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Wearable and Implantable Soft Robots

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Shukun Yin, Dickson R. Yao, Yu Song, Wenzheng Heng, Xiaotian Ma, Hong Han, and Wei Gao*

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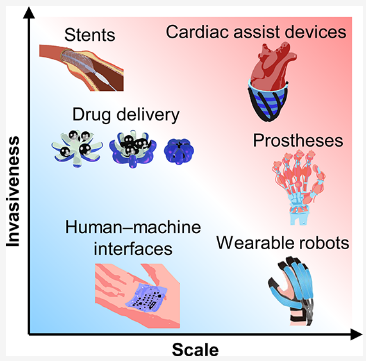
ABSTRACT: Soft robotics presents innovative solutions across different scales. The flexibility and mechanical characteristics of soft robots make them particularly appealing for wearable and implantable applications. The scale and level of invasiveness required for soft robots depend on the extent of human interaction. This review provides a comprehensive overview of wearable and implantable soft robots, including applications in rehabilitation, assistance, organ simulation, surgical tools, and therapy. We discuss challenges such as the complexity of fabrication processes, the integration of responsive materials, and the need for robust control strategies, while focusing on advances in materials, actuation and sensing mechanisms, and fabrication techniques. Finally, we discuss the future outlook, highlighting key challenges and proposing potential solutions.



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1. INTRODUCTION

Robotic technologies have significantly evolved over the past few decades, initially focusing on rigid robotic systems. These systems, renowned for their ability to deliver high output forces and execute fast, precise position control, have been instrumental in industries requiring meticulous task execution and robust operational capabilities.[1] As robotics technology advances, the interface between humans and machines becomes increasingly critical, particularly in contexts where direct interaction is inevitable.[2] Rigid robots, however, pose inherent risks due to their hardness and inflexibility, which can be hazardous in close-contact scenarios. The necessity for a paradigm shift toward designs that prioritize human safety and comfort becomes increasingly apparent.[3]

Traditional robots are composed of rigid components connected by discrete joints. When a robot has more degrees of freedom (DOFs) than necessary, it is said to be redundant. An example is the da Vinci Surgical System (Intuitive Surgical Inc.) used for minimally invasive surgery.[4] Continuum robots were inspired by natural structures like trunks, snakes, and tentacles, with their number of DOFs approaching infinity.[5,6] Such characteristics allow them to adjust and modify their shape at any point along their length, enabling them to work in confined spaces and complex environments where rigid-link robots cannot.[7] Natural systems, however, often match or exceed the performance of continuum robots. Invertebrates like the octopus and vertebrates like humans can achieve manipulation and locomotion at an extreme level.[5] Once again inspired by nature, engineers started to explore soft-bodied robots composed of compliant materials, which are often referred to as soft robots.[8]

Soft robots utilize materials such as silicone rubbers, which have flexibility and compliance similar to skin or muscle tissue, with a Young's modulus ranging from 10^4 to 10^9 Pascals. These robots offer a safer alternative for physical human–robot interaction by deforming and absorbing much of the energy arising from a collision.[5,9–12] They have the potential to exhibit unparalleled adaptation, sensitivity and agility. To achieve their full potential, components for sensing, actuation, control, power and communication must be embedded.

One of the natural advantages of soft robots is the compatibility of their moduli with those of natural tissues for wearable and implantable applications (Figure 1). Critical to these applications are the scale and invasiveness of devices. Generally speaking, a smaller scale can lead to better portability but increases complexity in design, fabrication, control, and limitations in power supply. Less invasiveness brings more comfort and reduces surgical complexity and risks but places higher demands on the device's scale and the biocompatibility of its materials. Therefore, developing more advanced wearable and implantable soft robots relies heavily on innovations in design, fabrication, control, power, and materials.

This review aims to provide a comprehensive overview of the burgeoning field of wearable and implantable soft robots. Starting from the actuation mechanisms, materials, and fabrication of general soft robots, we then survey the landscape of their medical applications, including rehabilitation and assistive devices, organ simulators, surgical tools, and therapeutic robots. We explore the integration of emerging materials and discuss ongoing scientific challenges such as biocompatibility, scalability, actuation, and fabrication. Finally, the review examines the current state and future directions of soft robotic design, with a focus on achieving harmonized actuation, control, and sensing in order to fulfill complex biomedical roles.

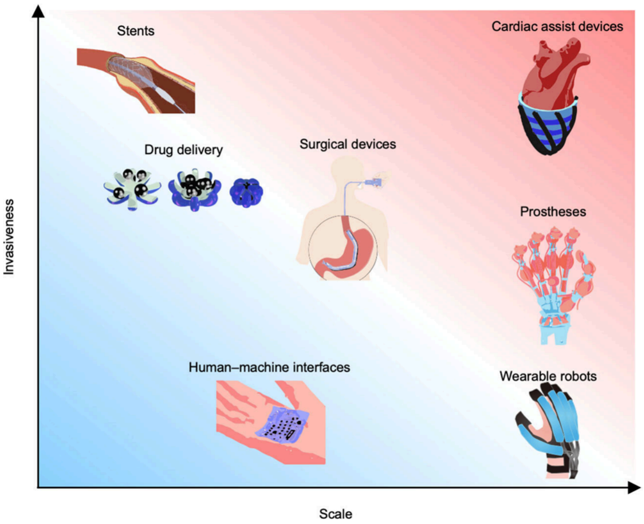

Figure 1. Different types of wearable and implantable soft robots. Scale and level of invasiveness are compared.

2. ACTUATION MECHANISMS, MATERIALS, AND FABRICATION FOR SOFT ROBOTS

Actuators are crucial components in soft robotics, enabling functionalities ranging from precise micromovements in minimally invasive surgeries to robust handling in rehabilitation devices.[13,14] The choice of actuation mechanism significantly influences design parameters, including fabrication complexity, sensing accuracy, control fidelity, and adaptability to various working environments.[15] This section explores the actuation mechanisms, promising materials, and advanced fabrication technologies that highlight the potential of soft robotics in wearable and implantable technologies. We emphasize their operational principles, advantages, and limitations.

2.1. Actuation Mechanisms

2.1.1. Pneumatic/Hydraulic Elastomers. Pneumatic and hydraulic actuation systems represent a primary mechanism in soft robotics, utilizing air or fluids to drive movement through the inflation or deflation of elastomeric chambers (Figure 2a).[16–19] Besides metallic valves and electric circuits, they can also be controlled by 3D-printed pneumatic logic gates with low manual effort and high pressure tolerance.[20] These systems are particularly advantageous due to their simplicity and the ability to generate significant forces. By incorporating materials with varying stiffness and incorporating asymmetric designs or inextensible layers, these actuators can achieve complex motions such as bending, twisting, or expanding. However, the dependency on external pumps for pressurization introduces challenges related to system size, weight, and autonomy, which are critical considerations in the design of portable or implantable devices.[21] Moreover, the inherent nonlinear properties of elastomeric materials used in fluidic actuators

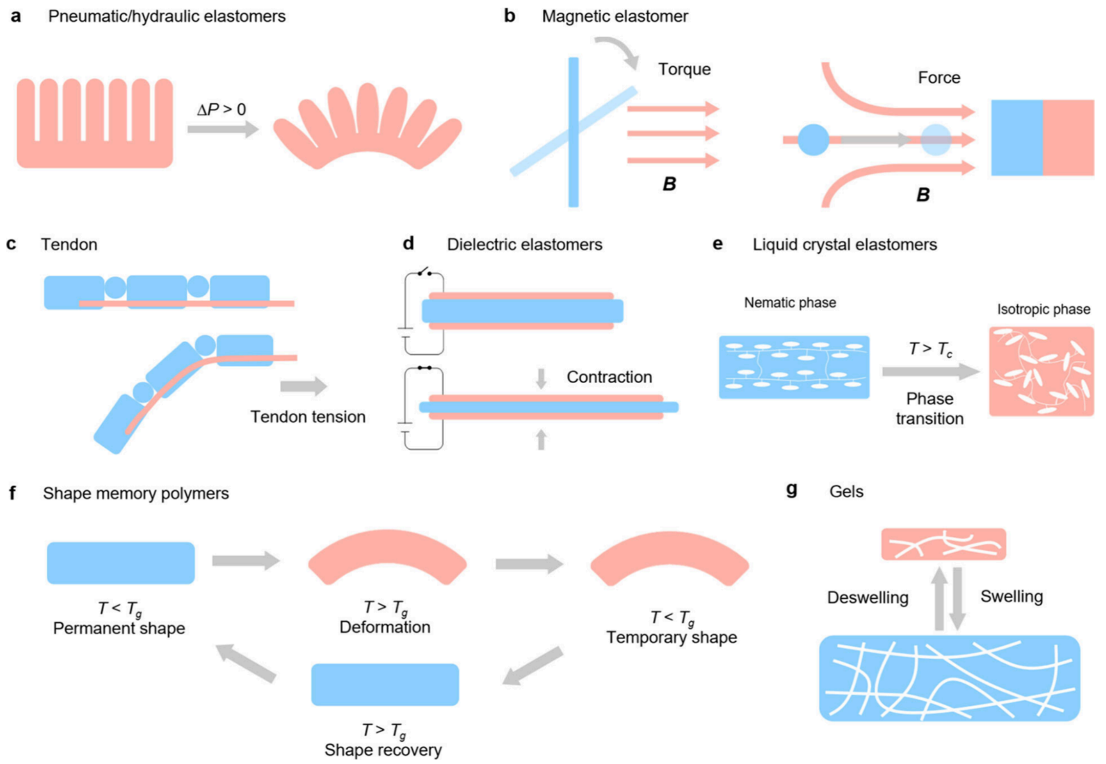

Figure 2. Actuation mechanisms for soft robotics categorized by material types. (a) Pneumatic/hydraulic elastomers: Fluidic pressure within the robot's internal cavities controls movement. (b) Magnetic elastomers: Soft elastomers embedded with magnetic particles offer precise control via torques or forces in response to an external magnetic field. (c) Tendon: Tension applied to tendons leads to deformation of the structure; elastic hinges store energy to return the actuated parts to their initial states. (d) Dielectric elastomers: Electrostatic forces between compliant electrodes compress a sandwiched dielectric material, resulting in deformation. (e) Liquid crystal elastomers: Stimuli induce phase changes in liquid crystal elastomers, affecting polymer chain orientation and length, thus altering the material's configuration. (f) Shape memory polymers: Actuation is triggered when the temperature surpasses a specific threshold, enabling shape-memory materials to revert to predefined shapes. (g) Gels: Environmental stimuli prompt volume changes in gels, dynamically influencing their shape and size.

require sophisticated control strategies to achieve precise movements, often involving real-time feedback and advanced algorithms to manage dynamic changes in pressure and volume.[22]

2.1.2. Magnetic Elastomers. Magnetic actuation in soft robotics leverages the remote controllability and flexibility of magnetic fields to manipulate objects without direct physical connections. This method utilizes materials embedded with magnetic particles whose alignment can be controlled externally, providing a means to initiate and direct movements. An applied magnetic field can be used to align the magnetization of distributed magnetic particles in an elastomer scaffold to generate a magnetic torque that drives deformation of the magnetic elastomer morphology (Figure 2b).[23,24] Magnetic torque actuation is especially useful for creating complex shapes that can be used different soft robot gaits, such as grasping tasks or locomotion to traverse through the body. Alternatively, magnetic force actuation relies on attractive forces between opposite poles of magnetic particles to an externally applied nonuniform magnetic field.[14] Magnetic force actuation can trigger deformations in magnetic elastomers that include shortening, elongation, bending, and buckling.[25] Furthermore, the attractive forces can be used to pull a magnetic elastomer toward an electromagnet or strong permanent magnet to drive movements of a soft robot.[26] The primary advantage of magnetic actuation is its capability for untethered operation, ideal for navigating constrained spaces within the human body, such as in targeted drug delivery systems or intravascular procedures.[27,28] The actuation can be finely tuned by varying the magnetic field's strength and orientation, enabling precise control over the robot's position and movement.[29] Challenges include the need for complex electromagnetic setups to ensure accurate and safe operation, particularly in sensitive biological environments. Additionally, designing magnetic actuation systems often involves balancing the magnetic properties and the biocompatibility of materials, ensuring that the actuators do not adversely affect the human body while maintaining effective performance.[15]

2.1.3. Tendon. Tendon-driven actuation systems mimic the natural movement mechanics found in biological organisms, where tendons transmit forces from muscles to bones. In soft robotics, tendon actuation uses flexible cables or threads connected to motors, which pull on the soft structure to induce desired movements, such as bending or twisting (Figure 2c).[30,31] This mechanism allows for a high degree of control over the robot's motion, making it suitable for applications that require precise manipulation capabilities, such as robotic surgery or fine motor rehabilitation devices. The design of tendon-driven actuators focuses on achieving a balance between flexibility and force transmission, often incorporating advanced materials that can withstand repeated stress without losing elasticity. One of the significant challenges in tendon-driven systems is miniaturization, as the inclusion of motors and cables can increase the complexity and size of the device, potentially limiting its applicability in wearable contexts.[15]

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Table 1. Comparison of Actuation Mechanisms for Soft Robots

materials	advantages	disadvantages	power density (W/kg)	energy density (kJ/m^3)	ref
Pneumatic/Hydraulic Elastomers					
inner elastic bladder: latex rubber, silicone, polyurethane	high compliance	require external pumps	40–20000	300–500	11, 79, 80
outer braided mesh sleeve: nylon fibers, polyester fibers, Kevlar	simple fabrication process	complex control			
	large deformations	difficult to miniaturize			
	fast response				
	large force output				
Magnetic Elastomers					
base materials: silicone (PDMS, Ecoflex) or polyurethane	precise and remote control	require bulky and complex external systems for magnetic fields	10–100	10–50	25, 27, 88
magnetorheological fluids	favorable for small-scale fabrication				
magnetic particles: Fe_3O_4 (magnetite), NdFeB (neodymium iron boron), or iron nanowires					
Tendon					
synthetic fibers: nylon, polyester fibers, Kevlar, polyethylene, polypropylene	high tensile strength	require pulleys or motors, prone to wear and tear difficult to miniaturize	N/A	N/A	89, 90
	lightweight				
	high flexibility				
	fast response				
	high actuation power				
Dielectric Elastomers					
PDMS, polyurethane, acrylic polymer, fluoroelastomers, polybutadienes (BR), polyisoprenes	high energy density	require high electric fields	100–5000	100–3500	32, 33, 36, 91, 92
	large actuation strain	dielectric breakdown risk			
	fast response	limited operational lifetime			
Liquid Crystal Elastomers					
cross-linked polymers containing mesogens, such as RM82 as mesogenic monomers, RM257 as cross-linkers	reversible actuation	slow response	10–400	150–2000	45, 48, 49, 54, 55, 60, 93
	easy to miniaturize	high transition temperature			
	remote actuation	low efficiency			
		hysteresis			
Shape Memory Polymers					
polycaprolactone (PCL), polylactic acid (PLA), polyurethane (PU), polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), poly(methyl methacrylate) (PMMA), poly(butyl methacrylate) (PBMA)	easy to miniaturize	slow response	1–10	100–6000	46, 65, 67, 94–98
	remote actuation	require external stimuli			
Gels					
poly(*N*-isopropylacrylamide) (PNIPAM), polyvinyl alcohol (PVA), polyacrylamide (PAAm), polyethylene glycol (PEG), alginate, chitosan, agarose, gelatin	reversible actuation	slow response	0.01–10	0.01–100	18, 99–104
	untethered operation	soft and brittle			
	self-sensing ability				
	easy to miniaturize				
	large actuation strain				

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2.1.4. Dielectric Elastomers. Dielectric elastomers, a subgroup of electroactive polymers, function as capacitive actuators where a thin elastomeric film sandwiched between two compliant electrodes expands and contracts in response to electrical stimulation (Figure 2d).[32−36] This actuation method is prized for its efficiency, rapid response, and ability to produce large strains with relatively low power consumption.[36] Dielectric elastomers are particularly effective in applications requiring quick and significant shape changes.[37] The primary challenge lies in managing the high voltages typically required to induce significant deformation, which can lead to issues such as electrical breakdown and material fatigue over time.[38,39] Different from rigid dielectrics with a fixed value of breakdown strength, dielectric elastomers are actuated under the cyclic electromechanical coupling process. Therefore, they are prone to premature breakdown failure during the dynamic actuation.[40−42] Besides dielectric breakdown, other failure modes include pull-in and material strength. Dielectric breakdown dominates at high stretch rates, while pull-in failure occurs at low stretch rates. Material strength failure is generally less significant in most cases.[43] Additionally, to achieve practical forces and movements, dielectric elastomers often require mechanical prestrain and rigid frames, which can complicate the design and integration of these materials into fully soft systems.[15,44]

2.1.5. Liquid Crystal Elastomers. Liquid crystal elastomers (LCEs) combine the mechanical properties of cross-linked polymers with the anisotropic ordering of liquid crystals, allowing them to respond dynamically to environmental stimuli such as temperature and light (Figure 2e).[45,46] This unique property makes LCEs particularly suitable for applications where reversible, controllable actuation is required.[47−49] LCEs can be programmed to undergo significant shape changes, which can be precisely controlled by adjusting the stimulus type and intensity.[50] The main advantage of using LCEs in soft robotics is their ability to perform complex and repeatable movements without the need for hard mechanical components.[51] However, the challenges associated with LCEs involve optimizing the material formulations and structural designs to improve response times, actuation strain and operational stability under varying environmental conditions.[46,52−54] For example, comparatively high temperatures (typically above 60 °C) are required to disrupt orientation in LCE to achieve meaningful work output.[54−56] To use LCEs in wearable and implantable applications, actuation at or below ambient temperature is desired (e.g., <50 °C for skin regeneration).[56,57] Generally speaking, using thiol-Michael addition reactions for chain extension methods,[57] lower curing temperature, higher ratio of cross-linker and lower ratio of liquid crystal molecule can enable a lower actuation temperature.[56] The most drastic reduction in actuation temperature has been achieved by direct replacement of liquid crystalline content with nonliquid crystalline polyethylene glycol (PEG) molecules, but it also reduces the overall actuation strain.[57−59] In another instance, to improve actuation strain and response speed, material and structural design can be adopted. LCE microfibers fabricated with a facile electrospinning technique can generate ∼60% actuation strain, a response time of less than 0.2 s and a power density of 400 W/kg.[60] LCE fibers and bundles fabricated with exfoliated graphene fillers within a uniaxial liquid crystalline matrix achieve ∼45% actuation strain, ∼90% s^{-1} strain rate and a power density of 293 W/kg.[55] On the other hand, a mechanics-guided design of LCE metamaterials in the form of a 2D periodical lattice pattern of straight ribbons achieve 52% actuation strain.[56]

2.1.6. Shape Memory Polymers. Shape memory polymers (SMPs) are smart materials that can return from a deformed state to their original shape upon exposure to an external stimulus, typically heat (Figure 2f).[61] This characteristic is highly beneficial in applications requiring self-adjusting or responsive elements. SMPs can be engineered to exhibit a wide range of mechanical properties and activation temperatures, allowing for their use in diverse environments and applications.[62−64] The design of SMP-based devices often involves programming the material's shape-memory behavior during the manufacturing process, which can include 3D printing techniques for creating complex, patient-specific geometries.[65−67] While SMPs offer significant potential for innovation in soft robotics, they face challenges related to the predictability and repeatability of their actuation behavior, especially under varying loading conditions and in biological environments.[15]

2.1.7. Gels. Gels, particularly hydrogels, are polymeric materials that can absorb and retain large amounts of water, making them highly soft and flexible (Figure 2g).[46,68] In the context of soft robotics, hydrogels are used for applications where gentle and adaptive interactions are essential, such as in wearable sensors that monitor body functions or soft actuators that assist with delicate surgical procedures.[69−71] Hydrogels can be designed to respond to specific stimuli, such as temperature changes, pH variations, or electromagnetic fields, allowing for controlled actuation and adaptation to the surrounding environment.[46] The main advantage of gels lies in their biocompatibility and similarity to biological tissues, which minimizes the risk of adverse reactions when in contact with the body. However, challenges remain in enhancing the mechanical strength and response speed of hydrogels to ensure their practicality in load-bearing applications and dynamic environments.[46]

2.2. Materials

The advancement of soft robotics hinges on the development of materials that offer a harmonious blend of high flexibility, significant strength, and durability.[15] Ideal materials for soft robots exhibit high elongation at break and tensile strength while maintaining a low Shore hardness, ensuring compatibility and comfort in wearable and implantable applications. Predominant materials include various polymers such as silicones, polyurethanes,[72,73] and hydrogels,[74] selected for their ability to undergo substantial deformation while maintaining structural integrity (Table 1).

Silicone elastomers, such as polydimethylsiloxane (PDMS) and Ecoflex, are favored for their exceptional mechanical properties. They typically exhibit tensile strengths ranging from 0.1 to 3.0 MPa and an elongation at break of up to 900%.[75] These materials offer excellent durability and chemical stability, making them suitable for prolonged contact with human skin and tissues in medical implants and wearable devices.[76−78] Their high compliance and ease of fabrication make them ideal for use in pneumatic/hydraulic and dielectric elastomer actuators.[11,79,80]

Polyurethanes are widely utilized due to their higher tensile strength—up to 50 MPa—and good abrasion resistance.[81−86] This makes them suitable for more robust applications, such as soft tactile surfaces in robotic grippers and durable films in prosthetic linings. Polyurethanes are versatile and can be formulated for use in dielectric elastomers and SMPs, contributing to high energy densities and efficient actuation.[46,65]

Hydrogels are particularly interesting for their high water content, biocompatibility, and softness, closely mimicking biological tissues. Although they generally have lower mechanical strength, usually under 0.1 MPa,[87] advances in hydrogel engineering have improved their mechanical properties. Hydrogels are effective in applications requiring gentle and biocompatible actuation, such as drug delivery systems and wearable sensors.[18] They are commonly used in gel-based actuators that respond to environmental stimuli with minimal energy input.

The choice of actuation mechanism significantly influences the energy requirements, efficiency, and application scope in soft robotics.[15] Actuation mechanisms vary in power and energy densities, affecting performance and suitability for specific applications.

Pneumatic and hydraulic actuators offer high compliance, large deformations, fast response times, and significant force output. However, they require external pumps and complex control systems, making miniaturization challenging. Their high power and energy densities make them ideal for applications requiring substantial force and rapid actuation, such as rehabilitation devices and industrial automation (Table 1).[11,79,80]

Magnetic elastomers offer precise and remote control, favorable for small-scale fabrication. While they have moderate power densities, magnetic elastomers are limited by the concentration of ferromagnetic particles that can be loaded into the elastomer scaffold, limiting the energy density in these systems (Table 1).[25,27,88] However, their ability to provide precise control without physical contact makes them suitable for delicate manipulation tasks.

Tendon-driven systems offer high tensile strength, lightweight construction, high flexibility, fast response times, and significant actuation power. They are known for their efficiency and high actuation power relative to their weight (Table 1).[89,90] They are commonly used in applications requiring rapid and powerful movements but may face challenges related to wear and tear and miniaturization.

Dielectric elastomers are notable for their high energy and power densities, enabling large actuation strains and fast response times. The high power density makes dielectric elastomers suitable for dynamic applications like adaptive optics and soft robotic grippers.[32,33,91] However, the necessity for high electric fields introduces risks of dielectric breakdown and may limit operational lifetime (Table 1).[36,92]

Both LCEs and SMPs enable remote actuation via thermal stimuli and are advantageous for applications requiring shape programmability and environmental responsiveness (refs 45, 49, 55, 65, 67, 94, and 95). Although with relatively low power densities, LCEs and SMPs can generate significant amounts of work for their size and weight. SMPs, particularly those based on polyurethane, can store significant amounts of energy, showing energy densities around 200 kJ/m^3. However, SMPs with supramolecular nanostructures have also been demonstrated energy densities as high as 6000 kJ/m^3.[105] LCE materials that are also heat sensitive have a similar range of energy density from 150 to 2000 kJ/m^3. While they do not have the flexibility of shape memory transformation into a complex predefined geometry, the alignment of LCE mesogens can be programmed locally for various shape actuation.[48] Rather than through a phase-change phenomena, synthetic fibers artificial muscles, such as nylon and other twisted yarns, employ thermal expansion for linear actuation.[106] As a result, these artificial muscles have a lower work density between 10−50 kJ/m^3.[107] However, temperature responsive shape actuating materials typically suffer from slow response rate and the need for external stimuli to trigger actuation are considerations that can restrict their use in rapid-response applications (Table 1).[46,48,54,93,96−98]

Gels offer reversible actuation, untethered operation, self-sensing ability, ease of miniaturization, and large actuation strains.[18] While they offer significantly less energy storage capacity, their high water content and intrinsic softness make them particularly effective in biomedical applications where gentle and biocompatible actuation is necessary, such as in drug delivery systems and sensors for soft robots (Table 1).[99−104] Hydrogels with higher work densities up to 15 kJ/m^3 have been engineered by designing reversible elastic-driven recoil into strong contractile hydrogels.[108] Meanwhile, organogels are typically tougher than hydrogels owing to nonaqueous solvents that form stronger interactions with the polymer network. Hence, organogel-based actuators can have energy densities over 100 kJ/m^3.[109]

Selecting an actuation mechanism in soft robotics involves balancing energy density, power density, mechanical properties, and response times. Higher energy and power densities allow for more robust actuations but may increase system complexity and energy consumption. Lower energy and power densities are suitable for applications where subtlety, flexibility, and energy efficiency are prioritized over raw power.

Other measures of actuator performance must also be carefully considered for the intended application, such as specific work that measures energy output per unit mass rather than volume.[106] Additionally, response time of actuators determine the power density of the soft actuating materials. Generally, response time is determined by the type of stimuli for the actuating mechanism, where electromagnetic and pneumatic stimuli act almost instantaneously, while heat and humidity are typically slow to permeate through a large volume of material. Understanding these trade-offs is essential for optimizing the design and functionality of soft robots across various applications, particularly in wearable and implantable technologies where energy efficiency and biocompatibility are paramount.[15]

2.3. Fabrication

The future of materials and actuation mechanisms in soft robotics is influenced by advancements in fabrication techniques. Traditional manufacturing processes struggle to fabricate actuated systems with high spatial resolutions and complex material arrangements that range from elastic to rigid.[110] Fabricating functional systems automatically and quickly with a wide range of elastic properties, resolutions and integrated actuation and sensing channels is still an open challenge.[13,110] Currently, different technologies based on subtractive, forming, and additive manufacturing can be used for the fabrication of soft robots. The suitability of each method is determined by material properties, including melting temperature, viscosity, solubility, and others.[46] In this subsection, important fabrication techniques will be overviewed.

2.3.1. Subtractive Manufacturing. Cutting is a variation of subtractive manufacturing. Cutting is often performed mechanically by using blades. Laser cutting and engraving are special cases, which offer important advantages: high resolution (down to 1−2 μm), fast speed, no wear/tear, and no defect formation.[111,112] Kirigami patterns by laser cutting and origami patterns by laser engraving can be designed and fabricated for

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soft actuators.[113,114] Machinery-based fabrication offers greater precision in design control and enhances the overall manufacturing process. However, like other subtractive manufacturing techniques, it does not permit the integration of multiple material types.

