Copyright 2021, Wiley

embroidery, sewing, etc. Since an existing fabric substrate can provide the textile structure, the bonding technique is simple and does not involve the formation of a new textile structure.

Micro- or nano-particle-based actuating materials dispersed in solution can be integrated with existing textiles through coating, casting, or printing. After the solvent in the solution evaporates, the solute layer containing the actuating materials precipitates on the surface of the textile substrate. For instance, Fig. 6a illustrates the dip-coating process of a solution containing MXene and AgNPs on a commercial Tencel fabric. This imparts excellent electrochemical and photothermal actuation properties to the surface of the fabric substrate [62]. Membrane-based actuating materials can be bonded to the surface of textile substrates using chemical glues and then mechanically pressed or heat-sealed to improve adhesion to the laminated structure. As shown in Fig. 6b, a textile actuator composed of biaxially oriented PP film (55 μm) and a fabric substrate (35 μm) is simply laminated with acrylic glue to a thickness of 90 μm, showing excellent flexibility. By feeding large-size raw materials into a roller press in parallel, large-scale production of textile actuators can be easily achieved [63].

Actuating materials can also be bonded to fabric substrates through embroidery and sewing. Embroidery, as one of the traditional Chinese folk crafts, uses needle and thread to decorate different patterns on textile substrates for making textile actuators. As displayed in Fig. 6c, SMA wires are embroidered into a highly stretchable PET fabric to supply sufficient deformation potential. Thus, the actuating function is implemented for the textile matrix without compromising its mechanical properties [64]. Sewing, including hand sewing and machine sewing, has been widely used in bladder textile actuators. Machine sewing involves the automatic movement of fabric under sewing feet, providing accurate and efficient sewing for large-scale textile actuators. Hand sewing can be used for complicated sewing paths, non-flat fabrics, and even intubation. A bladder textile actuator is fabricated through the sewing process, where a thermoplastic elastomer film bladder is sewn into two pieces of fabric to create an inflatable beam [65]. The beam is then folded and sewn again to control the expansion of the textile actuator when it is inflated to a pre-determined degree of bending.

Electrospinning

Electrospinning methods are expected to create nonwoven mats for the actuating materials with poor flexibility and discontinuous structures [66]. During the electrospinning process, the spinning solution formed at the tip of the needle elongates and travels towards the counter electrode or collector under an electromagnetic field. Then, a nonwoven structure is formed after the solvent in the solution evaporates. By regulating the viscosity and amount of the spinning solution, supply voltage, feeding and collecting speed, and distance between needle and collector, nonwoven mats with various fibrous nanostructures can be obtained. Recently, electrospinning technology has demonstrated great potential in preparing nonwoven mat actuators with simple textile structures made of nanofibres, such as hydrogel fibres and carbon nanofibres. For instance, Bai et al. employ electrospinning technology to prepare cellulose acetate/CNT nanofibres for a multi-responsive actuator with high heavy-lift capacity. The actuator can lift a load 1050 times heavier than its own weight under thermal and light stimulation [67].

Pros and Cons

In general, knitting, weaving, and braiding are three common textile-forming techniques to achieve seamless integration of actuating materials and fabrics for textile actuators in smart wearables. However, these three different textile-forming technologies have several advantages and disadvantages in terms of the biocompatibility and mechanical properties of textile actuators based on the interlaced density of fibres or yarns [27]. Typically, knitted textiles with the lowest interlaced density offer the highest level of comfort, elasticity (5 ~ 80%), and breathability to well conform to the contour of the human body without producing pressure spots, even when raw yarns are not stretchable. Compared with knitted fabrics, woven textiles with higher interlaced density generally exhibit greater stiffness and greater dimensional stability but lower flexibility (1 ~ 2%). The interlaced density of braided textile surpasses that of knitted fabric but falls short of that of woven fabric. Therefore, the stretchability (1 ~ 3%) of braided textiles is lower than that of knitted fabrics but better than that of woven fabrics, while their stiffness and dimensional stability show the opposite behaviour. Owing to differences in porous structures attributed to the interlaced density of textile surfaces, the breaking force often increases in the order of knitted textiles, braided textiles, and woven textiles. Compared with weaving, knitting and braiding with higher elasticity make it easier to achieve 3D textile structures for textile actuators.

Knotting technology is relatively seldom employed to design textile actuators for smart wearables, yet it shows fascinating potential. Bonding strategies are very simple and easy to implement in multilayer structures for textile actuators, yet they often pose some problems. For instance, a new interface structure between actuating materials and fabric substrates may be introduced through bonding. For coating technology, micro- or nano-particle-based actuating materials are prone to agglomerating in solvents, making it difficult to form uniform and stable dispersions. This will lead to an uneven actuating layer on the surface of the fabric substrate. In addition, simple, effective, and low-cost drying

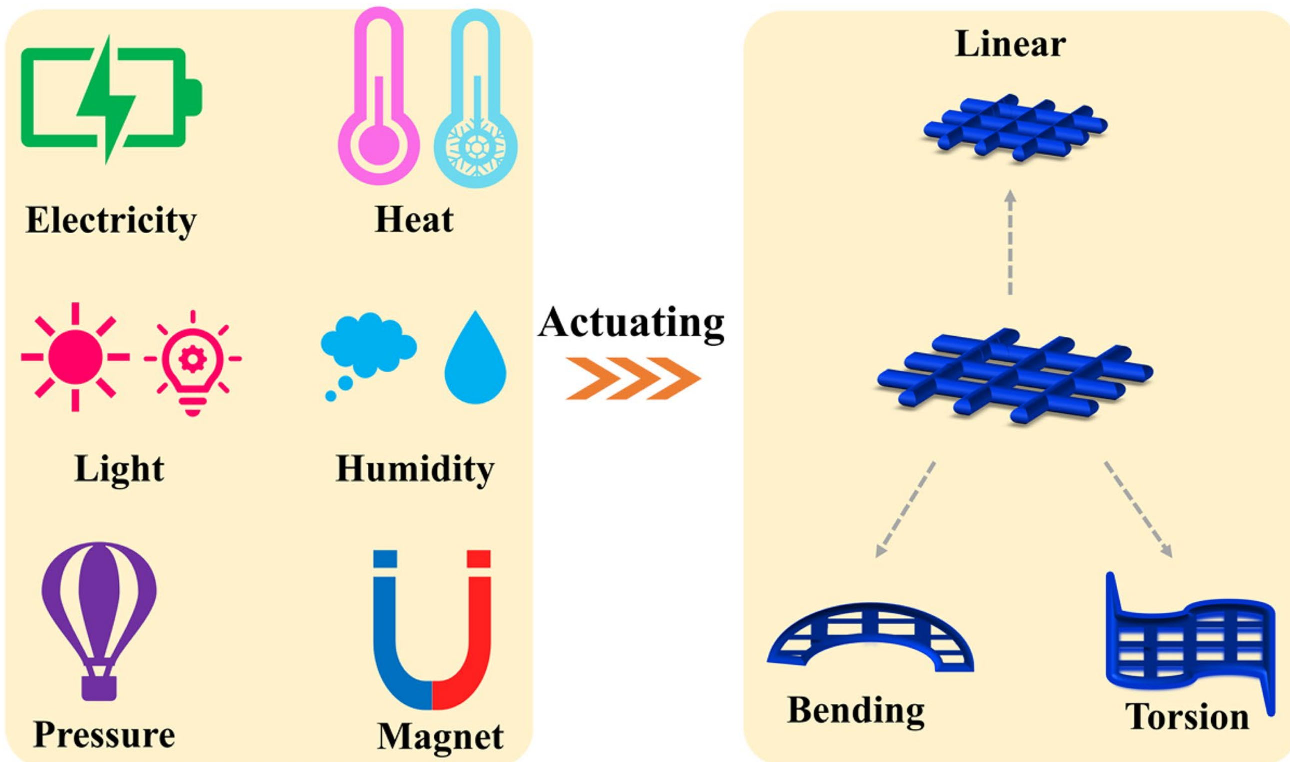

Fig. 7 Various actuating behaviours of textile actuators with different stimuli

processes are required for the coating strategy. For pasting technology, durability and washability seem to be obstacles to its application in wearables. Besides, electrospinning offers the possibility of multilayered nonwoven structures for textile actuators.

Flexible Textile Actuators

Textiles have been used as structural carriers as well as actuation components for soft actuators for more than a decade. We have conducted a survey on flexible textile actuator literature with high impact factors and citations in the past five years. The actuating behaviours, types, and essential performance metrics of textile actuators are described and summarised in this section.

Actuating Behaviours

Actuating behaviour is a fundamental consideration for textile actuators used in smart wearables. When subjected to environmental stimuli, changes in the structural and material properties of textile actuators can lead to reversible linear, bending, and torsional motions, as pictured in Fig. 7. The structural formation of textile actuators has been elucidated in the preceding section, and thus, the focus will be on the changes in material properties of textile actuators induced by external stimuli. Typically, changes in material properties manifest as changes in molecular chain order, volume, and distance. Different materials can generate various property changes under the same stimulus, whereas the same material can also show different changes in properties in response to multiple stimuli. In contemporary daily life, electricity, heat, light, and humidity are ubiquitous environmental stimuli, while pressure and magnetism can exist in certain environments.

Theoretically, changes in molecular chain order do not involve or involve only negligible mass exchange and volume changes when subjected to external stimuli such as electricity, heat, or light. For instance, the thickness of DE membranes sandwiched between two electrodes decreases to enlarge their area in the presence of an electric field. This is due to the electrostatic Coulomb force which causes reversible contraction along the static field direction. Also, SMAs or SMPs can be reconfigured upon thermal stimulation, because the interior molecular chains and crystal/molecular networks inside can be reordered and modified. When heated, SMAs or SMPs with deformed shapes can reversibly recover to their initial shapes, indicating the occurrence of the shape-memory effect. In addition, LCEs, one of the most representative SMPs, are composed of anisotropic liquid crystal molecules. These molecules can be reversibly transformed between liquid crystalline and isotropic phases when heated. LCEs with azobenzene groups can also reconfigure their trans structure to a cis structure when exposed to ultraviolet (UV) light. This is called photoisomerization deformation.

Generally, there are two types of volume changes, namely, volume changes owing to thermal expansion or phase transition and volume changes owing to absorption or intercalation. In the former case, the actuating materials undergo thermal expansion or contraction due to density differences in the actuating state; in principle, no mass exchange occurs. Highly twisted and coiled nylon, PE, and CNTs are representative materials of this type and have been widely developed in textile actuators. Melting, vaporisation, and crystallisation are examples of phase transitions that can generate volume changes; examples include bladder textile actuators with chambers containing air or fluid. In the latter case, the absorption/desorption and the intercalation/extraction of small molecules or ions induce mass transfer between the environment and materials, which drives the materials to expand or contract in all directions. In an electrochemical environment, charged ions can be selectively intercalated into or extracted from the pore structure of materials. CNTs, CPs, MXenes, and ionic gels have been used to design these types of textile actuators. In an environment with varying humidity, small molecules can be absorbed into or desorbed from materials owing to variations in concentration and chemical affinity, resulting in asymmetric swelling. To

