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Actuation for flexible and stretchable microdevices

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Flexible and stretchable microdevices incorporate highly deformable structures, facilitating precise functionality at the micro- and millimetre scale. Flexible microdevices have showcased extensive utility in the fields of biomedicine, microfluidics, and soft robotics. Actuation plays a critical role in transforming energy between different forms, ensuring the effective operation of devices. However, when it comes to actuating flexible microdevices at the small millimetre or even microscale, translating actuation mechanisms from conventional rigid large-scale devices is not straightforward. The recent development of actuation mechanisms leverages the benefits of device flexibility, particularly in transforming conventional actuation concepts into more efficient approaches for flexible devices. Despite many reviews on soft robotics, flexible electronics, and flexible microfluidics, a specific and systematic review of the actuation mechanisms for flexible and stretchable microdevices is still lacking. Therefore, the present review aims to address this gap by providing a comprehensive overview of state-of-the-art actuation mechanisms for flexible and stretchable microdevices. We elaborate on the different actuation mechanisms based on fluid pressure, electric, magnetic, mechanical, and chemical sources, thoroughly examining and comparing the structure designs, characteristics, performance, advantages, and drawbacks of these diverse actuation mechanisms. Furthermore, the review explores the pivotal role of materials and fabrication techniques in the development of flexible and stretchable microdevices. Finally, we summarise the applications of these devices in biomedicine and soft robotics and provide perspectives on current and future research.

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1. Introduction

Over the past decades, device miniaturisation, flexibility, and stretchability have received increasing attention to enhance portability and wearability, overcome dimensional constraints and functionality limitations, improve conformability on complex and curved body surfaces, and achieve long-term stability and reliability.1 These superior properties can enable broad applications of flexible and stretchable microdevices on electronic skin,2 smart fabric,3 wearable energy harvesters,4 wireless communication devices,5 emerging displays,6 etc.

Flexible and stretchable microdevices consist of highly deformable structures capable of precise micro and millimetre scale deformation. Accurate, adaptable, and versatile actuation is critical to control the device structures and fulfil the functionality of flexible microdevices.

Actuation is the principle and mechanism to translate the energy of various formats into the mechanical motion of devices or device components for specific functions and tasks.⁷ The energy can be from mechanical, pneumatic, hydraulic, electrical, thermal, magnetic, and chemical sources.8 Many actuation mechanisms have been well developed for



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conventional macroscale rigid devices and machines such as automotive, aircraft, robotics, etc.9-11 For example, direct mechanical actuation converts one type of mechanical motion into another using machine elements such as levers, pulleys, gears, and linkages in robotics.7 Pneumatic and hydraulic actuation uses the potential energy of compressed gas and liquid to tune the flight control surfaces of aeroplane wings and the motion of the aeroplane. 12 Electric actuators such as electric motors convert electrical energy into mechanical motion. Thermal actuators attached to the chevrons on the tailing edges of jet engines, change shape absorbing the thermal energy from the combusted air to improve their acoustic performance. 13,14 Magnetic actuation is used in proportional pressure control valves in automobile antiskid braking systems to control the braking force precisely.¹⁵ Chemical actuators convert chemical energy into mechanical energy by combustion that facilitates movement in petrol car engines. 16 These actuation mechanisms have achieved great success and are widely used in everyday life.

However, the actuation mechanisms for the conventional rigid and large devices cannot be straightforwardly translated to flexible microdevices on the small millimetre or even microscale. There are many limitations, such as reduced efficiency, domination of surface effects at the microscale, and manufacturability for scaling down conventional actuation concepts from macro to microdomain. 17-19 Therefore, dedicated actuation mechanisms, novel materials, and advanced fabrication techniques are under development to address these issues. 20-27 For example, it is impossible to apply conventional electromagnetic motor-based actuation for microrobots used for targeted drug therapy for minimally invasive medicine because of the limited miniaturisation of the electromagnetic motors. microactuator structures such as helical propellers made of magnetic materials have been developed to navigate microrobots through external magnetic fields.²⁸ In addition, highly complex and dynamic environments demand microdevices with high flexibility, dexterity, and efficient force transmission in minimally invasive surgeries.²⁹ Conventional materials cannot satisfy all these requirements, and advanced materials such as shape memory alloy (SMA) have been developed for highly dexterous, miniaturised flexible devices.³⁰

Flexible devices have broad applications in biomedical technology, microfluidics, and soft robotics. Wearable and implantable devices in biomedical applications require microdevices to conform to the human body for real-time diagnosis and treatments.31 Therefore, the actuator structures inside the device must be highly flexible and stretchable for comfortable attachment to the body.32 Besides, fluid manipulation at the microscale through microvalves and micropumps is facilitated by pneumatically or hydraulically deforming flexible and stretchable microstructures.33-35 Soft robotics emulates the dexterity and compliance of natural organisms, enables safe navigation in complex and dynamic environments, and minimally invasive surgery.36-38 Although there are many reviews on soft robotics, 39 flexible electronics, 40 and flexible microfluidics,34 a specific and systematic review of

the actuation mechanisms for flexible and stretchable microdevices is still lacking.

This paper aims to systematically review the state-of-art actuation mechanisms for flexible and stretchable microdevices. We first elaborate on the fundamental working principle of different actuation mechanisms based on power sources of pneumatic,⁴¹ hydraulic,³⁶ thermal,⁴² electrical,⁴³ magnetic, 44 humidity, 45 chemical, 46 mechanical, 47 etc. The structure designs, characteristics, and performance of various actuators are discussed and compared. Next, we discuss the materials and fabrication techniques for developing flexible actuators and devices. After that, we summarise several typical applications of flexible actuation, such as microscale fluid handling, tissue engineering, organ-on-a-chip, and soft robotics (Fig. 1). Finally, we discuss current challenges and provide future perspectives on the actuation of flexible and stretchable microdevices.

2. Actuation principles

Many actuation mechanisms have been developed based on various energy sources such as fluidic pressure, electric, thermal, magnetic, chemical, etc. This chapter aims to familiarise the readers with the general actuation concepts, working principles, typical design features, and actuation performance. In addition, this section emphasises the relevance of these actuation mechanisms for flexible and stretchable devices, especially from recently reported works, but does not exhaustively discuss all the actuation mechanisms.

2.1. Fluid-driven actuation

Fluid-driven actuation relies on the deformation or displacement of one or more boundaries of an enclosed chamber due to the fluid pressure. 48 Compressed, 49 vacuumed, 50 or a combination of compressed and vacuumed^{51,52} fluids can be the driving source for the deformation or displacement of the flexible boundaries. Both liquid and gas can serve as the working mediums. 36,53-55 Fluid-driven actuation can be further classified as hydraulic and pneumatic actuation. In the following section, we will briefly describe the typical design of hydraulic and pneumatic actuators and discuss their characteristics and performance. Table 1 summarises and compares parameters related to the design, fabrication and performance of some reported fluid-driven actuators.

Pneumatic microactuators have a flexible structure that can deform under pressure or vacuum, Fig. 2A. The flexible element can be a flat membrane made of a flexible material, 56,57 or a flexible chamber.⁵⁸ These flexible structures have been widely used in pneumatic micropumps^{51,53,54,59–62} microvalves. 52,56-58,63,64 The flexible membranes used in microvalves and micropumps can be circular,⁵² rectangular,⁶⁴ or any other shape, depending on the enclosed microchannels. Also, the cross-sectional shape of the membrane is a decisive factor in accurately dispensing small fluid volumes through pneumatic micropumps. A flat, membrane creates a considerable dead volume, reducing the pumping efficiency. In contrast, arched

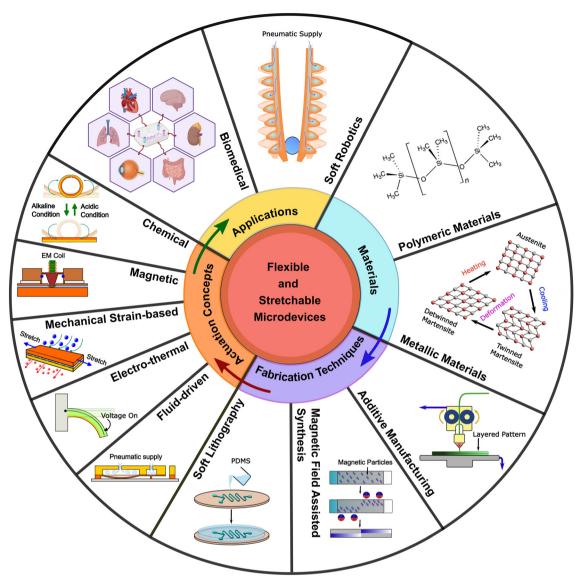


Fig. 1 A schematic overview of actuation mechanisms, device materials, fabrication techniques, and applications for flexible and stretchable microdevices.

membranes⁶⁰ can reduce the dead volume and improve the pumping efficiency. However, small clearances⁵⁶ between the flexible membrane and the sealing surface are also a solution for enhancing pumping efficiency. Furthermore, the flexible structure not only serves as a valve to fully close a microchannel in microvalves but also acts as a regulator by partially closing the microchannel to tune its fluidic resistance.⁶⁴

The performance of pneumatic actuators in micropumps and microvalves depends on many parameters. The thickness of the flexible membrane is the key parameter. For the same surface area, a thicker membrane requires a higher pressure to achieve valving and pumping functions. Next, the pumping rate in a micropump is greatly affected by parameters such as the membrane elasticity, the time taken to release the pressurised air, the applied negative pressure. Moreover, the flow rate also depends on the pumping frequency. The pumping frequencies reported in

the literature range from 1 to 40 Hz, and the flow rate of micropumps is pL min⁻¹ to mL min⁻¹.^{51,53,54,59-62} Theoretically, a high pumping frequency can obtain a higher flow rate.⁶⁵ Nevertheless, this is only true for the frequency below the first resonant frequency of the pumping membrane. The flow rate may decrease monotonically with increasing frequency after reaching a peak.⁵⁴ Depending on the dynamic behaviour of the system, pumping can either be unidirectional or bi-directional.⁶⁶