2.3.2. Forming Manufacturing. Molding is a cost-effective technique that enables the production of thousands of parts once a mold insert is created. Molding processes can be categorized into five types: injection molding,[115] reaction injection molding,[115] hot embossing,[116] injection-compressed molding,[115] and thermoforming.[117] However, like most molding methods, it is limited in terms of combining different materials and creating complex structures from multiple materials in a single production run. Molding is more suitable for large-scale manufacturing rather than prototyping. It is particularly applicable for fabricating with liquid materials that have long solidification times, such as PDMS.[46]

Spinning is a forming manufacturing technique in which material is neither added nor removed. Not all materials can form fibers, and a key property enabling fiber formation is that solidification must occur on a time scale shorter than the material's relaxation time.[46] Based on the method used to solidify fibers after spinning, fiber-spinning techniques can be divided into wet,[118] dry,[119] melt,[120] and gel spinning.[121,122] Electrospinning, a variation of dry and melt spinning, uses an electrical field to draw fibers from a solution or melt. This method offers several advantages, including small fiber diameters (ranging from several nanometers to micrometers) and a high surface area.[123] A key benefit of fiber spinning is the ability to create fine structures with dimensions as small as 100 nm and high aspect ratios. However, the structures produced are continuous rather than discrete, which is the main limitation of fiber spinning.[46]

In addition, mechanically guided 3D assembly methods exploit controlled mechanical deformations to transform planar electronic devices into 3D ones with various geometric configurations.[52] Based on loading schemes and deformation characteristics, mechanically guided 3D assembly methods are classified into rolling assembly,[124] folding assembly,[125,126] curving-induced assembly,[127−131] and buckling-guided assembly.[132,133] 3D assembly methods are highly compatible with established fabrication processes for planar inorganic flexible electronics, making them valuable tools for producing soft robots and their embedded sensors with precisely designed structural configurations and functionalities.[134,135]

2.3.3. Additive Manufacturing. Additive manufacturing refers to the production of physical objects by successively layering materials. A subset of this, 3D printing, creates three-dimensional objects from digital design files by precisely depositing material layers. This method reduces the marginal cost of design iterations and fabrication, allowing for rapid prototyping and the creation of complex single components.[110]

Common 3D printing techniques include fused deposition modeling (FDM),[136−138] direct ink writing (DIW),[139] selective laser sintering (SLS),[140] inkjet printing,[141] and stereolithography (SLA).[142] In FDM, a thermoplastic filament is melted and extruded through a heated nozzle, depositing and fusing layers. DIW involves the flow of liquid ink through a nozzle, which solidifies upon deposition.[143] SLS uses a laser to selectively heat and fuse thermoplastic powder, with fresh powder spread over the bed between each cycle. When used with thermoplastic polymers, SLS is also referred to as selective laser melting. Inkjet printing ejects tiny droplets of liquid ink from print heads, which solidify in response to heat or light, layer by layer. SLA employs a liquid photopolymer that solidifies when selectively exposed to light, layer by layer, within a bath of resin.[110] Across all these methods, the raw material—whether filament, ink, powder, or resin—transforms from a fluid or mobile state into a solid structure during the manufacturing process.

Finally, the key advantage of utilizing and integrating 3D printing technologies lies in the ability to incorporate actuators, sensors, controls, and power systems into fully autonomous soft robots through a seamless, on-demand digital fabrication process.[110] Multimaterial 3D printing is a promising candidate, which enhances the complexity and functionality of printed objects by integrating different materials with high spatial and compositional precision. Light-based methods are less suited for this due to the challenge of altering material composition during printing.[144] In contrast, ink-based techniques like FDM, inkjet printing, and DIW are better suited for multimaterial fabrication.[145] FDM and inkjet printers can print primary materials alongside sacrificial supports, enabling the creation of complex features. Inkjet printing offers higher resolution and allows for precise voxel-by-voxel material patterning, enabling variations in mechanical properties.[141,146] DIW is the most versatile, capable of printing structural, electrical, and biological materials.[145] Techniques like microfluidic printheads,[147,148] core−shell printing,[149−151] multinozzle arrays,[152,153] and functional nozzles[154] significantly reduce build times and enable the simultaneous deposition of multiple materials. Embedded 3D printing further expands these capabilities by enabling free-form fabrication of soft materials, offering unparalleled flexibility. For example, an untethered soft robot's actuators, sensors, control systems, and power sources can all be built from multiple elastomers at near-micron resolutions using soft lithography and multimaterial embedded 3D printing.[155]

The advancement of soft robotics is intricately linked to innovations in fabrication techniques and materials science. The future of 3D printing technologies holds the potential to directly fabricate soft robots with integrated functional components. For instance, robots could incorporate embodied energy systems, where parts of the robot's structure decompose to release energy on demand, serving dual roles as structural and power elements.[141,156−158]

While a combination of manufacturing techniques may be the best approach, current 3D printing technologies face limitations in resolution, speed, material compatibility, and scalability. Techniques like SLS and FDM are restricted to thermoplastics, which may not meet the performance requirements for resilient, functional components. In contrast, liquid ink-based methods, such as DIW, allow for chemical material modification and multimaterial printing, though they are limited by a trade-off between speed and resolution.[143] Inkjets enable rapid multimaterial printing but are limited by the availability of elastomers that can exceed 200% strain, and processing parameters must be precisely controlled. Challenges also remain with directly printing complex architectures, where sacrificial supports and additional steps are often necessary.[110] Printing in buoyant media like SLS powder beds or SLA liquid resin can provide passive support, but the removal of unreacted material adds complexity. Innovations like orthogonal photopolymerization chemistries could allow multimaterial printing in SLA, making it a powerful tool for fabricating advanced soft robots.[110,159] Moreover, structural design approaches, such as incorporating multistable structures, are another way to enhance 3D printing for soft robots.[160−163] As a soft robot possesses more DOFs, the

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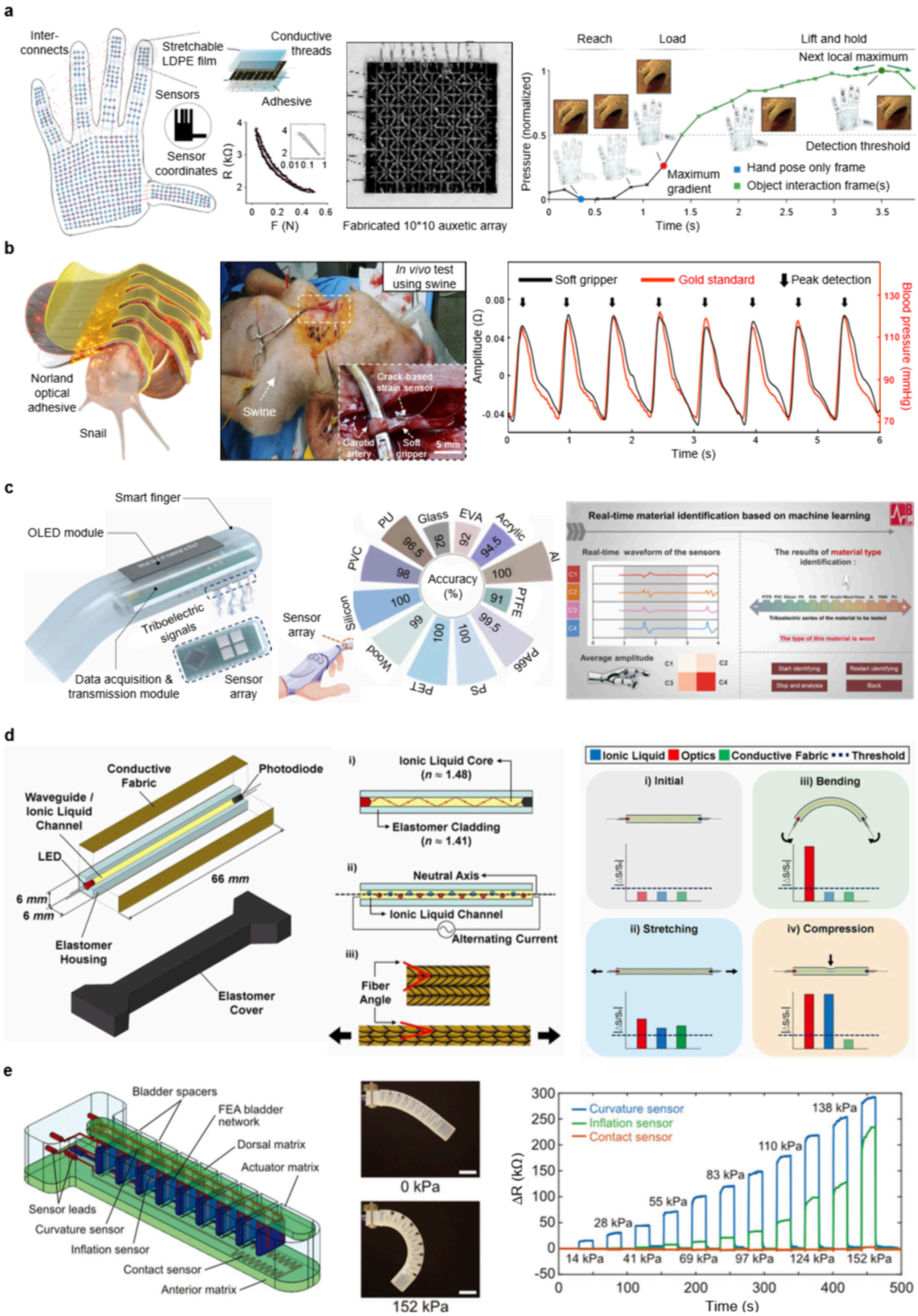

Figure 3. Exteroceptive and proprioceptive sensing for soft robotics. (a) Scalable tactile glove learning from the signatures of the grasp to decompose a tactile map. Reproduced with permission from ref 186. Copyright 2019 Springer Nature. (b) Miniaturized, nature-inspired, hand-shaped soft gripper for in vivo vital sign monitoring. Reproduced with permission from ref 187. Copyright 2021 The American Association for the Advancement of Science. (c) Triboelectric artificial tactile perception smart finger for material identification. Reproduced with permission from ref 189. Copyright 2022 The American Association for the Advancement of Science. (d) Multifunctional soft sensor for mechanoreception and proprioception of soft robots. Reproduced with permission from ref 190. Copyright 2020 The American Association for the Advancement of Science. (e) A soft robotic gripper combines multiple somatosensitive actuators with embedded sensors, providing proprioceptive and haptic feedback including deep and fine touch sensing. Reproduced with permission from ref 191. Copyright 2018 Wiley.

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difficulty of actuation and control also increases.[164] Multistable structures have fewer or even zero DOFs, making them easier to actuate and control.[165,166] Finally, 3D printing resolution has been greatly improved by using nanoscale fabrication techniques, such as two-photon polymerization, to create structures with extremely fine details.[167,168] This technology enables the production of complex, high-precision components at the nanometer scale, such as a feature size down to 100 nm from Nanoscribe, expanding possibilities in 3D printed soft robots.

3. SENSING FOR SOFT ROBOTS

Soft robots currently possess limited or no sensory capabilities. Due to their compliance and morphology, soft robots cannot effectively use conventional sensors like encoders, metal or semiconductor strain gauges, or inertial measurement units (IMUs).[5] To implement advanced functions, next-generation devices must detect their own deformation states, applied forces, and varying environmental conditions.[110] This section will explore several of the most prevalent sensing methods for soft robots.

3.1. Exteroceptive and Proprioceptive Sensing

The ultimate aim in the field of soft robotics is to develop robots capable of exteroception and proprioception, making decisions based on situational contexts and performing physical actions or specific functions.[14,169] The physical movements of these robots are governed by the interaction between environmental data and their inherent mechanical properties. Drawing inspiration from nature, the development of these robots leverages efficient sensory and responsive mechanisms achieved through innovations in sensors and actuators. Exteroceptive and proprioceptive sensors gather environmental information and detect deformations within the soft robot, while actuators are essential for applying forces and making internal structural adjustments.[170,171] The robot's intelligence interprets signals from the sensors and modulates actuator dynamics, ensuring a swift response to environmental stimuli and enabling precise task execution.[110,172]

To advance soft robotics further, it is essential to develop high-performance electronics and sensors that can stretch seamlessly along with the robot's body. The intersection of electronic skins (e-skins), soft robotics, and machine learning is becoming increasingly prominent.[169] Soft actuators have seen remarkable improvements in their capabilities,[155,173,174] and soft sensors as well as e-skins now offer a wide array of complex functionalities. Recent efforts in artificial skin research have primarily aimed at enhancing individual sensor devices, focusing on better sensitivity, greater stretchability, and improved reliability over numerous use cycles.[175−178] To achieve fully biomimetic skin for soft robots, artificial skins should incorporate stretchable sensor arrays that cover large areas with high spatial and temporal resolution and mimic the multiple functions of diverse human skin receptors.[179−182] These features would enable robots to employ data-driven techniques to extract rich information from their surroundings.[169,183,184]

In terms of exteroceptive sensing, tactile perception plays the most significant role in the soft robotics.[185] By integrating sensors that can detect various biophysical signals such as pressure, strain, and temperature, soft robots can imitate the tactile perception and dexterity of human hands, opening up new avenues for practical applications.[170] Through learning from the signatures of the grasp, the scalable tactile glove could decompose a tactile map to introduce a novel approach of tactile sensing for soft robotics (Figure 3a).[186] By analyzing the intricate signatures of grasps through a tactile glove equipped with sensors, researchers can decipher complex tactile maps and extract valuable information about object properties and interactions. This innovative method not only enhances the perception capabilities of soft robots but also lays the foundation for developing more sophisticated tactile feedback systems that can enable accurate control and manipulation tasks.

In a different application domain, a multifunctional soft gripper has been proposed for in vivo vital sign monitoring (Figure 3b).[187] Such hand-shaped gripper is capable of conforming to irregular surfaces and delicate objects, to noninvasively monitor vital signs when equipped with temperature and pressure sensors. Such configuration offers a promising solution for continuous health monitoring and medical diagnostics. By seamlessly integrating tactile sensing with soft robotic actuators,[2] this technology exemplifies the potential of soft robotics in revolutionizing healthcare delivery.

Besides pressure sensing, tactile perception also includes the direct response to environmental stimuli and psychological parameters associated with brain recognition. Assisted with triboelectric working mechanism,[188] an artificial smart finger are developed for material identification (Figure 3c).[189] Through the integration of triboelectric sensing and machine learning, a unique triboelectric fingerprint output could be generated when the sensor is in contact with measure object as each material has different capabilities to gain or lose electrons. By analyzing the tactile feedback from these sensors, soft robots can discern the types of objects and distinguish between different materials with high accuracy. This capability holds significant implications for applications such as quality control in manufacturing, environmental monitoring, and object recognition in robotics.

Apart from tactile sensing that relies on direct contact, exteroceptive sensing can also be achieved without physical touch. Benthobatis moresbyi possesses specialized organs that emit electric fields and electroreceptor arrays to detect objects in its surroundings.[192,193] Inspired by the electric sensory systems of such deep-sea fish, there is potential to design and integrate flexible electroreceptor arrays for noncontact spatial perception in soft machines.[194] Cetaceans use echolocation to detect nearby objects in darkness, which has inspired the development of a flexible acoustic transceiver.[193,195] This device consists of piezoelectric electrodes attached to a flexible substrate, offering potential for distance communication and sensing for soft robots.[174,193,196]

Humans rely on feedback from proprioceptors—sensory receptors—to achieve manual dexterity, motor skills, and other physical abilities.[190] The field of soft robotics seeks to replicate these human capabilities with soft sensors for uses such as robotic handling,[197] wearable technology,[198] and autonomous soft robots.[155] Most of the traditional soft proprioceptive sensors can detect one deformation mode at a time. However, a soft sensor with heterogeneous sensing mechanisms, combining optical, microfluidic and piezoresistive sensing, can decouple combined deformation modes (Figure 3d).[190] This soft sensor can detect and decouple modes of stretching, bending and compression, as well as detect individual deformation modes. Consequently, the multifunctionality of this sensor is suitable as a method for human−machine interfaces (HMIs) and for mechanoreception and proprioception of soft robots. Another soft somatosensitive actuator, fabricated with embedded 3D

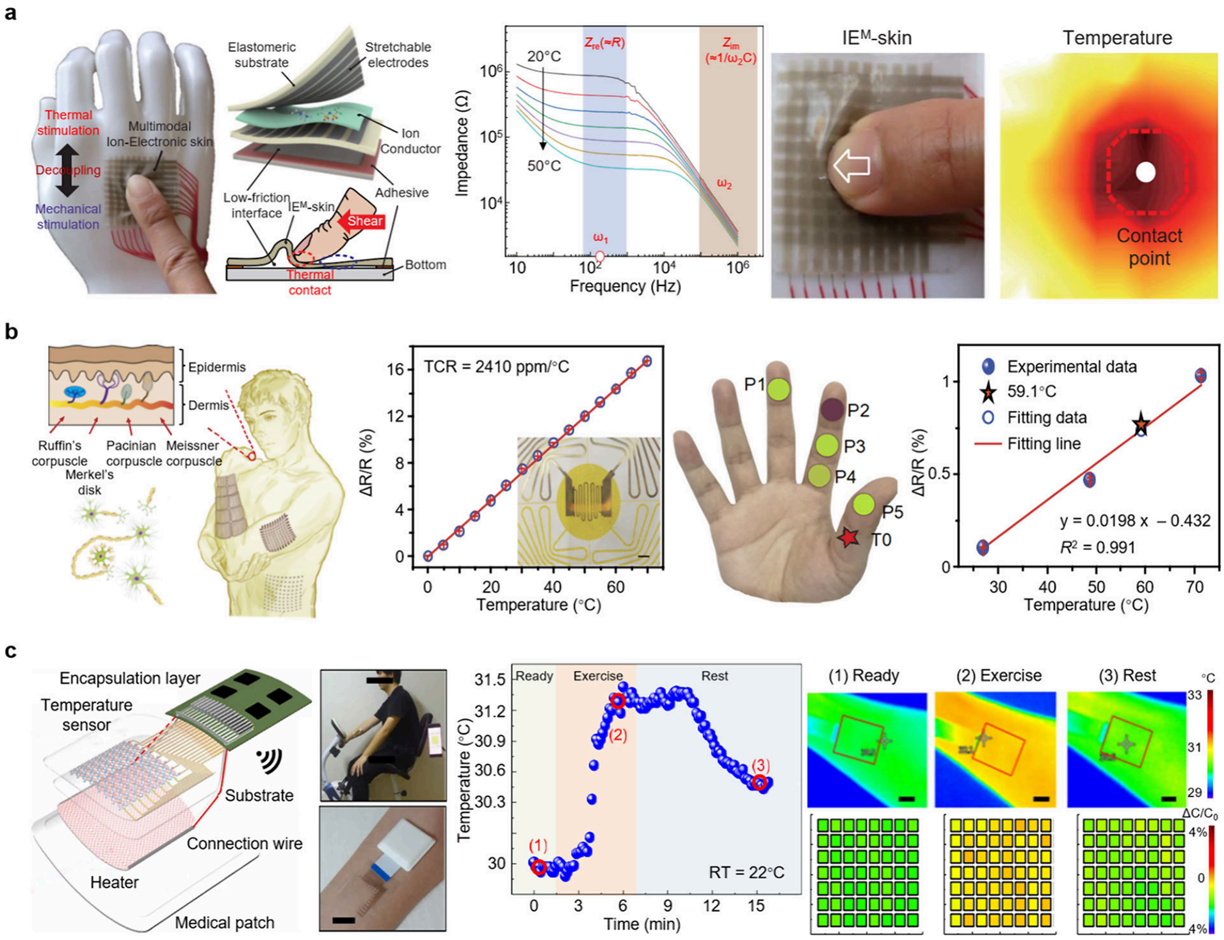

Figure 4. Temperature sensing for soft robotics. (a) Schematic of the multimodal ion-electronic skin and the responses under a unidirectional shear applied by the forefinger with the corresponding profiles of temperature. Reproduced with permission from ref 207. Copyright 2020 The American Association for the Advancement of Science. (b) Skin-inspired highly stretchable and conformable matrix networks with the linear changes along the temperature for the intelligent prosthetic hand configuration. Reproduced with permission from ref 208 under CC BY 4.0. Copyright 2018 Springer Nature. (c) Wireless skin-mounted graphene-based thermal patch for obtaining temperature distribution. Scale bar, 2 cm. Reproduced with permission from ref 209. Copyright 2022 The American Association for the Advancement of Science.

printing, are equipped with multiple conductive elements that enable simultaneous haptic, proprioceptive, and thermoceptive sensing.[191] A soft robotic gripper is designed with multiple such actuators, providing proprioceptive and haptic feedback via embedded sensors that detect curvature, inflation, and contact, including sensors sensitive to both deep and fine touch (Figure 3e).[70,191] Besides soft sensors, electrically driven fluidic or liquid-containing actuators naturally possess self-sensing capabilities. Liquid metal, or eutectic gallium indium (eGaIn), is a promising candidate for such liquid.[149,199] Similar to liquid, light transmitted in optical fibers can also be used to interpret deformation of an elastomer.[200] In addition to materials integration, structural design with one material is another approach, such as fluidically innervated architected design and metamaterials.[201,202] Finally, in addition to noninvasive approaches, sensory streams obtained from surface electromyographic (sEMG) sensors can also be delivered via intraneural stimulation through electrodes implanted in the median and ulnar nerves.[203]

In addition to physical signals, the environment also contains electrical,[193] biological, and chemical signals.[204] Mechanisms for sensing these signals will be discussed in the following subsections.

3.2. Temperature Sensing

Temperature sensing plays a crucial role in the advancement of soft robotics,[15] enabling precise control, environmental monitoring, and enhanced safety in various applications. By employing various sensing techniques,[205] including thermocouples, resistance temperature detectors, and infrared sensors, soft robots can accurately measure temperature changes in their surroundings and within their own structures. This capability enables soft robots to operate in diverse environments, ranging from extreme temperatures to delicate biological settings.[206]

For soft robots, the integration of temperature sensors demands that these components possess high sensitivity, accuracy, and the ability to conform to the robot's flexible surfaces, which may undergo various motions and deformations. The sensors should exhibit characteristics such as rapid response times, consistent repeatability, a broad operational temperature range (typically 25 to 40 °C), and long-term stability under varying environmental conditions. For example, to mimic human skin with different types of receptors that can distinguish various mechanical stimuli from temperature, an artificial ion-electronic skin is proposed, which are capable of detecting temperature changes under applied shear stress (Figure 4a).[207] When subjected to shear stress, the skin generates electrical signals corresponding to changes in temperature, allowing soft

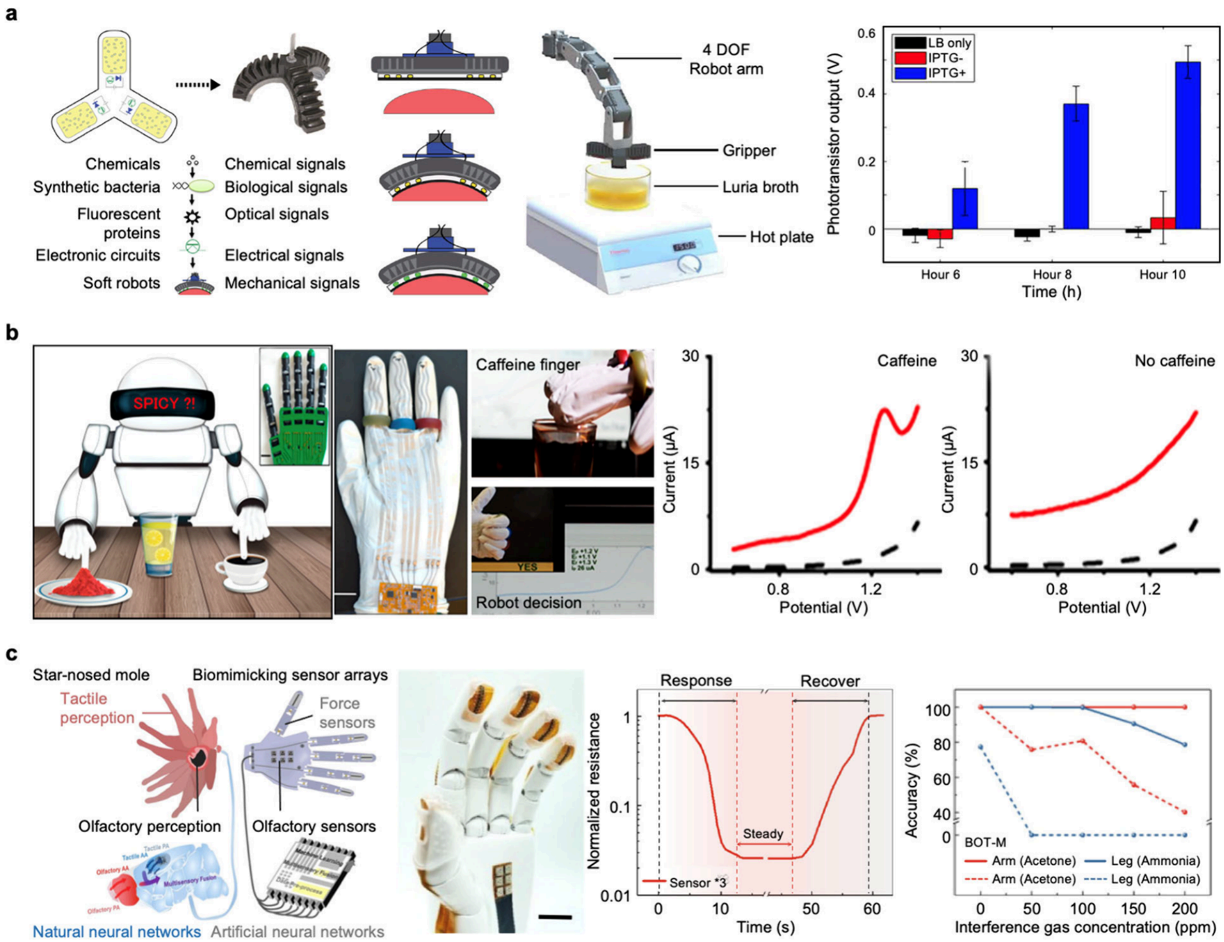

Figure 5. Biochemical sensing for soft robotics. (a) A biosensing soft robotic arm for autonomous parsing of chemical signals in an aqueous environment. Reproduced with permission from ref 212. Copyright 2019 The American Association for the Advancement of Science. (b) Chemical sensing at the robot fingertips for automated taste discrimination in food samples. Scale bar, 5 cm. Reproduced with permission from ref 213. Copyright 2018 American Chemical Society. (c) Bioinspired tactile-olfactory bionic sensing array for response during the gas flow with high recognition accuracy. Scale bar, 3 cm. Reproduced with permission from ref 214 under CC BY 4.0. Copyright 2022 Springer Nature.

robots to perceive and respond to their surroundings in real-time. This sensing approach holds promise for applications such as human−robot interaction, where tactile feedback and temperature sensing are essential for safe and intuitive collaboration.

Moreover, the materials used in these sensors must be soft, biocompatible, ultraflexible, lightweight, and capable of enduring repeated use without degradation. For instance, a skin-inspired stretchable and conformable matrix that can detect temperature changes. With innovative materials and optimized design, it enables soft robotics to adapt and respond to temperature variations with high precision (Figure 4b).[208] By integrating these matrix networks into intelligent prosthetic hands, it is feasible to configure hand temperature estimation while grasping. The enhanced functionality of prosthetic devices shows the potential to improve the quality of life for individuals by providing more natural control.