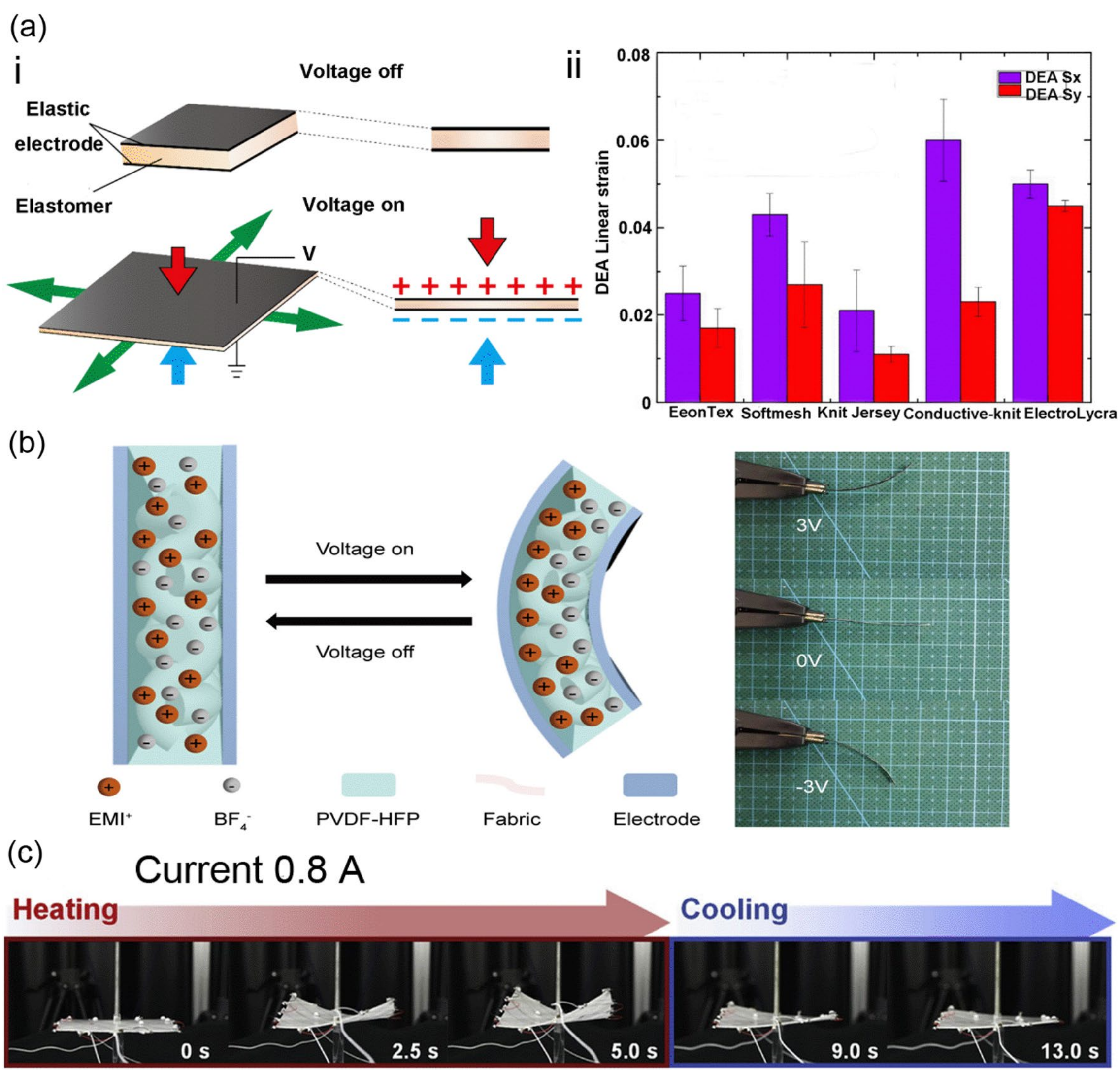

Fig. 8 **a** Operating principle of a DE layer when actuated by electricity (i); Reproduced with permission from Ref. [68], Copyright 2019, Amer Chemical Soc. Linear strains of textile actuators with DE films at 6 kV (ii); Reproduced with permission from Ref. [69], Copyright 2019, MDPI. **b** Electrochemical actuation of textile actuators composed of CPs; Reproduced with permission from Ref. [70], Copyright 2020, Frontiers Media Sa. **c** Joule heat actuation of a woven textile actuator at 0.8 A; Reproduced with permission from Ref. [51], Copyright 2020, Elsevier Sci Ltd

date, many natural or synthetic hydrogels with water-swollen 3D networks have been developed to fabricate humidity-responsive textile actuators.

In electric or magnetic fields, electrostatic or magnetic effects produced by inherent conductivity or magnetism can alter the distance between actuating units. This may lead to changes in the overall architecture of textile actuators. Furthermore, a change in distance may drive the deformation of textile actuators through the expansion or contraction of actuating units. In brief, the change in distance for a textile actuator mostly occurs in the fabric structure formed by actuating fibres or yarns.

Diverse Types

Flexible textile actuators can be mainly divided into six categories based on daily environmental stimulation and some extreme environmental stimulation. These categories include electric textile actuators, thermal textile actuators, optical textile actuators, humidity textile actuators, bladder textile actuators, and magnetic textile actuators.

Electric Textile Actuators

Electric textile actuators use a class of electrical-responsive materials to convert electrical energy into mechanical energy, such as DEs, CPs, carbon-based materials, metal nanomaterials, ion gels, MXenes, SMAs, and SMPs. Electric textile actuators have three main driving modes, including electrostatic effect, electrochemical drive, and electrothermal effect. These modes are based on the various responsive mechanisms of actuating materials to electrical signals. For example, high voltages of several kilovolts commonly generate changes in the molecular chain order of DEs because of electrostatic forces, as illustrated in Fig. 8a(i) [68]. The electrostatic attraction between opposite charges yields a force exerted on the DE layer, contracting its thickness and expanding its area. A DE film is adhered between two conductive fabric electrodes to fabricate a dielectric elastomer actuator (DEA) (Fig. 8a(ii)) [69]. When exposed to a voltage of 6 kV for 10 s, the DEA generates an actuation force on the top surface of the DEA to expand. Although DEA has been illustrated to provide adjustable breathability and temperature regulation, it is not safe for smart wearables due to the risk of using high stimulation voltages.

Furthermore, relatively low voltages (e.g., several volts) are sufficient for CNTs, CPs, MXenes, or ion gels to generate ion adsorption/desorption or insertion/extraction through electrochemical double layers or Faradaic reactions. This will give rise to volume changes. Figure 8b introduces a bending textile actuator composed of two PEDOTs: PSS-coated fabric electrodes that are wetted with ionic electrolytes. When a voltage of 3 V is applied, the cations and anions in the electrolyte migrate to the cathode and anode of the textile actuator, causing the expansion and contraction of the actuator [70]. Consequently, the textile actuator undergoes a large displacement deflection, which opens up the possibility of application in smart wearables. However, such actuators must be outfitted with ionic electrolytes, which reduces body comfort and adds practical operation complexity.

Moreover, various magnitudes of voltage, ranging from a few volts to tens of volts or even hundreds of volts, have the ability to transfer electrical energy into joule heat in several electrothermal materials. These electrothermal materials present the same driving mechanism as that of heat, including CNT, SMAs, SMPs, AgNWs, and MXenes. In Fig. 8c, when an activation current of 0.8 A is input to generate Joule heat, the woven textile actuator beam with SMA wires can bend upward or downward in about 5 s. After the current flow stops, the actuator returns to its original shape owing to cooling [51].

Thermal Textile Actuators

Thermal textile actuators are mainly driven in three ways to achieve mechanical movement. They are the electrothermal effect caused by joule heat (Fig. 8c), thermal radiation, and near-infrared (NIR) photothermal effect. Typically, thermal-responsive materials are activated based on changes in the molecular chain order of SMAs and SMPs, as well as changes in the volume of polymer and CNT fibres or yarns. Figure 9a gives an actuation example of a textile actuator composed of SMA wires at different temperatures [66]. At 85 °C, the active textile achieves a maximum actuation contraction of 12% at a load of 3.2 N and a maximum specific energy of 0.07 kJ kg^{-1} at a load of 4.7 N. As the temperature increases to 145 °C, the actuating contraction and specific energy increase to 25% at a load of 4.7 N and 0.24 kJ kg^{-1} at a load of 6.1 N. The multiple tunable actuation responses of textile actuators have been successfully demonstrated in prototypes of smart wearables, such as assistive wrist sleeves and conforming shoes.

In addition, some photothermal agents like AgNPs, CNTs, MXenes, and graphene have been developed for textile actuators. They can absorb NIR light and convert it into heat to generate thermal expansion or phase transition, resulting in bending or other movements, as depicted in Fig. 9b(i) [62]. When the active textile coated with MXene/Ag is exposed to 16 kLux NIR light for 30 s and 90 s at room temperature, the resistance and temperature change at the same time (Fig. 9b(ii)). This causes the synchronous enhancement of temperature and bending angle (Fig. 9b(iii)). In Fig. 9b(iv), the textile actuator reaches the maximum bending angle of 149° within 31 s, which means that fast photothermal actuation capability is endowed for smart wearables.

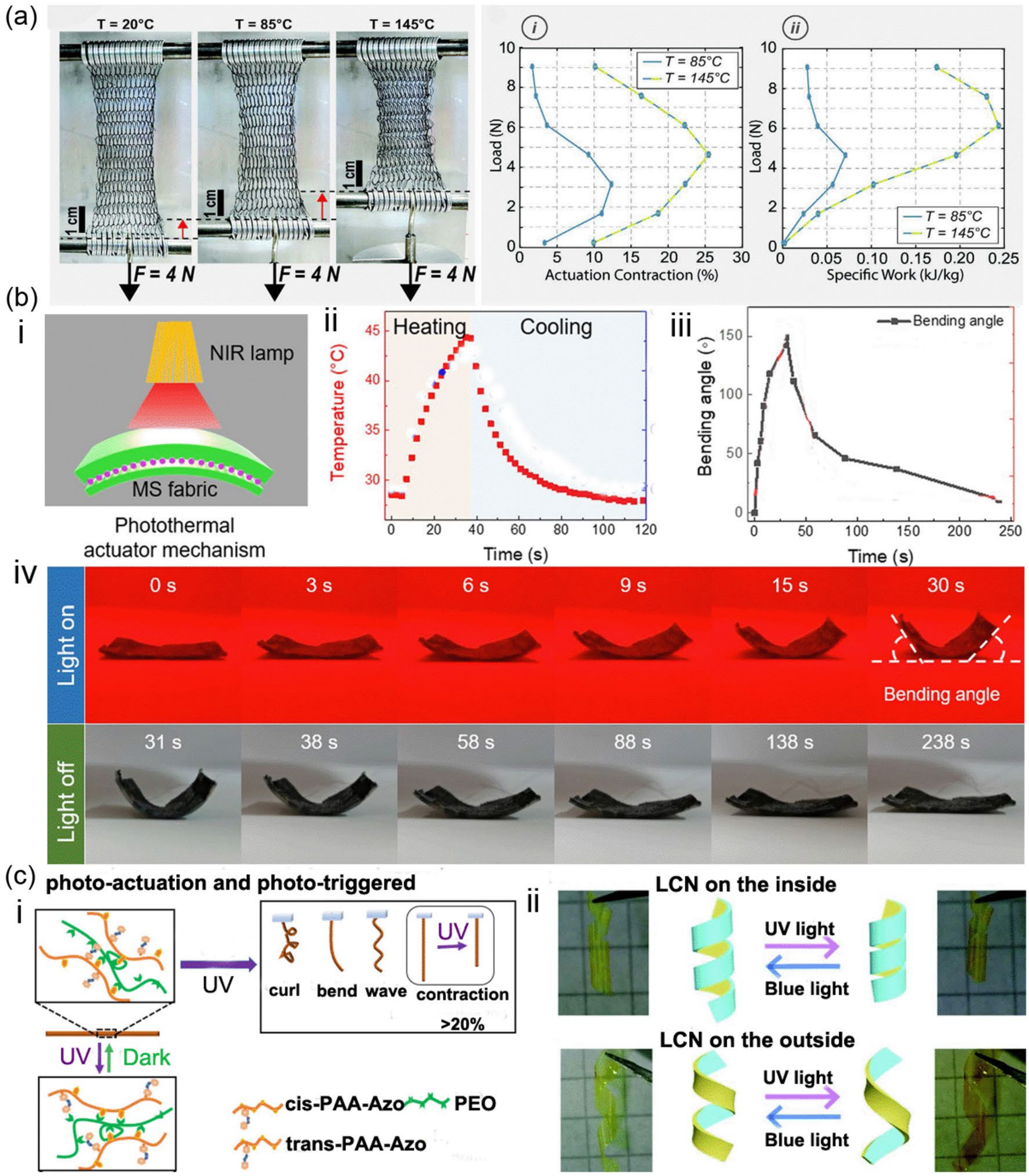

Fig. 9 **a** Contraction of a textile actuator with SMA wires during heat; Reproduced with permission from Ref. [71], Copyright 2021, Wiley. **b** NIR photothermal actuating mechanism of a textile actuator coated with MXene/Ag (i), Temperature curve of time upon NIR (ii), Bending angle curve of time (iii), Actuating moments upon NIR light (iv); Reproduced with permission from Ref. [62], Copyright 2022, Springer. **c** UV photochemical actuating mechanism of hydrogel with azobenzene groups (i); Reproduced with permission from Ref. [72], Copyright 2021, Springer Nature. Actuating modes of LCE film with azobenzene groups under UV light (ii); Reproduced with permission from Ref. [73], Copyright 2020, Wiley–VCH Verlag Gmbh

Optical Textile Actuators

Basically, optical textile actuators have two actuation strategies, including the photothermal effect (Fig. 9b) and the photochemical effect. The second one achieves actuation motion through the cis–trans isomerization of azobenzene functional groups under UV light. As shown in Fig. 9c(i), azobenzene functional groups have been successfully incorporated into hydrogels [72]. When UV light is applied, the trans–cis transition of azobenzene induces the motion. In Fig. 9c(ii), a helical bilayer actuator is made of LCE film with azobenzene inside or outside. It can wind or unfold