Hydraulic microactuators use flexible structures that deform under pressurised liquid to facilitate actuation. These flexible elements include membranes,⁶⁷ flexible chamber structures like bellows,⁶⁸ soft tubular structures,³⁶ Fig. 2B, or artificial tentacles.⁶⁹ These flexible elements have been used in transportation units,⁵⁵ micropumps,³⁶ and microvalves.⁶⁷ In addition, some bio-inspired flexible actuators^{68–70} were also designed based on this actuation principle. For a given

Table 1 Fluid-driven actuation principles

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Actuation	Actuator type	Dimensions	Material(s)	Fabrication method(s)	Pressure input (kPa)	Mode of actuation	Max. Flow rate (μL min ⁻¹)	Force	Application(s)	Ref.
Pneumatic	Micro pumps	D – 2 mm T – 200 μm	PMMA, PDMS	Micromachining (pneumatic and fluidic layers) with oxygen plasma bonding	300 (air)	Peristaltic	1633	NA	Blood plasma extraction	53
		D – 5.2 mm T – 250 μm		Soft lithography with oxygen plasma bonding	(-)39.9 (vacuum), 13.8 (air)	Reciprocating	360	NA	Detection of NT-proBNP biomarker	59
		D – 2 mm T – 25 μm	PMMA, TPU	Laser machining with thermal fusion bonding	70 (N ₂)	Peristaltic	3.5	NA	Cell culture	54
		L – 200 μm W – 200 μm T – 20 μm	Glass, PDMS	Soft lithography with oxygen plasma bonding	100 (N ₂)	Peristaltic	0.026	NA	Heart/cancer on a chip	61
		T – 250 μm	Glass, PDMS	Soft lithography with oxygen plasma bonding	(-)40 (vacuum), 6.8 (air)	Reciprocating	1999	NA	Aptamer identification	62
	Micro valves	L – 1.5 mm W – 500 μm T – 150 μm		Soft lithography with oxygen plasma bonding	172.4 (air), Vacuum	Reciprocating (on-off)	NA	NA	Aptamer-affinity separation	52
		L – 200 μm W – 50 μm T – 10 μm	Glass, PDMS	Soft lithography with oxygen plasma bonding	~71 (air)	Reciprocating (on-off)	NA	NA	Single-cell sorting	63
		L - 10 mm W - 5 mm	PDMS	3D printing and sacrificial manufacturing technique	15 (air)	Simultaneous squeez/release (on-off)	NA	NA	Analysis of enzyme kinetics	58
rr de l'		L – 300 μm W – 50 μm T – 20 μm	Glass, PDMS	Soft lithography with oxygen plasma bonding	200 (air)	Reciprocating (flow controlling)	1.3	NA	Generation of dynamic concentration of diffusible molecules	64
Hydraulic	Micro pumps	L - 5 mm W - 2 mm $T - 120 \mu\text{m}$	PDMS	PDMS replica moulding with oxygen plasma bonding	(Ionic liquid)	Peristaltic	5	NA	Compact fluid delivery systems	67
	Bellows	$D - 50 \mu m$ $T - 1 \mu m$ $V - 4.9 \times 10^{-4} \text{ mm}^3$	IP-DIP resin	2PP 3D printing	31 (uncured IP-DIP)	Compression	NA	200–300 μN	Soft robotics	68
	Muscle	L – 235 mm D – 3.18 mm	TPU, Ecoflex™, yarn	3D printing, soft moulding	$\Delta P = -1500$ (water)	Expansion and contraction	174 × 10 ³	34.2 N	Robotics and medical	36

L – length; W – width; T – thickness; D – diameter; V – volume.

design, the applied liquid pressure is the main parameter for the output displacement. Cheng et al. Showed that increasing the injected water volume from 0.7 to 1.25 mL in their hydraulic actuator caused a curvature change from 18 to 42.6 $\rm m^{-1}$. The working liquid of hydraulic microactuators is generally supplied externally. Still, there are instances

where the working liquid is already enclosed in the actuation chamber during the fabrication process, eliminating the requirement for external sources. 68

Hydraulic actuators have great potential in microscale applications, 71 such as transmitting high forces and creating three-dimensional motions. 68 Hydraulic actuation also

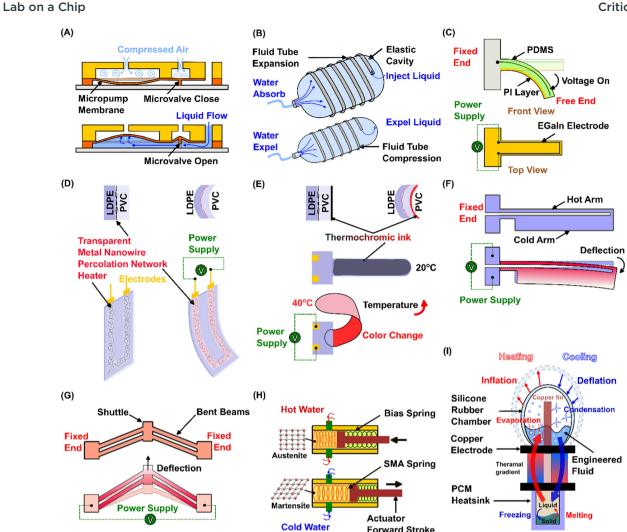


Fig. 2 Actuation schemes. (A) Microfluidic pumps and valves operated by compressed air and vacuum.⁵¹ (B) A micropump works by expansion and contraction of a tubular structure and bi-directional fluid flow.³⁶ (C) A non-metallic bi-morph actuator embedded with an eutectic Galn heater.⁷² (D) An anisotropic transparent shape morphing actuator consists of transparent silver nanowire (AgNW) percolation network as the heating element.⁷³ (E) A color-changing electro-thermal actuator consists of thermochromic pigments coated on the passive layer.⁷⁴ (F) A hot and cold arm electro-thermal actuator deflects under an applied electric voltage. (G) A bent-beam electro-thermal actuator diverts under an applied voltage. (H) A shape memory alloy (SMA) linear actuator retracts and extends under the temperature-induced phase change of spring-type element.⁷⁵ (I) A soft-thermo-pneumatic actuating module consists of thermoelectric element facilitating actuation cycles.⁷⁶

provides more portability than pneumatic actuation in some environments.⁶⁸ Because the working liquid of the hydraulic actuators can be stored within the actuator structures eliminating external reservoirs and making actuators more portable. Besides, the working liquid and the materials of the flexible structures in hydraulic actuators play important roles in their performance. For example, the working liquid for self-containing hydraulic microactuators must be carefully selected to minimise viscosity variations, evaporation, and hygroscopic nature that would affect long-term performance. Speller et al.67 developed a self-contained hydraulicallyactuated microfluidic (SCHAM) device that uses 1-methyl-3butylimidizaolium-based ionic liquids as the working liquid. The team demonstrated that the ionic liquid-based SCHAM performs better than the water-based counterparts because of less change in fluidic mass due to evaporation. In addition,

the viscosity of the working fluid is a significant factor because higher viscosities cause slow response and hysteresis. For example, a fully enclosed hydraulic microactuator that uses uncured IP-DIP (Nanoscribe GmbH) (dynamic viscosity, $\mu = 2420$ mPa s) resins as the working fluid shows less efficient and slower response than IP-PDMS (Nanoscribe GmbH) ($\mu = 2$ mPa s) resins.⁶⁸

In summary, fluid-driven actuation has the advantages of reliability, fast operation, scalability, and contamination-free operation. However, limitations exist, such as the need for external pressure or vacuum sources and leakproof designs, making fluid-driven actuators more bulky than other schemes. Compared to pneumatic actuation, hydraulic actuation provides higher power density with promising performance in the microscale, ⁶⁸ particularly in soft robotics. Overall, the low compressibility of liquids compared to gases

7

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Ref. 83

Table 2 Electro-thermal actuation principles

72

85

makes hydraulic actuation more precise than its pneumatic counterparts.

2.2. Electro-thermal actuation

Electro-thermal actuators operate based on Joule heating and the associated thermal effect in actuator materials. The temperature increase causes the materials to deform due to thermal expansion or phase change, performing actuation tasks. Therefore, electro-thermal actuation mainly consists of thermal expansion and phase change mechanisms. Structure designs based on the thermal expansion mechanism include bimorph,⁷⁷ hot and cold arms,⁷⁸ and bent-beam.⁷⁹ The phase change mechanism has been applied in smart material actuation, 75,80 and thermo-pneumatic actuation. 81 Table 2 summarises and compares critical parameters (e.g., maximum deformation, temperature, and voltage), fabrication methods, and applications of some reported electro-thermal actuators.

Thermal expansion-based actuators undergo deformation according to temperature changes. The following equation describes the length change of material under increasing temperatures,

$$L - L_0 = L_0 \alpha \Delta T \tag{1}$$

where L and L_0 are the final and initial lengths of the materials, and α and ΔT are the coefficient of thermal expansion (CTE) of the material and the temperature difference, respectively. Applying an electric current across the material causes joule heating and increases in the temperature. The temperature increase results in the expansion of the materials.