Additionally, scalable sensor arrays or networks that maintain functionality and structural integrity under mechanical stress are essential for complex robotic systems, ensuring robust and reliable performance across multiple sensing points and during dynamic interactions. The development of a wireless skin-mounted graphene-based thermal patch offers a portable and noninvasive solution for obtaining temperature distribution data in soft robotics (Figure 4c).[209] With great adhesion to the skin and wireless transmission of temperature measurement, this lightweight and flexible patch allows for remote monitoring and analysis of temperature variations in real-time. With its high sensitivity and spatial resolution, this thermal patch is ideal for applications such as medical diagnostics, environmental monitoring, and industrial automation, where precise temperature sensing is critical for ensuring safety and efficiency.

Temperature sensing serves as a fundamental building block for the advancement of soft robotics, enabling precise and accurate respond to temperature variations. By leveraging innovative technologies, the integration of temperature sensing with soft robotics shows promising applications in diverse environments.

3.3. Biochemical Sensing

The involvement of biochemical sensing can fundamentally advance sensory, diagnostic, and therapeutic functionality of soft robotics.[210] It allows for the capability to perceive and interact with chemical information,[204,211] and this convergence of biology and robotics holds immense promise, offering opportunities to address challenges across a spectrum of industries, from healthcare and environmental monitoring to food quality control and beyond.

Most of current soft robotics are impeded by the lack of soft-matter architectures that interface synthetic cells with

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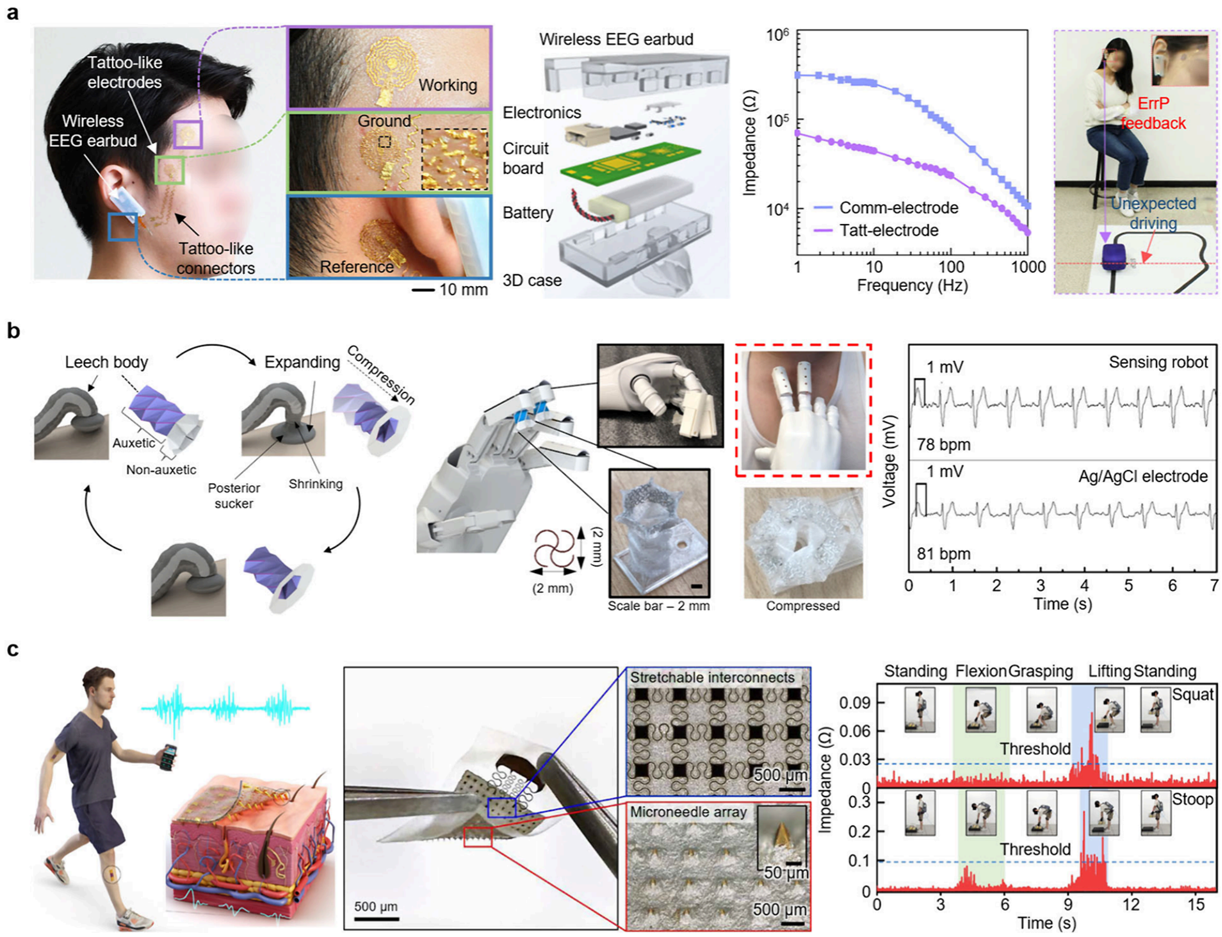

Figure 6. Electrophysiological sensing for soft robotics. (a) Wearable EEG tattoo electronics for enhancing machine decision-making with the brain-AI closed-loop system in real time. Reproduced with permission from ref 217 under CC BY 4.0. Copyright 2022 Springer Nature. (b) 3D-printed leech-inspired origami dry electrode in sensing robot for ECG monitoring. Reproduced with permission from ref 218 under CC BY 4.0. Copyright 2022 Springer Nature. (c) Stretchable microneedle adhesive patch with EMG sensing for exoskeleton robot control. Reproduced with permission from ref 219. Copyright 2024 The American Association for the Advancement of Science.

electronics and actuators for controlled stimulation and response during robotic operation. A soft gripper using engineered bacteria is proposed for detecting chemicals in the environment with soft actuators to convert electronic signals to movement of the gripper (Figure 5a).[212] Through the integration of biochemical sensors, this soft robotic gripper boasts a versatile platform capable of real-time detection and feedback of chemical signatures. Such integration shows promising applications from environmental monitoring to pollution detection and water quality assessment.

Meanwhile, mimicking the human sensing capabilities is also crucial for the interaction and cognitive abilities of soft robotics.[215] Although soft robots with embedded pressure or temperature sensors have been widely discussed, there are still challenging to realize biochemical sensing modalities in robotic platforms. By printing taste-sensing electrochemical devices on stretchable robotic glove, it allows accurate discrimination between sweetness, sourness, and spiciness, via the direct detection of glucose, ascorbic acid, and capsaicin (Figure 5b).[213] The realization of advanced wearable taste-sensing fingertip paves the way to automated chemical sensing machinery, revolutionizes the food quality control, and facilitates the robotic decision to practical food assistance applications.

The object recognition is a key basic survival skill of human beings, which requires the development of sensing and computational capabilities for the soft robotics. Inspired by the natural sense-fusion system of star-nose mole, a tactile-olfactory sensing array is proposed to seamlessly fuse tactile and chemical sensing modalities (Figure 5c).[214] Coupled with machine learning architecture, the flexible sensing arrays on the mechanical hand could acquire reliable tactile-olfactory information to achieve identification in rescue scenarios. Without visual input, the tactile-olfactory bionic sensing system shows superior tolerance to environmental interference and demonstrates great potential for robust object recognition, especially in difficult environments.

The biochemical sensing is quite important for the evolution of soft robotics, to broaden the practical applications in real life. The seamless integration of biochemical sensors into soft robotic platforms holds the potential for more intelligent, adaptive and responsive robotic systems, to realize the interaction between robots and the chemical world with sophistication and efficacy.

3.4. Electrophysiological Sensing

Electrophysiological sensing emerges as an interesting application in the realm of soft robotics, offering promising opportunities for robots to forge connections with both human body and the environment by harnessing and interpreting electrical signals.[216] Electrophysiological sensing

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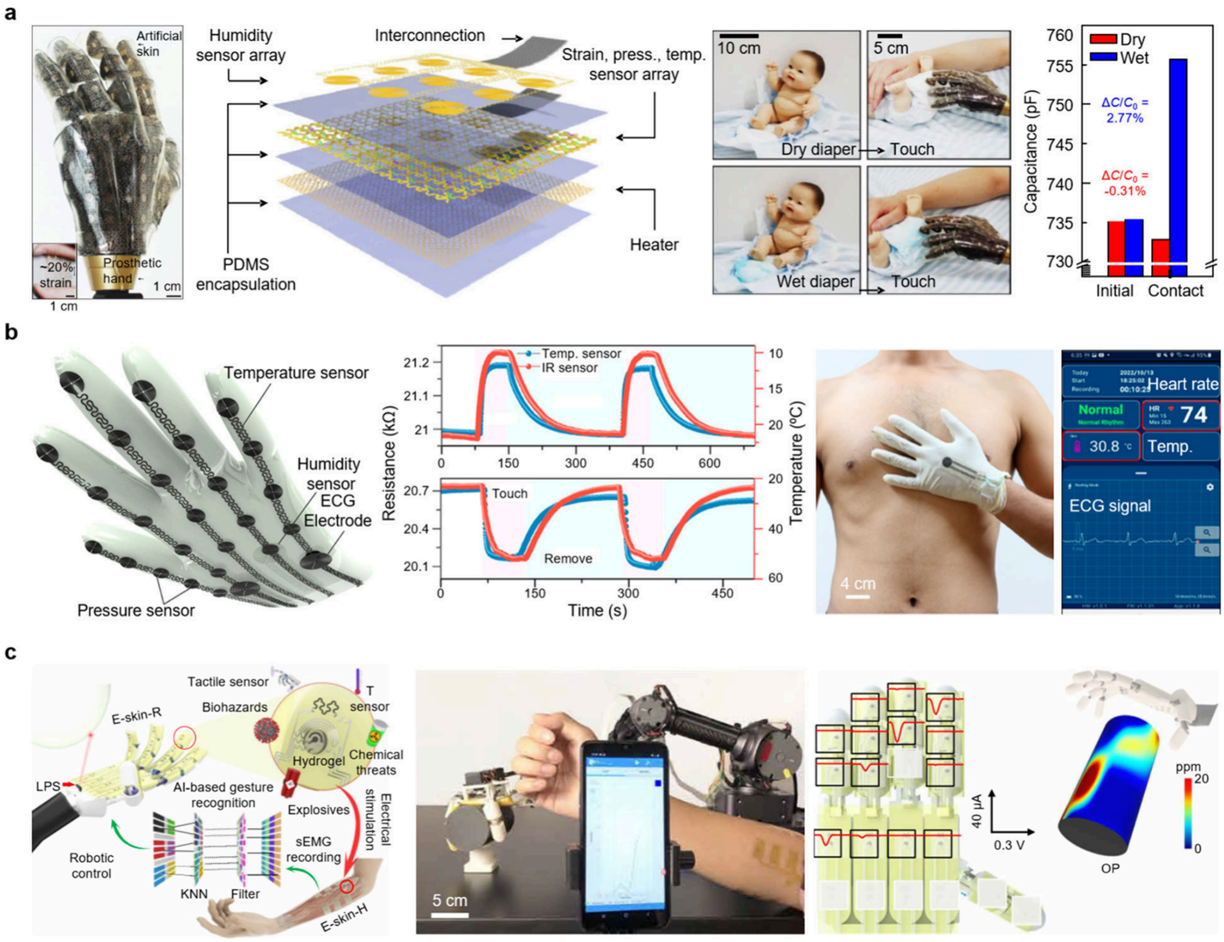

Figure 7. Multimodal sensing for soft robotics. (a) Smart artificial skin with stretchable sensors in various robotic-assisted situations. Reproduced with permission from ref 227. Copyright 2014 Springer Nature. (b) Stretchable electronic glove for simultaneous detection of multiple stimuli and demonstration of human−machine interfacing. Reproduced with permission from ref 228. Copyright 2023 American Chemical Society. (c) All-printed soft interface with robotic physiochemical sensing for gesture recognition with robotic control and mapping of hazardous distributions on the object. Reproduced with permission from ref 229. Copyright 2022 The American Association for the Advancement of Science.

empowers robots to further explore the biomedical applications in healthcare, rehabilitation and beyond. The convergence of electrophysiological sensing and soft robotics holds promise for revolutionizing how robots assist human in real-world scenarios.

Human nonverbal communication tools are very ambiguous and difficult to transfer to machines or artificial intelligence (AI). Regarding the electroencephalogram (EEG) recording, wearable EEG tattoo electronics integrating sensors into soft and flexible platforms,[220] enhance machine decision-making through a brain-AI closed-loop system in real-time. A wireless earbud-like EEG device, combined with tattoo-like electrodes, is proposed to enable continuous recording of high-quality EEG signals (Figure 6a).[217] It could reflect the human cognitive consequences of an unpredicted machine response and the AI could reinforce the decisions depending on the presence or absence of the signals. The introduction of such wearable EEG tattoo electronics marks a significant stride toward the realization of intelligent and empathetic soft robotic systems.

Besides EEG monitoring, electrocardiogram (ECG) is another essential signal for the heart monitoring and the direct contact with human skin is required to collect the cardiac signals.[221] However, there is an issue of high noise signals depending on the contact conditions. To monitor biomedical vital signs using a humanoid-sensing robot, a 3D-printed leech-inspired origami dry electrode is developed without the need for conductive gels or adhesives (Figure 6b).[218] It ensures comfortable and reliable contact during the ECG measurements compared with commercial ECG electrodes. Integrated into sensing robots, these electrodes enable continuous monitoring of cardiac activity in real-time, providing valuable insights into cardiovascular health and performance. This technology has applications in remote patient monitoring, sports performance analysis, and healthcare robotics, where noninvasive and long-term sensing is essential.

High-fidelity and comfortable recording of electromyogram (EMG) signals is essential for healthcare and HMIs. The development of microneedle electrodes offers a novel strategy for direct access to the epidermis and eliminate time-consuming skin preparation. A stretchable microneedle adhesive patch is presented to provide excellent skin penetrability and robust electromechanical skin interface for prolonged and reliable EMG monitoring under varying skin conditions (Figure 6c).[219] It could enable intuitive control of robotic limbs and prosthetic devices, enhancing the mobility for individuals with physical disabilities or injuries. This proof-of-concept demonstration in the closed-loop operation of an exoskeleton robot brings the broad impact on applications that require reliable EMG sensing, such as continuous health monitoring and neurological research.

Electrophysiological sensing represents an impressive approach to soft robotics, allowing robots to interface with the human body and environment in unprecedented ways. By leveraging EEG, ECG, EMG, and other electrophysiological signals, soft robots can achieve natural and intuitive interaction, enhancing their capabilities in various domains, from healthcare and rehabilitation to human−robot collaboration. The integration of electrophysiological sensing with soft robotics holds promises for creating a new generation of adaptive and humancentric robotic systems to address complex challenges and improve quality of life.

3.5. Multimodal Sensing

With the development of materials and manufacturing toward practical applications,[143,222,223] multimodal sensing is crucial for soft robotics, enabling robots to interact with precision and safety.[224] Recent researches have focused on the development of multimodal sensors, which integrate diverse sensing modules into platforms.[225] Upon integration into robotic systems, the multimodal electronic skin demonstrated remarkable enhancements in object manipulation and recognition,[226] paving the way for the advancement of intelligent robots.

Sensory receptors in human skin transmit a wealth of tactile and thermal signals from external environments to the brain, allowing the central and autonomic nervous systems to analyze and transform these sensory inputs into regulated physiological responses and motor outputs. Although there have been significant progresses in understanding the neural circuits underlying mechanical and thermal sensation, replicating these capabilities in artificial skin and prosthetics remains challenging. Recent advances in the design of prosthetic limbs integrated with rigid and semiflexible tactile sensors provide sensory reception to enable feedback in response to variable environments. For example, Kim et al. reported a stretchable prosthetic skin equipped with ultrathin single crystalline silicon nanoribbon strain, pressure and temperature sensor arrays (Figure 7a).[227] This collection of stretchable sensors and actuators facilitate highly localized mechanical and thermal skin-like perception in response to external stimuli, thus providing unique opportunities for emerging classes of prostheses and peripheral nervous system interface technologies.

Besides prosthetic electronic skin, electronic glove with their multimodal sensing capability, also holds a promising application in robotic skin and HMIs, endowing robots with a human sense of touch. Despite the progress in developing electronic gloves by exploiting flexible or stretchable sensors, existing models have inherent rigidity in their sensing area, limiting their stretchability and sensing performance. Through a scalable and facile manufacturing method, an all-directional strain-insensitive stretchable electronic glove could extend sensing functionality such as pressure, temperature, humidity and ECG information (Figure 7b).[228] As a proof of concept, such glove could simultaneously estimate the temperature and humidity of an object while contouring pressure distribution on the fingers, and efficiently monitor ECG signals and interpret hand movements and gestures to provide haptic perception, which can be further extended to humanoid robotics, home-based rehabilitation, and prosthetic hands.

Most of current robotic sensing technologies have primarily focused on monitoring physical parameters including pressure and temperature, while integrating biochemical sensors for autonomous detection on a robotic platform is rather challenging and substantially underdeveloped. An AI-powered multimodal robotic sensing with all-printed mass-producible soft electronic skin is presented for electrophysiological recording, tactile perception and robotic sensing of hazardous materials, such as nitroaromatic explosives, pesticides, nerve agents, and infectious pathogens (Figure 7c).[229] The printed electronic skin−based robotic sensing technology can be further generalized and applied to other remote sensing platforms, which can efficiently track the source of trace amounts of hazardous compounds through autonomous and intelligent decision-making algorithms. Such physiochemical multimodal sensing technology plays a crucial role in designing future intelligent robotic systems toward practical wearable and robotic applications.

Multimodal sensing shows increasing demand owing to the wide range of applications for soft robotics, enabling robots to perceive and interact with the world in a manner that parallels human capabilities. By integrating multimodal sensing modalities into soft robotics, it opens up new opportunities for applications in healthcare, manufacturing, and environmental monitoring. Further innovation in multimodal sensing holds the promise of obtaining greater capabilities in soft robotics, paving the way for the development of truly intelligent and responsive robotic systems.

Incorporating sensing capabilities into soft robotic systems without affecting their mechanical performance requires functional components to possess material properties closely matching the base elastomer.[15,110,230] However, recent advancements in soft, flexible electronics have paved the way for innovative solutions.[231−233] These developments leverage materials and structures that can undergo significant deformation without losing functionality, enabling the creation of sensors that are not only flexible but also highly sensitive and responsive.[234,235] Additionally, multimaterial 3D printing allows the creation of soft structures with distinct regions featuring varied optical, electrical, and magnetic properties, making it another promising solution.[152,154]

Despite substantial advancements in sensing, the broader adoption of intelligent soft robots still faces challenges, including data processing complexity, energy constraints, and the need for greater multifunctionality in practical settings. A deeper understanding of natural operational mechanisms and mimicry strategies is essential to overcoming these barriers and advancing intelligent soft robotics in research and real-world applications.[236]

4. REHABILITATION AND ASSISTIVE SOFT ROBOTS

Recently, rehabilitation and assistive soft robotic devices have seen rapid advancements, branching into various categories including mobility assistance for daily activities, robot-assisted therapy, and human augmentation. The adoption of naturally compliant materials has fostered the development of robotic systems that are safer, more comfortable, and more cost-efficient than their rigid counterparts. Studies in soft robotics have demonstrated that these systems improve human−robot interactions, enhance durability, and boost user comfort relative to rigid systems.[9,10] Looking ahead, rehabilitation and assistive robots hold the potential to empower many of the 1 billion people globally living with disabilities, enabling them to engage in daily activities unencumbered.[237] This field is burgeoning with promise, as emerging technologies increasingly redefine our understanding of wearable assistive devices.[238,239]

This section provides a detailed examination of how current research groups aim to assist the human body, organized into upper body and lower body categories. It explores trends in actuator methodologies within the field, identifying the benefits

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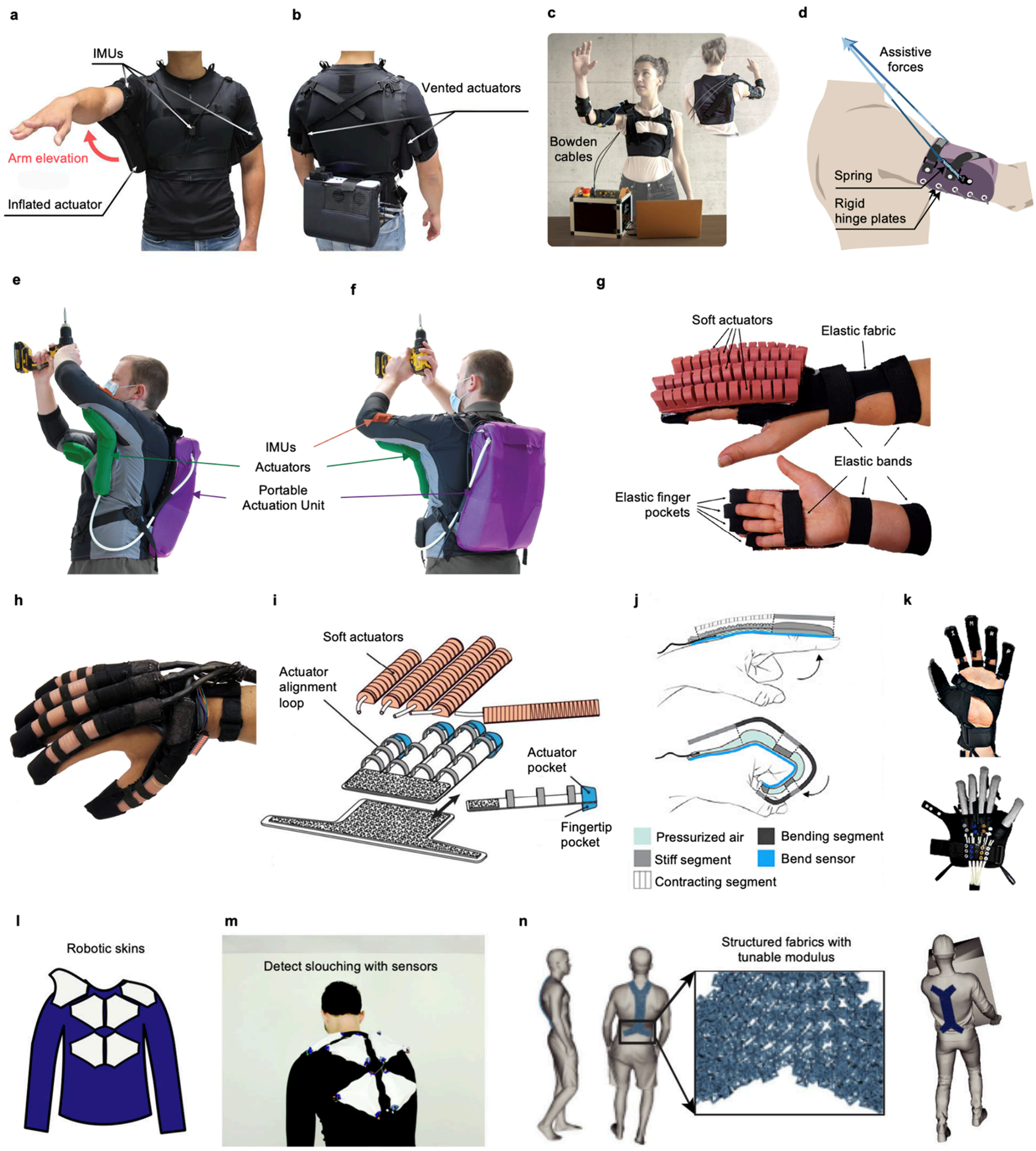

Figure 8. Upper body soft wearable robots. (a,b) Front (a) and back (b) views of an untethered, portable soft robotic wearable for restoring arm function. Reproduced with permission from ref 245. Copyright 2023 The American Association for the Advancement of Science. (c,d) Photograph (c) and schematic (d) of a textile exomuscle that supports the shoulder against gravity, with two Bowden cables highlighted in blue. Reproduced with permission from ref 248. Copyright 2022 Springer Nature. (e,f) Side (e) and back (f) views of an inflatable shoulder wearable robot to assist the shoulder during industrial work. Reproduced with permission from ref 249. Copyright 2024 The American Association for the Advancement of Science. (g) Top and bottom views of a soft pneumatic glove for hand rehabilitation. Reproduced with permission from ref 250. Copyright 2021 AIP Publishing. (h,i) Photograph (h) and exploded view (i) of a soft robotic glove with soft hydraulic actuators for combined assistance and at-home rehabilitation. Reproduced with permission from ref 251. Copyright 2015 Elsevier. (j,k) Schematic (j) and photographs (k) of a 2-DOFs inflatable soft glove with soft pneumatic actuators for improving motor function after stroke. Reproduced with permission from ref 252 under CC BY 4.0. Copyright 2024 Cambridge University Press. (l,m) Schematic (l) and photograph (m) of a modular, 2D soft robotic robot that can be reconfigured on the surface of passive, deformable bodies to produce deformations. Robotic skins attached to a garment detect poor posture and pulse to communicate with the wearer. Reproduced with permission from ref 253. Copyright 2018 The American Association for the Advancement of Science. (n) Reconfigurable fabrics for wearable medical supports (left) and exoskeletons (right). Reproduced with permission from ref 254. Copyright 2021 Springer Nature.

and drawbacks of each through a comprehensive analysis of recent work over the past decade.

4.1. Soft Wearable Robots

Over the past decade, soft mechatronic technologies have gained reliability, effectiveness, and recognition, positioning them as a preferred choice for wearable robotic technologies.[239] The industry has witnessed a shift from traditional rigid exoskeletons, which incorporate isolated compliant actuation methods, to a new standard of entirely soft, garment-like wearables that are nearly imperceptible to the wearer.[240] Materials such as silicone elastomers, fabrics, and other flexible substrates have been pivotal in advancing the development of lightweight, affordable, garment-like devices, steering clear of the cumbersome, bulky, and rigid components typical of earlier models.[241] These adaptable materials mitigate joint alignment issues commonly associated with rigid exoskeletons,[9] ensuring safer interactions with both users and their surroundings. Additionally, the inherent compliance of these materials allows them to easily conform to a variety of shapes — be it the environment, the user's joints, or interacted objects — offering unparalleled flexibility, comfort, and safety, thus enhancing usability.[242]

Upper body assistance primarily serves stationary rehabilitation, supports daily living activities, or helps prevent injury and fatigue.[243] The upper body's intricate structure features numerous DOF concentrated at specific joints, which are particularly sensitive to added weight, such as that on the hand. The need for continuous daily assistance renders traditional rigid-framed robots and exoskeletons less ideal for aiding upper limbs. These devices, typically designed with links and joints to apply torque to the user's impaired joints, are better suited for clinical settings rather than everyday use. Notable examples include Hocoma's ArmeoPower and Bionik Laboratories' InMotion, both of which are leaders in rehabilitative robotics for upper limbs.[243,244] Among the few portable rigid robots that have successfully assisted parts of the upper limb (elbow, wrist, hand) in individuals with impairments is Myomo's MyoPro. Launched in 2006, this device leverages surface electromyography (EMG) to adjust the level of assistance provided to its users.[245,246] Soft wearable robots offer distinct advantages for upper body assistance by eliminating the need to attach heavy components or restrict joint movement on the user's arms or torso.[247]

The shoulder joint, with its multiple DOFs and motions, exemplifies this complexity. The glenohumeral joint, a ball and socket type, facilitates movement across three-dimensional space and is linked to the acromioclavicular joint, which provides two extra degrees of freedom for motion. This setup forms one of the most versatile and mobile joints in the human body.[245,255] During some movements, these DOFs become interconnected, while in others, they function independently, adding to the difficulty of providing support with wearable devices. The shoulder not only facilitates several rotational DOFs with axes that intersect nonperpendicularly but also includes a translational DOF that adjusts the joint's center. This intricate functionality renders the shoulder a particularly challenging joint for assistance with rigid robots, which typically require the user to remain seated with their torso immobilized during use.[247]

Early research into soft wearable robots for shoulder support began around the beginning of the 21st century, with McKibben actuators being a prevalent choice. These early models were simpler and lighter than their rigid counterparts, yet the functionality of McKibben muscles was restricted to applying tensile forces, which limited the range of motion they could assist.[256] Challenges such as slippage and the uncomfortable transmission of force to the user's body were noted. As the 2010s progressed, the focus shifted toward cable-driven systems that employed tendons to manipulate the joint, allowing for less bulky designs that better conformed to the joint's shape, supported a broader range of motion, and facilitated support across multiple degrees of freedom.[242,247,257] Research into soft wearable robots for the shoulder intensified in the latter part of the 2010s, highlighted by significant developments like NASA's "Armstrong" suit, which used tendon-based systems for shoulder assistance.[258] This period also saw the advent of advanced textile actuators, which presented more refined designs than earlier McKibben muscles. For example, a soft, lightweight, portable robotic wearable was designed for restoring arm function (Figure 8a,b).[245] Three IMUs positioned on the torso and both upper arms are used to evaluate user movement and support the shoulder. Two textile-based soft actuators, positioned beneath the armpits, offer dynamic assistance through inflation. Despite these advances, the shoulder continues to be a challenging joint to assist, with ongoing research focusing on developing actuators that more accurately replicate the function and positioning of human muscles.