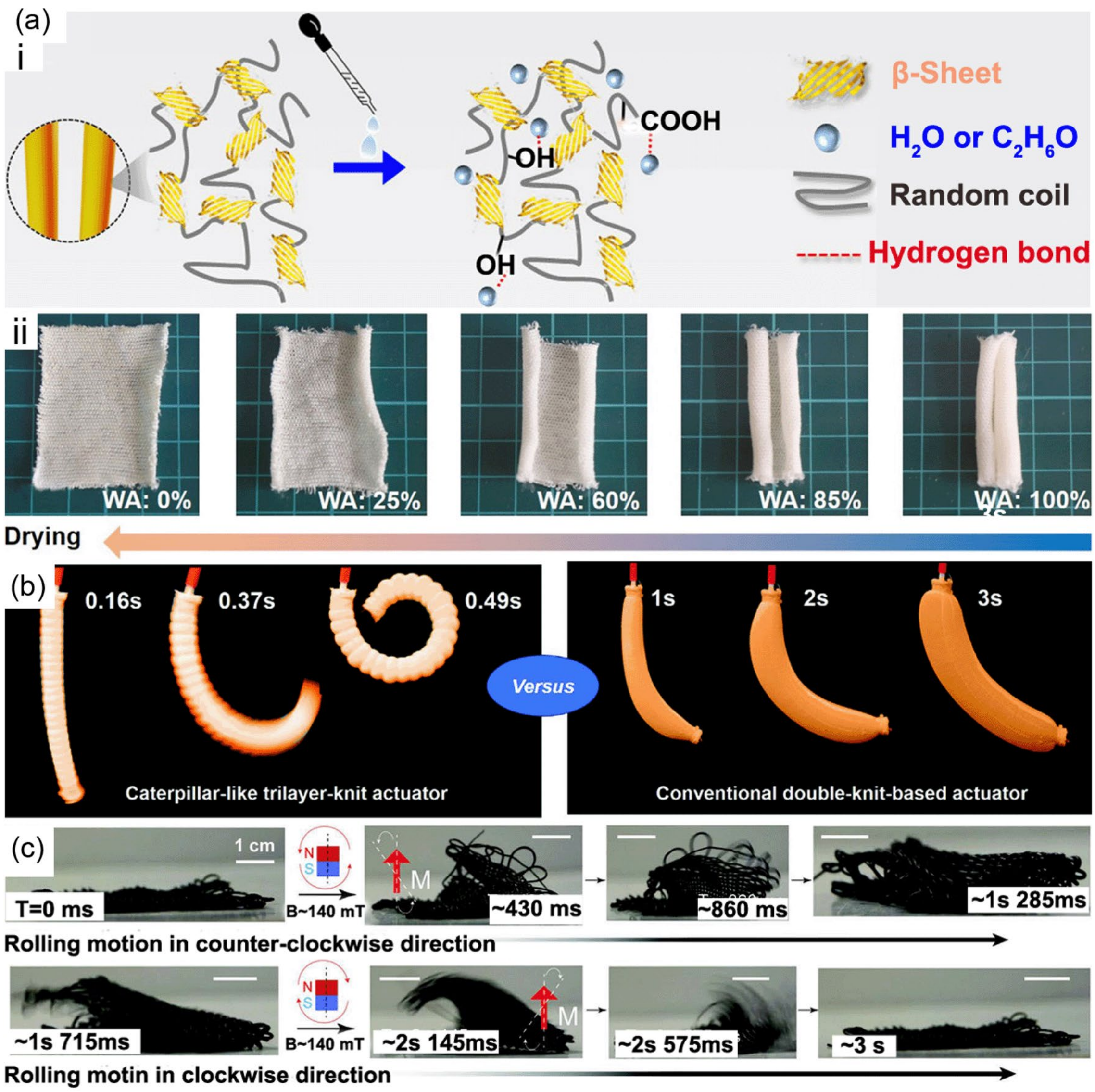

Fig. 10 **a** Humidity actuating mechanism of a silk actuator (i); Reproduced with permission from Ref. [22], Copyright 2019, Springer Nature. Curling process of a knitted fabric upon humidity (ii); Reproduced with permission from Ref. [74], Copyright 2021, Amer Chemical Soc. b Bending moments of textile actuators knitted with triple and double layers under pressure; Reproduced with permission from Ref. [49], Copyright 2023, Wiley–VCH Verlag Gmbh. **c** Rolling and unrolling moments of magnetic textile in a magnetic field; Reproduced with permission from Ref. [16], Copyright 2023, Wiley–VCH Verlag Gmbh

around the helix under UV light [73]. Although this flexible film has not yet been integrated with fabrics, it has promising potential for use in smart wearables.

Humidity Textile Actuators

Humidity textile actuators can be activated to deform in response to different moisture levels owing to the adsorbed or desorbed small molecules. The activation involves volume and mass changes. Compared with other textile actuators, the convenience and safety of water intake from the environment make humidity textile actuators easier to deploy in smart wearables and provide more comfortable thermal management for human body. A series of moisture-responsive materials for textile actuators have been developed, such as silk, lotus, wool, viscose, alginate, GO, and hydrogels. Figure 10a(i) demonstrates that silk fibres containing numerous hydrophilic groups absorb water or ethanol through hydrogen bonds, resulting in rotational motion [22]. A viscose knitted fabric exhibits a series of self-adaptive shape changes under different humidity levels, as summarised in Fig. 10a(ii) [74]. When the moisture content exceeds 25%, the curvature of textile actuator increases with the moisture content, and a considerable curl shape is obtained by overcoming the interwoven structure. Finally, the textile actuator has been used to fabricate garment sleeves for thermal management and sunshade fabric shutters for greenhouses, revealing widespread applications in daily smart wearables without the need for complex design systems.

Bladder Textile Actuators

As one of the earliest textile actuators, the bladder textile actuator produces desired movement through stimulation of internal air pressure or external force. Thanks to the large forces generated, bladder textile actuators offer interesting prospects in mobility-assistive exosuits, wearable rehabilitation suits, and wearable manipulative robots. According to the ingredient in the flexible bladder chamber, bladder textile actuators are generally classified into pneumatic textile actuators with air and hydraulic textile actuators with fluid. When pressurised, the elastomeric chamber is inflated to expand its volume, while the non-stretchable fabric as reinforcement regulates the movement of the textile actuator by limiting the expansion of the elastomeric chamber. Figure 10b designs two types of pneumatic textile actuators with double-layer knitted and trilayer knitted architectures [49]. Compared with the double-layer knitted actuator, the trilayer knitted actuator delivers a significantly larger bending angle (over 216°) in a shorter actuation time (0.49 s) under the same external pressure stimulation. Therefore, the output force of a trilayer knitted actuator sharply increases to 120 cN under an external pressure of 40 ~ 70 kPa, and the bending curvature dramatically increases to over 0.2 cm^{-1} under the external pressure of 20 ~ 40 kPa. After more than 50 actuating cycles under external pressures of 30 kPa and 50 kPa, the trilayer knitted textile actuator exhibits good stability, robust actuation force, and durability. It has been further used to prepare assistive wearables such as garment sleeves for arm mobility aids and gloves for finger movement assistance.

Magnetic Textile Actuators

Magnetic textile actuators often contain magnetic fillers in the fabric matrix, which is a special and intriguing type of textile actuator. In a magnetic field, magnetic fillers seek to align and interact with the field to generate different patterns of movement. By controlling the shape, dosage, type, and magnetic signal of magnetic fillers, diverse actuation structures and patterns of textile actuators can be achieved. Figure 10c presents a magnetic textile actuator woven from magnetic fibres containing thermoplastic elastomers and magnetic particles (NdFeCoB) [16]. When subjected to an external magnet of 250 mT, the actuator generates a force of 22 N. When the external magnet of 140 mT rotates clockwise or anticlockwise, the magnetic textile actuator rolls accordingly, fully folding or unfolding in the same actuation time of 1.28 s, which is expected to enable the fabrication of soft prosthetics for rehabilitation or assisted movement. Currently, high-performance magnetic textile actuators are not common.

Performance Metrics

To develop smart wearables, textile actuators must be designed based on the actual application environment by matching appropriate actuating materials and textile-formation approaches. In addition, the actuation motion, output force, strain, response time, and durability of textile actuators are often important performance metrics that need to be considered in smart wearables. Table 1 lists diverse high-performance textile actuators with different actuating materials and textile-forming techniques reported in the past 5 years. Obviously, textile actuators driven by electricity, heat, pressure, and humidity account for the vast majority of related research. Additionally, traditional textile-forming techniques and bonding methods are employed with similar frequencies in the structural shaping of textile actuators. Some facts may also be drawn from Table 1. For instance, electric textile actuators composed of DEAs, optical textile actuators with azobenzene functional groups, or magnetic textile actuators can exhibit good actuation performance, but they have received little attention. This may be caused by the unsafe and uncommon use of ultra-high voltage, UV light, or magnet fields. Moreover, thermal textile actuators with SMAs, humidity textile actuators, and electrochemical textile actuators may require a longer response time to generate actuation, but they do not require harsh actuating conditions. Besides, the bonding methods are favourable for fabricating bladder textile actuators with high output actuation performance.

Applications of Flexible Textile Actuators in Smart Wearables

Flexible textile actuators have autonomous environmental response ability, excellent textile processability, good breathability, high body compliance, long-term durability, diverse structural patterns, and a lightweight nature. They are increasingly being integrated with garments or auxiliary wearables to design smart wearables that can perceive and respond to human surroundings. Based on the execution of actuation force and deformation, smart wearables with textile actuators have great potential in various applications. In this section, we primarily comment on the applications of textile actuators over the past 5 years in wearable power suits using actuation force, comfort-adapting clothing exerting actuation deformation, and human–machine interaction.

Table 1 Actuation performance summary of textile actuators

Stimulus	Materials	Technique	Actuation performance					Refs.
			Motion	Force	Strain	Response time	Cycle	
Magnet-250 mT	Magnetic yarn	Weave	Roll	22 N	40 °	< 2 s		[16]
Humidity	Viscose yarn	Weave	Roll		> 180 °			[18]
Humidity-80%	Nylon/Ag-SEBS	Past	Bend		260°	~ 14 s	> 200	[23]
Electricity	SMA wire	Knot	Contract	32.3 N	~ 28%			[25]
Heat-80 ℃	SMA yarn	Knit	Contract		65%	< 5 s		[31]
Light-Sunlight	CP/LCE/MXene	Weave	Contract		52%	15 s	500	[45]
Pressure-99 kPa	Elastomer yarn	Knit	Bend		> 180 °			[48]
Pressure -50 kPa	PET/PU yarn	Knit	Bend	~ 60 cN	216°	0.49 s	50	[49]
Pressure -600 kPa	Nylon tube	Weave	Bend		23%			[50]
Electricity-0.8 A	SMA/nylon yarn	Weave	Bend	0.53 N	~ 200 °	5 s		[51]
Electricity-6 V	LCE/Ag yarn	Braid	Contract	18.7 cN	34%	10 s	100	[59]
Light-NIR	MXene/Ag	Coat	Bend		149º	31 s		[62]
Magnet	CF/BOPP film	Past	Bend		122º	~ 3 s		[63]
Electricity-12 V	SMA yarn/fabric	Sew	Bend		270º	13 s	> 10	[64]
Pressure -100 kPa	SEBS Film	Sew	Bend	0.2 N·m	60º	1.02 s		[65]
Electricity-6 kV	DEA film/fabric	Past	Expend		89%	10 s		[69]
Electricity-3 V	CP/fabric	Coat	Bend	0.6 mN	0.3%	< 5 s		[70]
Heat-85 ℃	SMA yarn	Knit	Contract	308 Nm^{-1}	40%	~ 30 s		[71]
Humidity-67%	Viscose yarn	Knit	Roll	7.4 mN	~ 180º	~ 3 s	50	[74]
Electricity-1.5 V	CP/fabric	Coat	Contract	125 mN	3%	< 800 s	8000	[75]
Electricity-3 V	Carbon/fabric	Coat	Bend		~ 0.8%	100 s		[76]
Electricity-15 V	SMP/CP yarn	Knit	Contract	0.2 N	~ 30%	20 s	< 10	[77]
Electricity-0.1 A	SMA yarn	Knit	Bend	0.37 N	114º	60 s		[78]
Electricity-0.5 A	SMA wire	Weave	Bend	7 mN·m	178º	10 s		[79]
Heat-70 ℃	Nylon66/Ag yarn	Weave	Contract	2.81 N	3.4%	> 50 s		[80]
Heat-45 ℃	SMA wire	Sew	Vibrate	2.3 N		27.4 s		[81]
Heat-70 ℃	SMP yarn	Weave	Bend			87 s	50	[82]
Heat-90 ℃	SMA yarn	Knit	Contract		70%			[83]
Heat-120 ℃	LCE yarn	Knit	Contract		~ 31%	~ 80 s		[84]
Light-NIR	SA/GO/PU/PDMS	Paste	Rotate		630º	7.43 s	50	[85]
Light-0.1 W cm^{-2}	MXene-PAM/PP	Weave	Rotate		537º	50 s		[86]
Light-UV	BZT/UHMW-PE		Contract	70 MPa	0.1%	< 1 s	100	[87]
Light-NIR	CNT yarn	Electrospin	Contract	2.5 MPa	6.7%	6 s	1000	[88]
Humidity	Lotus Yarn	Knit	Contract		66%	2 s	500	[89]
Humidity-water	HPHG/PDMS	Past	Roll		360º	1800 s		[90]
Humidity-70%	CNT	Coat	Rotate			~ 80 s	30	[91]
Humidity-90%	Silk film	Past	Bend		110º	~ 100 s	1000	[92]
Humidity	GO-alginate yarn	Weave	Rotate					[93]
Humidity	CNT/chitosan	Weave	Contract	> 10 mN	12 mm	45 s		[94]
Pressure-160 kPa	TPU Film	Sew	Bend	4 N	110º	0.2 s		[95]
Pressure-60 kPa	TPE layer	Sew	Bend	2.9 N	360º	1.01 s		[96]
Pressure-102 kPa	Elastic band	Sew	Bend	24.8 N	360º			[97]
Pressure-75 kPa	TPU	Past	Expend			140 s		[98]
Pressure-360 kPa	PAM film	Sew	Bend	285 N	120º	0.03 s	10^5	[99]
Pressure-500 kPa	PAM tube	Braid	Contract	14.8 N	34%			[100]

