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Advances in electroactive polymer-based haptic actuators for human-machine interfaces: from principles to applications

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Highlights:

- EAPs provide precise motion control for advanced haptic interfaces.
- Performance optimization of EAPs enhances their application potential.
- AI integration will enable smarter, personalized haptic interactions.

Abstract: In the context of rapid technological advancement, haptic human-machine interfaces (HMIs) enhance user experience by simulating touch. Electroactive polymers (EAPs) are smart materials with high responsiveness, flexibility, and tunability, making them suitable for haptic actuators and feedback applications. This review examines the role of EAPs in haptic interaction, analyzing driving mechanisms, structural design, functional materials, fabrication methods, and practical applications. We also address challenges like performance limitations and manufacturing complexities, while discussing future trends in material optimization, structural design, and innovative driving strategies. This review serves as a valuable reference for future research and technological advancements in EAPs.

Keywords: electroactive polymers; haptic; human-machine interface; actuators

1. Introduction

The skin is the largest organ of the human body, accounting for approximately 15% of body weight. Its dense network of tactile nerve endings and receptors enables it to detect mechanical, thermal, and chemical signals in the environment with remarkable sensitivity. As one of the primary means by which humans perceive the world, tactile sensation is crucial for maintaining and enriching various physical activities in our lives, making it a focal point of research in Human-machine interface (HMI) devices [1–6]. Electroactive Polymers (EAPs) have become key materials in haptic feedback due to their unique properties, such as high energy density, lightweight, stretchability, and good biocompatibility [7–10].

These smart materials can undergo changes in shape or volume under electrical stimulation, generating signals such as force, vibration, or temperature to achieve precise tactile feedback. This characteristic endows EAPs with significant potential in tactile drive technology, making them an ideal choice for innovative HMI devices.

Research on EAPs began in the 1960s, and with advancements in nanotechnology and materials science, researchers gradually introduced various types of EAP materials, including polymer gels, conductive polymers, and ionic polymers. They have progressively focused on enhancing response speed, force output, and durability to accommodate more complex tactile applications. Over the past decade, EAPs have experienced rapid development in the field of haptics, with researchers integrating EAPs into haptic human-machine interfaces to develop devices capable of simulating a range of tactile experiences, such as haptic feedback gloves and electronic skin in virtual reality [11–16]. However, despite the significant potential of EAPs in the realm of haptic actuators, several challenges remain [17]. For instance, improving the response speed and efficiency of EAPs, extending their lifespan, and effectively integrating them into existing electronic systems are ongoing issues. In specific application scenarios, such as medical prosthetics, EAPs also face challenges related to biocompatibility and long-term stability. In recent years, researchers have focused on optimizing the driving efficiency and stability of EAPs to achieve longer operational times and greater tactile precision, further enriching the tactile emotional experience.

Amid the rapid development of smart materials in the field of HMI, many research teams have provided detailed reviews [18]. Tan *et al.* [19] explored the high actuation performance of soft haptic actuators and the principles and challenges of their driving stimulation classifications. Meanwhile, Yang *et al.* [20] focused on the applications of active materials in virtual and augmented reality, discussing innovations in haptic technology, sensors, actuators, and future trends in remote haptic interaction. However, there is still a lack of systematic summaries regarding EAPs in the field of haptic actuators.

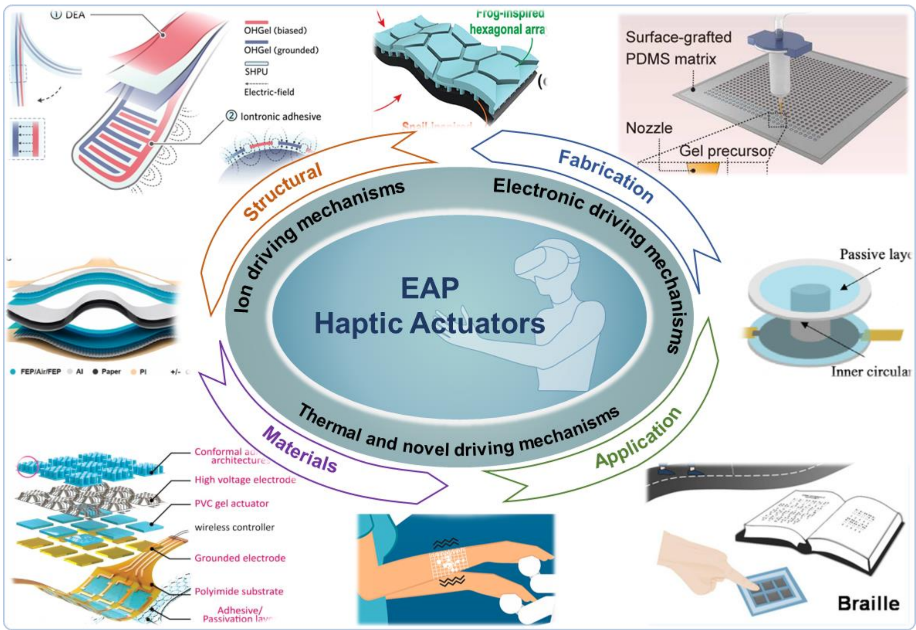

Figure 1. Overview of EAPs haptic actuators used in HMIs [21–28]. Reprinted with permission. Copyright 2023, John Wiley and Sons. Copyright 2024, Elsevier. Copyright 2021, Elsevier.

In this review, we categorize and summarize the driving principles of EAPs, exploring their structural design methods, material types, and preparation techniques for haptic actuators (see Figure 1). The focus will shift to practical application examples, analyzing the current challenges faced and outlining future development trends. Through this review, we aim to provide a reference framework for researchers and engineers engaged in tactile drive applications, while inspiring new research ideas and innovative designs.

2. Driving principles of EAPs

In exploring the applications and advances of EAPs in haptic HMIs, it is essential to first understand how these smart materials respond to external stimuli to generate mechanical motion. EAPs operate based on their ability to undergo mechanical deformation under an electric field. These smart materials typically exhibit dielectric elastomer properties, where the internal molecules realign in response to changes in the electric field when a voltage is applied. Consequently, the material's volume or shape changes, making EAPs an ideal choice for manufacturing tactile interaction devices. Based on the EAPs' driving principles and activation mechanisms, the most common driving principles for EAPs are outlined in Table 1, which summarizes the performance characteristics of different types of EAP-based haptic actuators.

Table 1. Performance of Different Types of EAP Haptic Actuators.

Mechanism	Structure	Materials	Input (electrical signal)	Output parameters / character	Array Actuator size	Application	Ref.
Ion driving mechanisms	Multilayer	Ionic liquid, lithium salt PEDOT:PSS electrodes	0.1–110 Hz ±2 V	0.48 mN Bending: 3 μm Ionic conductivities: 3.0×10^{-4} S/cm	Ring: 5 actuators Thickness: 55 μm Area: 20 × 4 mm^2	Finger ring-shaped haptic interface	[29]
	Fabric	Liquid metal-hydrogel	135 V	Stretchability: 400%	128 pixels over the palm	Fully integrated breathable haptic textile	[30]
Electronic driving mechanism	"Air-bubble" electret structure	FEP/Air/FEP/Al/PI films	10–500 Hz 5–20 V	Power density: 3.25 W/kg	Array: 3 × 3 Pixel size: 2 × 2 cm^2	Wearable electronics	[26]
	Multilayer chamber	Electret	100–150 Hz 200 V	Force :55 mN	18 pixels 6 × 3 cm^2	Cognitive Assistance Navigation Braille	[31]
	Multilayer	DEA	0–400 Hz 0–4 kV	Force: 8.48 N Displacement: 0.46 mm	Diameter < 15 mm Height < 10 mm	Fingertip tactile device	[25]
Thermal or novel driving mechanisms	Auxetic structure	Shape-memory alloys	2.5–7.5 V	Time to reach 60 °C: 1–10 s Resistive force:20 N	SMA: 350 μm WHAF: 80 × 75 mm	Wearable haptic fabric	[32]
	Chamber	PVC gel composite Dielectric liquid	0.1–300 Hz 0–2.1 kV	Vibrational force: 2.4 N Height: 2.2 mm	Area: 38 × 38 mm^2 Thickness: 1.5 mm	Tactile display	[33]
	Chamber Laminated	Dielectric liquid Dielectric shell PET film	0–200 Hz 0–6 kV	Forces: 2.3 N Actuation stroke: 2.44 mm	Ten-pouch actuators Area: 14 × 14 mm^2	Cutaneous electrohydraulic wrist-wearable device	[34]

2.1. Ion driving mechanisms

Ionic polymer-metal composites (IPMCs) are among the most representative materials in ion-driven mechanisms [35,36]. As shown in Figure 2a, when a voltage (1–5 V) is applied across the ends of an IPMC, an electric field forms within the base membrane. Cations within the membrane bind to water molecules and migrate from the anode to the cathode, causing water molecule expansion on the cathode side and contraction on the anode side, leading to the macroscopic bending deformation of the IPMC. Another type of ion-driven material is gel-based ionic polymers [37,38], which are generally composed of a hydrogel matrix and ion exchange resins. The hydrogel matrix provides a structure to retain water molecules, while the ion exchange resin facilitates ion migration. When voltage is applied, the water molecules within the hydrogel move accordingly, driving ion migration in the ion exchange resin and resulting in volume changes in the gel material. These volume changes can be tailored by designing gels with varying structures and material compositions to achieve diverse shapes and movement modes, offering a wider range of applications for haptic HMI. Key characteristics of these materials include fast response speed, large deformation amplitude, and low energy consumption.

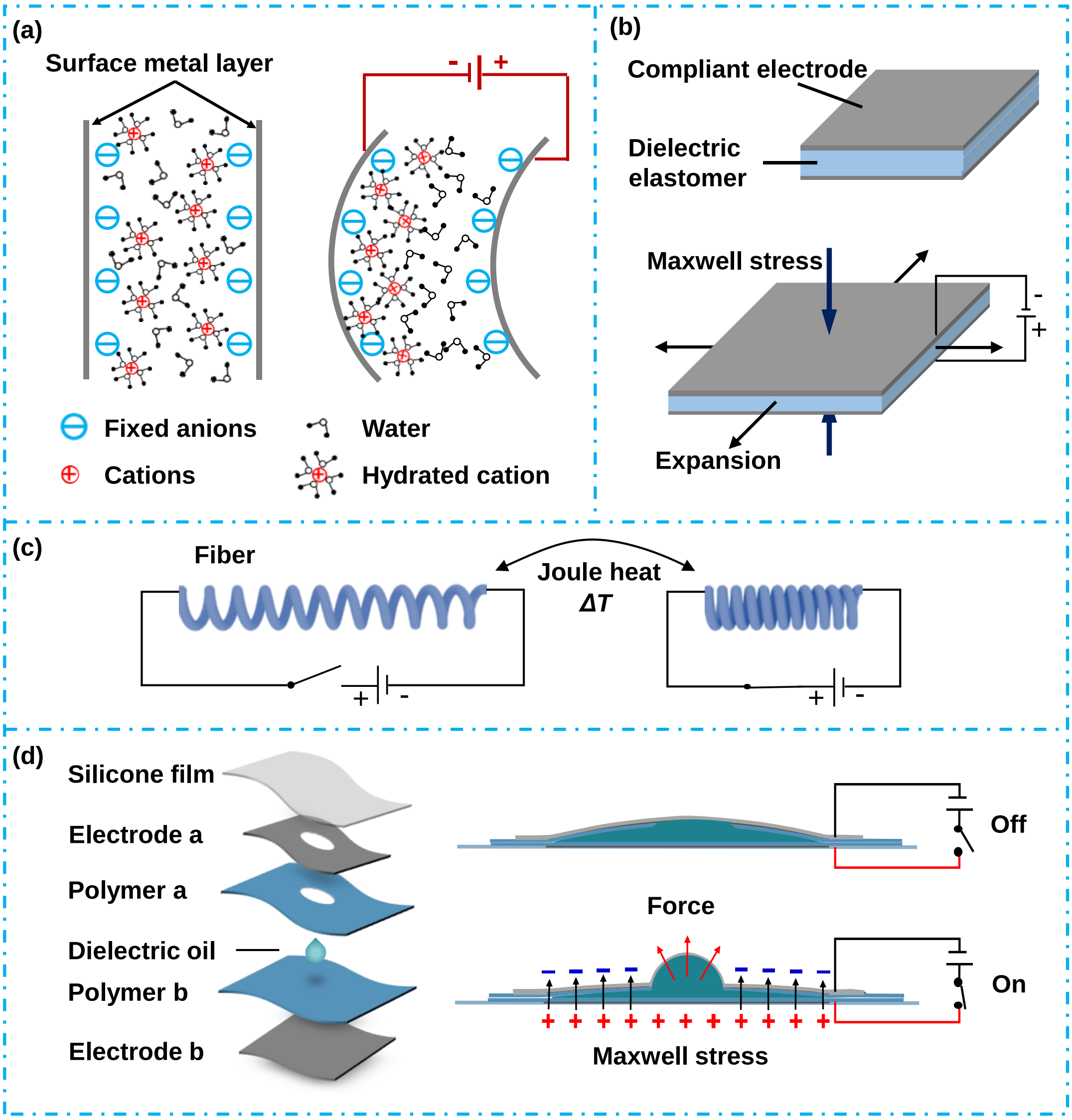

Figure 2. Driving principles of EAPs: **(a)** Ion migration. **(b)** Piezoelectric effect. **(c)** Electrically induced shape deformation. **(d)** Hydraulically amplified self-healing electrostatic.