Soft wearable robots designed for elbow assistance are used in contexts ranging from rehabilitation to injury prevention. Initially, these systems employed McKibben muscles to aid in elbow rehabilitation without impeding user movement, much like early systems for shoulder assistance. Nonetheless, the challenge of converting tensile forces into torque at the elbow joint prompted a shift toward cable-driven systems. Given the elbow's single degree of freedom, many designs have incorporated simultaneous assistance for both the elbow and shoulder joints using underactuation. Cable-driven systems replicate the biological actions of the upper arm muscles, promoting flexion and extension. These systems attach cables at the base of the forearm and route them to a fixed anchor point at the shoulder, providing targeted assistance for controlled movement. For instance, a textile exomuscle that assists the shoulder and elbow during functional movements for everyday life was developed, driven by Bowden cables (Figure 8c,d).[248] A tendon, depicted in blue in Figure 8c, transmits a force between the shoulder anchor and the upper arm anchor. The upper arm cuff consists of two rigid hinge plates that clamp onto the arm when an assistive force is exerted on the lateral and medial tendons.

In the 2010s, fluidic actuation techniques for elbow assistance began to develop, offering a variety of designs tailored to specific requirements. Some models utilized bellows-type actuators that extended the elbow and drew it into flexion from the armpit area, such as a portable soft wearable robot with inflatable actuators to assist the shoulder and elbow with 6.6 N·m of torque, designed for industrial work assistance (Figure 8e,f).[249] Others employed rotary actuators mounted on the outer side of the elbow joint to provide rotational torque for flexion support. Elbow assistance continues to be a focal area of research and development, frequently incorporated into broader upper body systems to enhance posture and manage weight and load distribution effectively.

Soft wearable robots are particularly well-suited for assisting the human hand, due to their ability to accommodate complex motions and leverage compliance in underactuated mechanisms. These robots operate with minimal inputs for each segment of the hand, which reduces the need for extensive computing power and simplifies control systems, ultimately aiming to restore basic hand movement and functionality for daily life support. Over the past decade, various soft hand exosuits have been developed for rehabilitation purposes, capturing significant interest within the soft wearable robot community. Initial

Figure 9. Lower body soft wearable robots. (a) Photograph of a hip soft exosuit that can reduce the energy expenditure of walking, actuated by inner cable. Reproduced with permission from ref 262. Copyright 2018 The American Association for the Advancement of Science. (b) Components of the soft robotic apparel with cable-driven actuators and sensors for hip flexion assistance to avert freezing of gait in Parkinson's disease. Reproduced with permission from ref 263. Copyright 2024 Springer Nature. (c,d) Front (c) and back (d) views of a soft exosuit that reduces the metabolic rate for both running and walking via the hip extension. Reproduced with permission from ref 264. Copyright 2019 The American Association for the Advancement of Science. (e,f) Front (e) and side (f) views of a soft wearable robot with Bowden cable-based mechanical power transmissions to generate assistive joint torques, designed to augment paretic limb function during hemiparetic walking. Reproduced with permission from ref 265. Copyright 2017 The American Association for the Advancement of Science. (g,h) Front (g) and side (h) views of a tethered soft exosuit for metabolic cost reduction. Reproduced with permission from ref 266. Copyright 2017 The American Association for the Advancement of Science. (i,j) Neural networks-based controller training in simulation (i) and real-world deployment of an untethered exoskeleton without further training (j). Reproduced with permission from ref 267. Copyright 2024 Springer Nature.

models employed McKibben muscles to enhance mechanical behavior and actuator performance. As the popularity of cable-driven soft wearable robots increased, their design effectively replicated the natural mechanics of hand tendons, typically requiring motor placement on the arm or wrist for actuation. Additionally, methods like pneumatic artificial muscles, fluidic elastomers, and fabric-based inflatable actuators have been explored to provide varying degrees of assistance, predominantly using pneumatic systems. For example, a soft glove with pneumatic networks was designed to produce bending motions that can conform with the human finger motion (Figure 8g).[259] The four soft actuators were attached to the glove's upper surface, positioned individually above each finger, secured with thin Velcro straps. Another soft glove with molded elastomeric chambers with fiber reinforcements can induce bending, twisting and extending trajectories under fluid pressurization (Figure 8h,i).[251] The hydraulic soft actuators are installed on the back of the hand. Incorporated fluidic pressure sensors monitor the internal pressure of the actuators, enabling control of finger flexion and extension. The glove consists of two structural layers

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that collectively secure the device to the hand, connecting at both the wrist and fingertips. More recently, a soft glove with textile-based inflatable actuators was developed to control finger movement along 2 DOFs, extension or flexion (Figure 8j,k).[252] Combined with the benefits of telerehabilitation, the intervention can be supervised remotely, either fully or partially, by a therapist who offers guidance, evaluates progress, and assists the patient in following the therapy program. Fabric-based pneumatic solutions in particular have proven effective in addressing the bulkiness typically associated with pneumatic muscles and elastomers. Current research is expanding into soft exosuits for the wrist, focusing on preventive assistance and enhancing forearm pronation and supination capabilities.

Soft wearable robots are often employed to prevent injuries in the user's back or trunk by enhancing posture and providing lifting assistance. This functionality is particularly vital for factory or industrial workers, as well as others engaged in repetitive heavy lifting tasks.[260,261] Many soft systems employ passive actuation methods, such as pretensioned elastic bands or pulley systems, which provide back support precisely when needed to prevent injury. Actuation using tension aligned with the spine offers the advantage of storing and releasing energy during lifting through the trunk's flexion and extension. Recently, modular robotic skin with sensing and actuation capabilities was developed. Such robotic skin can be used to detect slouching with sensors and send pulse to alert user (Figure 8l,m).[253] Compared to large pieces of modular robotic skin, structured fabrics more resemble daily wearing clothes, while with tunable mechanical properties, it possesses great promise for personalized assistive support (Figure 8n).[254] Given the significant weight of the human trunk, actively assisting movement poses challenges in finding anchor points that do not restrict motion or transfer burdensome forces to other joints.

Lower body-assistive devices are commonly designed to assist or augment human gait. Assistance aims to restore a natural gait pattern for individuals with impairments, while augmentation seeks to increase walking capabilities or reduce the metabolic cost of walking/running. Using soft wearable robots for lower limbs is a significant advancement, allowing users to interface with the robot without adding weight to their legs. Adding weight during walking increases limb inertia, causing unnatural gait adaptations and balance issues, increasing the risk of trips and falls. Each joint is discussed separately, even if particular devices span across multiple joints.[247]

The human hip is crucial for transmitting force from the ground to the torso, assisting in standing, balancing, posture, and sitting tasks. Hip joint actuation with soft wearable robots primarily relies on cable-driven actuation due to the high torque output from cable tension. For example, a textile-based, cable-driven soft exosuit was developed for hip extension and flexion assistance during walking (Figure 9a).[262] It showed an improvement of more than 60% on metabolic reduction compared with state-of-the-art devices that only assist hip extension. Another textile-based, cable-driven soft robotic apparel was developed to avert freezing of gait in Parkinson's disease (Figure 9b).[263] Recent work has also shown the potential of fluidic actuators and passive actuation methods for hip assistance, applicable to both stationary sit-to-stand tasks and corrective gait therapy.

Soft wearable robots assist knee flexion and extension, providing stability to prevent knee buckling. Soft wearable robots for the knee are often stationary systems addressing gait symmetry issues by assisting in the swing or stance phase. Many designs are cable-driven systems pulling the knee into flexion and extension. For example, a soft exosuit for reducing the metabolic rate of walking and running, whose reduction magnitudes are comparable to the effects of taking off 7.4 and 5.7 kg during walking and running, respectively (Figure 9c,d).[264] Research on fluidic actuators for knee assistance has highlighted issues with actuator latency, while other methods include passive elastic elements for preventive microcorrections.[247]

Earlier ankle rehabilitation robots focused on seated therapies, adjusting or orienting the ankle into various positions. Designing wearable robots for the ankle has been challenging due to the joint's complexity and torque requirements, specifically for plantarflexion during walking. Cable-driven systems or other contracting actuation methods are commonly used for ankle assistance, mimicking tendon and muscle group functions. Research on cable-driven systems for ankle function has explored torque generation and metabolic cost reduction, with applications ranging from military assistance to poststroke rehabilitation. Fluidic actuation methods, including pneumatic artificial muscles and fabric-based inflatable devices, have also been used, often aiming to add stability and prevent trips and falls. For example, a cable-driven soft wearable robot engineered to enhance the residual capacity of a paretic limb for forward propulsion and ground clearance could promote more normalized walking after stroke. (Figure 9e,f).[265] These improvements in paretic limb function contributed an equivalent 32 ± 9% reduction in the metabolic burden associated with poststroke walking. Another tethered multi-articular soft exosuit directly applied assistance at the ankle joint (Figure 9g,h).[266] The metabolic rate of walking decreased by 22.83 ± 3.17% (mean ± SEM) compared to when the power was off.

Exoskeletons have shown potential to enhance walking performance in able-bodied individuals and to restore mobility for those with disabilities. Nonetheless, the control strategies for these devices often rely on either preset assistance profiles or extensive human testing, which can last several hours per participant, even for developing basic walking strategies.[268] Consequently, adapting the controller for different users or activities incurs significant costs. Additionally, custom control laws must be crafted for each specific activity, complicating the design process as the scope of activities broadens. This complexity hinders the widespread adoption of wearable robotic technologies. Recently, an experiment-free training method was developed. With versatile control policy in simulation, a textile-based hip exoskeleton can automatically generate assistance with reduced metabolic rates without human experiments (Figure 9i,j).[267]

Rehabilitation and assistive soft robots, such as exoskeletons and advanced prosthetics, are at the forefront of the technological revolution, enhancing physical capabilities in significant ways. Upper limb wearables, for instance, enhance grip strength and stabilize grasp during various manipulation tasks, while lower limb devices optimize walking patterns and reduce the energy required for movement. The initial phases of development in this field have primarily focused on mechanical design, integration with the human body, and limb movement sensing. These innovations have already yielded practical systems that support basic hand functions and enable more natural movement on flat surfaces.

Further advancements in wearable technology, however, hinge on the ability to accurately interpret the wearer's intentions to provide contextually appropriate assistance. For

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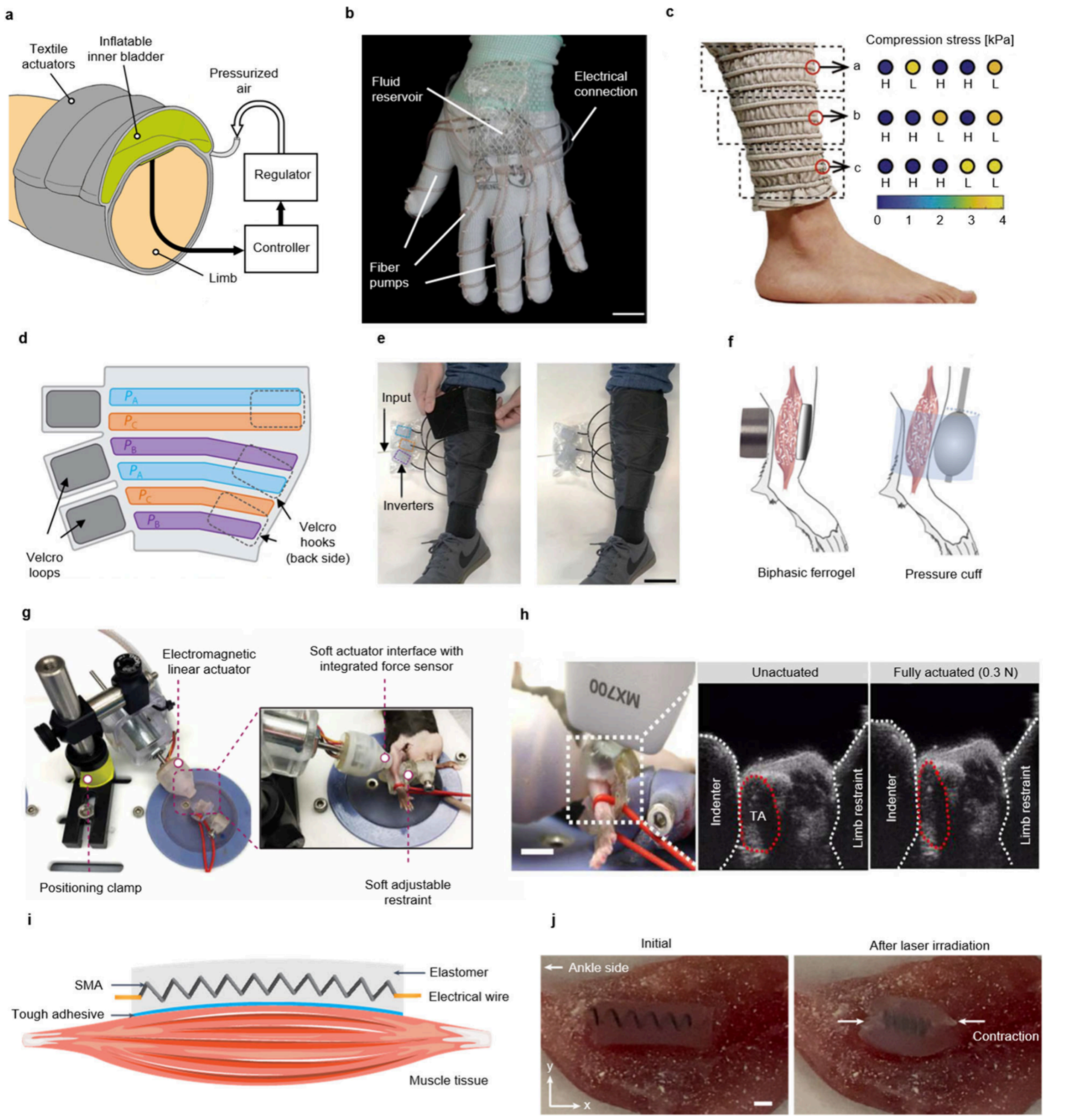

Figure 10. Soft robot facilitated therapy. (a) Sectional view of the textile-based soft robotic wearable device for mechanotherapy. Reproduced with permission from ref 271 under CC BY 4.0. Copyright 2022 Wiley. (b) A thermoregulatory and thermal haptic glove with controlled fiber pumps. Scale bar, 2 cm. Reproduced with permission from ref 272. Copyright 2023 The American Association for the Advancement of Science. (c) A compression garment with fluidic fabric muscle sheets for the lower limb. Reproduced with permission from ref 273. Copyright 2021 Wiley. (d,e) Schematic (d) and photographs (e) of a soft mechanotherapy device for the lower leg. Scale bar, 10 cm. Reproduced with permission from ref 274. Copyright 2019 The American Association for the Advancement of Science. (f) Biphasic ferrogels (left) and pressure cuffs (right) generate similar cyclic mechanical compressions for muscle regeneration. Reproduced with permission from ref 275. Copyright 2019 Springer Nature. (g) Photograph of robotic soft-interface actuator equipped with a force sensor and demonstration of the actuator positioned toward the injured tibialis anterior (TA) muscle of hindlimb of mouse. Reproduced with permission from ref 276. Copyright 2021 The American Association for the Advancement of Science. (h) Robot-actuated anti-inflammatory therapy enables regeneration of aged muscle. Scale bar, 1 cm. Reproduced with permission from ref 277. Copyright 2023 The American Association for the Advancement of Science. (i,j) A schematic (i) of a mechanically active tissue adhesive with a shape memory alloy spring that generates and delivers muscle-contraction-mimicking stimulation to a target tissue. Photos (j) of tissue deformation generated during actuation of wireless adhesive. Scale bar, 1 mm. Reproduced with permission from ref 278. Copyright 2022 Springer Nature.

example, a glove designed to aid in handling objects must discern the user's desire to grasp a specific item and adjust the grip accordingly to suit the task at hand. Similarly, leg-based devices such as exoskeletons or advanced prosthetics need to predict activities like stair climbing or navigating slippery surfaces, adjusting joint torques to enhance support and stability. Currently, the most common method for inferring intentions in lower limb wearables employs inertial sensors that gather kinematic data, such as detecting heel strikes to estimate walking phases. Control strategies often extrapolate from past

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movement patterns to predict current needs, while neuromuscular interfaces like EMG measure muscle electrical activity to interpret intended movements, particularly useful in upper limb prosthetics.[269] Integrating computer vision could significantly enhance the interpretation of the user's environment and intentions by providing detailed, real-time insights similar to human visual capabilities, which is essential for complex interaction scenarios.[270] Despite these advancements, the scope of tasks that can be efficiently supported by wearables remains limited, and user control can often feel cumbersome and unintuitive. This contributes to the high abandonment rates of such technologies, particularly in powered upper-limb prosthetics, indicating a crucial area for further research and development.

4.2. Soft Robot-Facilitated Therapy

Mechanotherapy, leveraging mechanical tissue stimulation, represents a promising frontier in the field of regenerative medicine and rehabilitation. This therapeutic approach aims to exploit the body's intrinsic ability to respond to mechanical forces through mechanotransduction—a process where cells convert mechanical stimuli into biochemical signals that can trigger tissue repair and growth. The application of mechanical stimuli, such as stretching, compression, and bending, has shown potential in influencing cell proliferation, force generation, and differentiation, crucial for tissue regeneration. Historically, the use of mechanical devices in medicine, such as in distraction osteogenesis, tissue expansion, and orthodontics, underscores the long-recognized benefits of mechanical forces in therapeutic settings.

However, the development of soft robotics for mechanotherapy introduces new complexities. One significant challenge has been engineering devices that can precisely control and apply mechanical forces directly to soft tissues in a manner that is both safe and effective. Additionally, creating a durable interface between these devices and biological tissues that can withstand repeated mechanical loading without causing damage or discomfort remains a formidable technical hurdle. These challenges necessitate innovative approaches in soft robot design and material science to realize the full potential of mechanotherapy, particularly in treatments that require precise control over mechanical loading for successful outcomes.

Soft robotics has introduced a transformative approach to mechanotherapy, leveraging various actuation systems integrated with advanced engineered materials and technologies. These systems are particularly effective in treating soft tissues, utilizing compliant materials such as elastomers and fabrics to closely conform to body contours, thus minimizing tissue damage and foreign body reactions often associated with more rigid devices. The diversity in actuation methods, including pneumatic, hydraulic, dielectric elastomer, and piezoelectric mechanisms, allows for the precise control and programmability of movement, essential for delivering therapeutic mechanical forces effectively.

Fluidic actuators are widely used due to their simplicity and robust force output. A textile-based inflatable soft wearable robot was utilized for applying controlled and repeatable forces for mechanotherapy (Figure 10a).[279] Additionally, incorporating pressurized fluidic circuits into textiles can enable muscular support, thermoregulation, and haptic feedback in a convenient wearable form factor (Figure 10b).[272] Furthermore, pneumatic fabric muscle sheets were developed for a compression garment for the lower limb. Pressure variations can yield peristaltic motions suitable for undulatory massage (Figure 10c).[17] Moreover, a soft, pneumatic ring oscillator that induces temporally coordinated periodic motion was developed for a mechanotherapeutic device that sequentially contracts around a human user's leg (Figure 10d,e).[274] These systems have proven beneficial in several therapeutic applications, from enhancing skeletal muscle regeneration to reducing the immune response to implantable devices, and supporting cardiac function. Their ability to provide gentle yet effective force is particularly suited to the delicate nature of soft tissue therapy.

On the other hand, nonpneumatic actuators, offer alternative benefits. For instance, magnetic actuation of biphasic ferrogel scaffolds implanted at the site of muscle injury resulted in uniform cyclic compressions, similar to pneumatic actuators (Figure 10f).[280] Besides, electromagnetic motors can be integrated with soft interfaces to deliver controlled mechanical stimuli to specific tissue sites, such as aiding in the healing of congenital defects in the esophagus or treating severely injured skeletal muscle (Figure 10g,h).[276,277] Their precise control over force and movement can be critical in scenarios where delicate manipulation of tissue is required.

Additionally, actuators based on shape memory alloys (SMAs) offer unique advantages for mechanotherapy due to their ability to return to a preprogrammed shape when exposed to specific thermal conditions. This characteristic enables SMAs to exert precise and repeatable forces and movements, which can be crucial in applications where exact manipulation and control of tissue deformation are required (Figure 10i,j).[278] These actuators are particularly effective in environments where fine mechanical tuning is necessary to match the dynamic requirements of biological tissues during healing processes. The inherent properties of SMAs, including robust mechanical behavior and high resilience, make them ideal for integrating into soft interfaces that can gently yet effectively engage with and stimulate biological tissues.

Each of these actuation methods offers distinct advantages and potential applications in mechanotherapy, highlighting the versatility and adaptability of soft robotic systems in medical treatments. As technology progresses, the integration of these various systems with real-time monitoring and feedback mechanisms will likely enhance the efficacy and customization of treatments, further solidifying the role of soft robotics in facilitating effective and noninvasive rehabilitation and tissue regeneration strategies.

4.3. Soft Prosthetics

Conventional rigid prosthetic limbs are typically made of metal, plastic, and other stiff materials, which can provide basic support and mobility functions. However, due to the lack of flexibility, they struggle to replicate the smooth, natural motions of human joints. Moreover, the heavy weight of these devices often leads to user fatigue. The rigid design also lacks the coordinated function with the user's natural muscle and skin, which can cause issues like pressure-induced pain. To overcome the limitations of traditional rigid prosthetic limbs, soft robotic prostheses fabricated with silicone, elastomeric polymers, and other compliant materials have emerged in recent years. These soft structures can better mimic the natural motions of biological muscles and joints. The primary actuation approaches for soft prostheses are pneumatic and tendon-driven mechanisms, each with its own advantages and trade-offs. Pneumatically driven soft prostheses have a relatively simple structure, typically comprising inflatable chambers, and can provide large actuation

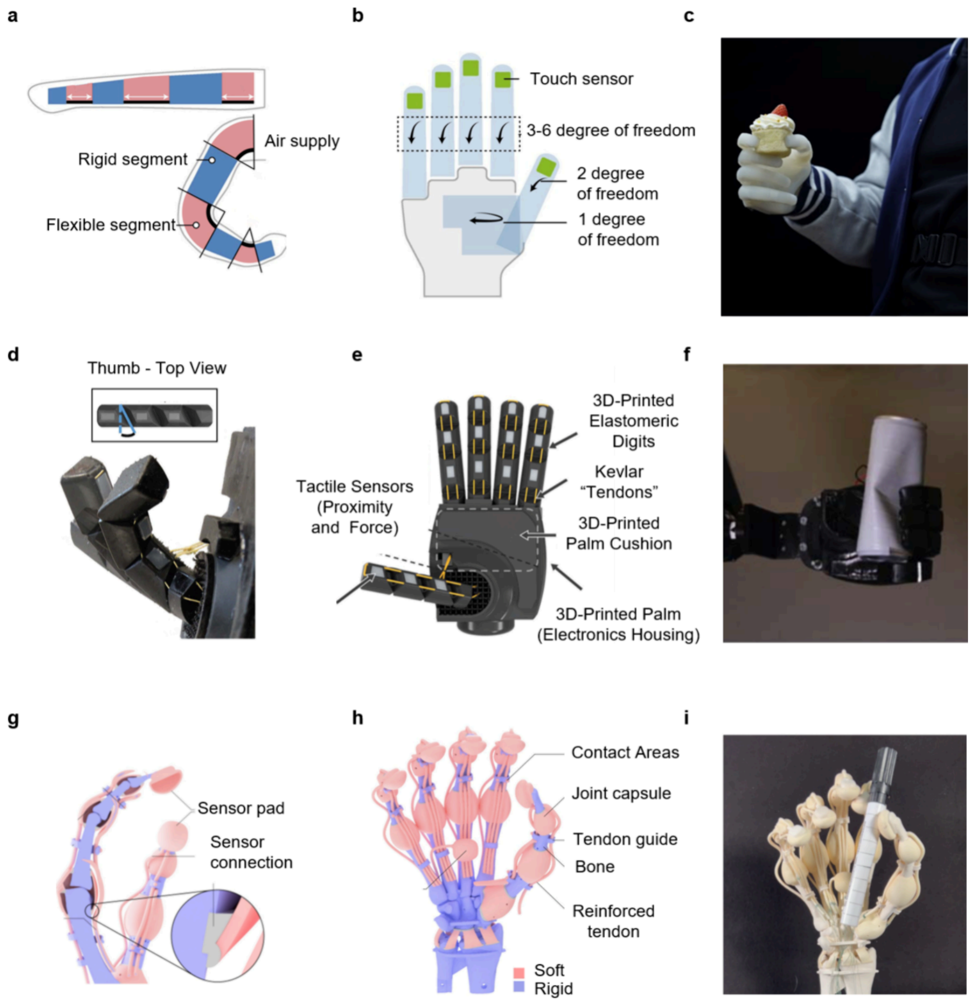

Figure 11. Soft prosthetics. (a) A soft pneumatic neuroprosthetic hand. Fiber-reinforced elastomeric tubular structure expands radially and contracts axially when inflated, enabling pneumatic actuation and control of soft fingers. (b) Schematic shows six active degrees of freedom for dexterous grasping and manipulation capabilities. (c) Photo of a transradial amputee wearing the soft neuroprosthetic hand, grasping a cupcake demonstrating its functionality. (a−c) Reproduced with permission from ref 283. Copyright 2023 Springer Nature. (d) A line-tendon driven robotic hand. Time-lapse image depicting thumb flexion achieved through line-driven tendon/cable actuation. (e) Schematic illustrating the line-tendon driven actuation mechanism for the prosthetic hand. (f) Utilizing elastomeric passive transmission technology, this robotic hand can balance speed and force output. (d−f) Reproduced with permission from ref 286. Copyright 2018 The American Association for the Advancement of Science. (g) 3D printed multimaterial bionic hand. Cross-sectional view of the index finger reveals the internal tendon structure, sensor cavity, and joint geometry. (h) Schematic with different colors representing the distinct materials used in the 3D printed construction. (i) Image shows various objects grasped by the bionic hand, enabled by a control algorithm for versatile grasping. (g−i) Reproduced with permission from ref 292 under CC BY 4.0. Copyright 2023 Springer Nature.