Bimorph microactuators consist of two layers of materials with different CTEs bonded together, Fig. 2C. The temperature increase results in thermal expansion in both material layers, but the mismatched thermal expansion coefficients cause the deflection to be orders of magnitude higher than the intrinsic expansion. According to eqn (1), parameters such as L_0 and ΔT are the same for the two layers, but the layer with higher CTE elongates more than the layer with lower CTE. Since the two layers are bonded, the bimorph structure bends toward the layer with the lowest CTE,82 resulting in actuation stroke and force. Bi-morph actuators are classified into in-plane, out-of-plane, 72,83,84 twodimensional (2D) spiral,77 and three-dimensional (3D) spiral⁸⁵ according to their spatial motion. The most recent advancements of bi-morph actuators are the transparent electro-thermal,86 Fig. 2D, and color-changing electrothermal,74 Fig. 2E, as well as actuators that are categorised based on the visual appearance. The transparent electrothermal actuators consist of transparent thermoresponsive layers and a heating layer. This brings the advantage of optical transparency to the actuators. Ko et al. 86 reported a shape-morphing transparent electro-thermal actuator made of low-density polyethylene (LDPE) and polyvinyl chloride (PVC) as thermoresponsive layers and highly transparent

assembly, human-soft actuator interaction, artificial muscles. Reconfigurable 3D Bionic soft robots Soft microrobots Application(s) Biomedicine, microrobots actuator weight 11.2 mN Deformation/speed Force NA Linear – 2.96 mm s⁻¹ Angular – 116° Angular – 10° Angular -1080° Angular -3D rotary-spiral 2D rotary-spiral Out-of-plane Out-of-plane actuation Mode of 119 62 Voltage (V) 30 MEMS manufacturing Direct laser scanning 3D printing (EGaIn), spin coating (PDMS) TPP 4D printing, liquid metal microfluidic injection (LIG on PI), spin coating (PDMS) Fabrication method(s) (IP-S)-Galinstan-(IP-S) PDMS-EGaIn-PI PI-LIG-PDMS NiTiNOL-Al Material(s) nanofilms A - (IP-S: 2050Galinstan: 2500) μm^2 T – ratio: 10:1 (PDMS: PI) $L - \sim 800 \; \mu \text{m}$ Dimensions *T* – PDMS: 200 μm PI: 40 μm, 50 μm \sim 1500 μm Z/W: 8:1 Bi-morph Actuator type Actuation expansion Thermal

Actuation	Actuator type	Dimensions	Material(s)	Fabrication method (s)	Voltage (V)	Temp.	Mode of actuation	Max. Deformation/speed	Force	Application(s)	Ref.
		L - 10-20 mm T - PDMS: 50-150 µm Graphene: 25 µm	Graphene– PDMS	Spin coating (PDMS), adhesion (graphene on PDMS)	0-10 pulses	86	Out-of-plane	Linear – 6.89 mm s ⁻¹	~0.12 mN	MEMS, artificial muscles, switches	84
	Hot-cold arm	Hot arm $L-$ 1000 μ m Cold arm $L-$ 850 μ m Hot arm $W-$ 10 μ m Cold arm $W-$ 50 μ m $T-$ 50 μ m	Silicon-on- insulator (SOI)	Integrated circuit fabrication process	NA	278	In-plane	9.45 µm	~0.14 mN	~0.14 mN Microgripper	96
	Bent beam	Primary beam $W-6 \mu m$ Secondary beam $W-6.6 \mu m$ $T-SOI$: 25 μm	Silicon-on- insulator (SOI)	SOIMUMPs ^{TM26} micromachining	ıo	86.4	In-plane	26.3 µm	NA	Human RBC characterisation	103
		Beam L – 303 μ m Beam W – 20 μ m T – Al: 2 μ m Angle: 2°	Aluminum	Surface micromachining	0-1	201	In-plane	11 µm	NA	Micro-object manipulation	79
		Beam L – 3100 μ m Beam W – 50 μ m T – SOI: 125 μ m Angle: 1 $^{\circ}$	Silicon-on- insulator (SOI)-Au	Double-sided etching process with an inductively coupled plasma (ICP) technique	4	NA	In-plane	80.75 µm	NA	Actuators in miniature mechatronic systems	101
Phase change	Thermo- pneumatic	Bellows V – 26.4 mm ³	PDMS	3D printed soluble melding technique	0.55	492	Out-of-plane	2.184 mm	90.2 mN	Soft micro- robots	81
	SMM	PE flat wire $A - 0.05 \text{ mm}^2$ SME wire $D - 100 \text{ \mum}$	NiTiNOL	SMM PE flat wire NiTiNOL Commercially SMA $A=0.05~\mathrm{mm}^2$ wires combined SME wire $D=0.05~\mathrm{mm}^2$ with 3D-printed 100 $\mathrm{\mu m}$ structures	5.4	73	Out-of-plane	0.8 mm	20 kPa holding pressure	Microvalves, micropumps	80

Table 2 (continued)

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silver nanowire (AgNW) as the resistive heating element. This actuator showed a bending curvature >2.5 cm⁻¹ at 40 °C. In addition, the team also applied thermochromic pigments on the surface of the transparent actuator structure that allows intuitive color changes depending on the temperature, resulting in color change electro-thermal actuators.⁷⁴ The performance of bi-morph actuators can be improved by altering the thickness ratio of the material layers. Ultra-thin structures83,87 improve the dynamic characteristics of the microactuators because of fast heating and cooling rates due to the high surface-to-volume ratio. A recent study showed that a bi-morph electro-thermal microactuator consisting of layers with thicknesses from 400 to 500 nm could undergo precise and rapid actuation (up to 100 Hz) within a temperature bandwidth of less than 52 °C.83 However, combining materials such as LDPE and PVC that show high directional (anisotropic) and isotropic thermomechanical behaviours respectively provides bimorph actuators with large CTE mismatch, enabling large deformations.86 Also, liquid metals such as eutectic GaIn (EGaIn),72 and Galinstan⁸⁵ as the conductive paths can improve resistance stability and rapid heating of the bi-layers. Furthermore, the transparent AgNW percolation networks⁸⁶ electrothermal actuators improve the transparency of the actuators while serving as the conductive path. Laser-induced graphene (LIG) used for the conductive layers of a bi-morph actuator can serve as a sensor, where the deformation of LIG causes a resistance change.88 Compared to other thermal expansion-based actuator types, bi-morph actuators can produce precise and fast actuation tasks in the microscale.

The pseudo-bimorph thermal actuator, 89 also known as a hot and cold arm or folded beam actuator, consists of two arms connected in a series, Fig. 2F. In this configuration, both arms are made of the same material. Differences in parameters such as length, 90 cross-section, 91 and doping levels⁹² of the two arms lead to a mismatch in resistance, causing an asymmetrical temperature distribution between the hot and cold arms. As a result, dissimilar expansion causes the connected beams to bend toward the cold arm. Multiple hot arms were used to improve the performance of this actuator. 93 Structural design optimisation could improve the bending displacement of a pseudo-bi-morph actuator.94 This type of actuator can also provide both in-plane94 and out-of-plane95 motions. The actuation performance of pseudo-bi-morph actuators primarily depends on the temperature difference between the hot and cold arms. A higher temperature difference can be achieved by removing the excess heat generated at the hot arm. Zhang et al. 96 used a fin structure connected to the hot arm in their microgripper design, improving the excess heat dissipation. This results in increased temperature difference, providing higher displacement of the actuator.

The V-shape or chevron-type actuators, also known as bent-beam actuators,97 work based on linear thermal expansion similar to the above actuators. A bent-beam actuator has a planar configuration where two planar arms are anchored at opposite ends, and the other ends are connected with a common point known as a shuttle, Fig. 2G. The In-plane displacement of the bent-beam actuator can be obtained by a coupled thermo-mechanical mechanism. 98,99 Geometrical parameters, such as the initial beam inclinations, lengths, and the location of the fixed ends of the beams, determine the motion of the shuttle. 100 Higher inclination angles cause adverse effects on the effective displacements. Therefore, inclination angles should be as low as possible to achieve higher in-plane displacements. For instance, Dai et al. 101 chose 10 inclination angles for the designed bent-beam actuator and achieved 80.75 µm in-plane displacement with a 4 V input voltage. The configurations of bent-beam actuators include beam-array, 102 cascaded bentbeam, 103 Z-shape beam, 100 and out-of-plane bent-beam. 104 Moreover, bent-beam type actuators can be improved by carefully selecting the number of beams to provide higher displacements while improving the mechanical performance. 103 The main reason for the improved performance is the close arrangement of beams that isolate the actuator from its surroundings, resulting in a higher operating temperature. The bent-beam actuator configuration is more robust than other electro-thermal actuators.

Electro-thermal actuators based on phase change convert input energy to work through the change in the material phase. 105 Once mechanically deformed, smart materials such as shape memory alloys change crystal structure and return to undeformed shape (shape memory effect) upon altering the temperature,⁷⁵ Fig. 2H. This phenomenon is known as solid-solid phase transformation or crystallographic transformation.80 In addition, thermo-pneumatic actuation uses the expansion of gas,81 or a change in the volume of liquid or solid in a confined space under heat input. 106 The phase change happens with liquid evaporating into gas^{76,107} or solid melting into liquid, resulting in considerable volume expansion. This phenomenon increases pressure to deflect the flexible walls of the confined space and do external work on the environment. The actuating flexible structures can be in the form of membranes, 108 inflatable chambers, 76,107 or bellows,81 where the surrounding walls deflect to create the actuation. Yoon et al. 76 reported a phase change soft actuator capable of bi-directional operation by thermoelectric heating and cooling. They used Novec™ 7100 Engineered Fluid (Sigma-Aldrich, SHH0002) with a boiling point of 61 °C as the working medium inside the inflatable chamber. Thermoelectric heating changed the phase of the fluid from liquid to gas, which enhances the pressure and induces inflation. In contrast, thermoelectric cooling changes the phase of the evaporated gas to liquid, decreasing the pressure and resulting in deflation, Fig. 2I.

2.3. Magnetic actuation

Magnetic actuators use the potential energy of the magnetic fields to produce mechanical motion. 109 The working principles of magnetic actuators are based on permanent magnets, 110

electromagnets, 111,112 magnetorheological fluid, 113 magnetic hydrogel,⁴⁴ magnetic shape memory materials,¹¹⁴ magnetostriction. 115 Among these schemes, the straightforward is utilising attractive and repulsive forces between permanent magnets. On the other hand, the force generated on a ferromagnetic core by current-carrying coils or a current-carrying conductor in a magnetic field is used in electromagnetic actuation. Moreover, magnetorheological fluids are magnetic particle suspensions, and their fluid properties depend on the magnetic field. Varying a magnetic field causes magnetic shape memory materials to shift between different material structures and enable actuation. Magnetostrictive materials are ferromagnetic and undergo strains when subjected to magnetic fields. Table 3 summarises and compares parameters related to the design, fabrication and performance of some reported magnetic actuators.