2.2. Electronic driving mechanisms

Electronic driving mechanisms are common in dielectric elastomers (DEs) [39–41], a type of electroactive polymer material that operates based on the inverse piezoelectric effect. As shown in Figure 2b, when voltage is applied across the two sides of the DE, electrical energy is converted into mechanical energy. According to Maxwell's equations, the applied electric field generates mechanical stress within the material, causing a change in its internal polarization direction and leading to mechanical deformation [42,43]. Specifically, when voltage is applied along the thickness direction of the material (typically in the range of several kilovolts), the dielectric membrane undergoes strain due to the Maxwell stress induced by the high electric field. This strain causes the membrane to decrease in thickness and expand in area, resulting in a volume change. This volume change drives mechanical motion in the DE, such as expansion, contraction, or bending.

2.3. Thermal and novel driving mechanisms

In addition to traditional electronic and ionic driving mechanisms, thermal driving mechanisms and other novel driving technologies have gained widespread application in the field of haptic HMIs in recent years. Thermal driving mechanisms primarily rely on the deformation of materials when heated, typically achieved through thermal expansion or phase transitions (see Figure 2c). Unlike electronic driving mechanisms, the advantage of thermal driving is that it can directly drive material deformation using temperature differences or heat sources, without the need for complex circuits or high voltage. This offers a safer and simpler driving solution.

Thermal driving materials often use shape-memory polymers (SMPs) or thermally responsive materials [44–46], which undergo physical deformation upon heating and exhibit self-recovery or memory functions. SMPs are a special class of EAPs with shape memory properties. When an electric current is applied, SMPs undergo Joule heating, resulting in phase changes and shape alterations. This characteristic allows SMPs to achieve sustained deformation in haptic HMIs without the need for continuous current application to maintain the shape, thus reducing energy consumption. While SMPs do not possess inherent electrical conductivity, they can acquire electroactive capabilities by being combined with conductive materials.

In addition to thermal driving, other novel driving mechanisms are also being explored, such as light-driven, magnetic-driven, and chemical-driven mechanisms [38,47,48]. Light-driven mechanisms utilize light energy to trigger material deformation, typically for driving light-responsive materials or photoactive polymers. Magnetic driving uses external magnetic fields to influence magnetic materials, demonstrating unique advantages, particularly in miniature and nanoscale applications. Furthermore, chemical-driven materials undergo deformation through chemical reactions or ion exchange, and their tunability and environmental friendliness make them an emerging driving technology.

Although DEAs exhibit excellent electromechanical performance, they face challenges in the field of haptic actuators such as low driving force and difficulty in expressing complex shapes. To address these issues, the hydraulically amplified self-healing electrostatic (HASEL) actuator has emerged as a new type of artificial muscle, incorporating dielectric oil into the interior of DEAs [49]. The HASEL actuator integrates fluid-driven technology into the basic structure of DEAs, solving the issue of fluid's amorphous nature while also achieving self-healing properties. The basic structure of a HASEL actuator consists of a deformable flexible shell filled with liquid, with flexible electrodes partially covering the surface of the shell (as shown in Figure 2d). Under the influence of electrostatic forces, HASEL actuators compress the liquid, which is concentrated in areas not covered by electrodes (acting like pumping fluid) [50–52]. Herbert Shea's team [53] expanded on the principle of HASEL actuators by adding a stretchable thin film. When subjected to electrostatic forces, the liquid is compressed, resulting in strains exceeding 100%.

These novel driving mechanisms not only bring diverse options to the EAP field but also offer broad prospects for flexibility and functionality expansion in practical applications.

3. Structural design

In exploring the applications and advancements of EAPs in haptic HMIs, structural design emerges as crucial. The application of EAPs in haptic actuators primarily lies in their ability to mimic biological muscle characteristics, generating shape or size changes through electrical stimulation to achieve actuation. To enhance mechanical force output, researchers have developed various structural configurations for haptic actuators.

3.1. Multilayer structure

As shown in Figure 3a, stacking multiple layers of EAP films can significantly amplify the actuation stroke and force [54–59], thereby enhancing the intensity of tactile feedback. Additionally, combining EAPs with other materials, such as metals, ceramics, or different polymers, can improve the mechanical strength and durability of the actuators while maintaining their electroactivity (as illustrated in Figure 3b) [60,61]. This structure typically consists of two or more layers of dielectric materials, such as silicone rubber, with electrodes sandwiched between the material layers [62]. When voltage is applied, the dielectric material deforms due to electrostatic attraction, thereby generating tactile feedback. Hinchet and Shea [63] coated a poly(vinylidene fluoride-trifluoroethylene-chlorotrifluoroethylene) (P(VDF-TrFE-CTFE)) layer with shape memory polyurethane and using an insulating layer to control the friction coefficient and achieve precise control over the clutch's sliding force. These design approaches are particularly suitable for the manufacturing and integration of large-area soft electronic devices.

On the other hand, for small-area actuators, Zhao *et al.*[64] designed DEAs using a multilayer structure composed of silicone rubber and carbon nanotube (CNT) electrodes. By incorporating pre-stress between the electrode layers, the actuator achieves significant axial expansion and force output when an electric field is applied. The introduction of pre-stress not only improves the mechanical stability of the actuator but also enhances its response speed and force output during dynamic operations, ensuring the actuator performs well during repeated use (see Figure 3c).

3.2. Chamber structure

EAP actuators with a chamber structure generate haptic feedback by applying voltage to the electrodes, which causes the chamber to contract and deform [65–68]. Yu *et al.* [66] proposed a novel self-sensing soft pneumatic actuator (SenAct), which can achieve high-precision force and vibration feedback through closed-loop control, thus simulating realistic haptic perceptions. The design of the actuator employs a sandwich structure (as display in Figure 3d) which includes a stable and fast-response capacitive sensor that can simultaneously generate output force and monitor changes in capacitance. In another study, Chen *et al.* [22] developed a programmable, ultra-light, ultra-thin wireless wearable tactile electronic skin capable of fast response, large mechanical feedback force, and significant displacement output. Each actuator can be independently adjusted to generate a maximum normal force of 150 mN and normal displacement of 0.58 mm, while also enabling the presentation of textures in haptic feedback. This system relies on a portable multi-channel control circuit, allowing precise control of each electrohydraulic actuator to achieve various haptic modes. This design not only provides excellent responsiveness but also offers rich tactile experiences for complex applications.

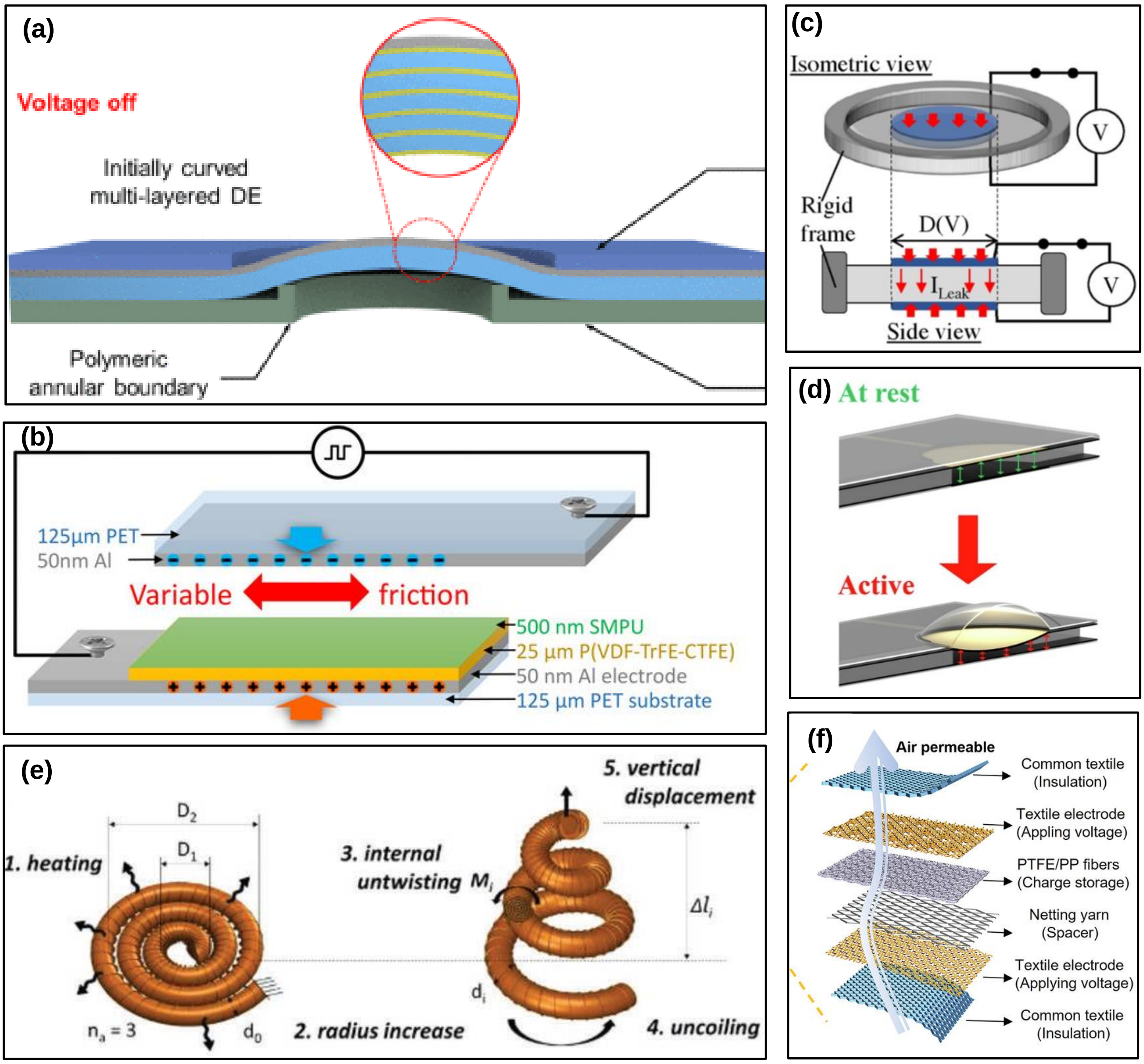

Figure 3. Structural designs: **(a)** Stacking multiple layers of the EAP film structure [69]. **(b)** Composite structure [63]. **(c)** Pre-stressed structure [70]. Reprinted with permission. Copyright 2021, Elsevier. **(d)** Chamber structure [66]. Reprinted with permission. Copyright 2022, Elsevier. **(e)** Twisted spiral structure [71]. Reprinted with permission. Copyright 2019, John Wiley and Sons. **(f)** Mesh fabric construction [72]. Reprinted with permission. Copyright 2022, John Wiley and Sons.