torques. They also offer inherent safety as there is no direct electrical contact.[197,281,282] For example, a novel soft, low-cost, and lightweight (292g) neural-controlled prosthetic hand uses a fiber-reinforced elastomeric tubular structure to simulate the soft joints and rigid skeletal structure of human fingers, providing 6 active degrees of freedom along with additional passive compliance to enable dexterous, adaptive grasping (Figure 11a−c).[283] However, pneumatic systems tend to have lower control precision, slower response times, higher noise levels, and greater overall energy consumption, as they require carrying a compressed air tank, which can hinder daily mobility. In contrast, tendon-driven soft prostheses can achieve more precise joint motion control, faster response, lower noise, and easier portability, making them more suitable for everyday living applications.[284,285] As an tendon-drive soft hand example, the incorporation of adaptive mechanisms for the cable transmission can significantly increase the grip force (up to 3 times) without sacrificing the closure speed, reaching maximum fingertip forces of about 32N and finger closing speeds of around 0.5s (average radial velocity of 180°/s), providing a simple yet effective solution to the strength, speed, dexterity, and size requirements of prosthetic hands (Figure 11d−f).[286] However, tendon-driven systems have a more complex structure, requiring multiple subsystems like motors and controllers, leading to higher power consumption and potential electrical safety concerns. In summary, each actuation approach has its own merits, and the choice should be made based on the specific application requirements, such as energy consumption, control precision, and operational environment. Emerging smart and efficient new actuation technologies, such as electroactive polymers,[287,288] thermally driven actuating polymers,[55,289] and electrostatic polymers,[290,291] which generally fall under the tendon-driven category, are also being explored to further enhance the capabilities of soft robotic prostheses, though they still face

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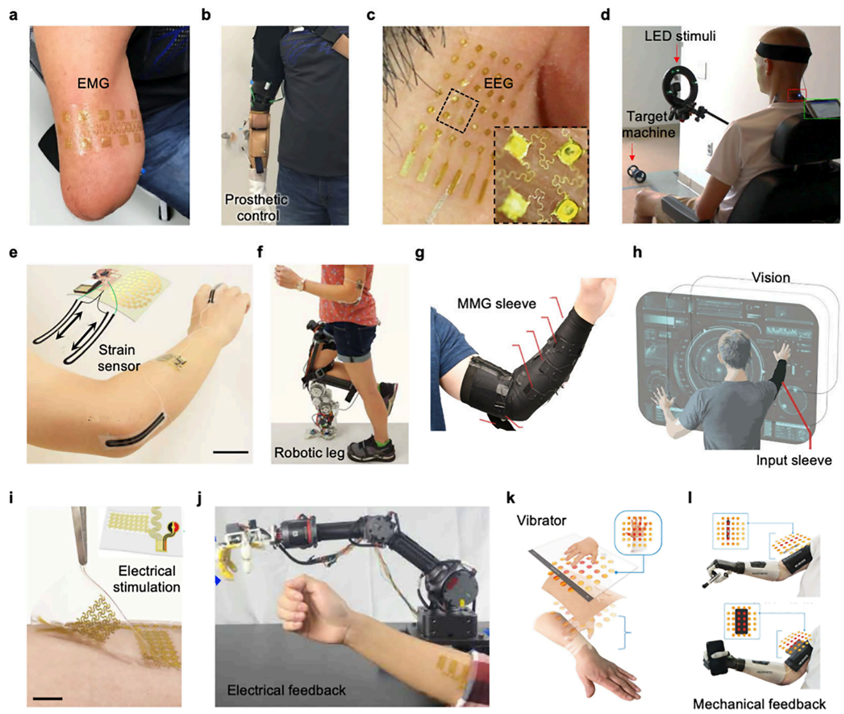

Figure 12. Soft human−machine interface. (a) A large-area flexible skin EMG electrode. A person with amputation wearing the flexible electrode on the skin surface. (b) The user controlling a prosthetic limb using the flexible electrode. (a,b) Reproduced with permission from ref 130. Copyright 2019 Springer Nature. (c) A flexible electrode for EEG signal acquisition. The flexible electrode conformably adhered to the neck area. (d) Acquiring EEG signals via the electrode to control a target machine. (c,d) Reproduced with permission from ref 299. Copyright 2019 Springer Nature. (e) A strain sensor system powered by a flexible sweat biofuel. The system adhered to the elbow area, detecting elbow bending signals. Scale bar, 5 cm. (f) Utilizing the strain signals to control the motion of a prosthetic limb. (e,f) Reproduced with permission from ref 303. Copyright 2020 The American Association for the Advancement of Science. (g) A sleeve integrated with flexible strain sensors. Using the sleeve to acquire stretch-induced MMG signals from the arm. (h) MMG signals serving as an input source for control. (g,h) Reproduced with permission from ref 304. Copyright 2020 Springer Nature. (i) A flexible skin electrode for electrical stimulation feedback. The electrode conformably adhered to the user's skin surface. Scale bar, 1 cm. (j) Relaying external information perceived by a robot to the user through electrical stimulation feedback. (i,j) Reproduced with permission from ref 305. Copyright 2022 The American Association for the Advancement of Science. (k) A mechanical vibrotactile feedback array. Schematic illustration of the vibrotactile feedback array in a human−machine interaction application. (l) A person with amputation perceiving external information acquired by the prosthetic limb through the feedback array. (k,l) Reproduced with permission from ref 306. Copyright 2020 Springer Nature.

various challenges, like actuating speed, force, which need to be addressed.

The manufacturing of soft prosthetics has greatly benefited from the advancements in 3D printing technology. The process involves using 3D scanning or modeling to capture the structural data of the affected limb, followed by the fabrication of a flexible shell using 3D printing, into which the corresponding actuation mechanisms are integrated.[20,293,294] First, in terms of materials, 3D printing technology can extensively utilize flexible materials such as silicone and elastic polymers to manufacture prosthetic shells. These materials boast excellent biocompatibility and conformity, better emulating the soft characteristics of natural human limbs and enhancing comfort during use. Compared to traditional metal or plastic prosthetics, these flexible materials integrate more seamlessly with the human body. Second, regarding cost, 3D printing significantly reduces both the expense and time required to manufacture prosthetics. Traditional prosthetic production necessitates custom molds and complex processes, resulting in higher costs. In contrast, 3D printing only requires digital modeling and the printing process, considerably shortening the production cycle and lowering costs. This is beneficial for increasing the availability of prosthetics, allowing more individuals with disabilities to obtain affordable assistive devices. In terms of manufacturing precision, 3D printing enables highly customized and detailed manufacturing of prosthetic structures. By acquiring the data of the user's affected limb through 3D scanning or modeling, prosthetics with a higher degree of fit can be produced to cater to individual characteristics. Additionally, the resolution of 3D printing is continually improving, allowing for the creation of complex and intricate internal structures, such as integrated actuation mechanisms, which contribute to the adaptability and functionality of the prosthetics. On the aspect of personalization, the evolution of 3D printing technology has made it possible to custom-design prosthetics. As each person's limb morphology varies, traditional prosthetics cannot adequately meet individual needs. However, 3D printing allows for the customization of unique prosthetics tailored to the specific conditions of the user, achieving personalization in appearance, functionality, and wearing experience. This not only improves the user experience but also enhances the psychological acceptance of the wearer. An example of this technology is a material jetting 3D printer integrated with a machine vision system. This system, composed of four cameras and two laser sources, can scan the contours of printed layers, while also enabling visual compensation and dynamic adjustments during printing. By incorporating tactile sensors and an independently controllable tendon-driven system, the 3D-printed anthropomorphic hand can achieve autonomous grasping and touch detection, demonstrating the

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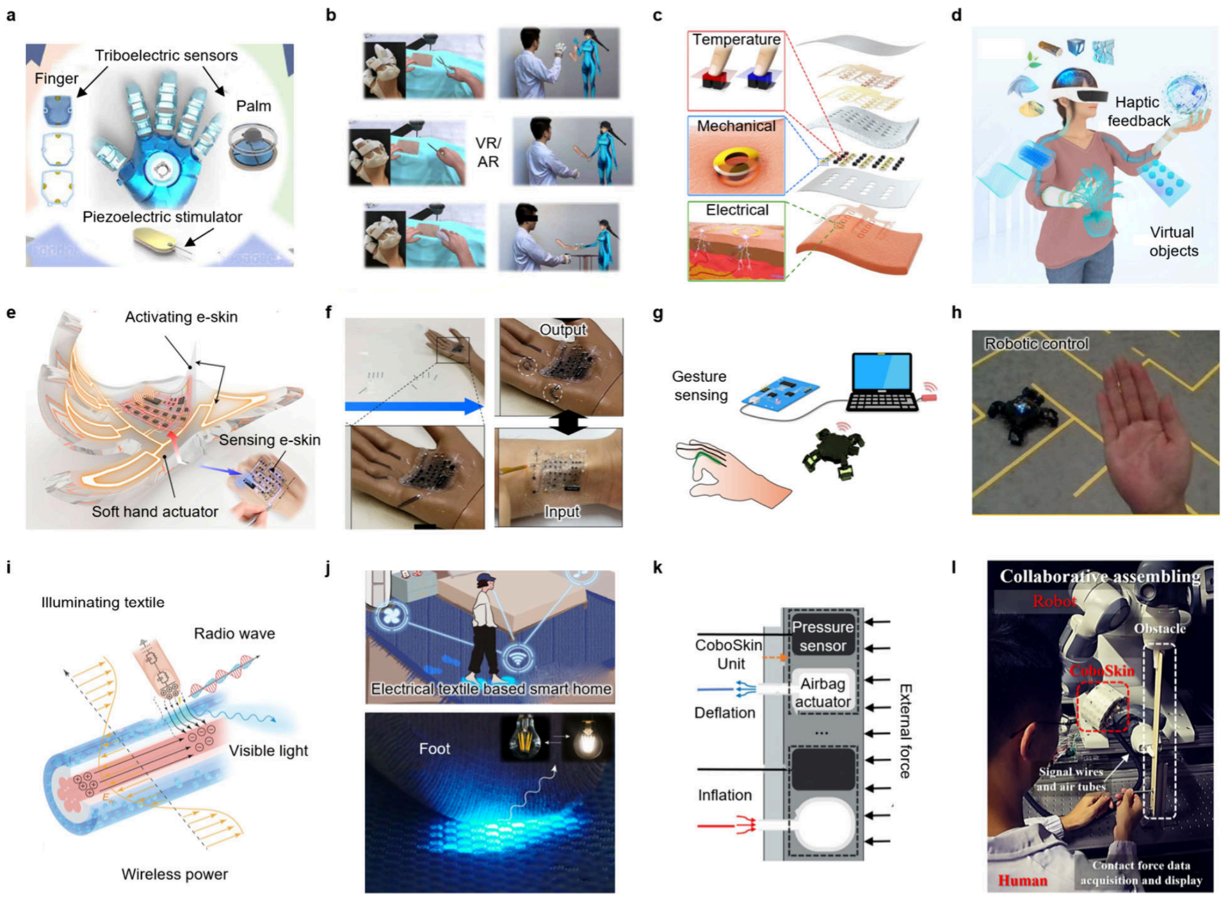

Figure 13. Soft HMI applications. (a) An HMI glove with integrated sensing and stimulation. The integrated structure of sensors and stimulators in the glove. (b) The HMI glove applied in AR/VR applications. (a,b) Reproduced with permission from ref 315. Copyright 2022 The American Association for the Advancement of Science. (c) A multimodal feedback HMI device with various stimulations. An integrated structure with temperature, mechanical, and electrical stimulation modalities. (d) The array applied in AR/VR for multimodal information feedback. (c,d) Reproduced with permission from ref 316. Copyright 2023 Springer Nature. (e) A flexible electronic skin for input and output. Schematic illustration of controlling a soft robotic hand using the electronic skin. (f) Application scenario image. (e,f) Reproduced with permission from ref 318. Copyright 2018 The American Association for the Advancement of Science. (g) A flexible strain sensor system for gesture recognition. Schematic illustration of the system used for robot control. (h) Real-world application scenario. (g,h) Reproduced with permission from ref 317. Copyright 2020 Springer Nature. (i) A body-coupled chipless interactive textile. The principle of body-coupled chipless interactive fiber. (j) Potential application of the interactive textile in a smart home. (i,j) Reproduced with permission from ref 319. Copyright 2024 The American Association for the Advancement of Science. (k) A robot skin for human−machine interaction safety sensing and protection. Schematic illustration of the robot skin for variable sensitivity external force sensing and collision protection. (l) The robot applied in a real-world human−machine interaction scenario. (k,l) Reproduced with permission from ref 322 under CC BY 4.0. Copyright 2022 IEEE.

flexible manipulation capabilities of 3D-printed human hands (Figure 11g−i).[292]

4.4. Soft Human−Machine Interface

HMI is regarded as the essence of soft prosthetic systems. Effective HMI not only enhances the maneuverability and sensory experience of the prosthetic but also bolsters the user's acceptance and trust in the artificial limb. The prevalent input methods for HMI include surface EMG signals, which involve electrodes placed on the skin to capture electrical signals generated by muscle contractions and translate them into movement commands for the prosthetic. This one of the most common method, directly utilizes the user's biological signals.[295,296] For instance, a broad interface monitors EMG signals in patients who have undergone targeted muscle reinnervation surgery to control multifunctional prosthetics, while also allowing for long-term EEG monitoring and concurrent structural and functional MRI (Figure 12a,b).[130] Implanted EMG signals, gathered through microelectrodes embedded in the residual limb muscles, offer higher signal quality but require more complex surgical procedures signals.[71,297] Surface brainwave, detected by scalp-placed electrodes that pick up faint electrical activity from the cerebral cortex, are converted into control commands.[298] For example, a fully portable, wireless, and flexible scalp electronics system uses convolutional neural networks for time-domain analysis, accurately and in real-time, distinguishing occipital lobe steady-state visually evoked potentials, suitable for electric wheelchairs, electric vehicles, and keyboard-free presentations (Figure 12c,d).[299] This noninvasive method is relatively simple to operate but limited in signal quality. Further, direct collection of electrical signals from the brain or peripheral nervous system achieves a more natural neuro-mechanical coupling, making HMI closer to natural physiological processes, though this requires more complex neural interface technology.[62,300,301] Mechanical signals, using the user's natural mechanical movements such as joint activity and limb position changes to control prosthetic actions, can emulate human instinctive movements to the greatest extent, providing an intuitive and natural operation.[302] For example, a flexible strain sensor powered by a lactate biofuel cell from sweat, attached to a joint, can control lower limb prosthetics (Figure 12e,f).[303] Moreover, muscle relaxation and tension can reflect the intent of human gestures, forming HMI signals, albeit with relatively simple corresponding commands (Figure 12g,h).[304]

Tactile feedback technologies used in soft prosthetic systems primarily include electrical stimulation feedback and mechanical feedback. Electrical stimulation feedback involves implanting microelectrode arrays on the prosthetic surface or the user's skin, using finely controlled electrical currents to simulate natural touch. When the prosthesis detects contact, the control system applies a corresponding electrical stimulation pattern to the electrodes, causing the user to experience neural excitation and producing delicate tactile feedback similar to actually touching an object. This technology can provide a tactile sensation close to the natural level, and the feedback information can be flexibly adjusted according to different environmental and task requirements, achieving a relatively simple mechanical design.[307] For example, a flexible electrode system can be directly applied to human skin to measure EMG, process signals, control a mechanical arm, and provide electrical stimulation feedback (Figure 12i,j).[229] In contrast, mechanical feedback includes vibration feedback and force feedback. The former integrates small vibration motors on the prosthetic surface to produce vibratory stimuli that simulate the rough texture of an object's surface and contact impulses.[308] A wireless, battery-free electronic system and tactile interface platform can softly conform to the skin's curvature, transmitting information to the body through programmable local vibration patterns, providing new technical support for applications such as prosthetic control feedback (Figure 12k,l).[306] The latter applies resistance or driving force to the user, allowing them to feel the natural resistance of joint movement and the weight of objects.[309,310] These mechanical feedback technologies can provide an experience closer to natural touch, but their structures are relatively complex, and they consume more energy. Natural feedback also includes temperature, scent feedback, and other experiences that simulate real-world scenarios.[311,312]

These human–machine interaction technologies are not only applied to prosthetic systems but also significantly enhance the immersion and interactive experience in AR/VR fields. Tactile and force feedback allows users to truly perceive the shape, texture, and weight of virtual objects, achieving more natural tactile interactions. At the same time, visual feedback can provide users with immersive virtual scene information, enhancing the sense of visual immersion (Figure 13a,b).[309,313–315] The application of these feedback technologies will make human–machine collaboration in AR/VR more intuitive and natural. For example, a skin-integrated wireless tactile interface based on an actuator array, through various feedback modes such as mechanical, electrical stimulation, and temperature, selectively activates different skin receptors, providing users with diverse tactile sensations and reproducing detailed textures, roughness, sliding, force, and temperature information (Figure 13c,d).[316] In the field of robot teleoperation, these human–machine interaction technologies can also be utilized. When operators remotely control robots to perform various tasks, tactile, force, and visual feedback can significantly improve the naturalness and control of human–machine collaboration (Figure 13e–h).[317,318] Operators can more intuitively perceive the robot's motion state and external environment, making more accurate control decisions. Additionally, these human–machine interaction technologies can be applied to emerging fields such as flexible displays. By integrating touch functions into flexible display devices, users can not only experience the visual presentation of images or text but also perceive the flexible deformation and tactile characteristics of the display itself (Figure 13i,j).[319] This can make human–machine interaction more natural and lively, enhancing the user experience.[320,321] Furthermore, the application of some flexible electronic devices can improve the safety of human–machine interaction. For example, a bionic robot active muscle skin array called CoboSkin, integrating sponge pressure sensors and air chambers with adjustable stiffness, can be used for safe human–machine collaboration and reducing collision injuries (Figure 13k,l).[322,323]

In summary, the development of soft prosthetic technology, especially the application of 3D printing manufacturing, flexible actuation, and advanced human–machine interaction technologies, will undoubtedly provide disabled individuals with more intelligent and naturally fitting assistive devices, greatly improving their quality of life. The future application of these technologies will benefit many fields, driving the continuous advancement of human–machine collaboration.

The future of rehabilitation and assistive soft robots is closely tied to advancements in materials, actuation and fabrication technologies. Besides, the integration of AI, optimization techniques, and simulation models have greatly advanced them, too. AI algorithms enhance these robots by enabling real-time adaptation to user movements and environments, optimizing the assistive functions based on continuous learning from sensor data. Meanwhile, optimization and simulation tools play critical roles in improving the design and functionality of these devices, ensuring that they are not only effective but also efficient in delivering personalized rehabilitation and assistance, maximizing therapeutic outcomes and user comfort.

5. SOFT ROBOTS FOR ORGAN SIMULATORS

Taking advantage of the soft mechanical properties of soft actuators that match the softness of biological tissue, soft robotic medical devices can be implanted into the body seamlessly.[324] This is in stark contrast to conventional actuators based on bulky and rigid materials that make safe implantation prohibitive, as movements cause large mechanical stress on tissue and can induce chronic immune reactions. On the other hand, actuators made from soft materials prevents application of large stresses that could damage tissue, even during actuation. Furthermore, the stimuli that drives actuation, including magnetic field, fluidics, humidity, and temperature are significantly safer than the large electrical currents required to power conventional electric motors.[325] Soft actuators are adaptive and compliant to the diverse morphologies of organs, enabling new avenues of implantable medical devices that modulate physiological function through supplemented mechanical actuation.[326]

5.1. Artificial Organs

Muscles and muscle fibers are biological soft actuators that comprise organ systems. While chronic disorders can result in dysfunction of muscles, wearable and implantable soft robotic actuators open an avenue to augmenting or restoring organ function by supplementing their actuation. Such artificial muscles or artificial organs can supplant the mechanical deformations provided by their biological counterparts for life sustaining functions. Furthermore, soft robotic actuators have

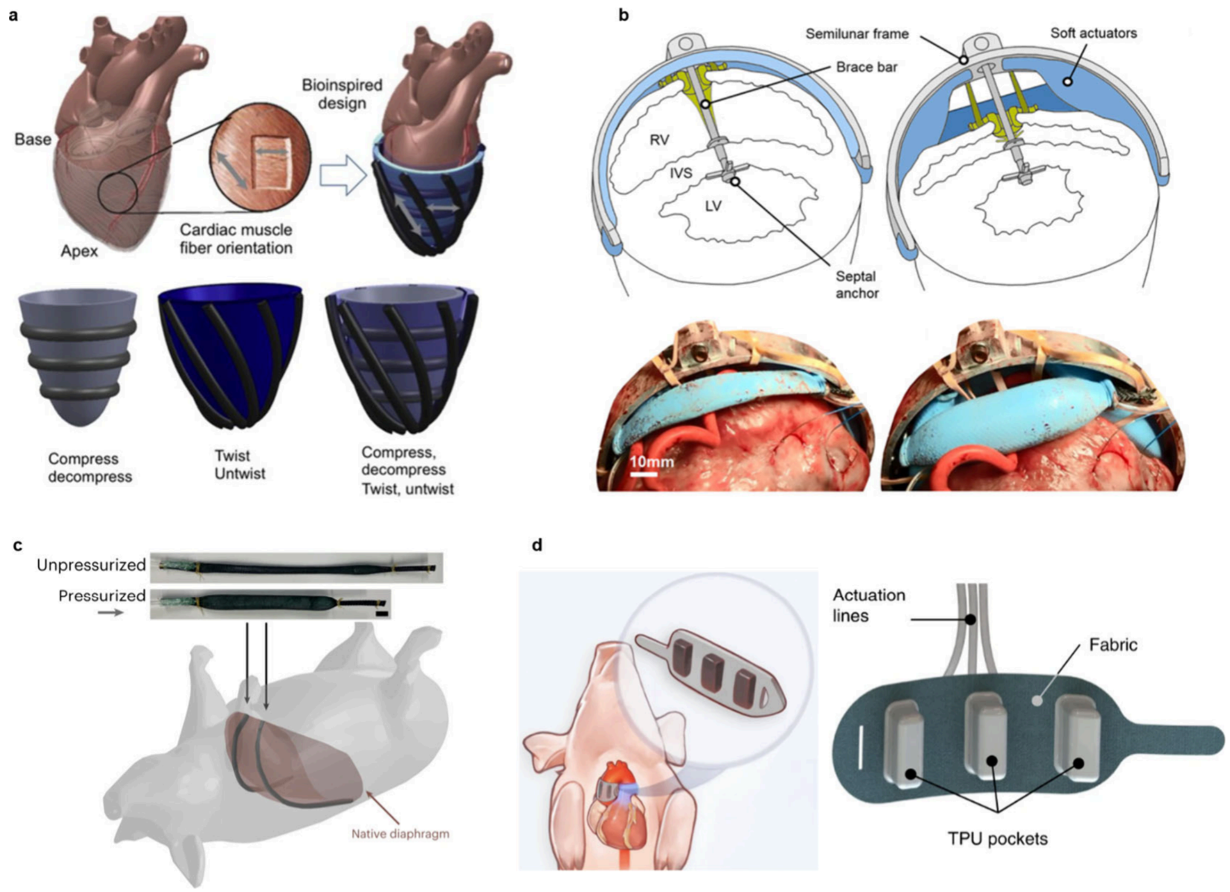

Figure 14. Soft robotic artificial organs. (a) Pneumatic heart sleeve that includes channels for compression and twisting motions that mimic the heart. Reproduced with permission from ref 328. Copyright 2017 The American Association for the Advancement of Science. (b) Intracardiac septal brace with pneumatic soft actuators that can interact with the left and right ventricle. Reproduced with permission from ref 329. Copyright 2017 The American Association for the Advancement of Science. (c) McKibben-type pneumatic artificial muscles for an implantable ventilator on the diaphragm. Reproduced with permission from ref 330 under CC BY 4.0. Copyright 2023 Springer Nature. (d) Aortic sleeve with three pneumatically actuated thermoplastic polyurethane pockets to modulate cardiac hemodynamics. Reproduced with permission from ref 331. Copyright 2022 Springer Nature.

been implanted as body simulators to replicate physiological conditions to model disorders in the body.[327]

Especially important for life support is to ensure the proper pumping of blood by the heart for cardiovascular functions.[332] While ventricular assist devices can aid with mechanical circulation of blood to treat chronic heart failure, they are bulky and require anticoagulants to prevent blood clot formation as they directly contact blood with valves at openings in the aorta and heart. Instead, soft robotic sleeves that surrounds the heart to were developed to support heart function via pneumatic actuation.[328,333−335] The silicone elastomer-based heart sleeves were molded with circumferential and helically oriented actuators for selective compression and twisting deformations that mimic the movements of the heart (Figure 14a). Additionally, they were shown to restore the cardiac output in porcine models with acute heart failure, returning the rate of fluid pumped from the heart to the healthy baseline. While this heart sleeve covered a large area of the heart, targeting biventricular heart failure, a soft robotic ventricular assist device was instead anchored to the interventricular septum to provide more targeted interaction with either ventricle for heart failure that is isolated to the left or right ventricle (Figure 14b).[336,329] Furthermore, echocardiography was used to guide the implantation of the septal brace to avoid open heart surgery. The bracing assembly consisted of the septal anchoring mechanism, a bracing bar that passes the ventricle wall, a bracing frame that surrounds the heart, and soft actuators based on McKibben pneumatic artificial muscles, which could deliver up to 100 N of load. The assistive device was demonstrated on in vivo porcine models of left heart failure induced by a coronary artery ligation procedure for ischemia. Other soft robotic devices that support end-stage heart failure have included electrothermally actuated cardiac sleeves using twisted nylon fibers and electrochemically active polymers using polypyrrole for contraction.[337−339]

Another application of soft pneumatic artificial muscles involved an implantable ventilator to augment respiratory functions in a pig model (Figure 14c).[330] In contrast with conventional mechanical ventilators that require a permanent tether to the mouth or an invasive tracheostomy procedure for an opening in the windpipe, which can affect a patient's speech, ability to swallow, and mobility, this soft implanted ventilator could significantly improve the quality of life for patients that have severe diaphragm dysfunction and respiratory failure. Implanted above the diaphragm, two McKibben type pneumatic actuators were employed, with a strain-limiting mesh over an inflatable bladder that could contract with a force of 40 N under 20 psi of pressure. By detecting inhalation with a spirometer and

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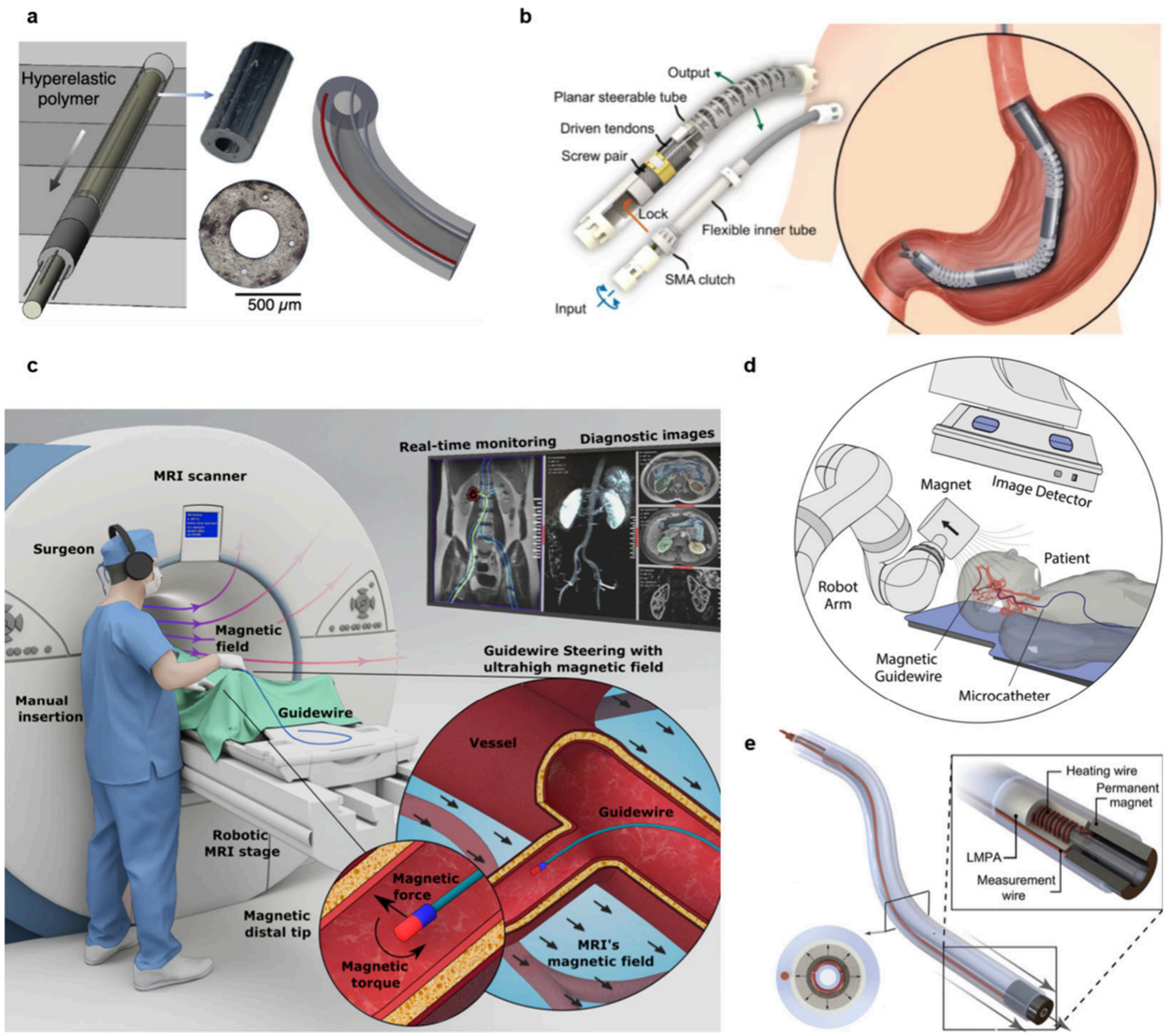

Figure 15. Steerable tethered robotic tools. (a) Hyperelastic microcatheter with four hydraulically actuated channels. Reproduced with permission from ref 347. Copyright 2021 The American Association for the Advancement of Science. (b) Hand-held robot with shape memory alloy clutch for bending modules. Reproduced with permission from ref 348 under CC BY 4.0. Copyright 2024 Springer Nature. (c) MRI-controlled magnetic guidewire that can operate under ultrahigh magnetic fields. Reproduced with permission from ref 349 under CC BY 4.0. Copyright 2023 The American Association for the Advancement of Science. (d) Telerobotic controlled robotic arm to manipulate a ferromagnetic soft continuum robot for neurovascular surgeries. Reproduced with permission from ref 350. Copyright 2022 The American Association for the Advancement of Science. (e) Variable stiffness catheter with a low-melting point alloy, heating coil, and permanent magnet tip. Reproduced with permission from ref 351 under CC BY 4.0. Copyright 2022 Wiley.

setting a threshold to trigger actuation, the implant synchronized to the timing of native respiratory functions, providing assistance to increase tidal volume and ventilation flow rates to a normal healthy range.