Magnetic microactuators also utilise membranes 111,112,116 and flexible structures 113,117,118 for actuation purposes. generated by and repulsive forces electromagnetic coil deflect the flexible membranes attached to permanent magnets. 112 For example, Liu et al. 116 developed a normally closed microvalve using an electromagnetic coil surrounding a ferromagnetic core, Fig. 3A. Initially, the flexible membrane attached to the core deflects under an extension of an external spring and closes the microchannel. The valve opens by recovering the membrane deflection as the electromagnet is energised to contract the external spring. In this work, the membrane thickness is an important parameter that dictates the magnetic force required to deflect the membrane for the actuation.

Liquid metal microfluidic networks embedded in elastomer matrix membranes can be used for unique actuation tasks where Lorentz forces can locally deform the membranes. Lorentz forces act on the liquid metal channel as the current passes through it, locally deforming the membrane, Fig. 3B. The electric current and magnetic flux density determine the magnitude of the Lorentz force and, in turn, the membrane deflection. The performance of flexible actuators developed by embedding liquid metal layers in elastomeric membranes significantly depends on the viscoelastic response of the membrane. In addition, the time taken to recover the deformation of flexible membranes is another critical factor in the design of flexible membrane-based electromagnetic actuators. Life

Magnetorheological (MR) fluid changes its apparent viscosity when exposed to a magnetic field. This phenomenon happens because the magnetic microparticle suspended in MR fluid aligns with the magnetic flux lines. Hence, MR fluid-based flexible actuators can be locally controlled by exposing a specific area to a magnetic field. McDonald *et al.*¹¹³ developed a soft actuator integrating MR fluid valves, Fig. 3C. Here, the MR fluid circulates through the flexible actuator structure using an external pressure source. As a magnetic field is applied, magnetic particles in the MR fluid align with the magnetic flux lines and induce a local increase in viscosity. This phenomenon creates a valving action and causes a pressure increase between

the source and the location where the magnetic field is applied, consequently resulting in the deflection of the actuator structure. Electromagnets can be used to control the magnitude of the field, which in turn controls the viscosity of the magnetorheological fluid.

Magnetic nanoparticles suspended elastomeric soft actuators show promising performance for localised and distinctive deformation. The stiffness of the flexible structures used for the soft actuators reduces under magnetic fields while increasing the maximum actuator force. Lee $et\ al.^{117}$ revealed that Fe $_3O_4$ suspended PDMS tubular structure showed a 3500% improvement in blocking force while reducing the stiffness of the elastomeric matrix by 85% when exposed to a magnetic field.

Magnetic hydrogels are thermosensitive polymers embedded with magnetic nanoparticles. 122 Embedding functional additives such as magnetic nanoparticles enable the non-contact operation of hydrogel-based soft actuators. Magnetic hydrogels undergo a magnetothermal effect where the magnetic nanoparticles dissipate heat to the thermosensitive polymer network. Heat dissipation happens based on two mechanisms. When the magnetic particles rotate while a fixed magnetic moment is applied along the crystalline axes (Brownian rotation), heat generation occurs due to the shear stress in the surrounding fluid. In contrast, if the magnetic particle remains stationary while the magnetic moment rotates (Néel rotation), the heat generation occurs due to the rearrangement of atomic dipole moments within the particle. 123 So, the magnetisation of magnetic hydrogels is low under a static magnetic field. The improved magnetisation of the magnetic hydrogels can be obtained under an alternating magnetic field (AMF) whose amplitude time. 118 Also, adding more magnetic varies with nanoparticles to the hydrogel would result in higher magnetisation, and a higher magnetothermal effect causes the thermosensitive polymer network to shrink. Tang et al. 118 developed elastomer-magnetic hydrogel bilayer elements to create shape-morphing structures under AMFs. Strong adhesion between magnetic hydrogel layers and the elastomer is crucial for the bending performance of the flexible structure, Fig. 3D.

Magnetic shape memory materials (MSMM) can be used to develop micropumps where the MSMM material serves simultaneously as valves, channels, and pumps. A diametrically magnetised permanent magnet was rotated to create an identical magnetic field along the cross-section of the MSMM element, where the shrinkage of the material allowed the fluid to move from the inlet to the outlet, Fig. 3E. The shrinkage of the MSMM happens due to the magnetic field, and it will enable fluid to enter through the inlet. Then fluid moves along the channel because of the shrinkages created by the movement of the magnetic field. This method is capable of contact-free pumping of various liquids, including air, and is self-priming. The MSMM micropump developed by Smith *et al.* 119 has a 6 μm thick Ni–Mn–Ga element that creates 30 μm shrinkage under the effect of a

Actuation	Actuator type	Dimensions	Material(s)	Fabrication method(s)	Magnetic field (T)	Mode of actuation	Deformation Force	Force	Application(s)	Ref.
Electromagnetic	Shape morphing surfaces	Ribbon: L – ~48 mm W – 900 μ m T – 400 μ m Membrane: T – 5 μ m	Dragon Skin TM , Ecoflex TM , EGaIn	Laser cutting, soft lithography	~0.2	Out-of-plane reversible deformation	2.4-9.6 mm	per ribbon	Tunable optics, flexible/stretchable electronics, soft machines, biomimetic skins	111
	Micro pumps	Membrane: D – 5 mm T – 400 μ m Magnet: D – 700 μ m T – 1.4 mm	PDMS, stainless steel	PDMS casting, spin coating, thermal bonding, µWEDM	0.11	Reciprocating	шт 8	NA	Fluid handling	112
MR fluid-based	Soft structures	Structure: L – \sim 4 cm W – \sim 1.5 cm T – \sim 3.5 cm Magnet: D – 12.5 mm T – 12.5 mm	Dragon Skin TM , Ecoflex TM , acrylic sheets, silicone tubes, MR fluid	Laser cutting, spin coating	0.02	Out-of-plane flexion and extension	NA	NA	Medical robotics	113
Magnetic hydrogel-based	Shape morphing structures	L - 20 mm W - 2 mm T - 2.05 - 2.55 mm	Magnetic PNIPAm, very-high bond tapes	Laser cutting, adhesive bonding	0.15@187 kHz	Flexion and extension	0.23 mm ⁻¹	NA	Robotics, biomedicine	118
MSMM	Micro pumps	Element: $L-10$ mm $W-2.5$ mm $T-1$ mm $T-1$ mm Pump: $L-17.5$ mm $W-10$ mm $T-4.7$ mm $T-4.7$ mm	Ni–Mn–Ga MSMM, polycarbonate, PDMS	Wire sawing, electropolishing, mechanical polishing, curing	0.5@135 Hz	MSMM twinning and recovery	NA	NA	Lab-on-a-chip, point-of-care diagnostics	114,

L – length; W – width; T – thickness; D – diameter.

Table 3 Magnetic actuation principles

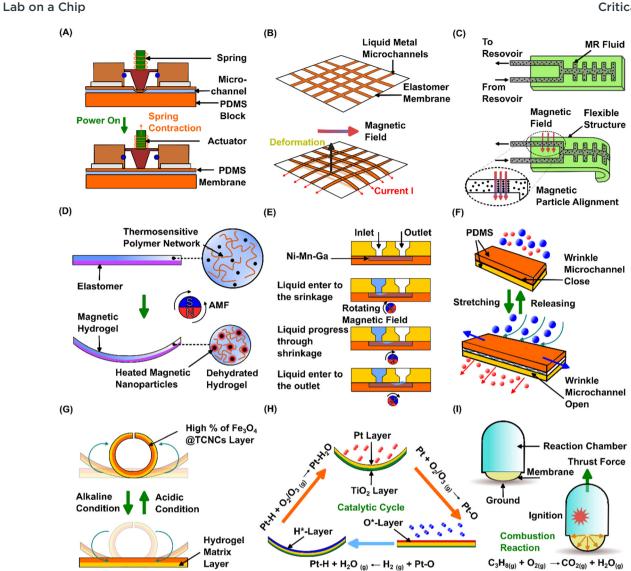


Fig. 3 Further actuation schemes. (A) Normally-closed electromagnetic (EM) microvalve opens by the electromagnetic actuator that works against the spring force. (B) A Lorentz force-based shape morphing structure shows arbitrary shapes under selective current supply through liquid metal conductors. (C) A magnetorheological (MR) fluid-based flexible actuator deforms under blockage of the fluid flow by magnetic particles that concentrated at the locally applied magnetic field. (D) Shape morphing of hydrogel in an alternating magnetic field (AMF). (E) Magnetic shape memory alloy micropump operates under rotating magnetic field. (F) Strain-tuneable wrinkle microvalve for selective transfer of particles by stretching. (G) Asymmetric hydrogel actuators deflect under variation of pH around the actuator structure. (H) Surface-catalysed chemical actuator operates under moisture absorption and undergoes catalytic reaction. (I) Chemical combustion-driven soft actuator.

500 mT magnetic field. The micropump could deliver a water volume of 110 \pm 15 nL per pumping cycle. The pumping characteristics depend on the surface effects and viscosity of liquids.

2.4. Mechanical strain-based actuation

Mechanical strain-based actuation utilises mechanical forces to bend,¹²⁵ twist,¹²⁶ and stretch⁴⁷ microdevices to achieve specific functions. Actuation is entirely based on stretching⁴⁷ or combining electric fields,^{127–130} magnetic fields,¹³¹ and temperature sources^{132,133} to generate displacements and forces. However, mechanical deformation in initiating and supporting actuation cycles is significant in this actuation

method. Table 4 summarises and compares parameters related to the design, fabrication and performance of some reported mechanical strain-based actuators.