3.3. Fiber structure

EAP actuators with a fiber structure enhance material flexibility and response speed by utilizing elongated fiber forms, providing higher precision and flexibility for haptic feedback. These actuators typically employ one-dimensional fiber arrays or three-dimensional networks based on fiber weaving, where fiber deformation occurs upon applying voltage, enabling the realization of complex haptic feedback patterns [73–75]. Compared to traditional film or sheet structures, fiber structures offer greater flexibility and faster response times, allowing for more precise simulation of various tactile sensations.

Lamuta *et al.*[71] provided an innovative example (illustrated in Figure 3e) with their development of twisted spiral artificial muscles activated by electrothermal stimulation. These twisted spiral artificial muscles mimic the texture deformation abilities of cephalopods and achieve significant deformation at low voltages, opening new possibilities for soft robotics and smart skin designs.

Cao *et al.* [76] developed a large-area seamless haptic feedback interface based on silk, where customized circuits apply current to the silk substrate, generating virtual tactile sensations on the palm. This technology leverages the softness and conductivity of silk to provide an innovative solution for haptic feedback systems. In addition, Li *et al.* [72] used composite materials made from polytetrafluoroethylene and polypropylene electrostatic fibers as key materials. During the corona charging process, electrostatic charges are stored in the fibers (as depicted in Figure 3f). When a time-varying voltage signal is applied, the electrostatic force generated between the electrode layers acts on the electrostatic fibers, converting it into mechanical vibrations to achieve tactile feedback. The mesh design not only provides excellent breathability but also allows vibration modes to be adjusted by precisely controlling the frequency and amplitude of the voltage signal. This makes diverse tactile stimuli possible and offers a new technical solution for wearable wireless haptic feedback systems. With high flexibility, stretchability, adjustable modulus, and breathability, the device ensures functionality without interfering with fine hand movements or natural tactile perception.

In practical applications, designing EAP actuators requires careful consideration of factors such as material durability, operating voltage, power requirements, and size. EAPs are notable for their responsiveness to electrical stimulation, making them ideal for simulating touch sensations in tactile interaction interfaces. When constructing high-sensitivity and responsive interfaces, both the structure and integration of EAPs must be considered. Key design considerations include maximizing strain capacity while maintaining mechanical integrity and incorporating flexible circuits and sensors for precise detection and rapid response [77]. To achieve realistic tactile feedback, multimodal integration may be necessary, potentially using composite materials or multilayer structures to simulate various tactile properties. In summary, structural design should focus not only on material characteristics but also on innovative configurations and combinations to achieve advanced haptic HMI functions. This highlights the immense potential of EAP technology in simulating real tactile experiences, providing new possibilities for future HMIs.

4. Functional materials

EAPs come in a wide variety of materials, which can be categorized into two main types based on their actuation mechanisms under an electric field: electronic EAPs and ionic EAPs.

4.1. Electronic EAPs

Electronic EAPs are directly driven by an external electric field, characterized by fast response and high energy density. Details of some representative electronic EAPs are presented in Figure 4.

4.1.1. Dielectric elastomer actuator (DEA)

DEAs typically consist of a series of flexible polymer matrix and conductive electrodes, making them highly deformable soft actuators [78–82]. In 2000, Pelrine *et al.* [83] reported in *Science* on DE capable of significant deformation under an electric field, which is crucial for developing new actuator materials. The research team achieved over 100% strain by applying voltage to thin films of silicone rubber and acrylic rubber, using electrostatic compression to reduce film thickness and expand its area. Specifically, pre-stretching silicone rubber resulted in an activated strain of up to 117%, while acrylic rubber achieved an even higher activated strain of 215% through pre-stretching. In 2018, Zhao *et al.* [81] proposed an innovative flat DEA, significantly enhancing the actuator's operating range and output force through integrated magnetic modulation mechanisms. DEA not only surpasses natural muscles in terms of strain, pressure, and response time, but also exhibits a higher specific energy density compared to other electroactive materials.

Elastic polymers, as a key core material in haptic actuators, possess high elasticity and reversible deformation capabilities. They achieve mechanical deformation through electron migration in response to electric field stimulation. These materials are typically composed of DEs with high dielectric constants [84]. A representative of these materials is the ferroelectric polymer P(VDF-TrFE-CTFE) [85,86]. Their non-centrosymmetric crystal structure allows them to polarize and deform under an electric field. Polydimethylsiloxane (PDMS) is typically considered an amorphous polymer without long-range ordered arrangement, with molecular chains randomly arranged in space and lacking a fixed repeating pattern. However, PDMS can be endowed with electroactivity through specific processing methods or by adding particular fillers. For instance, mixing PDMS with Silbione can create a composite material that exhibits electroactivity under an electric field (Figure 4a) [87]. With ongoing research into DEA performance and continuous improvements in manufacturing technology, DEAs show great potential in haptic human-machine interfaces. Future research could enhance their durability and improve mechanical properties.

4.1.2. Electroactive graft elastomer (EGE) and liquid crystal elastomer (LCE)

In the field of EAPs, EGE and LCE have garnered significant attention due to their unique molecular structures. EGE are composed of flexible amorphous polymer chains and crystallizable graft polar polymers (Figure 4d) [88]. For instance, an elastic composite materials can be created by grafting polyaniline onto a polyvinyl chloride (PVC) based material using chemical grafting techniques [89]. The applied voltage forces the dipoles within the elastic composite to realign, resulting in a change in the material's volume.

In contrast, LCEs are composed of interconnected crosslinked elastic polymers and exhibits characteristics of mesogenic liquid crystal components (Figure 4c) [90]. Consequently, the LCEs combine the molecular mobility of liquid crystals with the elastic properties of elastomers [91,92]. In the absence of external stimuli, the orientational order of the mesogens forces the elastomer main chains to elongate along the alignment direction of the mesogens (nematic phase). When external stimuli such as heat, light, or electricity are applied, the ordered arrangement of the molecules is disrupted, causing the elastomer main chains to relax into their coiled conformation. Voltage-activated LCEs exhibit a fast response time, with the required electric field (1.5–25 V/m) being lower than that of most EAPs. However, their actuation strain is not ideal (typically below 10%), indicating that further improvements are needed in terms of strain and work efficiency for their application as actuators.

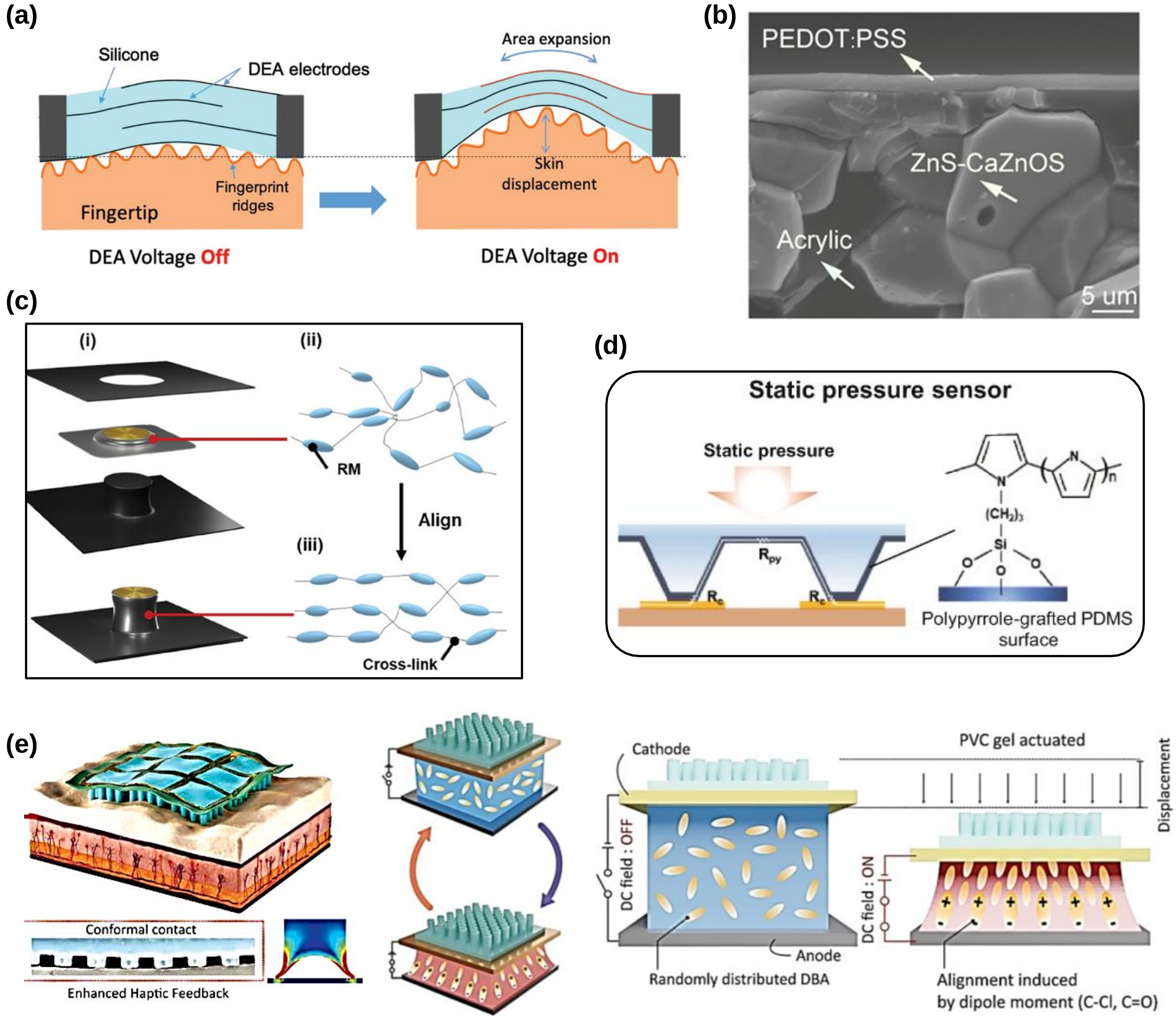

Figure 4. Electronic EAPs: **(a)** Dielectric elastomers [87]. Reprinted with permission. Copyright 2020, John Wiley and Sons. **(b)** Conductive polymers [93]. Reprinted with permission. Copyright 2022, American Chemical Society. **(c)** Liquid crystal elastomers (LCEs) [90]. **(d)** Electroactive graft elastomers (EGEs) [88]. **(e)** Polyvinyl chloride (PVC) gels [27]. Reprinted with permission. Copyright 2023, John Wiley and Sons.

4.1.3. Conductive polymers (CPs)

The conductivity of CPs arises from the conjugated system within their molecular structure, which allows electrons to move freely along the polymer chain. To achieve polymer conductivity, charges need to be introduced through oxidation or reduction reactions, a process known as doping (Figure 4b) [93]. For instance, PEDOT undergoes dimensional changes through ion doping and dedoping processes, exhibiting not only high electrical conductivity but also significant electroactive capabilities, particularly suitable for low-voltage-driven tactile feedback systems [31]. Since CP actuators rely on the presence of electrolytes, most CP-based haptic actuators require encapsulation to maintain their performance. Additionally, the strain range of these actuators typically falls between 1% and 40%. Consequently, some researchers have mixed carbon materials with excellent conductivity and mechanical properties, such as graphene and carbon nanotubes, with the polymers [48,94–96]. Xiang *et al.* [97] proposed an innovative Hard Magnetic Graphene Nanocomposite prepared by laser-induced doping of porous graphene with permanent magnetic particles. The hard magnetic graphene nanocomposite not only enhances the sensor's performance in electrophysiological signal, temperature, and metabolite concentration measurements but also enables reversible self-assembly of the sensor with flexible substrate bases through magnetic forces. This capability allows for customized adjustments in spatial layout and functionality of the sensors.