Implantable soft actuators have the potential to improve physiological functions in many muscular vital organs in addition to the heart and lungs. For example, aging can lead to weakened muscle function in the urinary system, making initiating urination difficult. Soft robotic actuators could contract to support smooth muscle in the bladder for urinating. Soft actuators could also improve intestinal motility to assist the digestive system. While pneumatic actuators have primarily been applied for implantable soft actuators that support organ function, they typically require a tether to a pneumatic source, limiting their applications for acute life support during surgical operations. Implanted soft actuators could be designed with wirelessly actuation mechanisms. Programmed magnetic soft actuators could be implanted and simply actuated by bringing a permanent magnet into proximity for wireless actuation.[326]

5.2. Pathological Simulators

Rather than applying soft robotic actuators to mimic the physiological function of an organ to provide treatment, soft actuators can also reproduce the pathological conditions of diseases to model disorders in living animals. Specifically, when the actuation time of soft actuators are synchronized with the activity of the organ counterpart, then the actuators assist with the organ function. However, if soft actuators act on the target organ asynchronously or create deformations that pose physiological challenges to impede organ functions, then soft actuators could instead simulate the pathology of various disorders.[327]

To model the hemodynamics and biomechanics of aortic stenosis, a customizable soft robotic aortic sleeve was developed

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that could constrict the aorta of porcine models (Figure 14d).[331] The soft robotic device consisted of three pneumatic thermoplastic polyurethane pockets that could expand to affect the blood flow patterns through the aorta and even induce left ventricular pressure overload. The three pneumatic pockets were individually addressable to produce different aortic stenosis morphologies, including unicommisural, bicommisural and stenosis constriction profiles, depending on the number of pockets that are actuated. Applying these dynamic actuation profiles in vivo, the blood flow velocity streamlines were measured to characterize the hemodynamics using MRI imaging. Additionally, CT scans of patients with aortic stenosis during constrictions were used to design patient-specific aortic sleeves by modifying the geometry of the inflatable pockets to match the morphology of aortic stenosis for individual patients. Building on this work, a left ventricular sleeve was also developed and coupled with aortic sleeves for improved aortic stenosis and ventricular remodeling that also captures the dynamics of diastolic dysfunction in 3D printed hydrodynamic systems that accounting for patient data.[340] Aside from an in vitro testing system, the left ventricular and aortic sleeve was also used in combination in porcine models to modulate cardiac hemodynamics of heart failure with preserved ejection fraction, which accounts for 50% of heart failure cases.[341] While the previous works applied pneumatic aortic sleeves in large animal models, testing in large animal models can be challenging due to poor time and cost efficiency. The authors later developed a single channel expanding pneumatic actuator for controlled aortic constriction in small animal models via aortic banding for partial ligation of the aorta.[342] Importantly, the pneumatic soft actuator improves on alternative methods of aortic banding with the ability to reverse pressure overload in rat models.

While soft robotics have also been used to create physiological models of healthy and diseased body parts on the benchtop, these simulations can be less realistic compared to in vivo body simulators.[343] Examining literature for benchtop body-part simulators provides many additional disease models that could be reproduced in the body using soft robotic pathological simulators.[14] For instance, soft robotic actuators could be used to exert forces on the bladder to simulate problems in the urinary system.[327] Similarly, obstructions can be produced in the gastrointestinal system, such as by constricting the intestine with soft actuators, to create digestive challenges. AI-powered multimodal modeling can further complement soft robotics for modeling various disorders.[344]

6. SOFT ROBOTIC SURGICAL TOOLS

Surgical tools are critically important biomedical devices that are temporarily implanted into the body to perform operations and removed post operation. Surgical tools that incorporate soft robotic actuators could improve the surgical outcome by minimizing stress and damage that is applied by an instrument onto tissue. Moreover, soft surgical tools that can navigate through the body decrease the invasiveness of surgeries as surgical targets can be more accessible without removing tissue to reach the target. Additionally, soft robotic tools could be functionalized for health monitoring and additional surgical procedures. Integrating soft actuators onto implantable medical devices can also improve the convenience of the surgical implantation procedure, as actuation can deform the device onto its target.[345]

6.1. Steerable Tethered Robotic Tools

Tethered surgical tools have been developed toward minimal invasiveness by accessing the body through natural orifices, or by miniaturization to enter through small incisions. These instruments include catheters, endoscopic tools, laparoscopy devices, and more. While long and flexible tethered surgical equipment have proven instrumental to many procedures, incorporating softer materials that enable steering through tortuous networks in the body could significantly improve surgical outcomes. Specifically, soft continuum robots with high degrees of freedom and soft mechanical properties would be well suited to navigate through the body. Many strategies integrating stimuli-responsive soft actuator materials into tethered surgical tools have been investigated to improve their utility inside the body.[346]

For the convenience of surgeons, a hand-controlled guidewire-free soft microcatheter was made with hydraulically actuated hyperelastic elastomers (Figure 15a).[347] The steerable catheter was molded with a 900 μm outer diameter and 400 μm inner diameter, and four 50 μm channels in the tube wall. By applying pressure to the microchannels, omnidirectional bending was achieved to navigate the steerable tip, placed at the distal tip of a 1.6 m long catheter. Despite the long catheter, the tip deflection had a response time under 1 s with changes to the input pressure. The hydraulically controlled microcatheter was demonstrated in an ex vivo silicone model fabricated from patient data, while computed tomography (CT) scans were used to visualize the location of the catheter. Additionally, the device was demonstrated by navigating through blood vessels and delivering an embolization coil through the inner lumen to the cerebral vessels of a porcine model in vivo.

A tethered surgical tool for transoral minimally invasive surgery was developed with SMA wires that could be selectively for better maneuverability (Figure 15b).[348] The soft continuum robot was connected to a single servomotor that could actuate three serial bending modules for expandable degrees of freedom. Endoscopic surgery could be performed with a camera, optical fiber, or endoscopic camera mounted at the tip of the robot.

While tendon-driven tethered instruments are most used in the clinic, magnetically steerable continuum robots have been gaining interest due to the ability to apply wireless and adaptive external magnetic fields to precisely maneuver magnetically responsive materials inside the body. Improving on magnetic guidewires that are manually pushed into the body, flow driven endovascular microrobotic probes with a cross-sectional area as small as 25 × 4 μm^2 were developed with remote steering enabled by a magnetic tip.[352] By taking advantage of the hydrokinetic energy of blood flow, the ultraflexible endovascular device could automatically advance through tortuous vascular networks, while magnetic actuation was used to dynamically steer the device at bifurcations in the blood vessel network. Additionally, a heater and flow sensor were integrated onto the tip for local flow characterization.

Although magnetic guidewires can be simply controlled by manually positioning a permanent magnet to apply a directional magnetic field, electromagnets can be programmed to dynamically apply magnetic fields with varying magnitudes and directions, such as with magnetic resonance imaging (MRI) scanners. Conventional catheters consisting of metal materials can also be actuated in an MRI machine via Lorentz forces, but high currents induced in the catheter causes heating.[353] Using the fringe field gradients from MRI coils, pulling and directional forces could be used to steer a magnetic guidewire (Figure

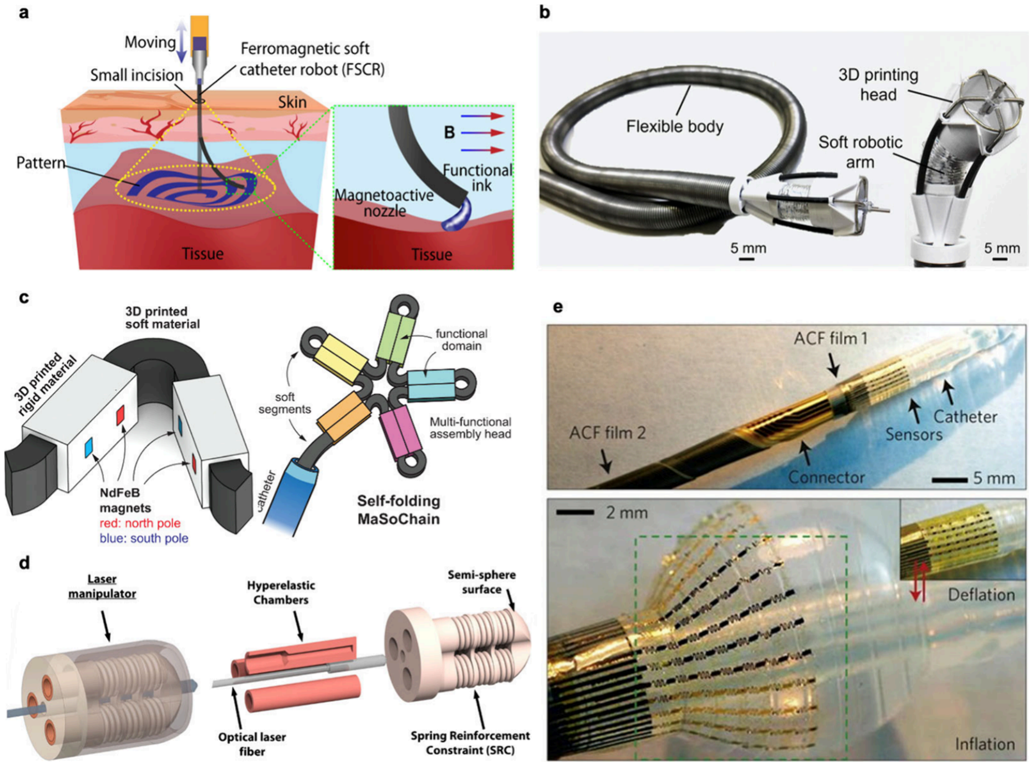

Figure 16. Functionalized catheters. (a) Ferromagnetic soft catheter robot for in vivo bioprinting through incisions through the skin. Reproduced with permission from ref 357 under CC BY 4.0. Copyright 2021 Springer Nature. (b) Flexible hydraulic arm for maneuvering 3D printhead with a tip that also has hydraulic XYZ control for precise positioning. Reproduced with permission from ref 358 under CC BY 4.0. Copyright 2023 Wiley. (c) Magnetic soft robotic chains for shape reconfiguration into multifunctional devices. Reproduced with permission from ref 359 under CC BY 4.0. Copyright 2023 Springer Nature. (d) Three channel hydraulically controlled laser manipulator for tumor ablation and microsurgery. Reproduced with permission from ref 360. Copyright 2021 The American Association for the Advancement of Science. (e) Multifunctional balloon catheter integrating sensors for temperature, pressure, flow, and electrophysiology monitoring. Reproduced with permission from ref 127. Copyright 2011 Springer Nature.

15c).[354] Low amplitude fringe magnetic fields were previously necessary because the ferromagnetic properties of magnetic guidewires can be affected under the ultrahigh magnetic fields of MRI machines, limiting their compatibility in most medical systems. By modeling the interaction of ultrahigh magnetic fields and permanent magnets in guidewires, controlled steering of magnetic guidewires composed of neodymium magnets was recently demonstrated in a 7-T MRI scanner.[349]

An alternative to wireless magnetic guidance by coordinating the activity of several electromagnets, such as in MRI, could be to move around a permanent magnet to manipulate a magnetically responsive robot. One report demonstrated remote control of a magnetically steerable guidewire through controlled spatial positioning of the large permanent magnet around a subject's head using a robotic arm (Figure 15d).[350] Notably, the robotic arm manipulator had seven revolute joints for seven degrees of freedom to position and rotate the applied magnetic field. Unlike conventional magnetic guidewires that consist of a miniature permanent magnet at the tip of a flexible wire, this ferromagnetic soft continuum robot was fabricated by incorporating hard magnetic nanoparticles in a soft polyurethane jacket, surrounding a nitinol core to provide a softer interface between the guidewire and tissue. Moreover, a pair of worm drives convert rotary motion from a DC motor to linear motion that advance or retract the microcatheter and guidewire. Not only was the telerobotic system demonstrated in neurovascular phantoms that represent human anatomy, but it was also coupled with an X-ray imaging system for navigation in the brachial artery of a porcine model in vivo. The robotic guidance system could be used for coil embolization to treat cerebral aneurysms and to treat ischemic stroke via clot retrieval thrombectomy. This telerobotic neurovascular surgical system could significantly reduce the hardware requirements for telerobotic surgery, in contrast to complicated and expensive MRI machines, enables the ability to reach lesions that are difficult to access, and minimizes radiation exposure to physicians.

In addition to magnetic steering of tethered surgical tools, a catheter also included material with variable stiffness at an instrument's tip so that it can soften to deform to the curves inside the body as it is advanced inward.[351] The variable stiffness catheter was equipped with a permanent magnet for steering, a gripper tool, and a heater that can soften low-melting point alloy that encase the catheter to reduce the rigidity of the device. As a result, the catheter could reduce the contact force up to a factor of 400 and was demonstrated in minimally invasive surgery through an eye phantom, steered with an electromagnet system. Alternatively, thermal-responsive shape memory polymer was used for variable stiffness instead of low-melting point alloys to avoid the need for encapsulation, allowing miniaturization.[355] A similar variable stiffness catheter incorporating SMPs with magnetic particles and a heating system was reported with submillimeter dimensions while maintaining high stiffness change. Further building on variable stiffness catheters, conductive particles were mixed into the shape memory polymer so that the composite could function as both the Joule heater and variable stiffness module.[356]

Various stimuli-responsive materials have been applied for different mechanisms of steering soft tethered surgical tools. Heating can be used to soften variable stiffness actuators, as well as for deformation by shape memory materials, but could also adversely affect the temperature of surrounding tissue. While fluidically driven actuators avoid heating tissue, careful patterning of hollowed fluidic channels is needed. Magnetic tools are wirelessly actuated and can be miniaturized as the components that provide stimuli are offboard the device.[25]

6.2. Functionalized Catheters in Surgery

Building on steerable catheters, a ferromagnetic soft catheter was used for minimally invasive bioprinting by extrusion printing from the distal tip of a hollowed catheter.[357] The ferromagnetic soft catheter robot consisted of a hard magnetic microparticles in a silicone matrix composite, surrounding a polylactide fiber supporting mesh to create a hollow channel that could transport the printing material (Figure 16a). The magnetic catheter bioprinter could print materials with varying viscosities based on PDMS and Ecoflex composites inks, and on various surface morphologies by using a strategy to account for three-dimensional nonplanar geometries. The system was demonstrated by printing conductive hydrogel on the curvilinear surface of liver in living rats through a minimal incision in their skin. However, this bioprinter was limited to a soft steerable magnetic tip, while the peripheries of the bioprinter remained rigid. Another approach used a hydraulically controlled flexible 3D bioprinter with all components integrated into the printhead to avoid a complex external magnet system for control (Figure 16b).[358] The soft robotic arm consisted of three soft fabric bellow actuators arranged in a triangle to enable omnidirectional motion of the printhead. While actuating one side of causes bending of the printhead, actuating all of them causes linear translational motion of the printhead. Furthermore, the printhead incorporated four soft microtubule artificial muscles to provide linear movement of the tip in three dimensions for more precise positioning. The bioprinting system was demonstrated by multilayer printing of various biomaterials, including chocolate, silicone elastomers, hydrogels, alcohols, olive oil, cationic polymers, and cell-laden living materials. Additionally, the flexible 3D bioprinter could be used as an advanced endoscopic surgery for treating colorectal cancer, as the authors proposed its use as an all-in-one tool, including performing lesion marking, saline injections, creating incisions and dissections, and showed bioprinting living biomaterials for tissue regeneration on an ex vivo porcine intestine model.

While magnetic steering is an appealing method for surgical instruments, magnetic actuation can also be used to for functional shape reconfiguration in minimally invasive surgical tools (Figure 16c). By including a chain of rigid magnetic segments interspaced with soft components, magnetic actuation was used to reconfigure the chain for various functionalities, including as a tweezer inside the body.[359]

Another tethered instrument applied soft hydraulic actuators to manipulate a laser for transoral microsurgery (Figure 16d).[360] The tool consisted of two soft robotic segments, with an active bending segment for navigation and a distal laser manipulator for fine control, including panning and tilting. Both segments contained three elastomeric hydraulic chambers that could inflate and deflate, while the laser manipulator section also contains miniaturized spring reinforced constraints to improve the repeatability of actuation. The use of hydraulics circumvents the problems from the high compressibility of air in pneumatics and allows actuation with less than 4 μL of fluid. The soft robotic system is compact (12×100 mm) and lightweight (200 g), with five degrees of freedom and generates zero electromagnetic interference for compatibility in MRI machines. The device was validated intraoperatively for MRI-guided laser ablation in ex vivo tissues and the oropharyngeal tissue of cadavers, which could be used to lesion laryngeal tumors through the natural oral orifice in the human body. In addition to using three hydraulic channels for steering inside the heart, a multifunctional soft robot used for cardiac interventions included semirigid spring steel that could be deployed by balloon angioplasty to stabilize the tool at the entrance of the heart.[361] After locking its shape at the superior vena cava to stabilize the position of the tool, distal force transfer significantly improved, making cardiac procedures much more convenient. The stabilized hydraulic soft robot was used for coronary sinus pacemaker lead placement and a reconstructive procedure for tricuspid valve implantation.

Balloon catheters that incorporate an inflatable balloon at the tip of the catheter are used for angioplasty procedures to widen arteries and blood vessels. Further enhancing balloon catheters by integrating bioelectronic devices into the balloon component can improve the functionality for biomedical applications. One balloon catheter integrated an array of piezoelectric micro-pyramids for measuring vascular stiffness to detect athero-sclerosis, which can lead to acute coronary syndrome.[362] Balloon catheters have also integrated stretchable electronics for electrical stimulation, ablation therapy, and thermal-based blood flow sensing by incorporating electrodes, a heater, and a thermistor.[363] Multifunctional balloon catheters have also included sensors for temperature, flow, tactile, optical and electrophysiological data, together with radiofrequency electrodes for local tissue ablation (Figure 16e).[127] Building on this multifunctional balloon catheter, the authors developed catheters with integrated soft multilayer electronics arrays for multimodal and multiplexed sensing during cardiac surgery.[364] Notably, the multilayer configuration of the electronics in this balloon catheter improved the density of spatiotemporal mapping for temperature, pressure, and electrophysiological sensing, as well as for electrical stimulation and radiofrequency ablation, and irreversible electroporation.

While tethered soft robotic surgical tools have been functionalized with a variety of devices for different operations, there is still room for expanding the versatility of such soft robotic tools. Soft robotics researchers could look to examples of pragmatic devices in conventional robotic surgical systems. For example, the da Vinci Surgical Systems includes needle drivers for suturing, forceps for manipulation, scissors for tissue cutting, clamps for holding, a camera for vision, ultrasonic shears, retractors for holding back tissue, and much more. Incorporating many devices into soft actuating surgical tools improves their practicality and potential for translation into the operating room.[345]

6.3. Integrated Soft Actuators for Bioelectronic Implants

Besides catheters, soft robotic actuators can be incorporated into a wide variety of implantable devices to minimize the invasive of devices.[346] Integrating bioelectronics with soft actuators enables robotic surgery that gently implant medical devices onto a target. This soft robotic surgery provides safer interaction with tissues, in contrast to current medical robots that are made of rigid materials. Furthermore, it allows for robust attachment as the

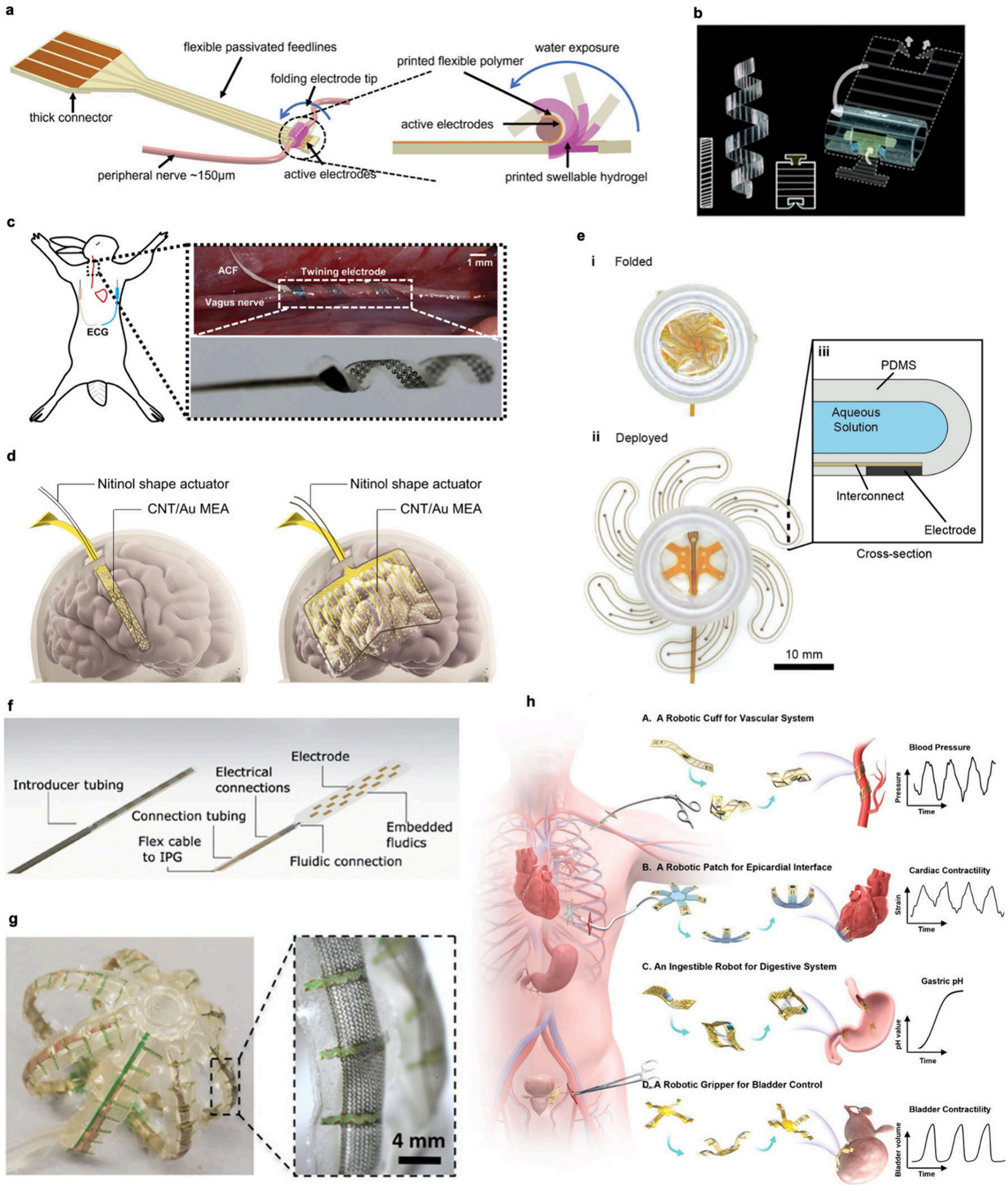

Figure 17. Soft robotic bioelectronics. (a) Self-folding hydrogel actuator for interfacing microelectrodes on small and delicate nerves. Reproduced with permission from ref 366 under CC BY 4.0. Copyright 2023 Wiley. (b) Programmable water-responsive spiraling actuator for a tight and conformal interface with peripheral nerves. Reproduced with permission from ref 367. Copyright 2023 American Chemical Society. (c) Bioinspired twining actuator based on shape memory polymer for vagus nerve stimulation. Reproduced with permission from ref 368 under CC BY 4.0. Copyright 2024 Springer Nature. (d) Large area electrocorticography microelectrode array deployed by a temperature-responsive shape memory alloy wire. Reproduced with permission from ref 369 under CC BY 4.0. Copyright 2024 Springer Nature. (e) Fluidic actuator for deploying everted and folded legs of an electrocorticography system. Reproduced with permission from ref 370. Copyright 2023 The American Association for the Advancement of Science. (f) Paddle-type spinal cord electrodes with fluidic channels for shape actuation. Reproduced with permission from ref 371 under CC BY 4.0. Copyright 2021 The American Association for the Advancement of Science. (g) Cardiac electrophysiology arrays hydraulically deployed from a catheter for mapping the left atrium. Reproduced with permission from ref 372. Copyright 2020 The American Association for the Advancement of Science. (h) Various shape adaptive actuators with embedded sensors to interact with different organs of the body. Reproduced with permission from ref 373 under CC BY 4.0. Copyright 2024 Springer Nature.

actuator can transform the shape of the device to the tissue morphology. Not only does this assist bioelectronics in creating a soft interface for recording biological signals or other functions, but it also addresses a major challenge in fixing soft bioelectronic materials onto organs by forming a tight interface. The intersection between soft robotic actuators and bioelectronic devices enhances their performance, reduces invasiveness, and opens many possibilities.