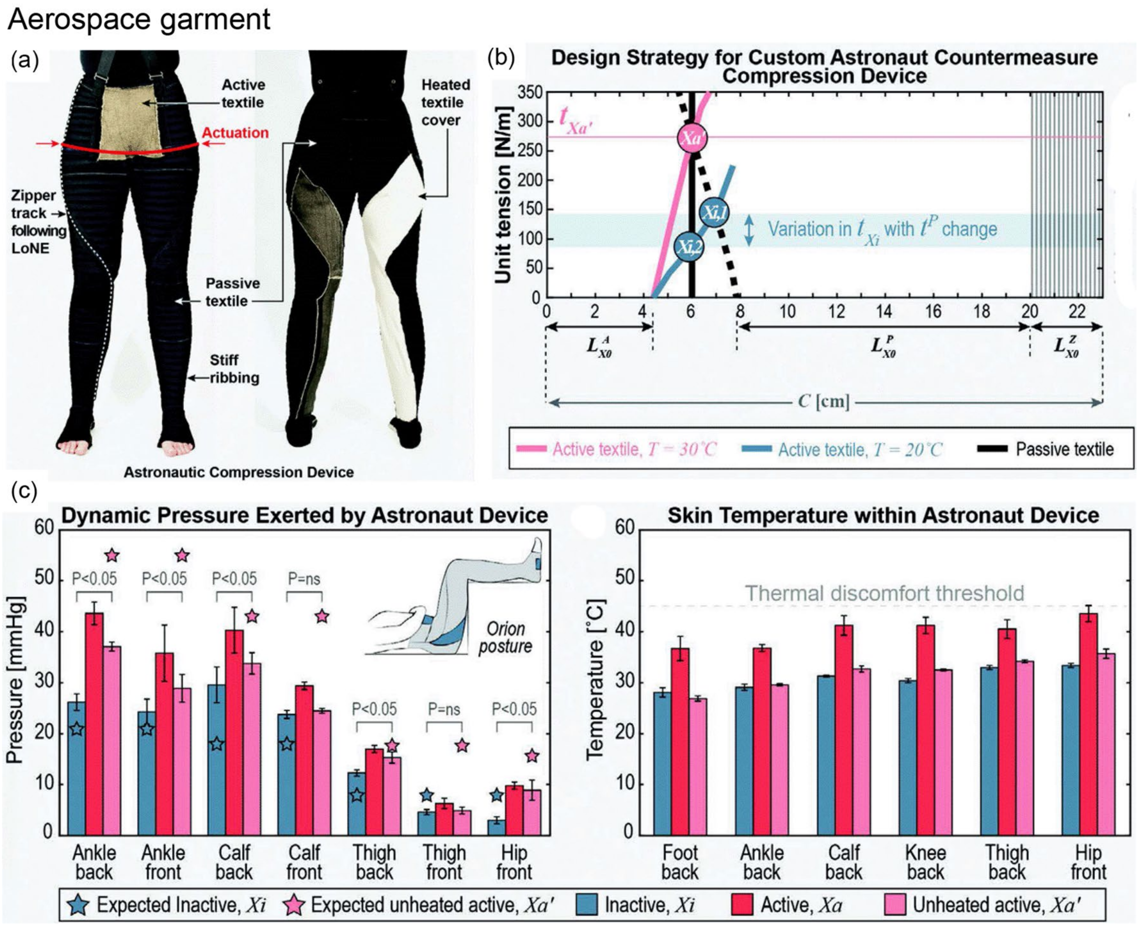

Fig. 11 **a** Aerospace garment using knitted SMA textile actuators for astronauts after spaceflight. **b** A design strategy based on unit tension. **c** Dynamic pressure and skin temperature upon stimulation; Reproduced with permission from Ref. [17], Copyright 2022, Wiley

Wearable Power Suits

Textile actuators in wearable power suits may exert various levels of actuation force to meet the power requirements for different applications. This could be achieved through diverse combinations of actuating materials and textile structures. Generally, the actuation forces that aerospace garments, healthcare wearables, and mobility-assistive exosuits exert may decrease in sequence.

Aerospace Garments

In aerospace exploration, astronauts are inevitably subjected to movement constraints against vacuum conditions during spaceflight, as well as orthostatic intolerance that occurs after spaceflight. To alleviate adverse symptoms experienced by astronauts during or after space travel, aerospace garments can supply mechanical countermeasures, promote blood circulation in the cardiovascular system, and prevent blood from accumulating in localised areas of the body. For a long time, pneumatic compression has been the predominant component of spacesuits. For example, the "Space Activity Suit" can provide a mechanical counterpressure of 222 mmHg against space vacuum, and the "American anti-gravity suit" can provide a pressure of 78 mmHg throughout the body for orthostatic intolerance [101, 102]. However, these traditional spacesuits have some deficiencies in terms of their large size, heavy weight, inconvenient mobility, and cumbersome donning or doffing.

With the advancement of textile actuator technology, several spacesuit prototypes with SMA textile actuators have been reported. In 2014, Newman's team first integrated SMA springlike coils into elastic fabric to fabricate a lightweight spacesuit, named MIT Knit BioSuit™. This is the first prototype of a compression spacesuit designed with SMA actuators to provide real-time pressure status and thermal regulation during planetary exploration activities. According to

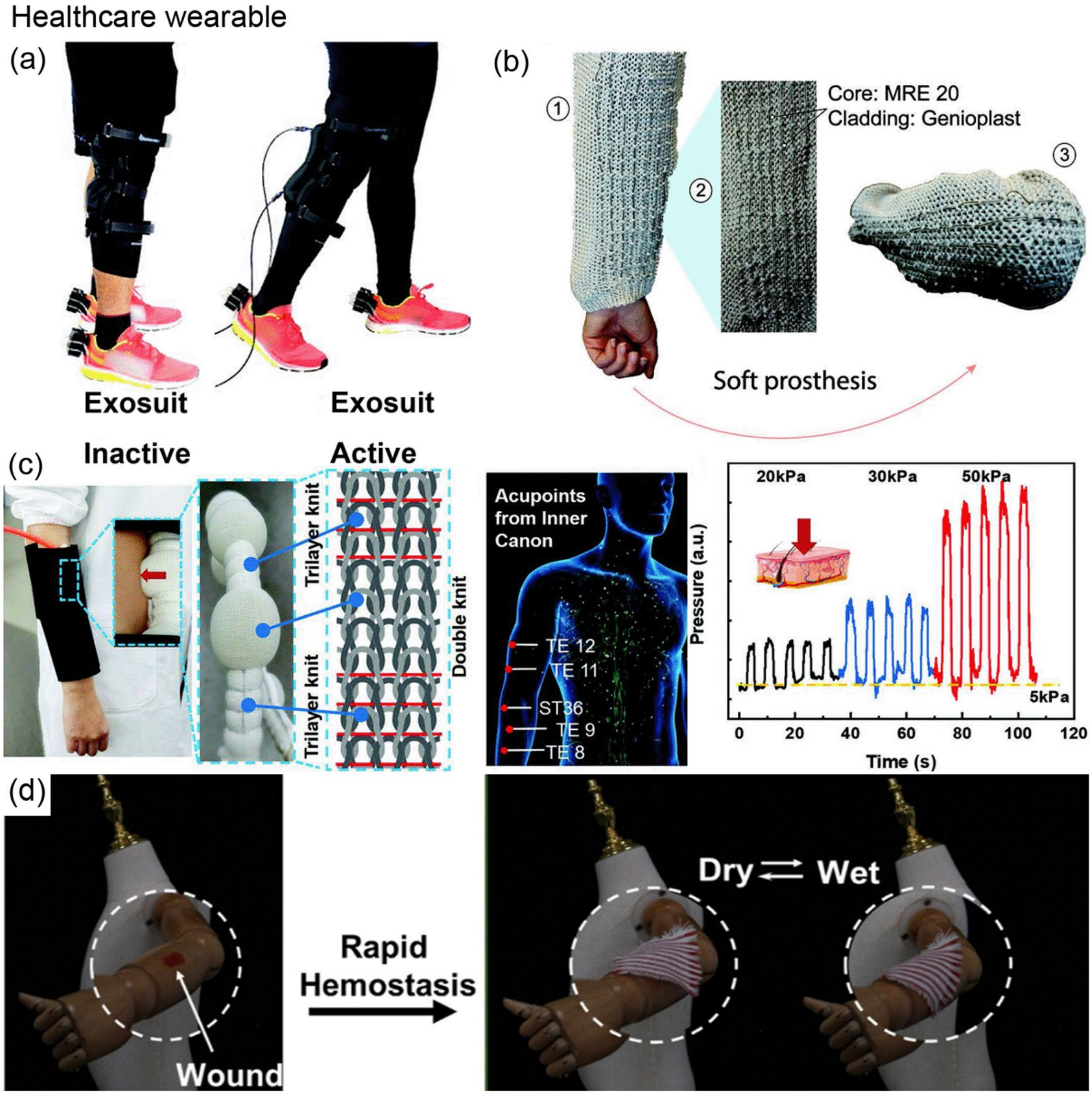

Fig. 12 **a** Soft exosuit with a bladder textile actuator for knee rehabilitation; Reproduced with permission from Ref. [107], Copyright 2018, Frontiers Media Sa. **b** Soft prosthesis using a magnetic textile actuator; Reproduced with permission from Ref. [16], Copyright 2023, Wiley–VCH Verlag Gmbh. **c** Massage sleeve with knitted bladder textile actuators; Reproduced with permission from Ref. [49], Copyright 2023, Wiley–VCH Verlag Gmbh. **d** Smart emergency tourniquet using a humidity textile actuator; Reproduced with permission from Ref. [108], Copyright 2022, Amer Chemical Soc

theoretical calculations, a spacesuit type designed with SMA textile actuators can provide dynamic actuation pressure of 16 ~ 105 mmHg at the ankle to meet the pressure requirements of orthostatic intolerance after spaceflight [103].

Moreover, Fig. 11a presents a dynamic and conformal spacesuit with knitted SMA textile actuators for astronauts returning from space exploration [17]. At low pressure of < 22 mmHg and room temperature, the spacesuit exhibits delayed and controlled actuation, allowing astronauts to alleviate discomfort prior to landing activities. As the temperature momentarily increases, the spacesuit is driven to a high pressure of > 55 mmHg until it is taken off and cooled. This makes it easier for astronauts to don and doff. As seen in Fig. 11b, the design of a spacesuit matches the geometric shape of the human body by adjusting the unit tension of passive and active textiles. Upon heat stimulation, the spacesuit exerts a dynamic pressure of 6.3 ~ 43.6 mmHg on different parts of the body (Fig. 11c). Additionally, the spacesuit can reach a relatively balanced temperature of ~ 30 °C within 30 min without causing body discomfort.