4.1.4. Other types of conductive polymer-based EAPs

In addition to the electronic-type EAPs mentioned earlier, there are other types of electronic EAPs that exhibit exceptional deformation capabilities under an electric field due to their intrinsic electronic structures. For example, PVC gel is a composite material made of PVC and plasticizers (Figure 4e), which can undergo significant volume changes under an electric field [27,98]. This volumetric change is generally attributed to ion migration and the rearrangement of polymer chains induced by the electric field. Shape memory materials are a class of smart materials, including metal alloys or polymers, that can memorize and recover their shape at specific temperatures [99,100]. These materials can achieve reversible shape changes through electrically induced heating, making them potentially valuable for applications in flexible electronics and biomedical devices.

4.2. Ionic EAPs

Ionic EAPs achieve deformation through ion migration, characterized by low driving voltage and softness. Details of some representative ionic EAPs are presented in Figure 5.

4.2.1. Ionic polymer-metal composites (IPMCs)

IPMCs are directly influenced by material properties such as ion exchange capacity (IEC), water uptake (WU), and ion conductivity (IC). Higher IEC and IC allow ions to move rapidly within the polymer matrix, resulting in higher driving speed and force [86]. At the same time, higher IEC and IC allow for faster ion movement within the ion layer, resulting in greater driving speed and force. Higher WU enhances the stability of IPMC, allowing for longer operation times and enhanced driving performance. Currently, commercially available ion exchange membranes (such as Nafion membranes) have excellent ion transport capabilities but are prone to hydrolysis and dehydration under high temperature or high humidity conditions. Guo *et al.* [101] introduced a porous structure by doping PVP and ionic liquids into PVDF, facilitating ion mobility (Figure 5a). Despite the advantage of requiring low voltages, these systems typically exhibit low strain in their actuation.

4.2.2. Ionic Polymer Gels

Ionic polymer gels are soft ion-conductive materials, typically consisting of a polymer matrix filled with an electrolyte solution in its interstices. Generally, these materials can respond to various external stimuli such as pH value, temperature, and others (Figure 5b,c) [23,102–104]. Ionic polymer gels exhibit high ion conductivity and flexibility, capable of generating significant deformation under low voltage. However, their slow actuation speed and the need for electrolyte encapsulation materials pose limitations on their applications.

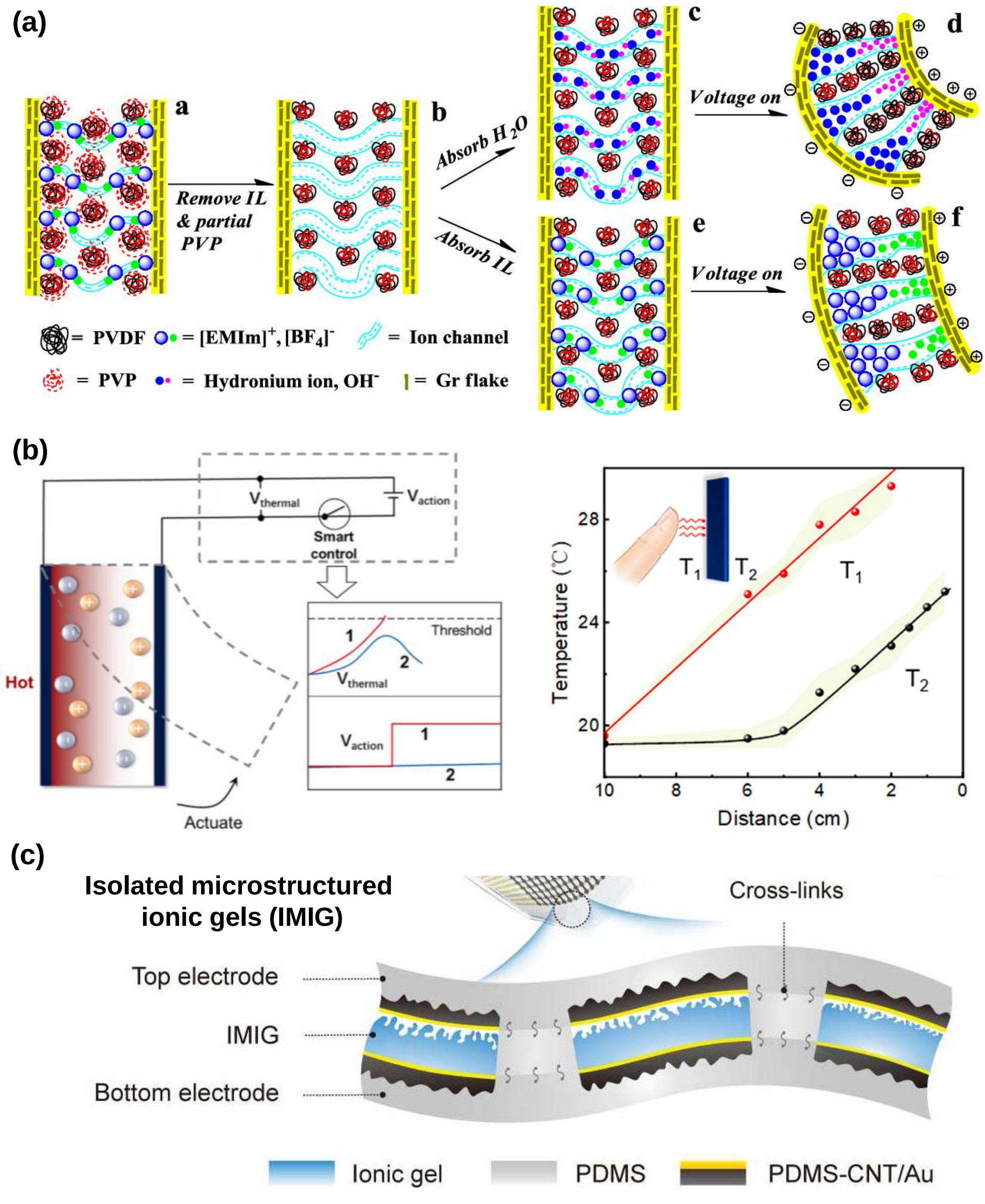

Figure 5. Ionic EAPs: **(a)** Ionic Polymer-metal composites (IPMCs) [101]. Reprinted with permission. Copyright 2019, American Chemical Society. **(b, c)** Ionic polymer gels [23,104]. Reprinted with permission. Copyright 2024, Elsevier.

5. Fabrication methods

The fabrication methods of electroactive polymer (EAP) actuators are crucial in their development, as they directly influence the actuator's performance and range of applications. Depending on the type of materials and structural requirements, common fabrication techniques include micro-nano patterning, electrostatic assembly, polymer synthesis, and engineering. Below is a brief overview of several common EAP actuator fabrication methods (Figure 6):

5.1. Micro-nano patterning techniques

Micro-nano patterning techniques are key methods for achieving high-precision and high-sensitivity electroactive polymer (EAP) actuators. By creating micro-nano structural patterns on the material's surface or within its structure, these techniques can significantly enhance the performance of EAP actuators, including their electrical responsiveness, mechanical strength, and flexibility. Micro-nano patterning enables actuators to produce more precise and complex deformations on a smaller scale, thereby increasing their potential applications in tactile feedback systems [105–107]. For example, by selecting appropriate electroactive polymer materials and utilizing 3D printing technology (Figure 6a), complex three-dimensional structures, even with functionally graded materials, can be directly fabricated. This method allows for the rapid production of EAP actuators with complex geometries and precise structures, making it particularly suitable for customized tactile feedback devices [21].

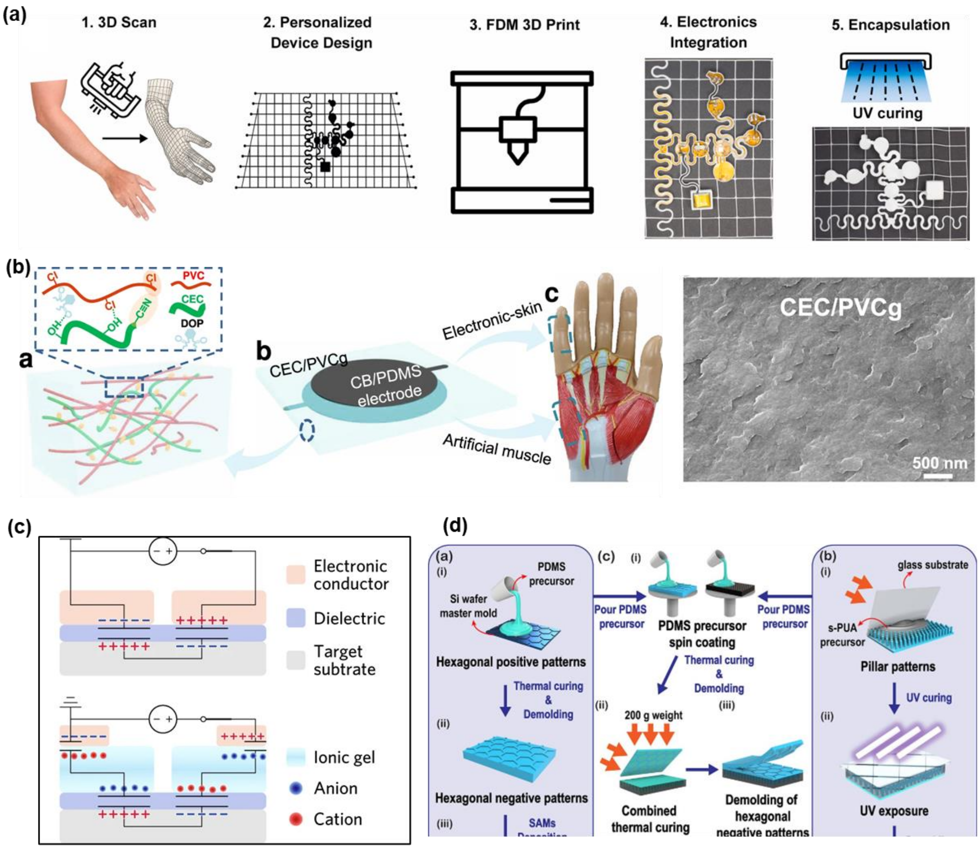

Figure 6. Common preparation methods of EAPs: **(a)** 3D printing technology [21]. Reprinted with permission. Copyright 2024, Elsevier. **(b)** Polymer synthesis [102]. **(c)** Electrostatic adhesion [28]. **(d)** Molding [24]. Reprinted with permission. Copyright 2023, John Wiley and Sons.

5.2. Electrostatic adhesion

Electrostatic adhesion is a widely used method for fabricating EAP actuators (Figure 6c). This technique leverages the electrostatic forces between charged particles or materials to assemble the actuator's components or layers. The process typically involves applying a voltage to generate an electrostatic field, which attracts or repels charged materials, causing them to self-assemble into the desired structure or configuration [108–110]. In EAP actuators, electrostatic adhesion can be used to align polymer layers or arrange conductive materials on the polymer surface to enhance their conductivity and mechanical properties. EAPs fabricated through electrostatic assembly typically exhibit good adhesion and conductivity, making them suitable for flexible sensors and actuators. For example, Gao *et al.* [38] proposed an innovative fabrication method based on supramolecular design, synthesizing a soft electronic adhesive from ion-organic gels and stretchable polyurethane. This method does not require complex machinery or high temperatures. Additionally, it can be applied to flexible or stretchable substrates, making it an ideal choice for developing soft, wearable, and flexible EAP actuators.