Recent developments have focused on integrating soft actuators into electrophysiology tools for neuromodulation and recording the electrical activity of neurons, which could have significant applications for brain-machine interfaces and advance neuroscience research. Applying soft actuators into neural probes enables triggerable shape deforming implants that conform to the geometry of the target structure with minimal mechanical stress applied onto body tissue. Not only does this circumvent chronic immune reactions caused by tissue damage that could lead to scarring, bleeding, and inflammation, but this is especially important as damaging delicate neurons could result in irreparable loss of physiological functions of the nervous system.[365] Furthermore, soft actuators have enabled implants that can be initially miniaturized when they are inserted into the body and expand in response to an external stimulus such that the area of body tissue that the device can interact with is significantly larger. This allows the size of the surgical opening to be minimized, and for devices to reach narrow regions of the body.

One target of interest that can be challenging to implant a device on are peripheral nerves, which have diameters as small as a few hundreds of microns. While commercially cuff electrodes have a precurved cylindrical geometry that can wrap around a nerve, they may require manually tightening the cuff using sutures to ensure the good electrical contact between the electrodes and the nerve. For a soft conformal interface that can automatically wrap around the nerve, stretchable 4D-printed self-folding cuff electrodes were developed using a super-absorbent hydrogel and passive polyurethane bilayer that undergoes bending actuation in response to swelling in water (Figure 17a).[366] The sodium acrylate-based hydrogel resin was patterned into stripes using a stereolithographic 3D printer to confine the direction of bending perpendicular to the hinge. This self-folding electrode cuff was demonstrated in vivo on the small metathoracic ganglion and nerves of locust insects. The cuff electrode proved to have excellent conformal contact with the ganglion as electrical stimulation of the ganglion varied the angle of a locust's leg, and spontaneous compound action potentials from afferent and efferent activity were recorded with six-channel electrodes. Similarly, an organic bilayer of poly(3,4-ethylenedioxythiophene) polystyrenesulfonate-polyurethane (PEDOT:PSS−PU) composite and poly(vinyl alcohol) (PVA) hydrogel was developed for a self-closing cuff electrode.[374] Unlike the 4D-printed cuff electrode, this self-closing electrode immediately curls when the prestrained PEDOT-polyurethane composite is removed from the substrate. Then, when implanted into a wet environment the PVA portion of the cuff swells close and reduce the diameter of the cuff for soft conformal contact onto nerves. This self-closing cuff electrode was implanted onto the vagus nerves of pigs, which have diameters around 2 mm, and in vivo nerve stimulation was shown to modulate the heart rate of the pig, measured using electrocardiography. Likewise, cuff electrodes fabricated on prestrained elastomer substrates were made with a water-soluble polymer to trigger the bending actuation.[375] In this design, a sodium alginate layer is used to increase the stiffness of the prestretched elastomer layer to prevent it from curling even when the elastomer is removed from its substrate. Rather than swelling in water as with hydrogels, once this device is implanted and the water-soluble sodium alginate layer dissolves, the prestretched elastomer curls automatically. This approach was demonstrated for electrical stimulation of the sciatic nerves in rats while electromyography activity of the corresponding limb was recorded.

While bending actuators can be incorporated into electrodes that wrap electrodes around peripheral nerves, the contact area between the cuff and nerve is small, which can limit the efficacy of electrical stimulation for neuromodulation-based therapeutic interventions. Instead of bending actuation, water-responsive actuators were developed with spiraling actuation to helically wrap around nerves for larger contact area and better mechanical robustness (Figure 17b).[367] To create water-responsive spiraling actuators, a bilayer of PVA was deposited onto a passive layer of polycaprolactone, and the PVA layer was scribed with a laser to program anisotropic constraints that trigger spiraling rather than bending upon exposure to water. The study showed that the angle of laser scribed parallel lines on the PVA layer programs the angle of the helix. This water-responsive 3D actuator was demonstrated in vivo to record neural activity in the sciatic nerve from mechanical stimulation of the hindlimb and to evoke movement of the hindlimb via electrical stimulation of the sciatic nerve. As an alternative to humidity-based actuators for peripheral nerve interfacing, SMPs have been shown to activate in response to body temperature for spiraling actuation (Figure 17c).[368] These SMP-based electrodes were inspired by twining plants that can grow to helically climb around a structure. Similarly, the twining electrodes were fabricated using 2D layer by layer lithography but undergo self-climbing shape transformation when heated to 37 °C, such as in the body. In vivo animal experiments showed the application of the twining electrodes for peripheral neuromodulation of the vagus nerve to reduce heartrate and action potential recording of the sciatic nerve.

Although soft actuators have been integrated into peripheral nerve electrodes that immediately respond to a physiological environment, this passive mode of actuation is difficult to control. For instance, if a spiraling actuator misplaces electrodes on its target, it can be difficult to remove the actuator without damaging the nerves or device. To overcome this problem, an electrochemical actuator is coupled with a microelectrode array for a controllably reconfigurable peripheral nerve interface.[376] The electrochemical actuator consisted of polypyrrole doped with dodecylbenzenesulfonate that is electrodeposited onto a gold electrode. The actuators operated at safe and low voltages, below 1 V, while exhibiting large bending deformations via cation transport. By integrating the soft robotic actuator with PEDOT:PSS microelectrodes, the neural probe was deployed around the sciatic nerve for electrophysiology recordings. Notably, the device was engineered with asymmetric distributions of the actuator to achieve spiraling actuation for better conformal contact on nerves that could have varying diameters. Applying the reconfigurable actuator in the implant enabled adjustable surgical placement of the device, safe contact with delicate nerves, and controlled retraction of the probe.

In addition to improving safe interaction with peripheral nerves, soft robotic actuators have been applied to neural probes to decrease the surgical footprint required to implant the device. Presently, implantation of an electrocorticography array requires craniotomy procedures to remove a large portion of the skull to place the array of electrodes across the brain. For instance, this may be necessary so that an electrocorticography array has wide spatial coverage of electrodes to localize the focus of an epileptic seizure and for other important applications. To minimize the invasiveness of such a procedure, nitinol SMA wires were embedded into an electrocorticography array, allowing the neural implant to be compressed for implantation through a small opening in the skull of rodent and canine models (Figure 17d).[369] After implanting the device onto the brain, internal body temperature was sufficient to trigger the phase transition of nitinol, expanding the electrode array for large-scale intracranial brain activity mapping across an expansive area of the brain. Specifically, while a cranial opening in rodents was 0.8 mm wide by 2 mm long, the electrode array unfolded to an area of 6 mm by 6 mm. Similarly, an electrocorticography system was deployed through a small burr hole opening, under 1 cm^2, via fluidic pressure-driven actuation in minipig models (Figure 17e).[370] In addition to neural electrodes, resistive strain sensors were integrated into each of six 6 mm by 4 mm sized legs to provide feedback of the deployment state. The neural implant was designed with an elastomer sleeve that is folded inward and sealed onto a loader that provides the fluidic pressure source. Applying a positive fluidic pressure differential fills the elastomeric sleeve with an aqueous solution to deploy the electrocorticography array by an eversion mechanism, unfolding the inward facing microelectrodes outward to contact the surface of the brain.

Aside from the peripheral nerves and the brain, robotic neural interfaces have also been applied to spinal cord electrodes, which could be used for chronic pain management. Conventional spinal cord electrodes include a 2D paddle-type probe architecture that requires highly invasive surgery to implant or a one-dimensional linear-type electrode array that can be inserted into the body with a needle percutaneously. Although 1D electrode arrays simplify the surgical procedures, their stimulation efficacy for pain management is poor due to limited spatial range and they are more likely to migrate post-implantation. On the other hand, paddle electrodes require less power due to better contact with the spinal cord, have up to 32 stimulation channels for precision therapy that can be accommodated by the extra width of the device (up to 12 mm), and have a better fixed position. Combining the advantages of both probe architectures, a paddle-type electrode array was designed to wrap onto a needle-like fluidic tubing that could be inserted into the spinal cord, and actuated to restore the paddle geometry (Figure 17f).[371] The probe was fabricated using gold electrodes on a parylene C substrate integrated over a silicone fluidic pocket, with an additional X-ray opaque mark cord surrounding the perimeter of the device such that the thin film device was visible under X-ray imaging during implantation. The device was successfully validated by inserting the carrier needle into the vertebrae of human cadavers, and simply actuated by pumping air from a syringe.

Besides deployable neural interfaces, a soft robotic multi-electrode array was developed to interface with the heart for cardiac voltage mapping (Figure 17g).[372] Specifically, thermoplastic polyurethane sheets were heat pressed to form hydraulically actuated soft robotic structures that could be deployed from a catheter to match the shape of the entire left atrium. Laser patterned stretchable serpentine electrode arrays were placed on individual actuators, and several actuators were assembled to create a balloon structure that could expand to map the whole left atria with 128 recording sites. To demonstrate the feasibility of the device, patient-specific models of the left atrium were 3D printed and the soft robotic sensor array was expanded in the models to show the conformability of the device, imaged by micro computed tomography. Furthermore, in vitro voltage mappings were used to performed by a single actuator leg in a cardiac tissue phantom. Such a device presents an exciting advancement for cardiac mapping to detect atrial fibrillation sources, which could then be ablated to prevent cardiac arrhythmia.

Biomedical devices that incorporate soft robotic actuators can be programmed to adapt to various organ systems. In addition to demonstrating a thermoresponsive hydrogel in a robotic system for measuring cardiac contractions and pacing, a poly(*N*-isopropylacrylamide) actuator system was proposed for measuring blood pressure on arteries, strain sensing on the bladder, and deployment in the digestive system (Figure 17h).[373] The hydrogel actuation layer was coupled with various sensors, including strain, pressure, temperature, and pH, for versatile applications. This actuation layer could be integrated with a Joule heater for on-demand actuation as PNIPAM responds to its lower critical solution temperature (34 °C). The sensor-integrated robotic devices were also delivered via a catheter, and thereafter respond to body temperature (37 °C) to trigger actuation so that device can better interact with the morphology of the target organ.

Incorporating soft robotic actuation into bioelectronic devices has led to less invasive devices and interfaces that have better contact with tissue.[377] Devices with soft actuators can be folded to reduce the footprint of the surgery and expand inside the body to interact with a larger portion of the target organ. Soft robotic bioelectronics can be triggered to deform and adapt to the morphology of the target for tighter, more robust mechanical interface, as well as for conformal contact, which can be critical for recording biological signals. Besides the soft actuator mechanisms that have been reported in soft robotic bioelectronics, other actuation stimuli could complement bioelectronics well. For example, photonic stimuli could be used both for actuation and for bioelectronics that require optogenetics.[378]

7. THERAPEUTIC SOFT ROBOTS

Therapeutic soft robots represent a significant advancement in medical technology, offering precise and adaptive treatments through innovative designs. Stimulus-triggered untethered soft robots, for instance, operate autonomously within the body, responding to specific physiological stimuli to deliver targeted therapeutic interventions. Catheter-assisted untethered soft robots provide a dynamic solution for navigating complex vascular networks, allowing for minimally invasive procedures that can be performed with enhanced precision and control. Additionally, soft robotic stents are revolutionizing patient care by adapting to the morphological changes within bodily conduits, ensuring sustained support and therapy without the rigidity of traditional stents. Together, these technologies demonstrate the potential of soft robotics to improve clinical outcomes through advanced intervention techniques that combine flexibility with functionality.[379]

7.1. Stimulus-Triggered Untethered Soft Robots

Untethered soft robots in the biomedical field hold great potential for therapeutic applications such as biopsy[380−383] and biomedical cargo delivery.[384] For clinical applications of cargo delivery, untethered soft robots need to be detectable and

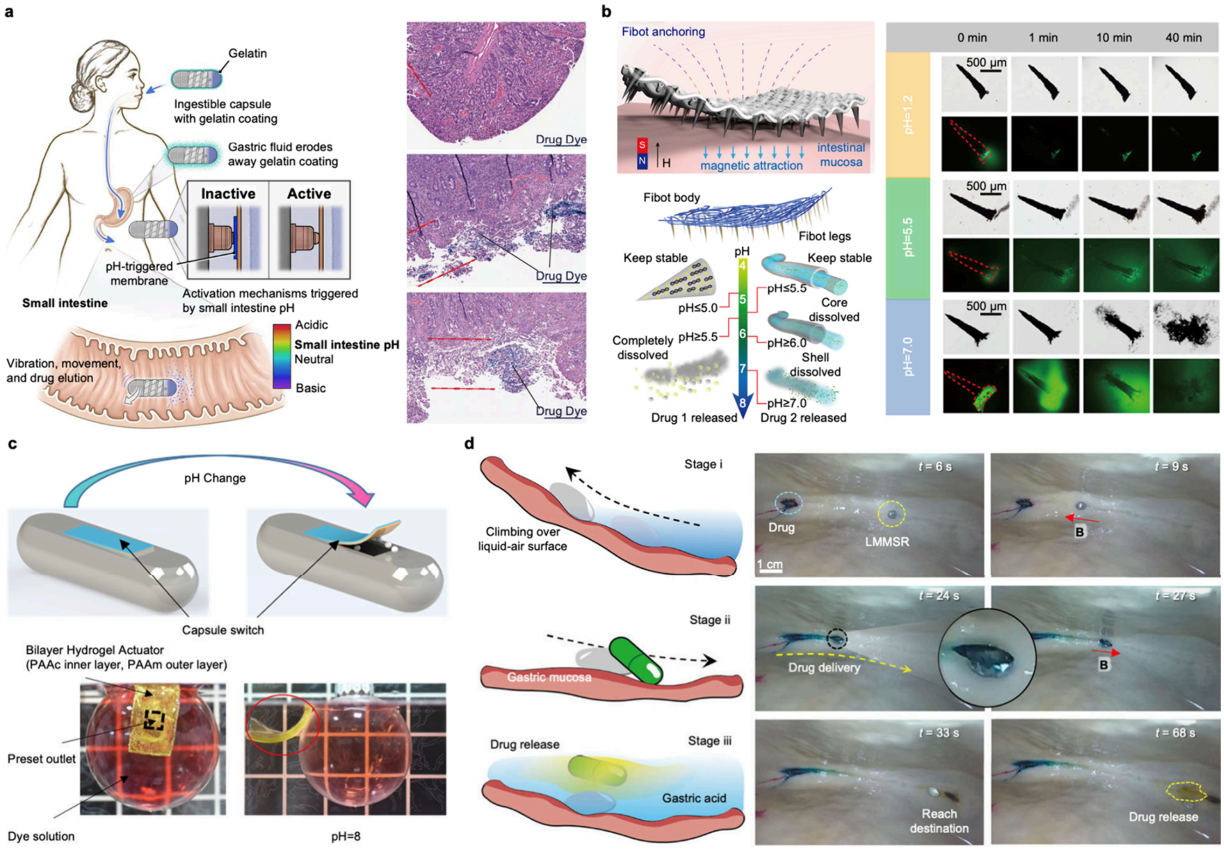

Figure 18. Local stimulus-triggered untethered soft robots. (a) Schematic of the robotic mucus-clearing capsule (RoboCap) for enhanced drug delivery triggered by local pH and the hematoxylin and eosin staining of cross sections of the small intestine with the control group and RoboCap-treated cases. Scale bars, 4 mm. Reproduced with permission from ref 385. Copyright 2022 The American Association for the Advancement of Science. (b) A nanofiber-constructed millirobot demonstrating drug release at different pH ranges. Reproduced with permission from ref 386. Copyright 2022 Elsevier. (c) A dual pH-responsive hydrogel soft robot for lipophilic drug delivery. Reproduced with permission from ref 387. Copyright 2020 American Chemical Society. (d) A nonwettable iron oxide in liquid metal soft robot for gastric acid triggered drug release. Reproduced with permission from ref 389 under CC BY 4.0. Copyright 2023 Springer Nature.

biocompatible. They should also be able to navigate through complex in vivo biological environments to reach the target area, preferably providing sustainable and controllable cargo release. The signal for cargo release can be stimulated by the local environment or triggered externally. Accurate stimuli to the release procedure ensure lower loading dosages, minimizing side effects compared with systemic injections or oral administration.

7.1.1. Local Stimulus-Triggered Untethered Soft Robots. When the robot is exposed to a new environment in the human body, surrounding stimuli may trigger the cargo release process. This generally requires a dramatic property change in the local environment, making the gastrointestinal tract an excellent candidate due to its pH gradient. For instance, a robotic mucus-clearing capsule consisting of a pH-triggered membrane continuously sensed the surrounding pH and activated only when it reached the small intestine to enhance drug absorption (Figure 18a).[385] Utilizing different pH ranges, a pH-responsive biodegradable nanofiber-constructed soft millirobot demonstrated precise delivery for two types of drugs with strong anchoring to the desired location (Figure 18b).[386] Another example includes a capsule fabricated with two layers of different pH-responsive hydrogels, which deformed into two configurations in varying pH environments for selective drug release (Figure 18c).[387] Additionally, a pH-responsive hybrid soft microgripper unfolded and released drugs in acidic environments, which could be potentially useful for cancer treatment.[388] Furthermore, a miniaturized liquid metal soft robot was injected inside the stomach via endoscope, magnetically controlled to the gastric acid, and released the drug (Figure 18d).[389]

Local temperature changes can be a trigger for drug release as well.[390] An example is the snake-inspired multilegged magnetic soft robot that could dissolve for drug release in warm water.[391] However, solely depending on the temperature changes of different parts of the human body might not be ideal due to the limited temperature variations. Additionally, while properties in the physiological environment of the body provide a passive and convenient method to release drugs, physiological triggers lack precise control as they stimulate drug delivery immediately and limited types of triggers are available. By designing mechanisms that trigger drug delivery from external stimuli, the timing of therapeutic release can be better controlled.

7.1.2. External Stimulus-Triggered Untethered Soft Robots. Introducing external stimuli for the release process offers more possibilities with on-demand control. To deal with the relatively constant body temperature challenge, near-infrared (NIR) laser as a biocompatible method is utilized to heat up the robots for cargo delivery. Thermoresponsive hydrogel plays an important role in this type of robot. A self-folding bilayer hydrogel microrobot encapsulating magnetic alginate microbeads demonstrated rapid opening by NIR laser irradiation, which increased the local temperature to over 40 °C

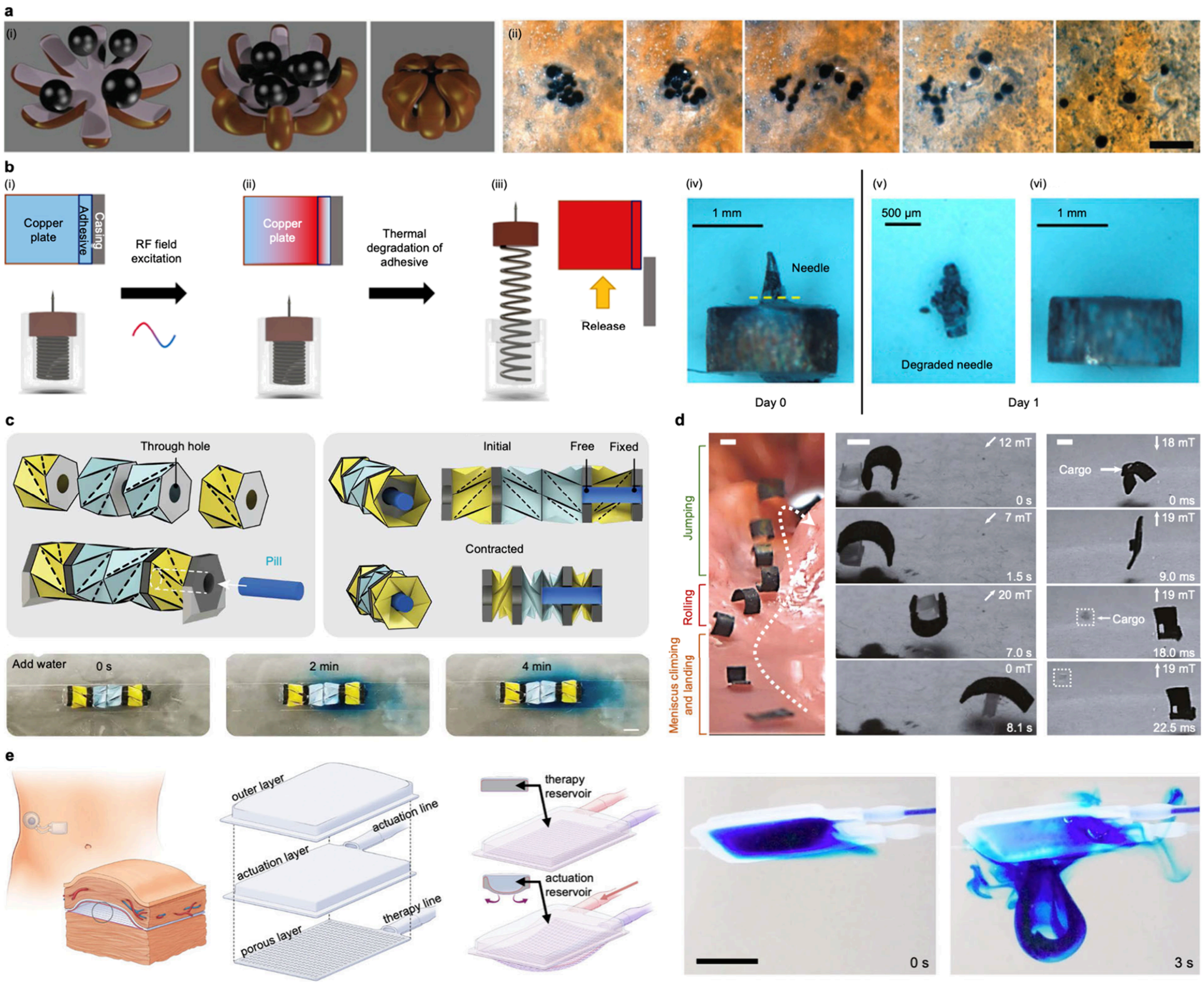

Figure 19. External stimulus-triggered untethered soft robots. (a) A thermoresponsive microgripper with the thermosensitive cargo release. Scale bar, 500 μm. Reproduced with permission from ref 392. Copyright 2014 Wiley. (b) A miniaturized soft millirobot with RF-induced thermoresponsive anchoring to the bladder wall with biodegradation ability. Reproduced with permission from ref 395 under CC BY 4.0. Copyright 2022 Proceedings of the National Academy of Sciences. (c) Origami soft crawler with on-site magnetically triggered cargo release. Reproduced with permission from ref 396. Copyright 2022 The American Association for the Advancement of Science. (d) A magneto-elastic soft millirobot with multimodal motion capability and on-demand cargo release. Scale bars, 1 mm. Reproduced with permission from ref 397. Copyright 2018 Springer Nature. (e) An implantable mechanotherapeutic drug delivery platform for long-lasting drug delivery and enhanced transportation. Scale bar, 5 mm. Reproduced with permission from ref 398 under CC BY 4.0. Copyright 2022 Springer Nature.