Actuators based on mechanical strain consist of structures such as layers, ⁴⁷ flat wires, ⁸⁰ capsules, ¹³³ membranes, ¹³⁴ and thin films. ^{132,135} This actuation scheme is a promising strategy in microfluidics to control fluid flow, serving as microvalves, ^{47,80} and micropumps. ¹³³ For example, Kotb *et al.* ¹³³ developed a micropump that integrates all components in a self-contained package to reduce the overall footprint, defined as a capsule micropump. The actuation happens by the temperature-induced strain of the shape memory alloy (SMA), and the recovery motion occurs through the elastic forces of the capsule material acting as a spring.

Ref.	47 ne	127	128	133
Application(s)	Cell-sorting, fluidic logic gates, biomedicine	Morphable 3D capacitors for LC-radio frequency circuits	Mechanobiology, energy harvesting	Drug delivery
Force	NA	NA	NA	NA
Deformation/speed Force Application(s)	Crack: $\Delta W = 18 \mu \text{m}$ $\Delta H = -2 \mu \text{m}$	Ribbon mesostructure: ~6 mm	NA	5.6 mm 11 mm s ⁻¹
Mode of actuation	Stretching and releasing	Out-of-plane Ribbon mesostr ~6 mm	Out-of-plane NA	Linear
Stress/strain	0–75%	Intermidiate pre-strain: 150% to 230% Nominal strain: $\sim 80\%$	Maximum strain: PZT: 0.3% Electrode: 1.2% SU-8: 3.5%	NA
Fabrication method(s)	Stretch-assisted micro irregularity formation, UV exposure	Spin coating and curing, femtosecond laser cutting, metal deposition	Sol-gel techniques, photolithography, and etching, electron beam evaporation, transfer printing	Moulding, coiling, 3D printing
Material(s)	PDMS	Celular graphene, PI, PET, Au, very- high bond tapes	SU-8, PZT, Ti/Pt, Cr/Au, Pl, Dragon Skin™	NiTi wires, Ecoflex [™]
Dimensions Material(s)	L-3 cm $W-1.2$ cm $T-1.2$ mm	$L - 180 \mu m$ to 6 mm $T - 8 \mu m$ to 50 μm	PZT: <i>L</i> – 200 mm <i>W</i> – 140 mm <i>T</i> – 500 nm	NiTi wire: $D-0.25$ to 0.5 mm Pump: $V-424.7 \mu L$
Actuator type	Crack and wrinkle microvalves	Dielectric elastomer (DE) actuator	Piezoelectric PZF: L – (PZT) actuator 200 mm W – 140 mm T – 500 r	Micropumps
Actuation	Mechanical stretch Grack and wrinkle microvalve	Buckling-guided Dielectric electro-mechanical elastomer (DE) actus		Smart material

L – length; W – width; T – thickness; D – diameter; H – height; V – volume.

The micropump can produce large strokes as the actuation follows the direction of the highest mechanical compliance with almost zero dead volume. Apart from the above concepts, mechanical instabilities or micro-patterns such as microcracks and micro wrinkles have been utilised as microvalves, ⁴⁷ Fig. 3F. These microvalves open and close by stretching and releasing. Liu *et al.* ⁴⁷ demonstrated that the size of the triangular microcracks shrank from 2.8 μ m in width and 5.8 μ m in height to 20.8 μ m and 3.8 μ m, respectively, when a 75% tensile strain was applied. As the applied strain exceeds 100%, the microvalves tend to break. The flow rate through the crack microvalve monotonically increased from 0.04 mm³ s⁻¹ to 0.34 mm³ s⁻¹ as the tensile strain rose from 25% to 100%.

Mechanical strain-based schemes can also create threedimensional (3D) actuation. 127,128 3D actuation is achieved by a pre-stretched elastomer substrate. In these designs, the 2D precursor structures are coated on a pre-stretched elastomer substrate. 127,128 Releasing the pre-stretched condition coordinated bucking-guided enables transformation, resulting in 3D structures. After forming the 3D structures, active materials such as lead zirconate titanate (PZT), 128 SMA 80,133 or elastomer materials with inherent dielectric properties 127,136 could actuate these highly flexible structures. The out-of-plane actuation performance and output force of strain-based schemes can be improved by introducing hybrid materials with enhanced dielectric and mechanical properties.¹³⁷

In addition, multilayer stacked structures 138 can improve the force output to achieve bi-directional actuation. Dielectric elastomer (DE) and PZT materials are promising candidates for strain-based actuators. In DE materials, coordinated deformations, such as translation, rotation, bending, and twisting, depend on the selected bonding locations of DE and strain-limiting fibres in the dielectric substrate. Strain-limiting fibres can constrain the displacements along desired linear or radial directions. 127 The overall performance of the DE actuators (DEAs) depends on the stiffness of the material, the dielectric constant, and the breakdown voltage. In contrast, PZT materials bonded with elastomeric substrates cannot achieve the large deformation of DEAs, but generate higher mechanical forces. 128 Meanwhile, shape memory alloy (SMA) actuators can provide out-of-plane forces, 80 but their response speed is generally slower than others. Also, the resonant frequency of the SMA actuators influences the actuation speed and deformations. Song et al. 126 studied a bending actuator by changing the design of the reinforcement structure embedded in the actuator. The reinforcement structures are made of 38-µm diameter SMA wires embedded along the length of the actuator above and below an acrylonitrile butadiene styrene reinforcement structure consisting of 250 µm thick layers in different patterns located at the centre. The team found that the reinforcement structure led to a change in the natural and actuation frequencies of the actuator.

2.5. Chemical actuation

Chemical actuation refers to the use of materials that can undergo controlled strokes and forces in response to chemical stimulations, such as pH change, surface catalysis, 46 moisture gradient, 139,140 organic solvent stimulations, 141 oscillatory Belousov-Zhabotinsky chemical reaction in hydrogel, 142 and chemical combustion. 143 Chemical stimulation through pH change can actuate materials that exhibit reversible deformations under alkaline and acidic solutions, 120 Fig. 3G. Surface-catalysed chemical actuators utilise catalyst-treated surfaces to speed up the reactions and generate surface stresses, 46 Fig. 3H. Moreover, moisture gradients 45,144,145 can achieve reversible actuation depending on the relative humidity of the environment. The deflection follows the absorption and desorption of water molecules, enabling moisture-driven microactuation. In addition, organic solvents in the form of liquids and vapor 141 can be used to stimulate materials that undergo swelling on the absorption and recover on desorption of the solvent molecules. The self-oscillatory Belousov-Zhabotinsky chemical reaction of synthetic polymer gels can convert chemical energy to useful mechanical work. This chemical reaction causes a large volume change. Aishan et al. 142 developed a micropump based on this actuating scheme where a PDMS membrane deflects by the large volume change of the polymer gel during the oscillatory Belousov-Zhabotinsky reaction. This pump generates a 0.28 µL min⁻¹ net flow rate. Chemical combustion-based actuation uses combustion reactions to generate energy that can be effectively used in actuation tasks, 146,147 Fig. 3I. However, quantifying actuator deformations and forces remains a challenge due to the complex and dynamic nature of the combustion process. 148 Yang et al.121 developed a combustion actuator operated through the combustion of a propane and oxygen mixture. The actuator consists of a combustion chamber and a membrane. The team developed a theoretical model to investigate the effect of combustion reaction on membrane deformation and the magnitude of the thrust force.

Chemically driven microactuators mainly consist of multiple material layers 45,46,141 where one layer is susceptible to chemical variations and undergoes deformation, while the other layers serve as the biasing substrate to support reversible actuation strokes. However, the multilayer approach is unstable in the long-term operation due to interfacial instabilities. Therefore, asymmetries within the same material were used to avoid this issue.120 Furthermore, the recent development of advanced synthesised materials 144,145 is an emerging trend in chemical actuation to replace the multilayer approach. The state-of-the-art surface-catalysed chemical actuators developed by Bao et al.46 demonstrated a complete actuation cycle within 600 ms at an average actuation rate of 0.8 μm^{-1} s⁻¹. In contrast, hydrogel actuators have limited capability for actuation speed but can be used for slow actuation. The frequency of hydrogel-based chemical actuators depends on deswelling rates in mediums of different pH values. 120 The directional deformations of Polypyrrole-based actuators can be programmed by predefined

cutting lines of the material layers⁴⁵ because the deformations under moisture variations happen along the cutting lines. Ge et al. 144 developed cellulose nanocrystal-derived photonic materials with promising flexible sensing and actuating characteristics. The actuator showed high bending angles (135° to -136°) and bending rates (4.6° s⁻¹). The moisture-driven actuators based on Ti₃C₂T_X MXene graphene film exhibited larger bending angles, faster-bending speeds up to 32° s⁻¹, reversible deformations, and good stability in actuation cycling. 145 The MXene graphene oxide films could lift loads many times heavier than their weight. Wang et al. 141 reported an organic solvent stimulus actuator consisting of carbon nanotubes (CNTs) padded in a PDMS layer connected with a poly (vinylidene fluoride) (PVDF) layer by a PDMS connection layer (PDMS/CNTs-PDMS-PVDF). This sandwich layer arrangement can undergo large deformations at shorter response time. The structure can swell due to the absorption of *n*-hexane molecules and bend towards the PDMS/CNTs layer in 10 ms, exhibiting a fast response. The bending angle can reach up to 900° depending on the stimulation location, and the bending angle can be accurately adjusted by changing the solvent type. Table 5 summarises and compares parameters related to the design, fabrication and performance of some reported chemical actuators.

3. Materials for actuators and flexible microdevices

Materials for flexible and stretchable devices should comply with the actuation principles. Very often, the actuators and the flexible microdevices are fully integrated into one platform and made of the same materials. It is challenging to differentiate explicitly between the actuators and the flexible devices being actuated. Therefore, we will discuss the fabrication materials and methods for flexible devices and actuators. A wide range of polymeric materials, electrically conducting materials, silicon, and glass have been used to construct flexible devices and actuators. Fig. 4 compares the characteristics such as elastic modulus and maximum strain of common materials used in flexible and stretchable microdevices.