5.3. Polymer synthesis and engineering

Molecular engineering plays a crucial role in the preparation of the EAPs [111], enabling the creation of materials with specific properties tailored to the required actuator performance. This method involves the design and synthesis of polymer materials that undergo significant deformation in response to external stimuli, such as electric fields, temperature changes, or light. The synthesis process typically includes the polymerization of monomers or oligomers, followed by post-processing techniques such as crosslinking, blending, or functionalization to enhance the material's electroactive properties. Jianjian Huang *et al.* [102] published a research paper in *Nature Communications* (Figure 6b) where they introduced cyanoethyl cellulose (CEC) into plasticized PVC gel (PVCg), significantly increasing the dielectric constant (up to 18.9 @ 1 kHz) and markedly reducing viscoelastic effects, achieving low mechanical loss (0.04 @ 1 Hz). CEC/PVCg actuators demonstrate higher driving performance under low electric fields compared to existing DEAs. The controllability of polymer synthesis and engineering techniques provides researchers with a powerful tool for developing the next generation of efficient, durable, and adaptable EAP actuators. The flexibility of this approach also allows for the creation of innovative materials with tunable properties, meeting specific application needs, making it an essential method in the advancement of EAP technologies.

5.4. Other methods

In addition to the aforementioned methods, EAPs can also be fabricated using casting, electrochemical deposition, spraying, and other techniques. In the casting method, the electroactive polymer is first dissolved in a solvent to form a homogeneous solution. This solution is then cast onto a flat mold, and after the solvent evaporates, a thin film structure is obtained (Figure 6d). This method is suitable for fabricating large-area thin films, and the thickness and electrical properties of the film can be adjusted by controlling parameters such as the solution concentration, casting rate, and temperature [112]. Electrochemical deposition is a method that uses electrochemical reactions to deposit electroactive materials onto the surface of an electrode. By adjusting factors such as current density, temperature, and solution composition, the deposition process is controlled to produce uniform thin films or layered materials. Electrochemical deposition is commonly used to fabricate EAP materials with high electrical conductivity and good electroactive properties [113]. Spraying is another common method for EAP material fabrication, particularly suitable for producing thin layers and multilayer structures. This method involves spraying a solution or suspension uniformly onto a substrate, which is then cured through heating or chemical processes. Spraying allows for efficient coverage of irregular surfaces and is well-suited for manufacturing flexible and wearable devices. By controlling spraying parameters such as spray rate and distance, the thickness and uniformity of the films can be precisely controlled [87,114]. In summary, efficient applications of EAPs in haptic HMIs rely on precise and diverse manufacturing techniques. From molecular scale to macroscopic structures, each manufacturing step requires careful consideration to ensure optimal material performance. With ongoing technological advancements, EAPs are expected to demonstrate broader applications in tactile interaction fields in the future.

6. Applications

EAP actuators, due to their excellent flexibility, response speed, and deformable characteristics, have become an essential component in haptic feedback systems. Compared to traditional electric drive technologies, EAP actuators can provide high-precision haptic feedback with lower power consumption, adapting to complex interactive needs. Here are some specific applications of EAPs in haptic actuators (Figure 7):

6.1. Wearable haptic devices

With the development of smart wearable technology, EAP actuators have begun to be applied in wearable haptic feedback devices (see Figure 7a). EAPs can simulate vibrations, pressure, and textures in wearable haptic feedback devices, significantly enhancing user immersion and interactive experience [115–121]. A pioneering work published by City University of Hong Kong in 2023 [122] introduced a skin-integrated multimodal haptic feedback interface. This interface leverages the properties of the EAPs and an integrated actuator array to achieve significant improvements in immersive haptic feedback for virtual and augmented reality systems. It combines three distinct feedback modes: mechanical, electro-tactile, and thermal stimulation, to selectively activate different tactile receptors in the skin. Highly flexible and sensitive fingertip haptic devices can be developed using EAPs. Fingertip haptic devices can simulate the haptic feedback of human fingers, enabling more precise operations and object grasping (see Figure 7c,d). By integrating EAPs into gloves or skin patches, they can detect and respond to user movements, providing real-time haptic feedback and enhancing the user’s experience [25,123,124]. Nevertheless, issues such as comfort and durability of these wearable devices under prolonged use remain under-explored.

Additionally, EAPs can be integrated into the surface of haptic devices to form smart skin (see Figure 7e), which can detect and respond to touch, pressure changes, and temperature variations [24,125]. Research by Li *et al.* [126] introduced a novel ionic electronic skin (I-skin), specifically a frequency-coded artificial ionic mechanoreceptor skin, capable of ultra-fast readout and interference-free sensing across a wide pressure range. This I-skin, by mimicking the tactile system of human skin, provides high-sensitivity capacitive response in a pressure range from 0.12–1880 kPa. Furthermore, the frequency-coded artificial ionic mechanoreceptor skin platform, combined with deep learning technology, shows promising applications in intelligent human-machine interaction and real-time dynamic robotic operations. However, the reliance on deep learning may require large datasets and complex algorithms that could hinder real-time applications.

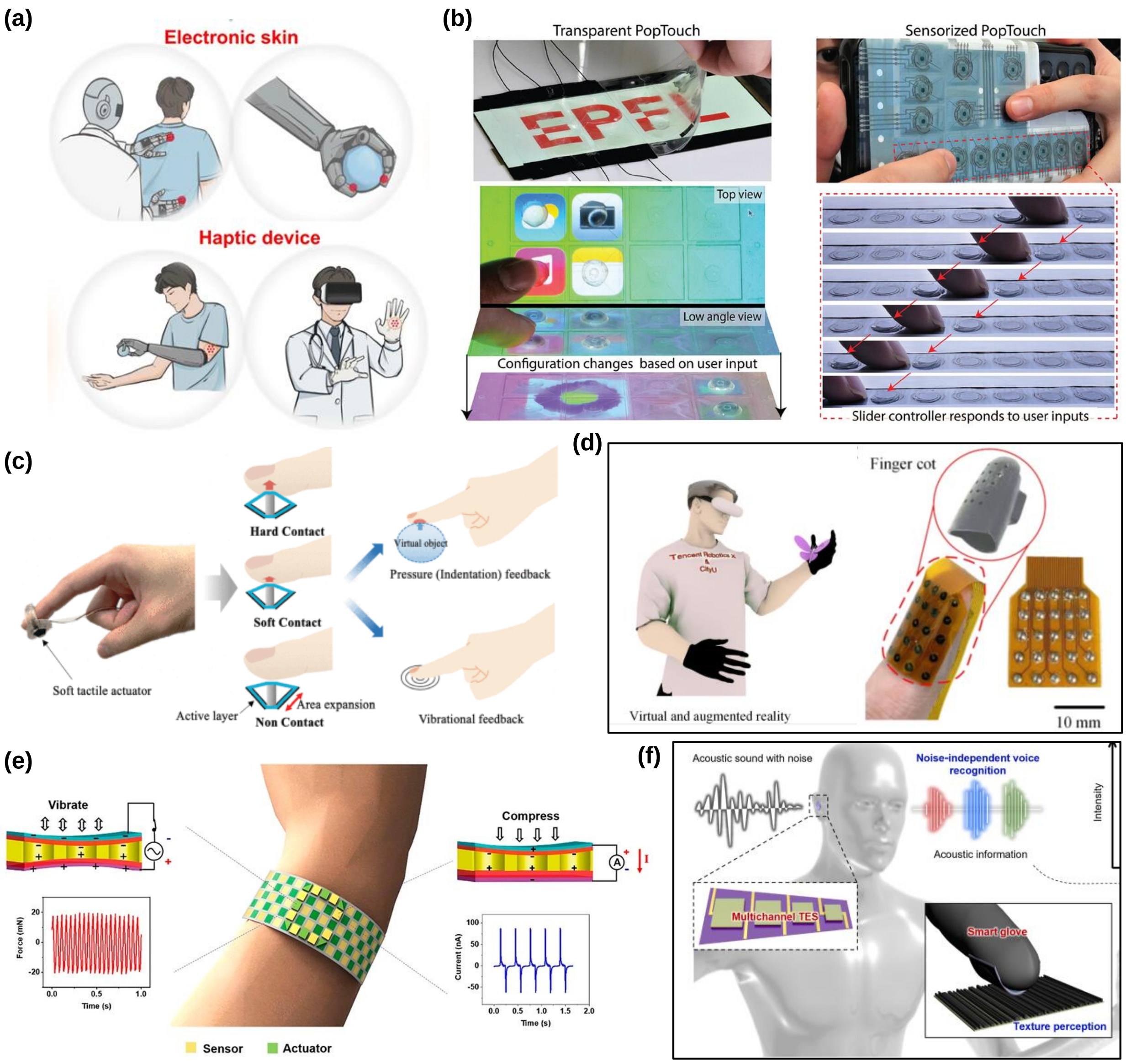

Figure 7. Applications of EAPs: **(a)** Immersive interactive devices [127]. **(b)** Touch screens [128]. Reprinted with permission. Copyright 2023, John Wiley and Sons. **(c, d)** Fingertip interactive devices [25,77]. **(e)** Wearable skin [125]. Copyright 2019, American Chemical Society. **(f)** Acoustic devices [129].

6.2. Medical haptic feedback systems

In the medical field, the application of EAP actuators in haptic feedback systems is primarily focused on rehabilitation therapy and patient monitoring. By using haptic feedback devices driven by EAP actuators, the motion status of patients can be monitored in real-time, assisting in rehabilitation training and enhancing patients' perception of movement feedback [78,130–132]. For example, EAPs have demonstrated great potential in the medical field. They can monitor patients' physiological signals and provide therapeutic electrical stimulation. Due to their flexibility and stretchability, EAPs conform exceptionally well to the skin, offering patients a comfortable treatment experience. Nevertheless, the integration of such devices into daily therapeutic routines still faces challenges in terms of user comfort and device customization.

6.3. Haptic display

Haptic feedback can significantly enhance the sense of immersion in human-machine interaction. Traditional interactions primarily rely on visual (display) and auditory (acoustic) feedback. In recent years, both haptic display and acoustic technologies have become essential components of haptic feedback systems. As HMI technologies continue to evolve, haptic display technology has progressed to not only simulate the shape, texture, and temperature of objects but also integrate with acoustic technologies to offer a richer and more immersive sensory experience. The combination of these two technologies enables more natural and engaging interactions, showcasing substantial potential across various applications.

In haptic display technology, EAPs are used to construct surfaces that simulate various tactile sensations, such as the texture of different materials [133]. Firouzeh *et al.* [128] introduced PopTouch, an innovative haptic interface technology capable of dynamically creating pressable physical buttons on touchscreens or other smooth surfaces. At the core of PopTouch is an actuator called hydraulically amplified electrostatic zipping taxels, which can generate significant normal displacement and provide intuitive mechanical feedback through finely tuned force-displacement characteristics. This technology not only simulates the 'click' sensation of physical buttons but also dynamically adjusts the button layout based on user interactions, offering a more intuitive and personalized interaction experience. However, challenges in ensuring long-term reliability and tactile feedback consistency remain unresolved, especially in high-use scenarios.

Acoustic technology plays an important role in haptic feedback systems, especially in enhancing haptic interactions and providing immersive experiences. Acoustic technology can generate physical vibrations through sound waves, and when combined with haptic feedback systems, it enhances the user's sensory experience [129]. By propagating sound waves and altering their frequency, the technology can stimulate the skin's surface and provide tactile sensations. Variations in sound frequency and amplitude can simulate different tactile patterns (see Figure 7f). For example, Li *et al.* [134] introduced a smart textile system based on electrostatic induction for converting Braille to speech. With the integration of machine learning algorithms, the system achieves an accuracy of 99.09% and 97.08% in translating Braille letters and 40 common words, respectively.