(Figure 19a).[392] This starfish-like structure can grab solid cargo such as capsules or microspheres with conformability.[393] The hydrogel material was integrated with magnetic microparticles interacting with the magnetic field for locomotion.[394]

Some robots also utilized the biodegradability of specific hydrogels.[399] A millirobot made of photothermal magnetic hydrogel could be guided through the oviduct phantom and facilitated drug release under laser heating.[400] In addition to the biomimetic structure, an aircraft-like soft robot embedded with cardiac cells for locomotion propulsion could stop moving upon NIR irradiation and unload the "airdrop" drug to the target region through thermo-triggered contraction and the expansion of its wings.[401] The temperature-dependent properties of hydrogels also facilitated the design of capsule-like robots.[402] A micro-origami capsule was designed to improve the drug-loading efficacy and movement for sustained drug release.[403] Moreover, NIR not only served as the trigger for the robots' structural transformation for delivery but also acted as the driving force to modulate their moving speed.[404] Using the swelling and deswelling of the NIPAM hydrogel, a spring-type medical microrobot was able to release doxorubicin with NIR irradiation to treat cancer in vitro.[405]

Other mechanisms to increase the local temperature includes radio frequency-induced heating, applied to a wireless spring-preloaded barbed needle soft robot. The fast release of the needle was strong enough to anchor in the tissue firmly, release drugs, and then biodegrade (Figure 19b).[395] Additionally, the magneto-thermal effect is used to elevate the temperature and promote the water-soluble drug release.[406] A multilegged robot coupled with liquid-metal soft electronics was able to move and sense remotely in the gastrointestinal tract, releasing doxorubicin by magnetocaloric effect.[407]

Besides thermo-triggered cargo release, the magnetic field is another ideal candidate with its biocompatibility, programmable remote control, and deep penetration depth in clinical settings. Magnetic field empowers complex locomotion and program-

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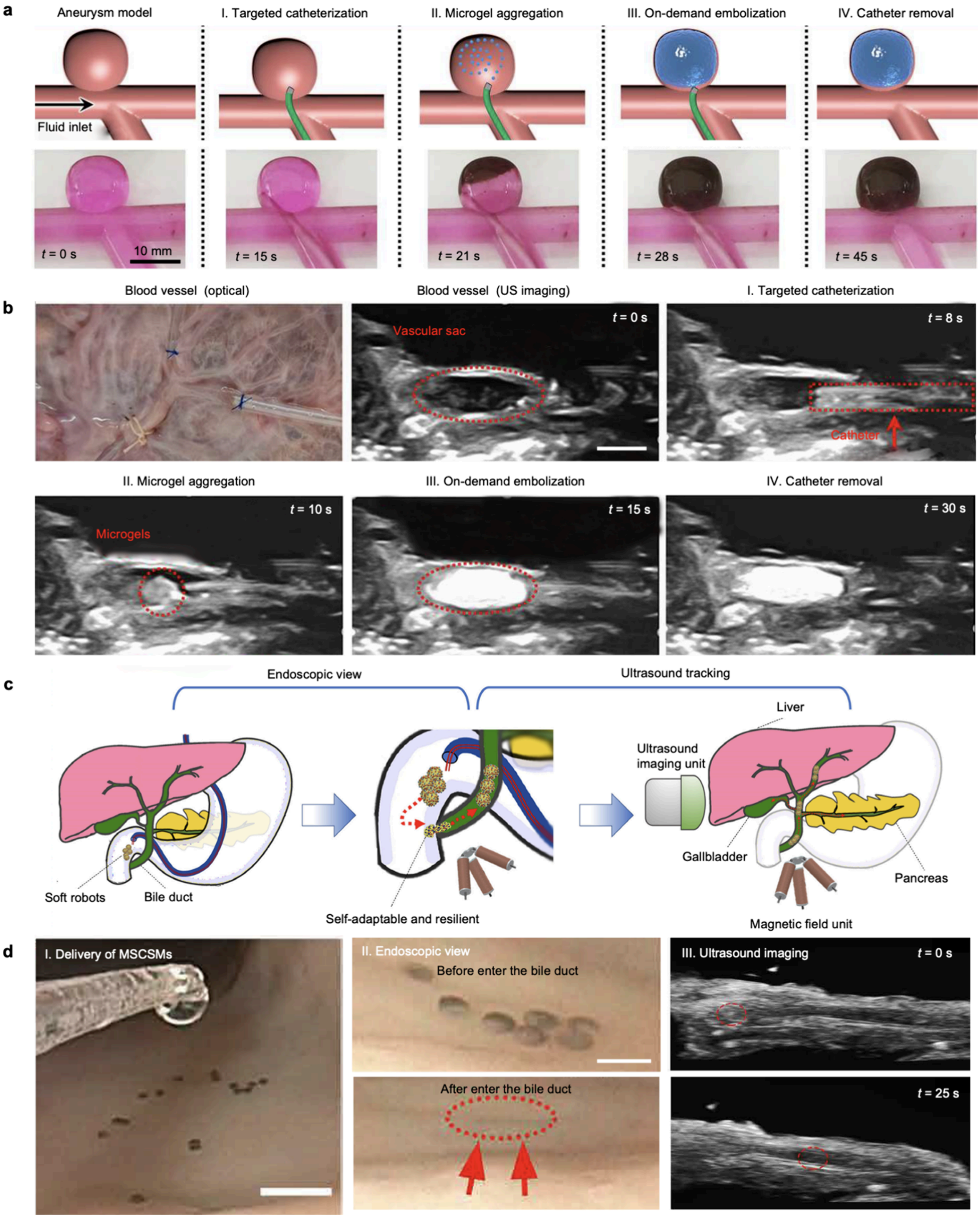

Figure 20. Catheter-assisted untethered soft robots. (a) Schematic and experimental results of embolization procedures in dynamic fluid, including (I) targeted catheterization, (II) deployment and active accumulation of swarming microgels into aneurysm sac under the actuation of robotic magnet, (III) on-demand embolization via mild acid stimulus, and (IV) the removal of catheter and robotic magnet. (b) Real-time US imaging of the embolization process in blood vessels, which clearly demonstrates the whole embolization procedures inside human placenta. Scale bar, 2 mm. (a,b) Reproduced with permission from ref 438. Copyright 2023 The American Association for the Advancement of Science. (c) Schematic of the endoscopy-assisted magnetic actuation with a dual imaging system (EMADIS) enables the rapid delivery of soft MSCSMs to the bile duct via a natural

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Figure 20. continued

orifice under combined imaging modalities in real time. (d) The endoscopic view and ultrasound imaging track the entire process in real time. (I) Delivery of the magnetic stem cell spheroid microrobots (MSCSMs) by the catheter equipped on an endoscope through the throat to the stomach and finally reaches the intestine. Scale bar, 5 mm. (II) Endoscopic view of MSCSMs toward the entrance of the bile duct under magnetic attraction. Scale bar, 1 mm. (III) Ultrasound imaging of the MSCSMs inside the bile duct under magnetic navigation. (c,d) Reproduced with permission from ref 439. Copyright 2021 The American Association for the Advancement of Science.

mable functions for precise delivery control.[408] Different types of magnetic soft robots have been designed to deliver cargo to various parts of the body. For example, by depositing a thin film of magnetic spray onto the surface, the inanimate structures became responsive to the magnetic field while keeping their original shapes.[409] Inspired by worms, a three-dimensional (3D) printed millirobot a drug reservoir could crawl through a human stomach phantom and squeeze out the model drug through the reservoir's membrane by deformation when reaching the target.[410,411] An earthworm-like soft crawler, consisting of a four-unit Kresling origami assembly and storing drugs within its internal cavity was magnetically actuated in the plane and released the pill (Figure 19c).[396] Moreover, a multilegged robot with tapered feet structures was capable of carrying the cargo nearly 100 times its body weight at an average speed of 0.5 mm/s on a wet surface with liquid film.[412]

Similar to the thermoresponsive grippers mentioned above, magnetic soft grippers could be actuated by magnetic fields, enabling grasping, transportation, and precise delivery control.[413−415] Sheet-like magneto-elastic millirobots could move agilely in 3D space by swimming, climbing, walking, and jumping, releasing the cargo on tissue surfaces or in aqueous environments (Figure 19d).[397] A magnetically hard but mechanically ultrasoft foam was tested to roll in the stomach phantom, delivering the drug stored inside its body by the contraction force applied by the magnetic field.[416] Furthermore, a magnetic multilayer soft robot patch demonstrated the ex vivo and in vivo on-demand adhesion to the gastric ulcer sites, which could potentially carry and release drugs to lesion regions.[417,418] A ring-shaped soft robot could carry model drugs and squeeze them out at target areas with the magnetic field, even moving on mucus-coated surfaces and against gravity.[419] Magnetically controlled robot capsules are typically integrated with magnetic parts, sensors, batteries, cameras, etc., allowing them to navigate inside the stomach, intestine, or cortex with controllable motion and release cargo at desired location via magnetic triggers.[420−425] Capsules are relatively bulky and, where ferrofluids take advantage of their arbitrary shape morphology. The shape-reprogrammable ability makes ferrofluids navigate through constrained lumens.[426]

Lastly, long-lasting drug delivery and enhanced transportation were achieved by an implantable mechanotherapeutic drug delivery platform to constantly actuate the drug release region and overcome the immune response (Figure 19e).[398,427,428] The FibroSensing Dynamic Soft Reservoir (FSDSR) is an advanced biocompatible soft robotic drug delivery device designed to sense and respond to fibrotic capsule formation in vivo.[429] By utilizing dynamic pneumatic actuation changes, the FSDSR can probe the foreign body response and adapt accordingly, enhancing the efficacy and longevity of implantable drug delivery systems.

Applying external stimuli to actuate soft robots for drug release opens diverse possibilities to design mechanisms for drug release. Opportunities that could be explored include the use of magnetothermal particles that heat in response to alternating magnetic fields for localized temperature changes for drug delivery.[430] Further programming ferromagnetic domains in magnetically actuators could improve their maneuverability and multimodal locomotion gaits.[431,432] Incorporating on-board stretchable electrohydrodynamic or electro-pneumatic pumps as sources for fluidic actuators can provide a complete soft wireless solution for drug delivery.[433,434]

7.2. Catheter-Assisted Untethered Soft Robots

The effective and precise navigation of soft robotics in complex and dynamic endovascular environments necessitates advanced microrobotic control and imaging methodologies, particularly within the vascular branches of the aorta where physiological blood flow velocities can reach up to 10 to 20 cm/s.[435−437] Catheter-assisted delivery and deployment of soft robots in these environments serve as a conduit through biological barriers, shielding microrobots from the body's immune system.[438−441] Under the real-time guidance of ultrasound imaging, the soft robot can be delivered precisely. Moreover, endoscopy-assisted untethered soft robotic system will offer the endoscopic view besides the ultrasound imaging and enable dual imaging modalities.

An innovative interventional catheterization-integrated swarming soft robotic platform has been developed for on-demand embolization of aneurysms within physiological blood flow.[438] Initially, a clinical catheter was inserted through a branched pipe, positioning its tip at the aneurysm neck (Figure 20a). Subsequently, a dynamic external magnetic field was applied via a robotic magnet, guiding the deployment of swarming microgels and their aggregation within the aneurysm sac. Upon accumulating sufficient microgels, an acidic buffer solution was released via the catheter, triggering the pH-responsive self-adhesive behavior of the microgels. This resulted in the welding of swarming microrobots into a cohesive structure to occlude the sac. Real-time ultrasound imaging monitored the entire embolization process within a specific blood artery (Figure 20b).

Another noteworthy development is the endoscopy-assisted magnetic actuation with a dual imaging system (EMADIS) (Figure 20c).[439] EMADIS leveraged the endoscope to provide a direct route for magnetic stem cell spheroid microrobots (MSCSMs), circumventing direct exposure to complex fluidic environments and facilitating their rapid passage through multiple biological barriers. Magnetic field actuation guided the high-precision delivery of MSCSMs to the targeted position postendoscopic deployment, while the combined endoscopic view and ultrasound imaging tracked the entire process in real time (Figure 20d). This approach enables swift and high-precision delivery of soft microrobots for targeted therapeutic intervention in hard-to-reach regions, which conventional endoscopes and medical robots may struggle to reach or visualize.

The integration of tethered endoscopy and untethered soft microrobots presents a comprehensive clinical imaging-based therapeutic/intervention system. This system extends the

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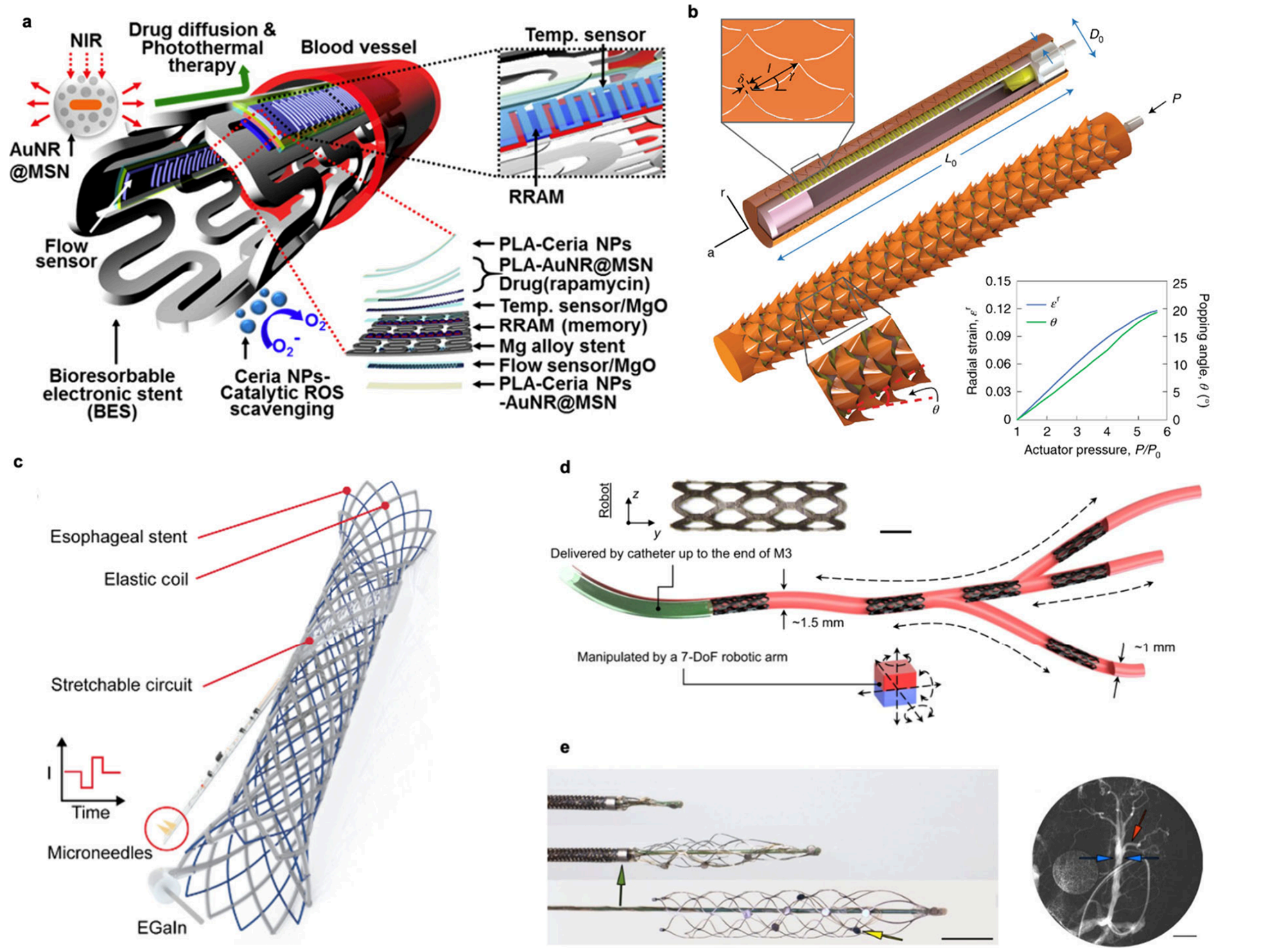

Figure 21. Soft robotic stents. (a) Bioresorbable bioelectronic stent with integrated sensors, wireless power and data transmission, and ceria nanoparticles for inflammation suppression. Reproduced with permission from ref 443. Copyright 2015 American Chemical Society. (b) Kirigami-inspired esophageal stent with drug-loaded polymers in microneedles for extended drug delivery. Reproduced with permission from ref 444. Copyright 2021 Springer Nature. (c) Nitinol stent with liquid metal antenna and stretchable circuits for electrical stimulation in the esophagus. Reproduced with permission from ref 445. Copyright 2023 The American Association for the Advancement of Science. (d) Shape memory polymer-based stent with magnetic particles for navigation in distal vasculature. Scale bar, 1 mm. Reproduced with permission from ref 446 under CC BY 4.0. Copyright 2022 Springer Nature. (e) Microelectrode array mounted onto a nitinol stent for a minimally invasive endovascular neural interface. Scale bar, 3 mm (left). Scale bar, 10 mm (right). Reproduced with permission from ref 447. Copyright 2016 Springer Nature.

working distance, enhances time efficiency for targeted delivery, and offers diverse functionalities with significant clinical value.

7.3. Soft Robotic Stents

Another device commonly delivered by catheter is stents, which are typically used to provide a physical support that opens arteries blocked by the buildup of plaque caused by atherosclerosis.[442] Cardiovascular stents often include soft actuator materials for deployment in blood vessels to open narrowed or blocked blood vessels. While stents can be loaded onto a balloon catheter and deployed by actuation of the ballon causing a mesh-like stent to deform and expand into place, stents are also commonly made out of SMAs and actuate when exiting an endovascular catheter in response to body temperature. Functionalizing stents have further enhanced their capabilities, such as with biosensors for chronic health monitoring, drug eluting stents that provide additional therapy, and bioresorbable stents.

One stent delivered by balloon angioplasty focused on creating an electronic stent from bioresorbable materials, with integrated sensors and drug delivery using nanoparticles (Figure 21a).[443] The bioresorbable stent included electronics for flow sensing, temperature monitoring, and wireless power and data transmission, as well as drug-infused nanoparticles for inflammation suppression and hyperthermia therapy.

Rather than expanding by the shape memory effect on current endovascular catheter platforms, a kirigami-inspired stent was instead integrated with a fluidically driven linear soft actuator for sustained local delivery of drugs to tubular organs (Figure 21b).[444] The stent consisted of a snake-skin-inspired kirigami shell with needles that pop out once actuated to penetrate tissue for extended drug delivery. The needles were coated with drug-loaded polymeric particles, advancing on drug eluting stents and drug-loaded balloons. Another bioelectronic stents was delivered transorally to target the gastrointestinal tract (Figure 21c).[445] A battery-free electronic stent was designed for wireless stimulation of the esophageal sphincter to treat gastro-esophageal reflux disease. The nitinol stent accommodated a stretchable antenna made of eutectic gallium−indium and a pulse generator circuit. Additionally, the stent used micro-needles for effective electrical stimulation across the mucosa, taking advantage of the adaptive stents actuation to form compliant contact for penetration of the microneedles.

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While most stents are fixed in location after they are deployed from a catheter, a stent made out of shape-memory polymer further incorporated magnetic iron oxide particles to enable navigation through distal vasculature (Figure 21d).[446] Notably, the adaptive stent could contract via external magnetic control to travel through narrowing lumen phantoms, shrinking from 1.5 mm diameter to 1 mm diameter, as well as traveling through the arteries of ex vivo porcine models.

Building on existing intracranial stent technology, an array of laser-cut 750 μm diameter platinum disc electrodes were mounted on commercially available self-expanding nitinol stent for chronic cortical neural recordings (Figure 21e).[447] The electrodes were placed 2.5 mm apart along the repeating stent strut cross-links to maintain the elasticity of the stent. This stent-electrode recording array was compressed and delivered via catheter angiography through the superficial cortical vein to the motor cortex of freely moving sheep. Chronic neural recordings were demonstrated for 190 days and the electrode array integrated the vessel walls after 1 week, enabling minimally invasive high resolution neural recordings comparable to electrocorticography arrays that normally require highly invasive craniotomy procedures for implantation. In addition to neural recordings, similar stents have been used for neuromodulation in the brain with the potential to treat neurodegenerative disorders, including Parkinson's disease, epilepsy, depression, and more.[448]

In summary, advanced stents have been enhanced with bioelectronics for chronic health monitoring, drug delivery mechanisms, and bioresorbable materials for better biocompatibility.[442] Expanding on conventional shape memory actuation and fluidically driven actuation, other mechanisms could be explored in stents to improve their performance. Hydrogels and water-responsive actuators could provide more biocompatible materials, which swell and expand into place after deployment as an alternative actuation method that respond to physiological triggers. Besides magnetic control that enable maneuverability of the stent, various wireless stimuli could be considered to assist stents in traversing through vasculature. One possibility could be to integrate LCE materials which have a phase transition temperature above body temperature. Then, by including nanoparticles such as magnetothermal or photothermal particles that respond to external stimuli, another actuation modality could be used to contract the stent so that it can contract to pass through narrower distal vasculature or even crawl along the walls of arteries.

8. OUTLOOK

The field of wearable and implantable soft robotics stands at the cusp of transformative advancements, driven by continuous innovations in actuation mechanisms, materials science, and fabrication technologies. As the integration of soft robotics into medical applications accelerates, several promising future directions and significant challenges emerge.

8.1. Actuation Mechanisms, Materials, and Fabrication

Future advancements in actuation mechanisms are poised to enhance the versatility and functionality of soft robots. Innovations such as biohybrid actuators, which integrate living tissues with abiotic materials, promise to create more adaptable and responsive systems.[449] Additionally, the development of novel actuators that mimic biological muscle movements will enable more precise and efficient motion control in wearable and implantable devices.

The evolution of materials is central to the progression of soft robotics. Emerging materials with the right balance of flexibility, strength, biocompatibility, and responsiveness to environmental stimuli will facilitate the creation of soft robots that can seamlessly interact with biological tissues. Advances in liquid crystal elastomers and hydrogels, which offer significant deformation capabilities and responsiveness to environmental stimuli, are particularly promising for applications requiring high adaptability and resilience. Moreover, the integration of conductive and responsive materials will enhance the sensory and actuation capabilities of soft robots, enabling more sophisticated interactions and functionalities.

Advanced fabrication techniques, such as 3D printing, soft lithography, and roll-to-roll processing, are critical for scaling up the production of soft robots while maintaining precision and reproducibility. The adoption of automated and scalable manufacturing processes will address current limitations related to the scalability and reproducibility of soft robotic components. Furthermore, the integration of multimaterial printing and hybrid fabrication methods will allow for the seamless incorporation of diverse materials and complex structures, facilitating the development of multifunctional and reconfigurable soft robots.

8.2. Soft Robotic Intelligence

The ultimate goal of soft robots is to create intelligent, multifunctional soft robots that can operate autonomously for extended durations, handle unpredictable situations, and execute complex tasks.[5,236] First, the ability to perform multiple functions and adapt to various modalities is essential for the deployment of soft robots in dynamic and complex environments. Future soft robots will be equipped with integrated sensor arrays and multifunctional actuators, enabling them to perform a wide range of tasks from precise medical procedures to adaptive rehabilitation therapies. For instance, soft robots capable of both locomotion and manipulation will enhance their utility in minimally invasive surgeries and patient-assisted movements, providing comprehensive support in clinical settings.

Second, reconfigurable soft robots, which can alter their shape and functionality in response to external stimuli, represent a significant advancement in adaptability. Techniques such as kirigami and origami-inspired designs, along with stimuli-responsive materials, will enable soft robots to dynamically adjust their configurations to navigate through confined spaces or perform complex tasks.[14] This reconfigurability is particularly valuable for implantable devices that must adapt to varying physiological conditions and for wearable robots that need to conform to different body shapes and movements.

Third, the integration of high-resolution, large-area sensor arrays is crucial for enabling soft robots to perceive and interact with their environments effectively. Future developments will focus on creating highly sensitive and biocompatible sensors that can monitor physiological parameters and respond to real-time changes in the surrounding environment. These sensors will provide comprehensive data that can be used to refine the robot's interactions, ensuring safe and effective operation in close contact with human tissues.

Finally, the vast amount of data generated by integrated sensors necessitates sophisticated processing algorithms. Machine learning and neural networks will play a pivotal role in interpreting complex sensory data, enabling real-time decision-making and adaptive control in soft robots.[236] The

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development of lightweight, low-power computational models tailored for soft robotics will enhance the autonomy and intelligence of wearable and implantable devices, allowing them to perform intricate tasks with minimal human intervention.

Embodied artificial intelligence posits that the physical structures and cognitive systems of robots should be developed together, much like how the bodies and brains of living organisms have coevolved.[5] Soft robotic systems can harness morphological computation to adapt to and interact with their environments in ways that rigid systems find challenging or impossible. By adhering to the principles of embodied artificial intelligence, soft robots enable the creation of biologically inspired artificial intelligence in methods that rigid-bodied robots cannot achieve.

8.3. Energy and Sustainability

The development of efficient, lightweight, and compact power sources is critical for the long-term operation of wearable and implantable soft robots.[236] Future research will focus on integrating energy-harvesting technologies, such as biofuel cells and flexible batteries, within the soft material framework to provide sustained power without compromising the robot's flexibility and biocompatibility. Innovations in thin-film batteries and microscale energy storage solutions will address the challenges of miniaturization and energy density, enabling soft robots to operate autonomously for extended periods.

Enhancing the energy efficiency of actuators and sensors will reduce the overall power consumption of soft robots, extending their operational lifespan and reducing the reliance on external power sources. The development of low-power actuators and the optimization of sensor networks will contribute to more sustainable and practical soft robotic systems, particularly for chronic implantable devices that require reliable, long-term functionality.

Addressing the environmental impact of soft robotics requires the development of sustainable materials that can degrade safely after their functional lifespan.[14] Researchers must innovate materials that not only perform effectively during use but also minimize waste and environmental harm upon disposal. This involves creating polymers and composites that can undergo controlled degradation processes without releasing toxic substances.

The future of wearable and implantable soft robotics is bright, with significant advancements anticipated in actuation, materials, fabrication, multimodality, intelligence, energy and sustainability. These innovations will drive the development of more adaptable, intelligent, and autonomous soft robots capable of transforming medical applications and enhancing human−robot interactions. However, realizing this potential requires overcoming substantial challenges. As the field progresses, interdisciplinary collaboration will be essential to realize the full potential of soft robotics in improving human health and quality of life.

AUTHOR INFORMATION

Corresponding Author

Wei Gao − *Andrew and Peggy Cherng Department of Medical Engineering, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125, United States;* orcid.org/0000-0002-8503-4562; Email: weigao@caltech.edu

Authors

Shukun Yin − *Andrew and Peggy Cherng Department of Medical Engineering, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125, United States;* orcid.org/0000-0002-8218-9219

Dickson R. Yao − *Andrew and Peggy Cherng Department of Medical Engineering, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125, United States*

Yu Song − *Andrew and Peggy Cherng Department of Medical Engineering, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125, United States;* orcid.org/0000-0002-4185-2256

Wenzheng Heng − *Andrew and Peggy Cherng Department of Medical Engineering, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125, United States*

Xiaotian Ma − *Andrew and Peggy Cherng Department of Medical Engineering, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125, United States;* orcid.org/0009-0000-8357-9916

Hong Han − *Andrew and Peggy Cherng Department of Medical Engineering, Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.chemrev.4c00513

Author Contributions

S.Y. and D.R.Y contributed equally to this work. CRediT: S.Y., D.R.Y., Y.S., W.H., X.M., H.H. contributed to investigation, methodology, writing-original draft, writing-review and editing. W.G. contributed to conceptualization, funding acquisition, investigation, project administration, supervision, writing-review and editing. CRediT: **Shukun Yin** conceptualization, investigation, writing - original draft, writing - review & editing; **Dickson R. Yao** conceptualization, investigation, writing - original draft, writing - review & editing; **Wenzheng Heng** investigation, writing - original draft, writing - review & editing; **Xiaotian Ma** investigation, writing - original draft, writing - review & editing; **Hong Han** investigation, writing - original draft, writing - review & editing; **Wei Gao** conceptualization, funding acquisition, investigation, writing - review & editing.

Notes

The authors declare no competing financial interest.

Biographies

Shukun Yin is currently a Ph.D. student of Medical and Electrical Engineering at the California Institute of Technology. He received his B.E. degree in Microelectronic Engineering from Wuhan University and M.S. degree in Medical Engineering from the California Institute of Technology. His research interests include soft robotics, reconfigurable structures, and wearable devices for medical and robotic applications.

Dickson R. Yao received his bachelor's degree in Engineering Physics from the University of British Columbia and his master's degree in Electrical Engineering from Columbia University. Currently, he is studying for his Ph.D. in medical engineering at the California Institute of Technology. His research interests include bioelectronic devices, medical implants, additive manufacturing, and soft robotics.

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Yu Song is currently a Presidential Assistant Professor of Biomedical Engineering at City University of Hong Kong. He received his Ph.D. at Peking University under the supervision of Prof. Haixia (Alice) Zhang and worked as a postdoctoral scholar in Prof. Wei Gao's group at Caltech. His research interests focus on bioelectronics, wearable sensors, advanced manufacturing, and digital medicine.

Wenzheng Heng received his B.S. degree in Mechatronics Engineering from Zhejiang University, Hangzhou, China, in 2020. He joined Dr. Wei Gao's research group in 2020 and is currently pursuing his Ph.D. degree in Medical Engineering at Caltech. His research interests include wearable devices for medical and robotic applications and breath monitoring devices.

Xiaotian Ma is currently a Medical Engineering Ph.D. student at the California Institute of Technology. He received his B.E. in Electronic Science and Technology from Huazhong University of Science and Technology and M.S. in Medical Engineering from the California Institute of Technology. His research interests focus on the biomedical applications of microrobots for drug delivery and precision surgery.

Hong Han is currently a Medical Engineering Ph.D. candidate at the California Institute of Technology. She received her B.S. in Chemistry at Nankai University and M.S. in Medical Engineering at the California Institute of Technology. Her current research interests include medical microrobot.

Wei Gao is currently a Professor of Medical Engineering at the California Institute of Technology. He received his Ph.D. degree in Chemical Engineering from the University of California, San Diego, in 2014. He then worked as a postdoctoral fellow in Electrical Engineering and Computer Sciences at the University of California, Berkeley, until 2017. His current research interests include flexible electronics, wearable devices, digital medicine, and micro/nanorobotics.

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ABBREVIATIONS

DEA = dielectric elastomer actuator
DIW = direct ink writing
DOF = degree of freedom
ECG = electrocardiogram
EEG = electroencephalogram
EMG = electromyography
E-skin = electronic skin
FDM = fused deposition modeling
HMI = human−machine interface
IMU = inertial measurement unit
LCE = liquid crystal elastomer
PDMS = polydimethylsiloxane
PEG = polyethylene glycol
PU = polyurethane
PVA = poly(vinyl alcohol)
sEMG = surface electromyographic
SLA = stereolithography
SLS = selective laser sintering
SMA = shape memory alloy
SMP = shape memory polymer
UV = ultraviolet

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