Fig. 13 **a** Assistive exosuit for walking and running; Reproduced with permission from Ref. [109], Copyright 2019, Amer Assoc Advancement Science. **b** Arm-lift-assistive exosuit with bladder textile actuators; Reproduced with permission from Ref. [15], Copyright 2022, Amer Assoc Advancement Science. **c** Arm-lift-assistive exosuit with bladder textile actuators; Reproduced with permission from Ref. [110], Copyright 2022, Natl Acad Sciences

Healthcare Wearables

Compression therapy (15 ~ 50 mmHg) is considered an effective and non-invasive way to treat many diseases. For instance, it can provide a calming effect for patients with sensory processing disorders and improve blood circulation and lymphatic drainage for patients with venous and lymphatic diseases [103]. Wearable compression therapy devices composed of textile actuators can provide the dynamic and customised pressure required for therapy. For instance, a compression vest composed of SMAs can produce a predicted compression of up to 52.5 mmHg on a child's torso when heated [104]. When a power of 43.8 W is applied, the vest creates an actual pressure of up to 37.6 mmHg, meeting the pressure required for compression treatment. Besides, a compression garment composed of bladder textile actuators is developed to exert a biomechanical force of 5 ~ 25 kPa on the wearer's lower limb within 25 s for compression therapy [105].

Furthermore, soft exosuits made of textile actuators have been shown to be effective in routine gait rehabilitation training for patients with limb paralysis after stroke [106]. For instance, a soft exosuit with a bladder textile actuator is designed for knee rehabilitation, as shown in Fig. 12a [107]. During the swing phase of gait training, the knee exosuit can increase the knee joint torque by 25% for patients, improving the recovery effect of the femur.

Besides, several healthcare wearables with textile actuators have been developed. As presented in Fig. 12b, a soft prosthesis with a magnetic textile actuator is expected to be used in genioplasty [16]. Additionally, a massage sleeve with trilayer knitted bladder textile actuators is developed

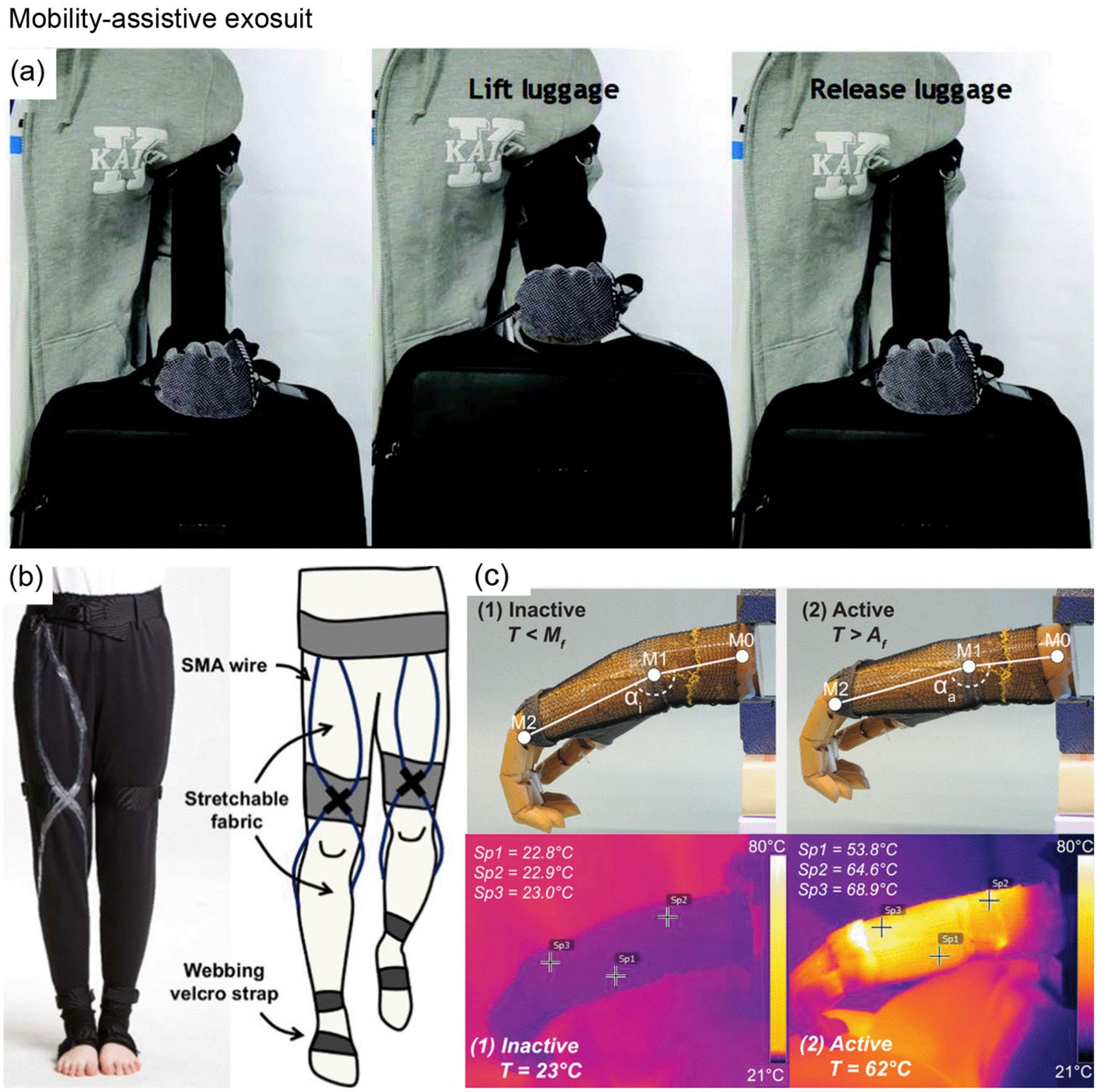

Fig. 14 **a** Household sleeve with knotted SMA textile actuators for arm; Reproduced with permission from Ref. [25], Copyright 2022, Wiley–VCH Verlag Gmbh. **b** Assistive exosuit with SMA textile actuators for ankle; Reproduced with permission from Ref. [111], Copyright 2020, IOP Publishing Ltd. **c** Assistive sleeve with knitted SMA yarns for wrist; Reproduced with permission from Ref. [71], Copyright 2021, Wiley

to simulate the acupuncture treatment of therapist (Fig. 12c) [49]. As supply pressure increases from 20 to 50 kPa, the massage intensity that the sleeve exerts increases by more than twofold, which is comparable to bulky massage devices. Uncommonly, a humidity textile actuator is woven into a smart emergency tourniquet (Fig. 12d) [108]. When a wound bleeds, the tourniquet can be curled to stop bleeding and recover to its normal shape after the wound stops bleeding.

Mobility-Assistive Exosuits

Mobility-assistive exosuits with textile actuators can exert extra mechanical forces on the human body to reduce muscle fatigue and protect skeleton joints from injury during movements like heavy lifting, grasping, walking, and running. In general, these exosuits exert certain actuating forces when stimulated to support the activities of the upper and lower extremities. Although these exosuits do not provide enough power to completely replace human activities, they

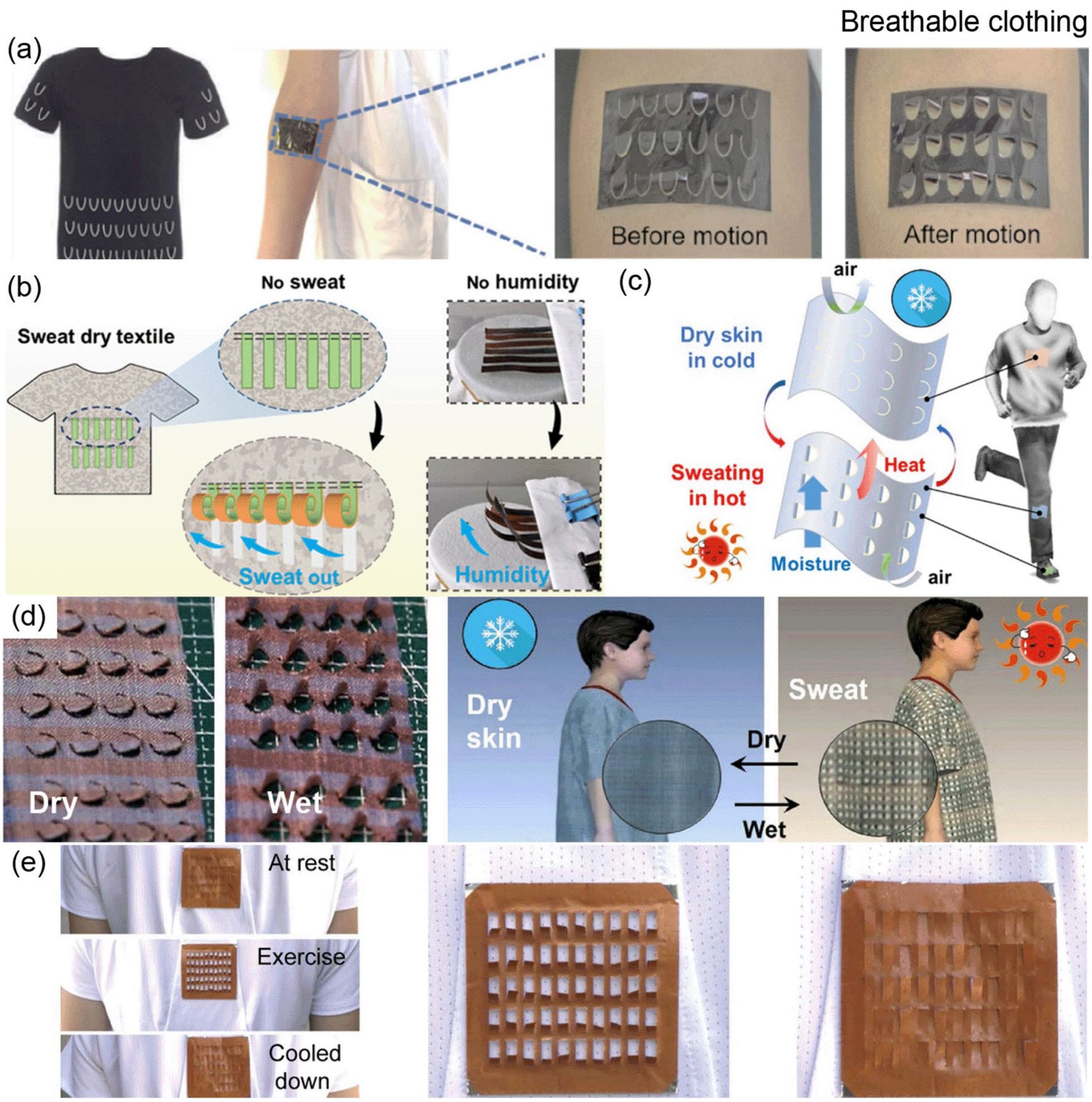

Fig. 15 **a** Moisture-sensitive clothing with a PPy/PET film; Reproduced with permission from Ref. [112], Copyright 2021, Amer Chemical Soc. **b** Sweat response clothing with SA/GO/PU/PDMS films; Reproduced with permission from Ref. [85], Copyright 2023, Amer Chemical Soc. **c** Humidity-responsive clothing with a wool textile actuator; Reproduced with permission from Ref. [44], Copyright 2022, IOP Publishing Ltd. **d** Breathable garment with viscose/PET textile actuators; Reproduced with permission from Ref. [18], Copyright 2023, Spring Nature. **e** Breathable garment with humidity textile actuators composed of nylon-Ag; Reproduced with permission from Ref. [23], Copyright 2021, Amer Assoc Advancement Science

have been demonstrated to significantly reduce the body's metabolism in daily activities.

Figure 13a presents a portable exosuit composed of a functional waist belt, two thigh warps, electric motors, and Bowden cable sensors, weighing up to 5 kg [109]. The exosuit applies an actuation extension torque around the wearer's hip joint, resulting in a 9.3% and 4.0% decrease in metabolic rate during walking and running, respectively. Essentially, the exosuit uses an electric motor as the actuation component instead of a textile actuator. To reduce the weight and size of mobility-assistive exosuits, bladder textile actuators are increasingly being employed as actuation components. As exhibited in Fig. 13b, an arm-lift-assistive exosuit is sewn with six bladder textile actuators [15]. Upon a pressure stimulation of 90 kPa, the actuators provide lifting torque to the wearer's shoulder to assist in raising the arm. A similar arm-lift-assistive exosuit is developed in Fig. 13c [110]. Six bladder textile actuators are firmly affixed to the garment beneath the shoulder joint, providing lifting torque to elevate the arm when applying an inflation force of ~ 25 N. As a result, the wearer's upper arm raises within 38 s after pressing the set button and descends within 87 s after pressing the reset button.