In summary, the application of EAPs in the field of haptics is continually expanding, offering new ways to create more natural, intuitive, and interactive user experiences. With ongoing optimization of EAP materials and driving technologies, future EAP actuators are expected to provide more precise and complex haptic feedback while consuming less energy and exhibiting greater stability. By integrating with advanced sensing technologies, EAP haptic systems have the potential to offer more immersive and personalized experiences in fields such as intelligent interaction, virtual experiences, and medical rehabilitation, driving human-machine interaction technologies toward smarter, finer, and more comfortable directions.

Although the prospects for EAP actuators in haptic HMI devices are promising, they still face several challenges. First, the scalability and cost of manufacturing EAP actuators are critical factors limiting their widespread adoption [135–138]. When scaling up production, how to maintain high performance while reducing costs remains a challenge. Second, EAP actuators typically require high energy input, which could pose energy consumption issues for long-wearing devices, affecting their sustained use. Therefore, improving energy efficiency and extending service life are key considerations when designing efficient wearable haptic devices. Additionally, although EAPs have flexibility and stretchability, their stability and durability in extreme environments still require further research, especially in high-intensity and high-frequency operations. Maintaining the long-term stability of EAP actuators under such conditions will be a crucial direction for future development.

7. Conclusions and perspectives

EAPs as a class of stimuli-responsive materials, generate strain under the action of an electric field, mimicking the movement of biological muscles to achieve soft and precise motion control. This provides a novel approach for haptic HMIs. In the field of functional materials, scientists continue to explore new types of EAPs and better ways to integrate these materials into haptic interaction systems. Some studies focus on improving the driving efficiency and stability of EAPs, which are crucial for the long-term stable operation of haptic interfaces. Through molecular design, doping techniques, and the development of composite materials, researchers have successfully enhanced the performance of EAPs, making them suitable for a wider range of applications.

However, there are still many challenges in the use of EAPs for haptic actuation. First, ensuring that EAPs can operate safely at lower voltages while improving power efficiency to achieve higher driving force remains an unresolved issue. Second, effectively integrating EAPs into existing electronic systems and smart material systems, addressing compatibility issues, and maintaining stable performance in various environments is another key research direction. Furthermore, the stability and durability of EAPs under long-term use or extreme conditions (such as high temperature, high humidity, or chemical corrosion) are critical challenges for improving material reliability and extending service life.

Despite these challenges, the application prospects of EAP actuators in haptic HMI devices remain broad. With the discovery of new materials and the rapid development of artificial intelligence, the application of EAPs in haptic human-machine interfaces will continue to expand, covering more fields and scenarios. In the future, the integration of EAPs with artificial intelligence will promote smarter and more personalized haptic interactions, further advancing the development and innovation of haptic HMIs.

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Conflicts of interests

The authors declare no conflict of interest.

Authors' contribution

Conceptualization, Y.C.; writing—original draft preparation, Y.C. and F.Z.; investigation, F.Z.; supervision, G.C. and Z.Z.; writing—review and editing, J.J., G.C. and Z.Z.; funding acquisition, J.J. and Z.Z.; project administration, Z.Z. All authors have read and agreed to the published version of the manuscript.

References

[1] Akhta A, Sombeck J, Boyce B, Bretl T. Controlling sensation intensity for electrotactile stimulation in human-machine interfaces. *Sci Rob.* 2018, 3(17):11.

[2] Pacchierotti C, Sinclair S, Solazzi M, Frisoli A, Hayward V, *et al.* Wearable Haptic Systems for the Fingertip and the Hand: Taxonomy, Review, and Perspectives. *IEEE Trans. Haptic* 2017, 10(4):580–600.

[3] Culbertson H, Schorr SB, Okamura AM. Haptics: The Present and Future of Artificial Touch Sensation. *Annu. Rev. Control Rob. Auton. Syst.* 2018, 1(1):385–409.

[4] Ozioko O, Dahiya R. Smart Tactile Gloves for Haptic Interaction, Communication, and Rehabilitation. *Adv. Intell. Syst.* 2021, 4(2):2100091.

[5] Bai H, Li S, Shepherd RF. Elastomeric Haptic Devices for Virtual and Augmented Reality. *Adv. Funct. Mater.* 2021, 31(39):2009364.

[6] Zhou K, Xia L, Liu J, Qian M, Pi J. Design of a flexible end-effector based on characteristics of tomatoes. *Int. J. Agric. Biol. Eng.* 2022, 15(2):13–24.

[7] Romasanta LJ, Lopez-Manchado MA, Verdejo R. Increasing the performance of dielectric elastomer actuators: A review from the materials perspective. *Prog. Polym. Sci.* 2015, 51:188–211.

[8] Jun K, Kim D, Ryu S, Oh IK. Surface Modification of Anisotropic Dielectric Elastomer Actuators with Uni- and Bi-axially Wrinkled Carbon Electrodes for Wettability Control. *Sci. Rep.* 2017, 7(1):6091.

[9] Cruz M, Kyung KU, Shea H, Bose H, Graz I. Applications of Smart Materials to Haptics. *IEEE Trans. Haptic* 2018, 11(1):2–4.

[10] Ankit, Ho TYK, Nirmal A, Kulkarni MR, Accoto D, *et al.* Soft Actuator Materials for Electrically Driven Haptic Interfaces. *Adv. Intell. Syst.* 2021, 4(2):2100061.

[11] Bohil CJ, Alicea B, Biocca FA. Virtual reality in neuroscience research and therapy. *Nat. Rev. Neurosci.* 2011, 12(12):752–762.

[12] Zhou Y, Zhao X, Xu J, Chen G, Tat T, *et al.* A multimodal magnetoelastic artificial skin for underwater haptic sensing. *Sci. Adv.* 2024, 10:eadj8567.

[13] Xiang SW, Chen GR, Wen Q, Li H, Luo XX, *et al.* Fully addressable textile sensor array for self-powered haptic interfacing. *Matter* 2024, 7(1):82–94.

[14] Zhang Z, Xu Z, Emu L, Wei P, Chen S, *et al.* Active mechanical haptics with high-fidelity perceptions for immersive virtual reality. *Nat. Mach. Intell.* 2023, 5(6):643–655.

[15] Lipomi DJ, Dhong C, Carpenter CW, Root NB, Ramachandran VS. Organic Haptics: Intersection of Materials Chemistry and Tactile Perception. *Adv. Funct. Mater.* 2020, 30(29):1906850..

[16] Liu J, Liang J, Zhao S, Jiang Y, Wang J, *et al.* Design of a Virtual Multi-Interaction Operation System for Hand-Eye Coordination of Grape Harvesting Robots. *Agronomy* 2023, 13(3):829.

[17] Gong Y, Zhang K, Lei IM, Wang Y, Zhong J. Advances in Piezoelectret Materials-Based Bidirectional Haptic Communication Devices. *Adv. Mater.* 2024, 36(33):2405308.

[18] Ahn J, Gu J, Choi J, Han C, Jeong Y, *et al.* A Review of Recent Advances in Electrically Driven Polymer-Based Flexible Actuators: Smart Materials, Structures, and Their Applications. *Adv. Mater. Technol.* 2022, 7(11):2200041.

[19] Tan MWM, Wang H, Gao D, Huang P, Lee PS. Towards high performance and durable soft tactile actuators. *Chem. Soc. Rev.* 2024, 53(7):3485–3535.

[20] Yang TH, Kim JR, Jin H, Gil H, Koo JH, *et al.* Recent Advances and Opportunities of Active Materials for Haptic Technologies in Virtual and Augmented Reality. *Adv. Funct. Mater.* 2021, 31(39):2008831.

[21] Tyree A, Bhatia A, Hong M, Hanna J, Kasper KA, *et al.* Biosymbiotic haptic feedback - Sustained long term human machine interfaces. *Biosens. Bioelectron.* 2024, 261:116432.

[22] Chen Y, Wu H, Wang X, Qiu P, Wan H, *et al.* Wireless programmable patterns of electro-hydraulic haptic electronic skins able to create surface morphology. *Chem. Eng. J.* 2024, 500:156612.

[23] Shi JL, Dai Y, Cheng Y, Xie S, Li G, *et al.* Embedment of sensing elements for robust, highly sensitive, and cross-talk-free iontronic skins for robotics applications. *Sci. Adv.* 2023, 9(9):eadf8831.

[24] Kim J, Hwang GW, Song M, Lim D, Kim JI, *et al.* A Reversible, Versatile Skin-Attached Haptic Interface Platform with Bioinspired Interconnection Architectures Capable of Resisting Sweat and Vibration. *Adv. Funct. Mater.* 2023, 34(17):2311167.

[25] Youn JH, Mun H, Kyung KU. A Wearable Soft Tactile Actuator With High Output Force for Fingertip Interaction. *IEEE Access* 2021, 9:30206–30215.

[26] Qiu W, Zhong J, Jiang T, Li Z, Yao M, *et al.* A low voltage-powered soft electromechanical stimulation patch for haptics feedback in human-machine interfaces. *Biosens. Bioelectron.* 2021, 193:113616.

[27] Hwang GW, Jeon SH, Song JH, Kim DW, Lee J, *et al.* A Spatially Selective Electroactive-Actuating Adhesive Electronics for Multi-Object Manipulation and Adaptive Haptic Interaction. *Adv. Funct. Mater.* 2023, 34(6):2308747.

[28] Gao D, Thangavel G, Lee J, Lv J, Li Y, *et al.* A supramolecular gel-elastomer system for soft iontronic adhesives. *Nat. Commun.* 2023, 14(1):1990.

[29] Liu C, Yoshio M. Ionic Liquid Crystal-Polymer Composite Electromechanical Actuators: Design of Two-Dimensional Molecular Assemblies for Efficient Ion Transport and Effect of Electrodes on Actuator Performance. *ACS Appl. Mater. Interfaces* 2024, 16(21):27750–27760.

[30] Yao K, Zhuang Q, Zhang Q, Zhou J, Yiu CK, *et al.* A fully integrated breathable haptic textile. *Sci. Adv.* 2024, 10(42):eadq9575.

[31] Jiang T, Qiu W, Li Z, Ye X, Liu Y, *et al.* Programmable Tactile Feedback Patterns for Cognitive Assistance by Flexible Electret Actuators. *Adv. Funct. Mater.* 2021, 32(4):2107985.

[32] Oh S, Song TE, Mahato M, Kim JS, Yoo H, *et al.* Easy-To-Wear Auxetic SMA Knot-Architecture for Spatiotemporal and Multimodal Haptic Feedbacks. *Adv. Mater.* 2023:e2304442.

[33] Jang SY, Cho M, Kim H, Choi M, Mun S, *et al.* Dynamically reconfigurable shape-morphing and tactile display via hydraulically coupled mergeable and splittable PVC gel actuator. *Sci. Adv.* 2024, 10(39):eadq2024.

[34] Sanchez-Tamayo N, Yoder Z, Rothemund P, Ballardini G, Keplinger C, *et al.* Cutaneous Electrohydraulic (CUTE) Wearable Devices for Pleasant Broad-Bandwidth Haptic Cues. *Adv. Sci.* 2024, 11(48):2402461.

[35] Feng GH, Hou SY. Investigation of tactile bump array actuated with ionic polymer–metal composite cantilever beams for refreshable braille display application. *Sens. Actuators, A* 2018, 275:137–147.

[36] Nan M, Bang D, Zheng S, Go G, Darmawan BA, *et al.* High-performance biocompatible nanobiocomposite artificial muscles based on ammonia-functionalized graphene nanoplatelets–cellulose acetate combined with PVDF. *Sens. Actuators, B* 2020, 323:128709.