3.1. Polymeric materials

Polymeric materials such as thermoplastics, elastomers, and thermoplastic elastomers³⁴ are widely used in actuators and flexible devices. Table 6 compares Young's modulus, tensile strength, and maximum strain for these materials and summarises their advantages, limitations, and applications.

Polydimethylsiloxane (PDMS) is an elastomeric polymer containing carbon and silicon. PDMS has advantages such as durability, corrosion resistance, biocompatibility, and high optical transparency.²² In addition, the low shear and Young's modulus, high strains at fracture, and ease of manufacturability enable the utilisation of PDMS in pneumatic^{52,57,58,63,64} and hydraulic microactuators.⁵⁵ Microdevices such as micropumps and microvalves are

Table 5 Chemical actuation principles

		Soldie								
Actuation	Actuator type	Dimensions	Material(s)	Fabrication method(s)	Stress/strain	Mode of actuation	Deformation/speed Force	Force	Application(s)	Ref.
pH change	Asymmetric hydrogel actuator	L - 28 mm W - 2 mm T - 1 mm	Fe ₃ O ₄ @TCNCs, acrylic acid, acrylamide	In situ polymerisation, magnetic field-assisted patterning	Tensile strength: 228 kPa Maximum strain: 872%	Out-of-plane	Angular – 601° 30° min ^{–1}	NA	Artificial muscles, photonic displays, soft manipulators	120
Moisture gradient	Supercontractile polymer actuator	Tensile test specimen: $L-15 \text{ mm}$ $W-5 \text{ mm}$ $T-90 \text{ μm}$	Poly(ethylene oxide), poly(ethylene glycol)-α- cyclodextrin inclusion complex	Cold drawing	400%	Contraction and expansion	Contraction: ~60% within 2 s	~0.13 N 60% decaying in 10 s	Biomedical	140
	Janus actuator	L - 20 mm W - 3 mm	Cellulose nanopaper, reduced graphene oxide, lignin, graphene oxide	Vacuum filtration, reduction, drying	Tensile strength: 141 MPa Maximum strain: 5%	Out-of-plane	~9.6° s ⁻¹ @ RH-70%	NA	Bionic devices, humidity sensors	139
Organic solvent stimulation	Strip-shaped actuator	L-8.5 mm W-2 mm $T-181 \text{ \mu m}$	PDMS/CNTs, PVDF, PDMS	Electrospinning, bonding	NA	2D rotary-spiral	Angular – 900° @ 15.76 s	NA	Healthcare, bioengineering, soft robots	141
Chemical reactions	Surface-catalysed chemical actuator	=	Pt sheets, TiO ₂ , SiO ₂ , Al and Al ₂ O ₃	Standard semiconductor NA process	NA	Out-of-plane	Translational: 10 µm Angular: 45° (2) 2 v% H ₂ 0.8 µm ⁻¹ s ⁻¹	NA	Robotics, medical devices	46
	Micropumps	Membrane: $D-5 \text{ mm}$ $T-100 \mu\text{m}$	Synthetic polymer gel, PDMS, glass	PDMS replica moulding and plasma bonding, polymer moulding	NA	Reciprocating	109.77 ± 12.39 µm	0.07 mN	Wearable devices, lab-on-a-chip	142
	Combustion actuator	Membrane: $D-60 \text{ mm}$ $T-8 \text{ mm}$ Chamber: $H-125 \text{ mm}$ $D-100 \text{ mm}$ $V-80 \text{ cm}^3$	Dragon Skin [™]	Centrifuging, vacuum defoaming and curing	NA	Out-of-plane	70 mm (a) premixed ratio: 3 with 30 mL reactants	630 N	Soft robotics	149

L – length; W – width; T – thickness; D – diameter; H – height; V – volume.

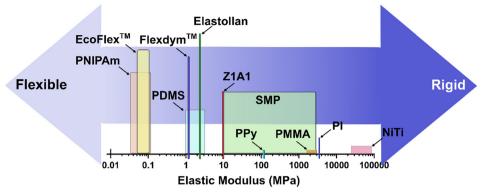


Fig. 4 Characteristics of the materials used for flexible and stretchable actuators. The height of the columns represents the maximum obtainable strains (see Table 6) for the respective materials.

generally made of multiple stacked layers, such as the supporting, fluidic, and control layers. PDMS is commonly utilised for the fluidic layers with flexible membranes due to its superb elastic properties. However, PDMS also has several limitations, such as its hydrophobic nature, porosity, and solvent incompatibility. The methyl (CH₃) groups in PDMS make the surfaces hydrophobic (contact angle with water $\sim 108^{\circ}$)²² limiting the applications such as electrophoretic separation¹⁵⁰ and droplet formation¹⁵¹ in microfluidics that require certain wettability of microchannel surfaces. However, methods such as Oxygen plasma treatment¹⁵² and surface coatings¹⁵³ can be used to make the PDMS surfaces hydrophilic. Moreover, PDMS materials have a certain porosity depending on curing conditions that can affect functionality in applications. These pores increase the surface area making absorption of small molecules altering the outcomes of quantitative analyses.¹⁵⁴ However, in terms of mechanical performance of flexible and stretchable microdevices, porous PDMS provides enhanced flexibility than non-porous PDMS. Certain solvents¹⁵⁵ cause the PDMS to swell leading to changes in microchannel features.

PDMS has been used in multi-material electro-thermal actuators. In these applications, non-metallic bi-morph actuation^{72,88} was implemented by combining materials such as polyimide (PI) and graphene with PDMS to form PI-PDMS, 72,77,88 and Graphene-PDMS⁸⁴ bilayer structures. In addition, acrylic-based photoresist materials, such as IP-PDMS (Nanoscribe GmbH)²⁵ and IP-S (Nanoscribe GmbH),⁸⁵ have also served as bi-morph structures. Their coefficient of thermal expansion (CTE) can be tuned by adjusting the degree of polymerisation. As an elastomer, PDMS is a suitable material for thermo-pneumatic actuators.81 The elasticity of PDMS structures can be tuned by altering the composition of the pre-polymer and curing agent 156 as well as the curing temperature¹⁵⁷ to obtain the required flexibility.

PDMS has been used as the flexible membrane for micropumps with electromagnetic actuation. 112,116 PDMS has a constant monotonic elastic modulus regardless of the influence of thickness and tensile loading.158 The PDMS reaches a steady state rapidly upon deformation, 159 allowing better performance with highfrequency electromagnetic actuation. Iron oxide (Fe₃O₄) nanopowder can be mixed with PDMS to form a magnetically responsive flexible material. 117 Carbon black particles were embedded in PDMS to form PDMS-encapsulated carbon black (PCB) and mixed with vinylsilane-rich silicone (VRS) to create PCB/VRS hybrid layers. The enhanced conductivity reduces the high operating voltages for silicone-based dielectric elastomer actuators, minimising the electrical breakdown and the creep rupture.137 PDMS was also used to fabricate microcracks and microwrinkles-based microvalves⁴⁷ due to the unique properties of the material, such as high elasticity, flexibility, and compatibility with the manufacturing process.

EcoflexTM is a commercial silicone elastomer that has recently become popular in highly flexible and stretchable devices. 160 The material has several advantages, such as low Young's modulus, high flexibility, tear strength, and large elongations. However, the material has limitations such as high viscosity and low chemical resistance. EcoflexTM has gained attention in the development of flexible microfluidic devices, biomedical applications, and soft robotics. For instance, the material was used to fabricate microchannels for magnetorheological fluid-based flexible actuators. 113 Dragon Skin™ is another commercial silicone elastomer material that is used for highly stretchable yet strong skinlike layers. 161 This material has a higher Young's modulus and tensile strength than Ecoflex™ and has been used as the strain-limiting layer of flexible actuators. 113 Dragon SkinTM material is also used to develop soft actuators with different layer stiffnesses for soft robotic grippers. 162

Thermoplastic elastomer (TPE) is a rubber-like material that combines the properties of thermoplastics and elastomers. Flexdym™ is a commercially available TPE material used in microfluidics20,163 because of its advantages such as high optical transparency, lower sweat absorption and water vapour transmission rate, and biocompatibility. Wu et al.20 developed a skin-interfaced flexible microfluidic device for sweat capture analysis. However, it is expensive at the prototyping stages, and the bonding treatments involve harsh conditions such as volatile chemicals and high-temperature.