Furthermore, several mobility-assistive exosuits are designed with thermal textile actuators composed of SMAs. For instance, Fig. 14a builds a highly stretchable and lightweight household sleeve knotted with SMA wires, which generates a contract force of 32.3 N under joule heat [25]. The assistive sleeve with excellent wearability weighs 30.7 g and can be easily worn on the arm in daily life to help carry heavy luggage. Upon a low voltage of 6.4 V, the sleeve is activated to complete the entire process of lifting and releasing heavy luggage within 13 s. In addition, an ankle-assistive exosuit is fabricated with SMA textile actuators (Fig. 14b) [111]. The exosuit contracts and provides a rotational torque of 100 N cm to the ankle in 0.5 s when activated with a current of 0.8 A. Figure 14c demonstrates an assistive wrist sleeve with knitted SMA textile actuators based on anatomical and dynamic design. The sleeve can produce a blocking force of up to 308 N m upon stimulation [71]. The sleeve contracts to apply stretching force to the wrist when heated, thereby lifting the wearer's hand.

Comfort-Adapting Clothing

Textile actuators in comfort-adapting clothing possess the ability to automatically deform in changing environments to improve the wearer's comfort and convenience. Unlike wearable power suits that focus on large actuation forces, conform-adapting clothing pays more attention to actuation deformation. Two typical representatives of conform-adapting clothing are breathable clothing for thermal management and self-fitting fashion garments.

Breathable Clothing

In the implementation of thermal management regulations, ventilating holes are often designed on the breathable clothing. These holes can automatically open or close in response to sweat and heat transfer generated by human skin, thus regulating the clothing's breathability. Among

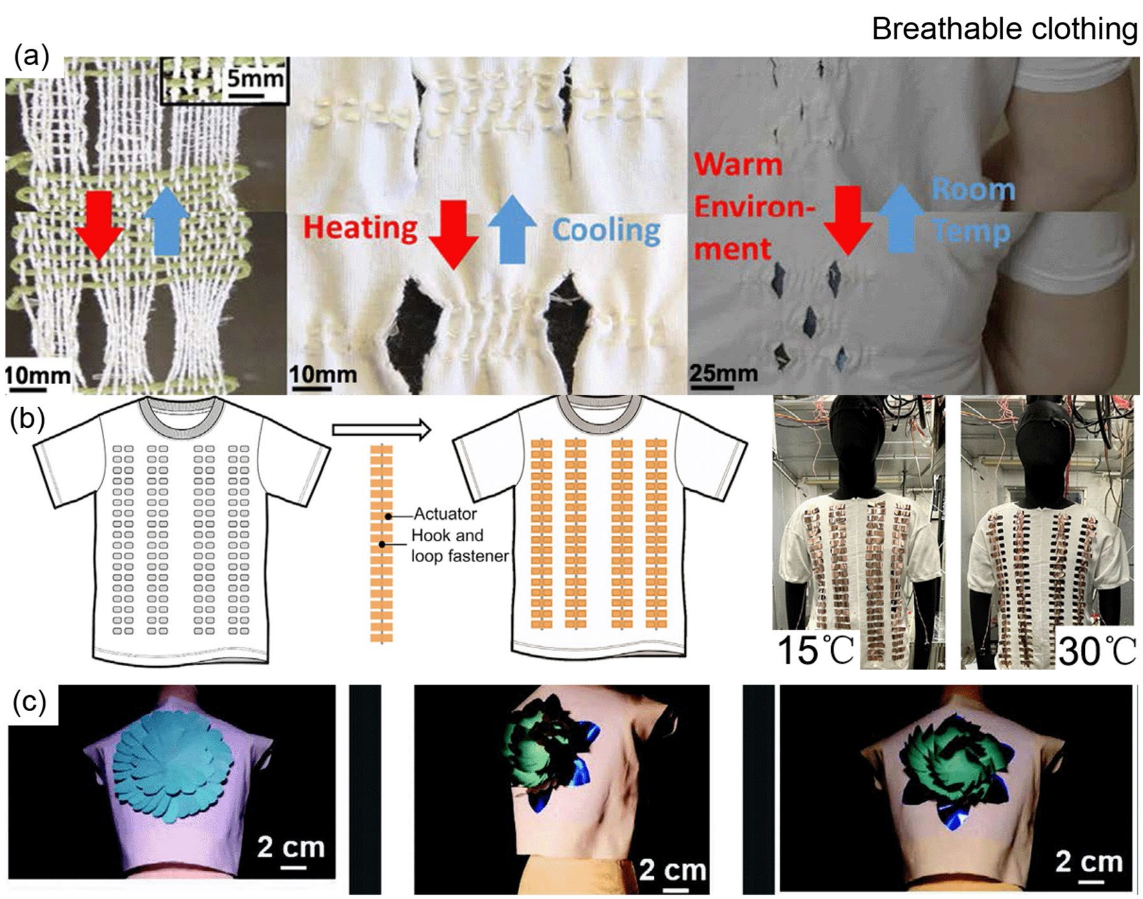

Fig. 16 **a** Breathable garment with a thermal textile actuator; Reproduced with permission from Ref. [84], Copyright 2019, Amer Chemical Soc. **b** Thermo-regulating T-shirt with thermal textile actuators; Reproduced with permission from Ref. [113], Copyright 2022, Elsevier. **c** Ventilated garment with photothermal actuators; Reproduced with permission from Ref. [63], Copyright 2020, Wiley

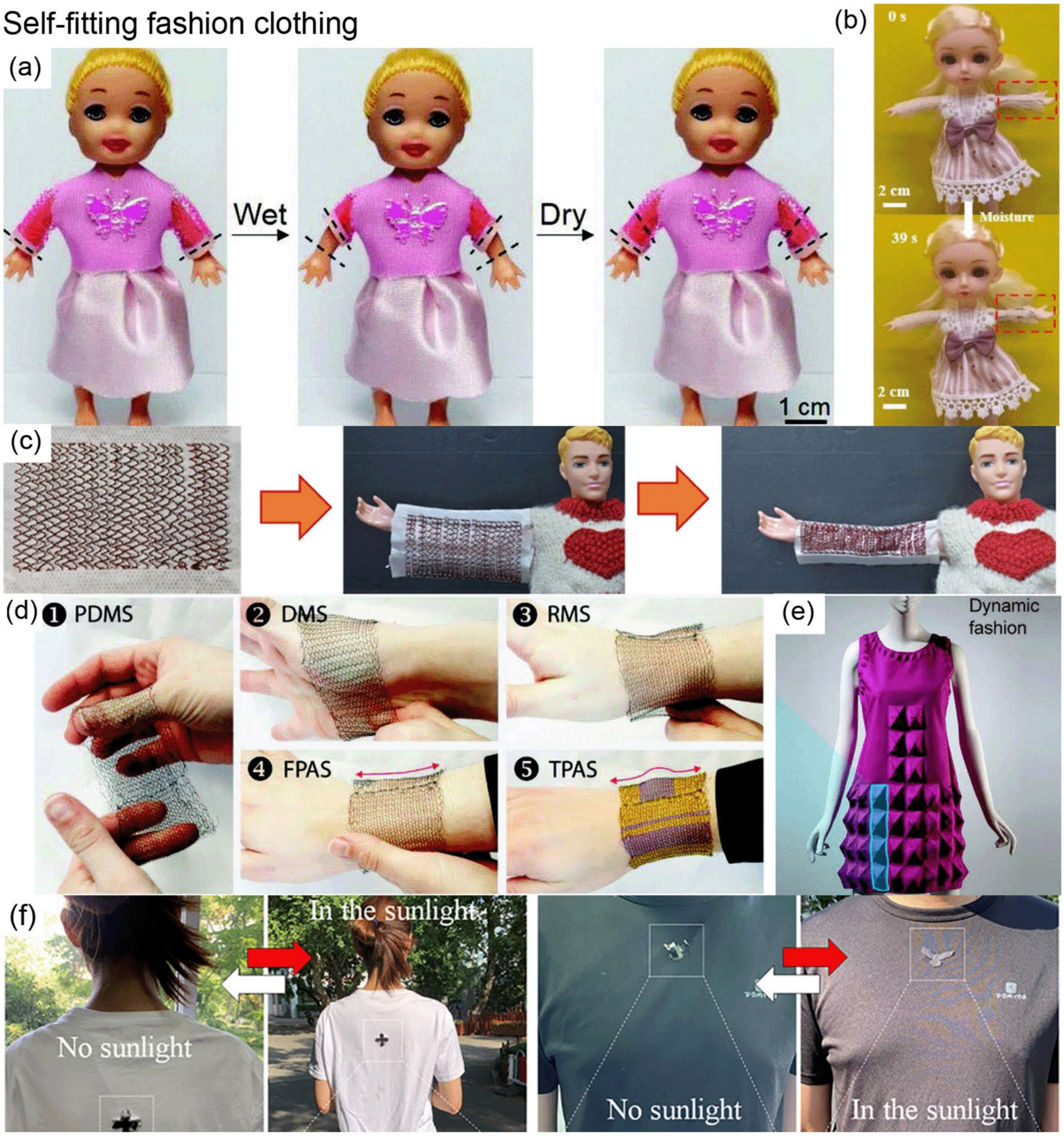

Fig. 17 **a** Self-fitting sleeve with a woven silk textile; Reproduced with permission from Ref. [114], Copyright 2019, Wiley–VCH Verlag Gmbh. **b** Self-fitting sleeve with a woven chitosan and CNT fabric; Reproduced with permission from Ref. [94], Copyright 2021, Wiley–VCH Verlag Gmbh. **c** Self-adapting dress using homochiral cotton-hydrogel; Reproduced with permission from Ref. [115], Copyright 2022, Springer Nature. **d** Self-fitting sleeve with a knitted SMA textile actuator; Reproduced with permission from Ref. [83], Copyright 2019, Wiley. **e** Dynamic fashion dress with bladder textile actuators; Reproduced with permission from Ref. [98], Copyright 2020, Wiley. **f** Wearable light-driven ornaments; Reproduced with permission from Ref. [116], Copyright 2021, Amer Chemical Soc

the six types of textile actuators, humidity and thermal textile actuators show great potential in manufacturing breathable clothing.

Humidity textile actuators with safe stimulation are well suited for breathable garments. In Fig. 15a, a PPy/PET film engraved with ordered fan-shaped openings is pasted on the fabric substrate of clothing [112]. During exercise, the openings on the clothing promptly switch from closed to open states, driven by sweat, to reduce skin heat and perspiration. Additionally, sodium alginate (SA)/GO/PU/PDMS films with customised shapes are attached to the fabric substrate to design an intelligent T-shirt (Fig. 15b) [85]. Activated by sweat, the actuators on the T-shirt flex, wicking away sweat and cooling down, thereby making the wearer feel more comfortable. Figure 15c shows another piece of breathable clothing with a series of semicircular stomas carved on a woven wool fabric [44]. These carved holes close in dry and cold conditions to keep the wearer warm, while they open in hot and sweaty conditions to evaporate sweat and lower the skin temperature. Also, woven viscose/PET textile actuators are developed for a breathable garment with array flappers (Fig. 15d) [18]. The flappers roll up to form small holes in a wet environment and unfold to close the holes in a dry environment, thereby managing the wearer's sweat and heat loss. Besides, moisture-responsive flaps made of nylon-Ag heterostructure are pasted on the fabric substrate to form a breathable garment (Fig. 15e) [23]. The flaps open to expel sweat vapour after the wearer starts exercising for ~ 5 s and returns to a closed state after the wearer stops.