[37] Yao K, Zhou J, Huang Q, Wu M, Yiu CK, *et al.* Encoding of tactile information in hand via skin-integrated wireless haptic interface. *Nat. Mach. Intell.* 2022, 4(10):893–903.

[38] Luo Y, Abidian MR, Ahn JH, Akinwande D, Andrews AM, *et al.* Technology Roadmap for Flexible Sensors. *ACS Nano* 2023, 17(6):5211–5295.

[39] Wu Y, Yim JK, Liang J, Shao Z, Qi M, *et al.* Insect-scale fast moving and ultrarobust soft robot. *Sci. Rob.* 2019, 4(32):eaax1594.

[40] Lee DY, Jeong SH, Cohen AJ, Vogt DM, Kollosche M, *et al.* A Wearable Textile-Embedded Dielectric Elastomer Actuator Haptic Display. *Soft Rob*. 2022, 9(6):1186–1197.

[41] Zhu S, Li Y, Yelemulati H, Deng X, Li Y, *et al.* An artificial remote tactile device with 3D depth-of-field sensation. *Sci. Adv.* 2022, 8:eabo5314.

[42] Qu X, Ma X, Shi B, Li H, Zheng L, *et al.* Refreshable Braille Display System Based on Triboelectric Nanogenerator and Dielectric Elastomer. *Adv. Funct. Mater.* 2020, 31(5):2006612

[43] Ji X, Liu X, Cacucciolo V, Civet Y, El Haitami A, *et al.* Untethered Feel-Through Haptics Using 18-µm Thick Dielectric Elastomer Actuators. *Adv. Funct. Mater.* 2020, 31(39):2006639.

[44] Qiu Y, Lu Z, Pei Q. Refreshable Tactile Display Based on a Bistable Electroactive Polymer and a Stretchable Serpentine Joule Heating Electrode. *ACS Appl. Mater. Interfaces* 2018, 10(29):24807–24815.

[45] Besse N, Rosset S, Zarate JJ, Shea H. Flexible Active Skin: Large Reconfigurable Arrays of Individually Addressed Shape Memory Polymer Actuators. *Adv. Mater. Technol.* 2017, 2(10):1700102.

[46] Besse N, Rosset S, Zarate JJ, Ferrari E, Brayda L, *et al.* Understanding Graphics on a Scalable Latching Assistive Haptic Display Using a Shape Memory Polymer Membrane. *IEEE Trans. Haptic* 2018, 11(1):30–38.

[47] Stubning T, Denes I, Gerhard R. Tuning electro-mechanical properties of EAP-based haptic actuators by adjusting layer thickness and number of stacked layers—a comparison. *Eng. Res. Express* 2021, 3(1):015015.

[48] Shi YX, Wang F, Tian JW, Li SY, Fu EG, *et al.* Self-powered electro-tactile system for virtual tactile experiences. *Sci. Adv.* 2021, 7(6):10.

[49] Acome E, Mitchell K, Morrissey TG, Emmett MB, Benjamin C, *et al.* Hydraulically amplified self-healing electrostatic actuators with muscle-like performance. *Science* 2018, 359(6371):61–65.

[50] Johnson BK, Naris M, Sundaram V, Volchko A, Ly K, *et al.* A multifunctional soft robotic shape display with high-speed actuation, sensing, and control. *Nat. Commun.* 2023, 14(1):4516.

[51] Mahanthappa M, Ko HU, Kim SY. Transparent and Flexible Actuator Based on a Hybrid Dielectric Layer of Wavy Polymer and Dielectric Fluid Mixture. *Polymers* 2024, 16(2):188.

[52] Leroy E, Hinchet R, Shea H. Multimode Hydraulically Amplified Electrostatic Actuators for Wearable Haptics. *Adv. Mater.* 2020, 32(36):2002564.

[53] Leroy E, Hinchet R, Shea H. Multimode Hydraulically Amplified Electrostatic Actuators for Wearable Haptics. *Adv. Mater.* 2020:2002564.

[54] Muthukumarana S, Elvitigala DS, Forero Cortes JP, Matthies DJC, Nanayakkara S. Touch me Gently: Recreating the Perception of Touch using a Shape-Memory Alloy Matrix. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, Hawaii, USA, 25–30 April 2020, pp. 1–12.

[55] Mun S, Yun S, Nam S, Park SK, Park S, *et al.* Electro-Active Polymer Based Soft Tactile Interface for Wearable Devices. *IEEE Trans. Haptic* 2018, 11(1):15–21.

[56] Ig Mo K, Kwangmok J, Ja Choon K, Jae-Do N, Young Kwan L, *et al.* Development of Soft-Actuator-Based Wearable Tactile Display. *IEEE Trans. Rob.* 2008, 24(3):549–558.

[57] Matysek M, Lotz P, Flittner K, Schlaak HF. Vibrotactile display for mobile applications based on dielectric elastomer stack actuators. In *Proceedings of Electroactive Polymer Actuators and Devices (EAPAD) 2010*, California, USA, 7–11 March 2010, pp. 83–91.

[58] Lotz P, Matysek M, Schlaak HF. Fabrication and Application of Miniaturized Dielectric Elastomer Stack Actuators. *IEEE/ASME Trans. Mechatron.* 2011, 16(1):58–66.

[59] Guo Y, Luo Y, Plamthottam R, Pei S, Wei C, *et al.* Haptic artificial muscle skin for extended reality. *Sci. Adv.* 2024, 10(43):eadr1765.

[60] Choi K, Gao CY, Nam JD, Choi HJ. Cellulose-Based Smart Fluids under Applied Electric Fields. *Materials* 2017, 10(9):1060.

[61] Hajiesmaili E, Clarke DR. Optically addressable dielectric elastomer actuator arrays using embedded percolative networks of zinc oxide nanowires. *Mater. Horiz.* 2022, 9(12):3110–3117.

[62] Pyo D, Ryu S, Kyung KU, Yun S, Kwon DS. High-pressure endurable flexible tactile actuator based on microstructured dielectric elastomer. *Appl. Phys. Lett.* 2018, 112(6):061902.

[63] Hinchet RJ, Shea H. Glove- and Sleeve-Format Variable-Friction Electrostatic Clutches for Kinesthetic Haptics. *Adv. Intell. Syst.* 2022, 4(12):2200174.

[64] Zhao H, Hussain AM, Israr A, Vogt DM, Duduta M, *et al.* A Wearable Soft Haptic Communicator Based on Dielectric Elastomer Actuators. *Soft Rob.* 2020, 7(4):451–461.

[65] Ankit, Tiwari N, Rajput M, Chien NA, Mathews N. Highly Transparent and Integrable Surface Texture Change Device for Localized Tactile Feedback. *Small* 2017, 14(1):1702312.

[66] Yu M, Cheng X, Peng S, Cao Y, Lu Y, *et al.* A self-sensing soft pneumatic actuator with closed-Loop control for haptic feedback wearable devices. *Mater. Des.* 2022, 223:111149.

[67] Ma J, Cheng X, Wang P, Jiao Z, Yu Y, *et al.* A Haptic Feedback Actuator Suitable for the Soft Wearable Device. *Appl. Sci.* 2020, 10(24):8827.

[68] Frediani G, Boys H, Ghilardi M, Poslad S, Busfield JJC, *et al.* A Soft Touch: Wearable Tactile Display of Softness Made of Electroactive Elastomers. *Adv. Mater. Technol.* 2021, 6(6):2100016.

[69] Mazzotta A, Carlotti M, Mattoli V. Conformable on-skin devices for thermo-electro-tactile stimulation: materials, design, and fabrication. *Mater. Adv.* 2021, 2(6):1787–1820.

[70] Shrestha M, Lu Z, Lau GK. High humidity sensing by ‘hygromorphic’ dielectric elastomer actuator. *Sens. Actuators, B* 2021, 329:129268.
[71] Lamuta C, He H, Zhang K, Rogalski M, Sottos N, *et al.* Digital Texture Voxels for Stretchable Morphing Skin Applications. *Adv. Mater. Technol.* 2019, 4(8):1900260.
[72] Li Z, Ma Y, Zhang K, Wan J, Zhao D, *et al.* Air Permeable Vibrotactile Actuators for Wearable Wireless Haptics. *Adv. Funct. Mater.* 2022, 33(8):2211146.
[73] Yan W, Noel G, Loke G, Meiklejohn E, Khudiyev T, *et al.* Single fibre enables acoustic fabrics via nanometre-scale vibrations. *Nature* 2022, 603(7902):616–623.
[74] Kanik M, Orguc S, Varnavides G, Kim J, Benavides T, *et al.* Strain-programmable fiber-based artificial muscle. *Science* 2019, 365(6449):145–150.
[75] Ramachandran V, Shintake J, Floreano D. All-Fabric Wearable Electroadhesive Clutch. *Adv. Mater. Technol.* 2018, 4(2):1800313.
[76] Cao C, Liu H, Zhang Y, Jia W, Zhang L, *et al.* A Seamless, Large-Area Silk-based Interface for Immersive On-Palm Tactile Feedback. *Adv. Mater. Technol.* 2024, 9(8):2301599.
[77] Lin WK, Zhang DS, Lee WW, Li XL, Hong Y, *et al.* Super-resolution wearable electrotactile rendering system. *Sci. Adv.* 2022, 8(36):11.
[78] Carpi F, Frediani G, De Rossi D. Electroactive elastomeric haptic displays of organ motility and tissue compliance for medical training and surgical force feedback. *IEEE Trans. Biomed. Eng.* 2009, 56(9):2327–2330.
[79] Keplinger C, Kaltenbrunner M, Arnold N, Bauer S. Rontgen's electrode-free elastomer actuators without electromechanical pull-in instability. *Proc. Natl. Acad. Sci. U.S.A.* 2010, 107(10):4505–4510.
[80] Lee HS, Phung H, Lee D-H, Kim UK, Nguyen CT, *et al.* Design analysis and fabrication of arrayed tactile display based on dielectric elastomer actuator. *Sens. Actuators, A* 2014, 205:191–198.
[81] Zhao YH, Li WB, Zhang W-M, Yan H, Peng ZK, *et al.* Performance improvement of planar dielectric elastomer actuators by magnetic modulating mechanism. *Smart Mater. Struct.* 2018, 27(6):065007.
[82] Tang C, Du B, Jiang S, Wang Z, Liu XJ, *et al.* A Review on High-Frequency Dielectric Elastomer Actuators: Materials, Dynamics, and Applications. *Adv. Intell. Syst.* 2024, 6(2):2300047.
[83] Pelrine R, Kornbluh R, Pei QB, Joseph J. High-speed electrically actuated elastomers with strain greater than 100%. *Science* 2000, 287(5454):836–839.
[84] Kanno R, Nagai T, Shintake J. Rapid Fabrication Method for Soft Devices Using Off-the-Shelf Conductive and Dielectric Acrylic Elastomers. *Adv. Intell. Syst.* 2021, 3(4):2000173.
[85] Fook THT, Jeon JH, Lee PS. Transparent Flexible Polymer Actuator with Enhanced Output Force Enabled by Conductive Nanowires Interlayer. *Adv. Mater. Technol.* 2020, 5(1):1900762.
[86] Poncet P, Casset F, Latour A, Domingues Dos Santos F, Pawlak S, *et al.* Static and Dynamic Studies of Electro-Active Polymer Actuators and Integration in a Demonstrator. *Actuators* 2017, 6(2):18.
[87] Ji X, Liu X, Cacucciolo V, Civet Y, El Haitami A, *et al.* Untethered Feel-Through Haptics Using 18-µm Thick Dielectric Elastomer Actuators. *Adv. Funct. Mater.* 2021, 31(39):2006639..
[88] Jin H, Kim Y, Youm W, Min Y, Seo S, *et al.* Highly pixelated, untethered tactile interfaces for an ultra-flexible on-skin telehaptic system. *npj Flex. Electron.* 2022, 6(1):82.