Table 6 Polymeric materials for flexible and stretchable microdevices

Material	Young's Modulus (MPa)	UTS (MPa)	Maximum strain (%)	Advantages	Limitations	Potential applications	Ref.
Polydimethylsiloxane (PDMS)	1-3	3-5	100–300	Low shear and Young's modulus, high optical transparency, durability, corrosion resistance,	Hydrophobic nature, incompatibility with solvents	Biomedical devices	34, 156, 157, 175, 176
Silicone elastomers (SE) $(e.g., \text{Ecoflex}^{\text{TM}})$	0.05-0.1	0.37-1.7	500-800	blocompatibility Low Young's modulus, high flexibility, high tear strength, and	Opaque, high viscosity, low chemical resistance	Prosthetic appliances	34, 156, 176, 177
Thermoplastic elastomers (TPE) $(e.g., Flexdym^{TM})$	1.18	7.6	720	large elongation High optical transparency, lower sweat absorption and water vapour transmission rate, biocompatible	Expensive to use at prototyping stages, requirement of bonding treatments with harsh chemical and temperature	Microfluidic diagnostic applications	20, 163, 178, 179
Thermoplastic polyurethane (TPU) (e.g., Elastollan, Z1A1)	2.4, 9.2	2, 27.7	893, ~400	High flexibility and elasticity, chemical resistance, ease of	conditions Hygroscopic nature	Wearable devices	20, 176, 180
Polyimide (PI)	3450	231	72	St. printing Biocompatibility, high thermal stability, good stability properties,	Opaque, hygroscopicity	Medical devices	34, 181, 182
Polymethylmethacrylate (PMMA)	1800-3100	48-76	rv.	cnemical inetrness High optical transparency, Low water absorption, biocompatibility	Low chemical resistance, susceptibility to warpage and porosity, poor	Instrument displays	183, 184
Poly(N-isopropyl acrylamide) (PNIPAm)	0.035-0.105	0.35-0.65	009	Structural tunability, low toxicity, temperature-responsive reversible sol-to-gel	rangue resistance Low biodegradability, low drug loading capacity, poor mechanical strength	Thermo- responsive biomedical applications	165, 167, 185, 186
Shape memory materials (SMM) $(e,g, \text{ shape memory } G,g, \text{ shape memory } G,g, \text{ shape memory } G,g,g,g,g,g,g,g,g,g,g,g,g,g,g,g,g,g,g,g$	SMP: 10-3000, NiTi: M: 28000-41000,	895	SMP: >400, NiTI: <10	SME and PE, corrosion resistance, biocompatibility, high energy density per	High fabrication cost	Flexible medical devices	23, 105, 187, 188
polymet (SMF), MIII) Polypyrrole (PPy)	A: 73000-83 000 108.57	61	4	Biocompatibility, ease of	Water insolubility,	Tissue engineering	45, 189, 190
Cellulose nanocrystals assembled poly(ethylene glycol) dimethacrylate [CNC-poly(PEGDMA)]	° }	42	104	syndresising, low cost. Improved solvent resistance, impressive toughness, and strength, vivid optical iridescence under strains	Instability Requirement of sophisticated and careful fabrication methods	Drug delivery, intelligent actuators	144, 191
A - austenite M - martensite	ite						

Thermoplastic polyurethane (TPU) is an elastomeric material that exhibits the properties of plastics while showing the flexibility of rubber material. Its high flexibility and chemical resistance allow for a variety of applications. Shaegh et al.54 used TPU as the flexible element in pneumatic micropumps. TPU has gained attention because of its compatibility with fused deposition modelling (FDM) 3D printing technology. 164 FDM creates 3D components by extruding thermoplastic filament in a series of layers. Properties such as flexibility, conformability, and excellent interlayer adhesion make TPU a better candidate for FDM technology. However, the hygroscopic nature of the material is the limiting factor in applications.

Polymethylmethacrylate (PMMA) is a synthetic polymer commercially known as Perspex or acrylic glass. The advantages of PMMA are high optical transparency, low water absorption, and biocompatibility. PMMA has been used to fabricate the supporting layers in micropumps and microvalves. 53,54 The drawbacks of PMMA include poor fatigue resistance, susceptibility to warpage, and low chemical resistance.

Hydrogels consist of a hydrophilic polymer network that can swell under the absorption of moisture and also hydrogels are thermo-responsive. Temperature increase collapses the polymer networks, leading to high volume shrinkages. Hydrogel materials such as poly(N-isopropyl acrylamide) (PNIPAm) possess a lower critical solution temperature of around 32 °C, 165 where the material changes from hydrophilic to hydrophobic nature. In addition, PNIPAm enables the development of flexible actuation with autonomic perspiration capabilities. structures Autonomic perspiration is sweating due to increased temperature through the dilation of a pore structure located on the actuator body. This process is essential to thermoregulate actuators operating at peak power for an extended period. 166 This material is promising for biomedical applications due to excellent structural tunability and low toxicity. The covalent bond of the polymeric chains in hydrogel promotes the easy construction of multilayer structures in actuators. 69,70 However, the elastic modulus of the hydrogel is low compared to polyurethanes and silicones. Thus, adding a small amount of hydrophilic polymer networks such as alginate can enhance the mechanical toughness of hydrogel.^{69,70} Furthermore, synthesised hydrogel materials with co-precipitating Fe₃O₄ nanoparticles of tunicate cellulose nanocrystals (TCNCs) (Fe₃O₄@TCNCs) form asymmetric hydrogel materials. 120 TCNCs enable better mechanical properties of hydrogels. Similarly, hydrogel responsive to magnetic fields can be prepared by precipitating Fe₃O₄ magnetic nanoparticles in the PNIPAm nanocomposite hydrogel matrix. 118 Despite many advantages, hydrogel materials have low biodegradability and limited mechanical strength.167

Polymeric materials such as polypyrrole (PPy) with particular patterns can be combined with inert polyethylene terephthalate layers to form humidity-sensitive bilayers. 45 Here, the PPy is electrochemically synthesised and doped with perchlorate to rapidly expand the material on water vapour absorption. PPy is suitable for developing microactuators because of its biocompatibility and simple synthesis. Moreover, cellulose nanocrystals (CNCs) assembled poly(ethylene glycol)dimethacrylate (PEGDMA) monomers in N,N-dimethylformamide can be synthesised to form flexible and stretchable materials sensitive to humidity variation. Ge et al.144 reported a CNC-poly(PEGDMA) made of equal amounts of CNC and PEGDMA with 104% in stretchability, 42 MPa in mechanical strength, and 31 MJ m⁻³ in toughness.

Resins, such as IP-DIP (Nanoscribe GmbH), 68 have also been used to develop highly flexible actuator structures for microhydraulic actuators. Smith et al.68 have used IP-DIP (Nanoscribe GmbH) resins to develop hydraulically actuated flexible bellows structures with a sidewall thickness of 1 μ m.

Dielectric elastomers belong to the group of electroactive polymers. Dielectric elastomers produce large strains as an electric field is applied to the material. High-performance dielectric elastomers should have low stiffness, high dielectric constant, and high electrical breakdown strength. Dielectric elastomers are most popular in mechanical strainbased flexible and stretchable actuators168 due to their advantages of high energy density, fast response, and large strains. 169 obtainable Polyvinyl chloride (PVC)-based demonstrate dielectric elastomers high actuation performance under low actuation voltages. 43 Moreover, pentablock copolymeric elastomers such as (SEHAS)2 can form high-performing soft microactuators, which work under relatively low voltages in contrast to the common driving voltage on the order of kilovolt. Chen et al. 135 reported a (SEHAS)₂-based ultra-thin actuator that operates under 680 V, providing a 93% strain. Piezoelectric polymers also belong to the electroactive polymers which produce mechanical deformation in response to an applied electric field. Poly(vinylidene fluoride) (PVDF) is one of the promising piezoelectric polymers due to its high efficiency and mechanical stability as well as fast response. 170 The conversion efficiency from electrical to mechanical energy is highly affected by the polarisation of the molecular structure.171 Won et al.172 reported an ultrafast, and programmable molecular structure transition process that uses continuous wave laser together with gold nanoparticles that enhance the thermal effects induced by the laser. They integrated monolithic PVDF layers to achieve a frequencydriven soft robot.

3.2. Electrically conducting materials

Apart from polymeric materials, electrically conducting materials have been used in flexible and stretchable actuators. Examples of electrically conducting materials for actuators include metals such as shape memory alloys steel, metal-silicone (SMAs), stainless aluminium, composites, Pt, TiO2, MXene, and derivatives of graphene such as graphene oxide (GO).

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SMAs are a class of shape memory materials (SMMs)¹⁰⁵ sensitive to temperature variations and undergo solid phase transformation, showing large recoverable strain that plays a significant role in strain-based actuation.⁷⁵ SMMs possess unique characteristics of the shape memory effect, 173 which is substantial in electrothermal actuators and pseudoelasticity.80 In addition, magnetic shape memory materials show crystallographic changes and deform upon applied magnetic fields. Magnetic shape memory materials such as Ni-Mn-Ga were used to develop magnetically operated micropumps. 119 SMA-based microactuators provide the most promising energy density compared to other actuation concepts, 80 despite their slow actuation frequency because of the requirement of efficient cooling.

Materials are combined to develop multi-material electrothermal actuators. For instance, bi-morph actuation could be implemented using metals such as aluminium-nitinol.83,87 However, the non-metallic bi-morph actuators require a separate heating circuitry to increase the temperature in nonmetallic layers. These conductive paths were made of liquid metals such as eutectic GaIn⁷² and Galistan. 85 Also, the conductive paths for electrothermal actuators can be directly formed on polymeric materials. The conductive layers, such as laser-induced graphene, 77,88,174 were formed with good electrical conductivity. Moreover, graphene was used as a layer to form bi-morph structures, eliminating the additional electrical circuitries.84

In addition, EGaIn in silicone elastomer has been used in electromagnetic membrane actuators.111 Stainless steel was used for mass-spring structures in electromagnetic actuators to support flexible membranes. 112 Aluminium is a suitable material for bent-beam actuators that require robustness and reliability.⁷⁹ Metal-silicone composites have also been used to make bent-beam actuators where the introduction of metal layers significantly reduces electrical resistance, resulting in low driving voltages. 101

Materials such as Pt and TiO2 have been used for bimorph actuation elements in surface-catalysed chemical actuators. The PtO_x layers on the Pt material react with H_2 and O_2/O_3 , and the induced surface stresses cause the bending of the structure.⁴⁶ Besides, Ti₃C₂T_X MXene and graphene oxide (GO) materials can be combined to form MXene graphene oxide (MGO) film actuators that are fast, reversible, and have good cycling stability. 145 The introduction of GO can significantly lessen the inherent brittle nature and rapid oxidisation of MXene.

3.3. Other materials

Glass, ^{51,59-61} and silicon⁵⁶ have been used in the supporting layers of the microdevices, such as micropumps and microvalves. Silicon was also used as a flexible element in pneumatic microvalves.⁵⁶ In addition, silicon was employed in pseudo-bi-morph and bentbeam microactuators based on the silicon-on-insulator substrate.96 Silicon-on-insulator actuators have been widely employed¹⁰¹ due to their excellent compatibility with materials for microelectronics and microelectromechanical systems.