Moreover, thermal textile actuators have also been used to design breathable clothing. For instance, Fig. 16a depicts a breathable shirt composed of an LCE textile actuator with pores [84]. The textile actuator contracts to open the pores after 10 min in a warm environment and expands to close the pores after 5 min at room temperature, thereby effectively regulating skin sweat and temperature. Figure 16b also shows a ventilated garment covered with rectangular thermal textile actuators composed of metalized PE films [113]. The actuators open in a high-temperature environment to enhance body heat dissipation and return to their initial flat shapes in a low-temperature environment to prevent heat

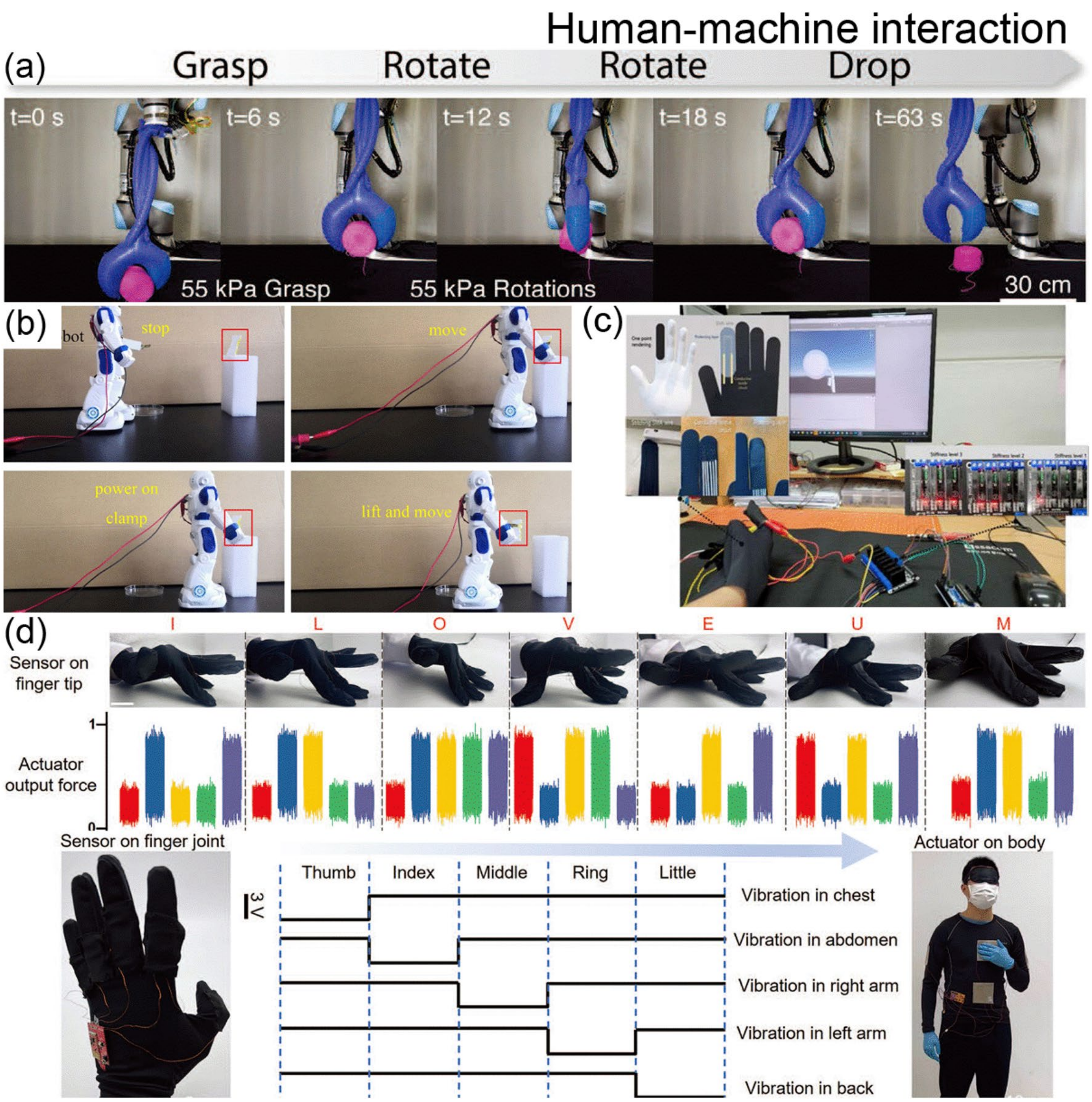

Fig. 18 **a** Motions of a multi-chamber claw gripper with knitted bladder textile actuators; Reproduced with permission from Ref. [48], Copyright 2023, Wiley–VCH Verlag Gmbh. **b** Gripping process of a smart robot with electrothermal actuators; Reproduced with permission from Ref. [117], Copyright 2020, Elsevier Science Sa. **c** Virtual reality glove with SMA textile actuators; Reproduced with permission from Ref. [81], Copyright 2022, Korean Fibre Soc. **d** Output force signals and haptic feedback of an actuating glove based on hand gestures; Reproduced with permission from Ref. [19], Copyright 2023, Wiley–VCH Verlag Gmbh

dissipation, thus automatically adjusting the temperature change of 2.2 ~ 2.6 °C to adapt to the ambient temperature change of 15 ~ 35 °C. Moreover, Fig. 16c indicates a photothermally driven ventilating garment made of 46 pieces of biaxially oriented PP (BOPP) petals [63]. Under an outdoor sunlight intensity of 0.1 W cm^{-2}, the petals curl like a flower, opening ventilating channels to evacuate skin heat and perspiration. Then, the petals recover to their original shapes in the darkness, covering the stomatal channels.

Self-fitting Fashion

Self-fitting fashion clothing with textile actuators can dynamically deform to adjust shape and size in response to varied environmental gradients. This can automatically improve body fit, aesthetics, and ease of donning or doffing. Humidity textile actuators composed of natural materials and thermal textile actuators made of SMAs have been designed as prototypes for self-fitting clothing.

Figure 17a demonstrates the application of a humidity textile actuator made of woven silk yarns in self-fitting sleeves [114]. The sleeves shrink by ~ 45% when exposed to moisture and then return to their original length after drying, making them suitable for automatic shape deformation of clothing under wet or dry conditions. Figure 17b presents a similar self-adapting sleeve made of a woven chitosan and CNT fabric [94]. In high humidity, the sleeve generates a large contraction within 39 s, thereby shortening the length of the sleeve. Also, a cotton-hydrogel textile actuator is rolled into a cylindrical shape to form a toy "dress" (Fig. 17c) [115]. Initially, the "dress" does not fit the size of the toy's arm. After applying water mist, the "dress" generates super contractions to fit the toy's arm.

Furthermore, SMA wires are knitted into a thermal textile actuator and used in a self-fitting wrist sleeve, as outlined in Fig. 17d [83]. The self-fitting process of the sleeve involves five states. They are pre-donned martensite state with an oversized shape, deformed martensite state with pulling force, relaxed martensite state, fitted-partially austenite state with heat contraction, and tight-partially austenite state with conforming to wrist curvature. Besides, textile actuators are also used to design dynamic and fashionable clothing. For example, a dynamic fashion dress composed of bladder textile actuators is exhibited in Fig. 17e [98]. Also, a wearable artificial flower and an eagle made of MXene/polyethylene films are integrated on the fabric substrates of shirts (Fig. 17f) [116]. Under sunlight, the petals of flower bow down to blossom, and the eagle spreads its wings, endowing the clothing with fashionable and aesthetic function.

Human–Machine Interaction

Human–machine interaction refers to the exchange of information between humans and machines through Internet technologies. Textile actuators in human–machine interaction can perceive external stimuli and provide interactive responses to the wearers, which have garnered growing attention. Wearable manipulative robots and haptic feedback gloves are two classic applications of textile actuators in human–machine interaction.

Wearable Manipulative Robots

Wearable manipulative robots with textile actuators are developed to provide safer, smarter, and more mechanised functions to replace humans in hazardous, heavy, complex, or tedious activities. As shown in Fig. 18a, a claw gripper with knitted bladder textile actuators is connected to a robotic arm. The arm can be actuated by a pressure of 55 kPa to grasp and rotate within 12 s [48]. Furthermore, Fig. 18b proposes a wearable gripper with electrothermal actuator films made of graphite paper and polyimide, which can generate 250° bending within 10 s at a voltage of 6 V [117]. The gripper worn on a robotic hand has outstanding manoeuvrability and can hold a plastic foam sheet of 122 mg, moving forth and back on command.

Haptic Feedback Gloves

Haptic feedback gloves with textile actuators can sense and provide tactile feedback vibrations for the wearer to interact with their surroundings. For instance, Fig. 18c validates an interactive system of a virtual reality glove with stitched SMA textile actuators. By touching the contour of an object through three various actions, a dynamic feedback force of 0.8 ~ 0.4 N can be provided to the wearer at the sensing point within 5.2 ~ 20 s [81]. In Fig. 18d, an air-permeable vibrotactile glove composed of electric textile actuators can convert electrical signals into mechanical vibrations through electrostatic effects. The glove can generate a dynamic output force of 0.02 ~ 0.06 N [19]. The actuator glove worn on the hand can perceive the vibration patterns of gestured words or sentences and transmit them from a sensor glove within 28 ~ 50 ms. After being seamlessly integrated with an ordinary garment, the actuator glove utilises coding rules to deliver controlled vibration signal feedback in real time by flexing fingers at different positions on the wearer's body.

Table 2 Applications of textile actuators in smart wearables

Application	Smart wearable suits	Textile actuator	Integrated micro-electronic system	Output performance					Refs.
				Force	Strain	Response	Other	Weight	
Aerospace garments	Compression garment	Thermal- ~ 70 °C		43.6 mmHg		~ 180 s			[17]
	Compression garment	Thermal-120 °C		67 mmHg	45%				[103]
Mobility-assistive exosuits	Sleeve	Thermal -6.4 V		53.4 N	30%	10 s		30.7 g	[25]
	Wrist sleeve	Thermal-62 °C			163°	~ 30 s			[71]
	Exosuit	Electrical	Bowden cable sensor, battery	0.17 N·m/kg			Aid ~ 9.3%	5,000 g	[109]
	Arm-lift	Bladder-50 kPa	Button valve, logic circuit	< 30 N	< 90°	38 s	20,000 cycles		[110]
	Ankle exosuit	Thermal		~ 10.5 N	2%	0.5 s		428.5 g	[111]
	Glove	Bladder-172 kPa	Padded wheel-chair	15 N	4.3%		Aid ~ 76.7%	78.6 g	[118]
	Knee exosuit	Bladder- ~ 40 kPa	Sensor, battery, electric circuit	25.7 N·m	30°	7.5 ms	Aid ~ 3.5×	298.3 g	[119]
	Wrist assistance	Bladder-100 kPa		190 N			6,000 cycles		[120]
	Shoulder assistance	Bladder	Sensor	16 N·m	90°		Aid ~ 9%		[121]
Healthcare wearables	Prosthesis	Magnet- ~ 185 mT							[16]
	Chinese massage	Bladder		10 kPa		< 8 s			[49]
	Vest garment	Thermal	Sensor	37.6 mmHg		< 500 s		~ 600 g	[104]
	Compression therapy	Bladder-50 kPa	Sensor, pump, control board	30–50 kPa		25 s			[105]
	Knee rehabilitation	Bladder	Sensor, control board				Improve 25%		[107]
	Tourniquet	Humidity				~ 30 s			[108]
	Compression garment	Bladder		4 kPa	110%		5,000 cycles		[122]
	Compression garment	Thermal	Sensor, control circuit	5.5 kPa	75%	30 s			[123]
	Compression garment	Thermal- ~ 34 °C		~ 40 mmHg		380 s			[124]
	Ankle–foot exosuit	Bladder-200 kPa		177.8 N		0.2 s	Improve 39%	203 g	[125]
Comfort-adapting clothing	Breathable shirt	Humidity-water			~ 180°	~ 28 s			[22]
	Breathable shirt	Light-0.1 Wcm^{-2}			~ 90°	~ 10 s			[63]
	Self-fitting sleeve	Thermal- ~ 45 °C		0.7 N	6%				[83]
	Breathable shirt	Thermal–80 °C			100%	600 s			[84]
	Breathable shirt	Thermal-31 °C				~ 300 s	Adjust ~ 1 °C		[86]
	Sleeve	Humidity			~ 1 cm	39 s			[94]
	Breathable shirt	Humidity- ~ 86%			~ 180°	~ 20 s	Adjust ~ 3 °C		[112]
	Breathable shirt	Thermal- > 30 °C				~ 50 s	Adjust ~ 2 °C	306.2 g	[113]
	Garment/sleeve	Humidity			~ 1 cm	75 s			[114]
	Sleeve	Humidity-water				~ 450 s	Supercontract		[115]

Table 2 (continued)

Application	Smart wearable suits	Textile actuator	Integrated micro-electronic system	Output performance					Refs.
				Force	Strain	Response	Other	Weight	
Human–Machine interaction	Feedback glove	Electrical	Sensor, coding/decoding/circuit	~60 mN		~0.05 s		1.65 g	[19]
	Gipper claw	Bladder-55 kPa	Arm			12 s	Grasp		[48]
	Feedback glove	Thermal-~40 °C	Sensor, control board, power	~0.8 N		~20 s			[81]
	Gripper	Electrical-6V	Robot, power	3.48 mN	250°	10 s	Grasp	0.06 g	[117]
	Gripper	Bladder-55 kPa	Arm	1.14 N		37 s	Grasp	162 g	[126]
	Haptic display	Electrical-1 kV	Battery, Bluetooth, circuit board	< 0.2 N		~500 s		600 g	[127]
	Feedback glove	Electrical-0.3 kV	Resistor capacitor, circuit	50 N		30 s		28 g	[128]

Design Challenges for Next-Generation Smart Wearables

Table 2 tabulates the application data of textile actuators in smart wearables. Several clear trends can be inferred. For example, wearable power suits, including aerospace garments, healthcare wearables, and mobility-assistive exosuits, perform with high actuation forces. They are primarily composed of bladder textile actuators and SMA thermal textile actuators. Furthermore, comfort-adapting clothing often employs humidity or thermal textile actuators to exert high actuation deformation, including breathable clothing and self-fitting fashion clothing. Unlike the applications in comfort-adapting clothing, textile actuators are always paired with other electronic devices in human–machine interaction. In line with these results, the five challenges associated with next-generation smart wearables composed of textile actuators are summarised in this section.