[89] Shimoga G, Shin EJ, Kim SY. Flexible Vibrotactile Actuator Based on Soft PVC Gel Embedded Polyaniline/Silicon Dioxide Nanoparticles. *IEEE Access* 2020, 8:122057–122064.

[90] Astam MO, Verheesen D, Lyu P, Weima SAM, Liu D. Localized and Limited-Dispersive Delivery of Thermal Stimuli to Liquid Crystal Oligomer Networks Through Radio-Frequency Media. *Adv. Funct. Mater.* 2024, 34(48):2407355.

[91] van der Kooij HM, Semerdzhiev SA, Buijs J, Broer DJ, Liu D, *et al.* Morphing of liquid crystal surfaces by emergent collectivity. *Nat. Commun.* 2019, 10(1):3501.

[92] Wu J, Yao S, Zhang H, Man W, Bai Z, *et al.* Liquid Crystal Elastomer Metamaterials with Giant Biaxial Thermal Shrinkage for Enhancing Skin Regeneration. *Adv. Mater.* 2021, 33(45):2106175.

[93] Ma X, Wang C, Wei R, He J, Li J, *et al.* Bimodal Tactile Sensor without Signal Fusion for User-Interactive Applications. *ACS Nano* 2022, 16(2):2789–2797.

[94] Sui C, Yang Y, Headrick RJ, Pan Z, Wu J, *et al.* Directional sensing based on flexible aligned carbon nanotube film nanocomposites. *Nanoscale* 2018, 10(31):14938–14946.

[95] Li AL, Lee S, Shahsa H, Duduta M. Real time high voltage capacitance for rapid evaluation of dielectric elastomer actuators. *Soft Matter.* 2022, 18(37):7123–7130.

[96] Chang EJ, Lin MF. Enhanced actuation performance of multiple stimuli responsive PDMS-based bilayer actuators by adding ionic liquid. *Sens. Actuators, B* 2024, 404:135300.

[97] Xiang ZH, Wang HB, Zhao PC, Fa X, Wan J, *et al.* Hard Magnetic Graphene Nanocomposite for Multimodal, Reconfigurable Soft Electronics. *Adv. Mater.* 2024, 36(14):2308575.

[98] Park WH, Bae JW, Shin EJ, Kim SY. Development of a flexible and bendable vibrotactile actuator based on wave-shaped poly(vinyl chloride)/acetyl tributyl citrate gels for wearable electronic devices. *Smart Mater. Struct.* 2016, 25(11):115020.

[99] McCoul D, Rosset S, Besse N, Shea H. Multifunctional shape memory electrodes for dielectric elastomer actuators enabling high holding force and low-voltage multisegment addressing. *Smart Mater. Struct.* 2017, 26(2):025015.

[100] Roh Y, Lee S, Won SM, Hwang S, Gong D, *et al.* Crumple-recoverable electronics based on plastic to elastic deformation transitions. *Nat. Electron.* 2023, 7(1):66–76.

[101] Guo D, Han Y, Huang J, Meng E, Ma L, *et al.* Hydrophilic Poly(vinylidene Fluoride) Film with Enhanced Inner Channels for Both Water- and Ionic Liquid-Driven Ion-Exchange Polymer Metal Composite Actuators. *ACS Appl. Mater. Interfaces* 2019, 11(2):2386–2397.

[102] Huang J, Zhang X, Liu R, Ding Y, Guo D. Polyvinyl chloride-based dielectric elastomer with high permittivity and low viscoelasticity for actuation and sensing. *Nat. Commun.* 2023, 14(1):1483.

[103] Park WH, Shin EJ, Yun S, Kim SY. An Enhanced Soft Vibrotactile Actuator Based on ePVC Gel with Silicon Dioxide Nanoparticles. *IEEE Trans. Haptic* 2018, 11(1):22–29.

[104] Hu H, Zhang S, Xu J, Salim T, Li Y, *et al.* Thermal-sensing actuator based on conductive polymer ionogel for autonomous human-machine interaction. *Sens. Actuators, B* 2024, 398:134756.

[105] Kim S, Kawahara Y, Georgiadis A, Collado A, Tentzeris MM. Low-Cost Inkjet-Printed Fully Passive RFID Tags for Calibration-Free Capacitive/Haptic Sensor Applications. *IEEE Sens. J.* 2015, 15(6):3135–3145.

[106] Zhai Y, Wang Z, Kwon KS, Cai S, Lipomi DJ, *et al.* Printing Multi-Material Organic Haptic Actuators. *Adv. Mater.* 2021, 33(19):e2002541.

[107] Gugliuzza AG. Review of techniques for future manufacturing of ordered and functional porous films: conceivable membranes for water desalination by membrane distillation processes. *Adv. Manuf.* 2024(2):0009
[108] Xiong Q, Liang X, Wei D, Wang H, Zhu R, *et al.* So-EAGlove: VR Haptic Glove Rendering Softness Sensation With Force-Tunable Electrostatic Adhesive Brakes. *IEEE Trans. Rob.* 2022, 38(6):3450–3462.
[109] Zhang K, Gonzalez EJ, Guo J, Follmer S. Design and Analysis of High-Resolution Electrostatic Adhesive Brakes Towards Static Refreshable 2.5D Tactile Shape Display. *IEEE Trans. Haptic* 2019, 12(4):470–482.
[110] Sirin O, Ayyildiz M, Persson BNJ, Basdogan C. Electroadhesion with application to touchscreens. *Soft Matter.* 2019, 15(8):1758–1775.
[111] Choi DS, Lee SH, Kim SY. Transparent and Soft Haptic Actuator for Interaction With Flexible/Deformable Devices. *IEEE Access* 2020, 8:170853–170861.
[112] Phung H, Hoang PT, Jung H, Nguyen TD, Nguyen CT, *et al.* Haptic Display Responsive to Touch Driven by Soft Actuator and Soft Sensor. *IEEE/ASME Trans. Mechatron.* 2021, 26(5):2495–2505.
[113] Marette A, Poulin A, Besse N, Rosset S, Briand D, *et al.* Flexible Zinc-Tin Oxide Thin Film Transistors Operating at 1 kV for Integrated Switching of Dielectric Elastomer Actuators Arrays. *Adv. Mater.* 2017, 29(30):10.1002/adma.201700880.
[114] Arbaud R, Najafi M, Gandarias JM, Lorenzini M, Paul UC, *et al.* Toward Sustainable Haptics: A Wearable Vibrotactile Solar-Powered System with Biodegradable Components. *Adv. Mater. Technol.* 2024, 9(5):2301265.
[115] Mulatto S, Formaglio A, Malvezzi M, Prattichizzo D. Using postural synergies to animate a low-dimensional hand avatar in haptic simulation. *IEEE Trans. Haptic* 2013, 6(1):106–116.
[116] Oliveira FC, Quek F, Cowan H, Bing F. The Haptic Deictic System-HDS: Bringing Blind Students to Mainstream Classrooms. *IEEE Trans. Haptic* 2012, 5(2):172–183.
[117] Park J, Lee Y, Cho S, Choe A, Yeom J, *et al.* Soft Sensors and Actuators for Wearable Human-Machine Interfaces. *Chem. Rev.* 2024, 124(4):1464–1534.
[118] Phung H, Nguyen CT, Nguyen TD, Lee C, Kim U, *et al.* Tactile display with rigid coupling based on soft actuator. *Meccanica* 2015, 50(11):2825–2837.
[119]Yin J, Hinchet R, Shea H, Majidi C. Wearable Soft Technologies for Haptic Sensing and Feedback. *Adv. Funct. Mater.* 2021, 31(39):2007428.
[120] Zhang F, Teng S, Wang Y, Guo Z, Wang J, *et al.* Design of bionic goat quadruped robot mechanism and walking gait planning. *Int. J. Agric. Biol. Eng.* 2020, 13(5):32–39.
[121] Ji W, He G, Xu B, Zhang H, Yu X. A New Picking Pattern of a Flexible Three-Fingered End-Effector for Apple Harvesting Robot. *Agriculture* 2024, 14(1):102.
[122] Huang Y, Zhou J, Ke P, Guo X, Yiu CK, *et al.* A skin-integrated multimodal haptic interface for immersive tactile feedback. *Nat. Electron.* 2023, 6(12):1020–1031.
[123] Botha I, Bright G, Collins J. Dielectric Elastomer Actuators and Optical Character Recognition in a Braille Display. *R&D J.* 2022, 38:31–42.
[124] Zhu ML, Sun ZD, Lee CK. Soft Modular Glove with Multimodal Sensing and Augmented Haptic Feedback Enabled by Materials' Multifunctionalities. *ACS Nano* 2022, 16(9):14097–14110.

[125] Zhong J, Ma Y, Song Y, Zhong Q, Chu Y, *et al.* A Flexible Piezoelectret Actuator/Sensor Patch for Mechanical Human-Machine Interfaces. *ACS Nano* 2019, 13(6):7107–7116.
[126] Li ZB, Yang J, Zhang YX, Geng PY, Feng JS, *et al.* Ultrafast readout, crosstalk suppression iontronic array enabled by frequency-coding architecture. *npj Flex. Electron.* 2024, 8(1):9.
[127] Chen S, Chen Y, Yang J, Han T, Yao S. Skin-integrated stretchable actuators toward skin-compatible haptic feedback and closed-loop human-machine interactions. *npj Flex. Electron.* 2023, 7(1):1.
[128] Firouzeh A, Mizutani A, Groten J, Zirkl M, Shea H. PopTouch: A Submillimeter Thick Dynamically Reconfigured Haptic Interface with Pressable Buttons. *Adv. Mater.* 2024, 36(8):2307636.
[129] Park J, Kang DH, Chae H, Ghosh SK, Jeong C, *et al.* Frequency-selective acoustic and haptic smart skin for dual-mode dynamic/static human-machine interface. *Sci. Adv.* 2022, 8(12):eabj9220.
[130] In H, Kang BB, Sin M, Cho KJ. Exo-Glove: A Wearable Robot for the Hand with a Soft Tendon Routing System. *IEEE Rob. Autom. Mag.* 2015, 22(1):97–105.
[131] Frank Z, Al-Rubaiai M, Tan X, Kim KJ. A study of electroactive polyvinyl chloride (PVC) gel actuators through the use of the electric modulus formalism and cyclic linear voltage sweeps. *Smart Mater. Struct.* 2022, 31(3):035020.
[132] Zhang F, Chen Z, Wang Y, Bao R, Chen X, *et al.* Research on Flexible End-Effectors with Humanoid Grasp Function for Small Spherical Fruit Picking. *Agriculture* 2023, 13(1):123.
[133] Han AK, Ji S, Wang D, Cutkosky MR. Haptic Surface Display based on Miniature Dielectric Fluid Transducers. *IEEE Rob. Autom. Lett.* 2020, 5(3):4021–4027.
[134] Li Z, Liu Z, Xu S, Zhang K, Zhao D, *et al.* Electrostatic Smart Textiles for Braille-To-Speech Translation. *Adv. Mater.* 2024, 36(24):2313518.
[135] Shi Y, Shen G. Haptic Sensing and Feedback Techniques toward Virtual Reality. *Research* 2024, 7:0333.
[136] Guo Y, Wang Y, Tong Q, Shan B, He L, *et al.* Active electronic skin: an interface towards ambient haptic feedback on physical surfaces. *npj Flex. Electron.* 2024, 8(1):25.
[137] Xia H, Zhang Y, Rajabi N, Taleb F, Yang Q, *et al.* Shaping high-performance wearable robots for human motor and sensory reconstruction and enhancement. *Nat. Commun.* 2024, 15(1):1760.
[138] Wu Q, Gu J. Design and Research of Robot Visual Servo System Based on Artificial Intelligence. *Agro Food Ind. Hi-Tech.* 2017, 28(1):125–128.