Safety

Although some textile actuators in smart wearables exhibit good output actuation performance, they are triggered by hazardous or uncommon external stimuli. For example, electric textile actuators composed of DEAs always require several kilovolts to generate actuation. Additionally, thermal textile actuators are typically heated beyond 45 °C to achieve thermal actuation. Besides, the pressure stimulation required to generate a high actuation force for bladder textile actuators normally exceeds 50 kPa. Obviously, these stimuli may bring risks or cause discomfort to the human body; thus, the application of textile actuators in smart wearables must focus on safety. In addition, electricity is often introduced into wearable power suits and human–machine interaction, which may cause harm to the wearer in the event of electrical leakage.

Human Body Fit

Most applications of textile actuators in smart wearables involve tiny or local prototypes, such as compression, assistive or deformation sleeves, assistive or haptic feedback gloves, and breathable clothing with holes on the back. Additionally, due to shape deformation or size changes caused by the actuation process of textile actuators, the pre-determined sizes of smart wearables may become inappropriate for the human body. Thus, the implementation and commercialization of textile actuators in actual smart wearables require solving the customisation problem of fitting the human body shape.

Some textile actuators composed of actuating fibres or yarns, including nylon, PET, and natural fibres, exhibit remarkable compatibility and friendliness to human skin. However, they do not possess strong actuation capabilities and cannot effectively serve as autonomous actuation components for smart wearables. To improve the actuation performance of textile actuators, supplementary actuating materials, such as SMA wires, CNT yarns, and micro- or nanoparticles, are often doped. Nevertheless, these actuating materials are not common components of clothing textiles, and their incorporation may reduce the skin affinity of smart wearables. These may lead to a reduction in body compatibility, skin friendliness, and breathability. In addition, these actuating materials may also introduce new structural interfaces between smart wearables and human skin. The interfaces may not only introduce discomfort or potentially severe skin damage during the actuation process but also unstable actuation performance.

Flexible Textile Actuator Technology

Thermal textile actuators and bladder textile actuators are widely used in smart wearables, accounting for nearly 33.3% and 30.8%, respectively. Nevertheless, most bladder textile actuators require connections to rigid power sources and control boards to provide the necessary pressure, which are not perfect candidate textile actuators for smart wearables. Most thermal textile actuators in smart wearables are composed of self-actuating SMA wires, which are suitable for integration into various kinds of smart wearables through textile-forming technologies. However, they must be manually reprogrammed to be driven repeatedly. Moreover, humidity textile actuators are popular for comfort-adapting clothing, but their low output force and slow response speed are troublesome issues for other types of smart wearables.

Actuating materials are essential for the development of textile actuators. However, potential difficulties may arise when using some actuating materials. For instance, the unsafety of activated high-voltage for DEs, the operational barriers to pairing electrochemically responsive materials with electrolyte media, and the harmful effects of UV radiation on human body. Thus, it is likely that only electrothermally or NIR photothermally actuating materials are suitable for developing electrically or photothermally thermal textile actuators for smart wearables. Thanks to the rarity of magnetic stimulation, magnetic-responsive materials for smart wearables have seldom been reported. Therefore, actuating materials confront various challenges in the development of textile actuators for smart wearables, like safety concerns, operational difficulties, poor output performance, etc.

The integration of fabrics and actuating materials relies heavily on textile structure formation technologies. They have a significant impact on the structural morphology, mechanical anisotropy, shape, size, and actuating behaviour of textile actuators in smart wearables. However, these textile-forming technologies possess their own pros and cons. For example, knitted textile actuators exhibit high flexibility but a tendency to slide at intersections during the actuation process. This may lead to suboptimal force transfer and uneven deformation. Besides, woven textile actuators show remarkable structural stability, but their maximum actuating deformation potential cannot be fully realized. Compared with knitted or woven textile actuators, braided textile actuators exhibit a more stable fabric structure but demonstrate a smaller actuation strain. In contrast, knotted textile actuators generally provide superior actuation performance, but the knotting process involves a greater degree of manual operation. Bonding techniques have been proven to effectively integrate actuating materials with the existing fabrics, but they introduce challenges for the interfaces between actuating materials and fabric substrates.

Output Performance

Textile actuators in smart wearables yield different output performance metrics. Nevertheless, there are several limitations in terms of the output performance, including inadequate output force, long response time, improper strain, and uncertain durability. For instance, the maximum output force of a thermal textile actuator using SMAs can reach 67 mmHg. The force is suitable for orthostatic intolerance (40 ~ 80 mmHg) after spaceflight but significantly lower than mechanical counterpressure of 222 mmHg during space extravehicular activities. Besides, the response speed of textile actuators in breathable clothing is not fast enough; often, tens of minutes are needed to reduce the skin temperature by 1 ~ 3 °C. In addition, the bending strain or contraction of textile actuators in mobility-assistive wearables is diverse, ranging from 30° to 163° or from 2 to 30%. Thus, these existing output performances pose challenges to the application of textile actuators in smart wearables.

Other performance indicators, including washability, weight, durability, and stability, are also important for smart wearables composed of textile actuators. However, these indicators are seldom discussed in the literature due to a lack of attention. For instance, significant advancements have been made in breathable clothing, but ventilation holes are always designed on the back of garments, which may compromise their durability during machine washing. Additionally, the shape, size, or weight of bladder textile actuators with inflated chambers is often large, which impedes the feasibility of developing portable or lightweight smart wearables.

Integrated Microelectronic System

Textile actuators in comfort-adapting clothing are typically not paired with other microelectronics. They can sense the wearer's surrounding environment or skin status, automatically adjust skin temperature and perspiration, or automatically alter garment shapes to fit the wearer's body. However, textile actuators in other smart wearables cannot autonomously execute the entire process without involving other microelectronic components, such as sensors, power supplies, control boards, and interconnections. As a result, the integration of these microelectronic components with textile technology is also urgent and important.

Sensors can detect various physical, chemical, or biological information and transform the information into electrical or digital signal output. They play a vital role in establishing the connection between human body and smart wearables, as well as facilitating communication between smart wearables and the surrounding environment [129]. For instance, several simple sensors have been developed to control the actuation process of electric or bladder textile actuators in smart wearables. Moreover, compatible combinations of sensors and actuators have been designed to achieve precise and efficient feedback and control, improving the human–machine interaction capability of smart wearables. Nevertheless, the key challenge for integrating sensors into smart wearables lies in the high performance and reliable stability of textile sensors.

Most smart wearables rely on electrical energy to power textile actuators through electricity, pressure, joule heat, or NIR radiation stimulation. Hence, energy power systems, including textile-based generators and energy storage devices, are being rapidly incorporated into textiles. Textile-based generators can collect various forms of energy from human body or ambient environment, like frictional energy, humidity, wind energy, or solar energy, and convert the energy into electrical energy. For example, many triboelectric generators have been integrated with commercialised fabrics to harvest energy from human motion and wind via contact-electrification and electronic induction [130, 131]. Recently, emerging moist electric generators that harvest energy from atmospheric moisture have attracted great attention in self-powered textiles [132]. Besides, thermoelectric generators that harvest energy from waste heat have been combined with fabric platforms [133]. Nevertheless, these textile-based generators often exhibit microwatt levels and instantaneous low-grade energy, which cannot meet the energy requirements of smart wearables. As a result, energy storage devices are expected to effectively store the energy produced by these textile-based generators to form textile-based power management systems. Textile-based supercapacitors, Li-ion batteries, Zn-ion capacitors, and Zn-ion batteries have become promising energy storage devices [134, 135]. However, the power, capacity, durability, and compliance of these textile self-powered systems still need to be further improved to satisfy the demands of smart wearables.

Perspectives

The employment of flexible textile actuators in smart wearables exemplifies some discernible trends. Over the past few decades, various theories and technologies have been developed for soft actuators in soft robotic applications. Many of these strategies may be applied to textile actuators for smart wearables. Nevertheless, there are inherent disparities between textile actuators and soft actuators in the integration of structural platforms and actuating materials. To better apply textile actuators in smart wearables, solutions or improvements to the above challenges should be gradually explored in the future. The following insightful perspectives are proposed as follows:

(1) Innovative, flexible textile-forming technology merits exploration. The integration of actuating materials and fabric structures includes, but is not limited to, actuating materials and textile-forming methods. These common textile-forming technologies often create 2D fabric structures for textile actuators, leading to insufficient output performance. A composite textile-forming technique may contribute to a novel 3D textile structure for textile actuators in smart wearables, improving output performance and human body fit. Textile machines, textile structures, actuating unit connections, and integrated strategies of other microelectronics should also be considered. Furthermore, twisting and coil insertion into fibres, yarns, or wires during the textile-forming process may greatly improve the output performance of textile actuators. In addition, surface modification may contribute to the immobilisation of micro- or nanoparticle-based actuating materials on the surface of fibrous substrates and the stability of output performance.

(2) Endeavours can be made to develop novel actuating fibres or yarns. Although non-fibrous actuating materials can be bonded with the existing fabrics to form textile actuators, actuating fibres, or yarns as textile units are more attractive. The actuating fibres or yarns may have a balanced compromise in terms of stretchability, skin affinity, and actuation performance. The introduction of new micro- or nanoparticle-based actuating materials into fibre substrates prior to spinning is regarded as an innovative approach for designing high-performance smart wearables. For example, modified LCEs with thermal memory behaviour are expected to be applied to smart wearables owing to their superior skin affinity and photo-responsive features. Besides, fresh natural fibres or polymer fibres with actuating properties, excellent skin affinity, and weavability are worth exploring. Furthermore, when applied to smart wearables, such as sleeves and back vents, the shape and size features often limit the output performance of textile actuators. To improve the output performance, the size and proportion of textile actuators in actual smart wearables should be customised from small to large areas to fit the human body shape.

(3) The seamless integration of other textile-based microelectronics into smart wearables remains an ongoing concern. Typically, sensors and power supplies are two important microelectronics used in smart wearables. Once loaded onto textile platforms, the raw performance of sensors and power supplies may be significantly degraded due to the stretchability of fabric substrates. To improve performance, attention should be

given to the integration strategies of microelectronics and fabrics. Many strategies, such as textile architectures, sensing mechanisms, and textile electrodes, have been proposed for textile-based sensors. For power supplies, some green textile generators have been paired with textile energy storage devices to achieve energy management for smart wearables. However, these devices are still unable to provide sufficient energy for smart wearables in real time due to the low amount of output energy and extended charging time. Connecting multiple textile-based generators and ion batteries in series can meet the energy needs of smart wearables over short periods of time. Increasing the size but controlling the weight of power supplies and developing new electrode or electrolyte materials with high energy are also effective methods.

(4) Safety protection systems need to be implemented in smart wearables. Recently, high-intensity stimuli such as UV radiation, temperatures greater than 45 °C, and input voltages beyond 36 V have been applied to textile actuators. For these unsafe stimuli, robust electrical and thermal insulation is required when applied to smart wearables. In addition, reducing the intensity of stimulation can achieve safe stimulation. Accordingly, the actuation behaviour of textile actuators in smart wearables should be reassessed after adding supplementary protective components or reducing the stimulus intensity.

(5) Smart wearables with long-term output performance and washability are in high demand. Daily conform-adapting clothing that requires laundering can be worn every day, whereas other forms of smart wearables are not disposable, even if they do not require frequent laundering. However, to date, little research has been conducted into these aspects of smart wearables. When evaluating the longevity and launderability potential of smart wearables, a special attention should be given to the damage, waterproofing, performance degradation, positional stability, and structural stability of textile actuators. By consistently prioritising the durability and washability of smart wearables, the prospects for large-scale commercialization may be significantly enhanced.

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Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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