4. Fabrication methods for actuators and flexible microdevices

4.1. Photolithography and soft lithography

Photolithography and soft lithography have been extensively used to fabricate flexible microdevices, 51,56 Fig. 5A. In photolithography, masks pattern photosensitive materials coated on a substrate after exposure to ultraviolet (UV) light, Fig. 5A(i). The exposed or unexposed photosensitive photoresist is selectively removed by a developer to obtain the required patterns depending on its properties. The exposed region is removed when using a positive photoresist, and the unexposed region is removed when using a negative photoresist. 192 Photolithography can then be combined with other methods, such as etching and deposition, to form microstructures for microdevices. Shibamoto et al.56 used photolithography and deep reactive ion etching to fabricate pneumatic microvalves. In addition, hot and cold arm microactuators were manufactured by integrated circuit fabrication technology, mainly involving sputtering and etching processes, where the subsequent fabrication steps were assisted by photolithography. 96 Foundry services such as multi-user MEMS process (MUMPs®) utilising silicon-on-insulator structures, also known as SOIMUMPsTM, 26 use photolithography as a subsequent step. SOIMUMPs™ was used to fabricate bent-beam actuators. 42,103 Moreover, SOIMUMPsTM allows for making multiple devices on a single silicon wafer. Thermal expansion-based actuators and phase change actuators, such as SMA-based thin film microactuators, can be fabricated by micromachining processes such as lowpressure chemical vapour deposition, sputtering, wet etching, and reactive ion etching that involve photolithography in these subsequent steps. 132,193

Soft lithography transfers the inverted patterns from a mould or master to elastomeric materials, Fig. 5A(ii). In this technique, the individual layers are made by pouring elastomer materials such as PDMS onto the SU-8 moulds. The solidified layers are peeled off and bonded after surface preparation under ultraviolet light irradiation in a vacuum. Soft lithography is frequently used to fabricate microdevices $micropumps^{51,59-62}$ pneumatic microvalves. 52,57,63,64 This fabrication technique has also been used for hydraulically actuated microdevices.⁵⁵ Ni et al.111 reported an electromagnetic actuator with liquid metal embedded in the microfluidic structures. The microchannels were formed in the thin PDMS layers using soft lithography and laser cutting 111,113 and bonded to a thin silicone membrane.

4.2. Additive manufacturing

Additive manufacturing is a technique to manufacture threedimensional objects by adding materials layer-by-layer, 194,195 Fig. 5B. Additive manufacturing is mostly famous and known as three-dimensional (3D) printing or fused deposition modelling (FDM) technology, Fig. 5B(i). Instead of the conventional material removal process to fabricate objects,

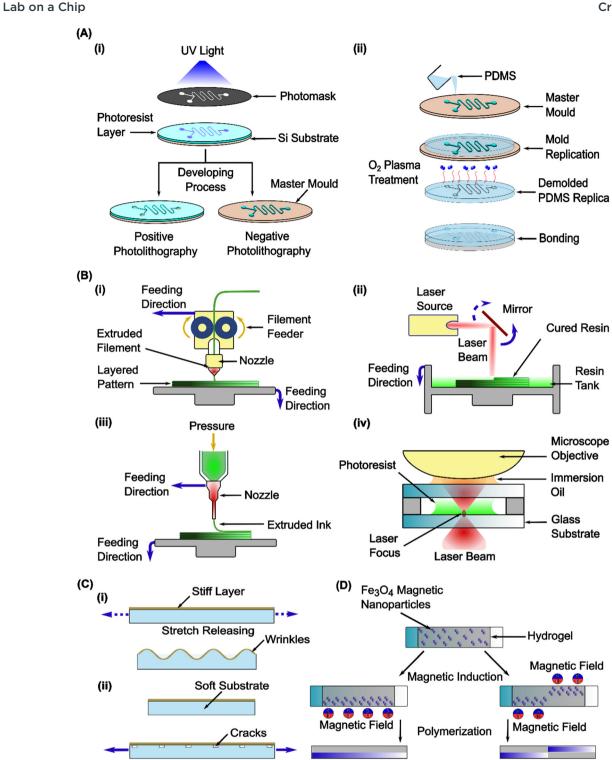


Fig. 5 Fabrication technologies. (A) Micropatterning. (i) Positive and negative photolithography, and (ii) soft lithography. (B) additive manufacturing technologies. (i) Fused deposition modelling (FDM), (ii) stereolithography (SLA), (iii) direct-ink-writing (DIW), (iv) two-photon polymerisation (2PP). (C) Crack and wrinkle microvalves formation through (i) prestretch releasing (wrinkle microvalves), (ii) stretching (crack microvalves). (D) Magnetic field assisted fabrication of asymmetric hydrogel structures.

Symmetric Hydrogel

additive manufacturing uses a layer-by-layer approach to generate 3D objects by depositing material layers according to a computer-generated model. 3D printing has the

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advantages of flexibility, short manufacturing time, and reduced material wastage. However, its resolution is generally lower compared to photolithography.

Asymmetric Hydrogel

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Additive manufacturing can eliminate the bonding process of multiple layers of soft lithography in fabricating flexible and stretchable devices. Microchannels fabricated by the soft lithography need to be sealed with another layer. In contrast, 3D printing can produce complex microchannel structures as a sacrificial mould that can be dissolved and removed. This technique is known as the embedded scaffold removing open technology (ESCARGOT).²⁷ This technique has been used to fabricate pneumatic microactuators to control fluid flow in a miniature fluidic system.⁵⁸ Moreover, 3D printing techniques can fabricate flexible and stretchable structures using soft polymeric and metallic materials. For instance, 3D printing was used to make conductive paths for non-metallic bi-morph actuator structures using EGaIn.⁷² Polylactic acid (PLA)-carbon black-shaped memory polymer material and acrylonitrile butadiene styrene (ABS) were used to print conductive and non-conductive areas of a bent-beam actuator, 196

Multi-material stereolithography (SLA) is one of the 3D printing techniques for fabricating multi-material structures, Fig. 5B(ii). This technique is a light-based approach that uses controlled photoirradiation to cure a liquid photopolymer ink selectively. SLA permits both micrometre resolution and rapid deposition rates. Recently, this method was used to fabricate a fluidic actuator using hydrogel. 166 In addition, direct-ink-writing (DIW) 3D printing permits complex structures of the modified hydrogel, including hollow and suspended features, 69 Fig. 5B(iii).

Two-photon polymerisation (2PP) is an advanced 3D printing technique based on two-photon absorption to polymerise a photosensitive material selectively, Fig. 5B(iv). This technique is superior in its high resolution and precision. Nano/micro scale 3D printing with 2PP²⁵ can be used to develop complex, compliant structures for flexible hydraulic actuators.⁶⁸ Moreover, 2PP four-dimensional (4D) printing¹⁹⁷ generates non-metallic bi-morph structures using the same material but making regions with different CTEs.85 This method fabricated bi-morph microactuators capable of high rotational motions that are impossible to fabricate using the MEMS fabrication methods. However, 4D printing introduces the dimension of time to printed 3D structures as they evolve as a function of time. 198 This is done by the use of stimulus-responsive materials that enable functional adaptations.199

4.3. Other fabrication methods

Additionally to the fabrication techniques mentioned above, other fabrication techniques have also been developed for flexible and stretchable actuators, including microwire electrodischarge machining, ultrasonication, reversible/fragmental transfer emulsion polymerisation, pre-stretching, magnetic field-assisted in situ polymerisation, laser cutting technique, and ultraviolet light-triggered free radical polymerisation.

Some electromagnetic actuators utilise mass-spring structures that can be easily fabricated by the microwire electrodischarge machining.¹¹² Magnetic nanoparticle-suspended synthesised elastomeric materials can be through ultrasonication, giving rapid and uniform nanoparticle dispersion compared with high-speed shear mixing. 117 These elastomers are then spin-coated to fabricate the flexible magnetic responsive actuators through a layer-by-layer approach. In addition, magnetic bilayer hydrogel-elastomer actuators are prepared using adhesive bonding between very high-bond tapes and magnetic hydrogel sheets. 118

Also, block copolymer structures of dielectric elastomer materials can be made by reversible/fragmental transfer emulsion polymerisation method, which improves the electromechanical performance of dielectric elastomer materials in the electric field-assisted mechanical strainbased actuators. 135 In addition, mechanical instability-based microdevices, such as cracks and wrinkle microvalves, are fabricated based on pre-stretching. In this method, releasing a pre-strained elastomer such as PDMS with a stiff surface layer results in wrinkled microchannels, Fig. 5C(i), and stretching the elastomer with a stiff surface layer leads to cracked microchannels, 47 Fig. 5C(ii).

Laser cutting can also create controlled patterns on polypyrrole polymer membranes, which are transferred to polyethylene terephthalate tape to create moisture-sensitive bilayer structures. 45 Ultraviolet light-triggered free radical polymerisation can be used to synthesise chiral nematic composites using cellulose nanocrystals and poly(ethylene glycol) dimethacrylate in N,N-dimethylformamide for humidity-sensitive actuation. 144

Furthermore, asymmetric hydrogel materials can be fabricated by magnetic field-assisted methods, Fig. 5D. In that process, co-precipitated Fe₃O₄ nanoparticles on tunicate cellulose nanocrystals (TCNCs) (Fe₃O₄@TCNCs) were evenly mixed in a polymer matrix followed by in situ polymerisation under applied magnetic fields to form asymmetric hydrogel materials. 120

5. Applications

5.1. Biomedical applications

Flexible and stretchable devices have many applications in biomedicine. This section mainly discusses the recently reported work on the actuation of flexible devices in biomedical applications, including fluid delivery, 36,53,58,200 particle and cell manipulation and separation, 201,202 and tissue engineering.^{203–213}

Pneumatically actuated on-chip microvalves micropumps are essential for efficient and accurate fluid delivery in biomedical analyses.^{51,61} Zhong et al.²¹⁴ developed diaphragm microvalves and micropumps for automated and parallel DNA solid-phase extraction from various biological samples to eliminate cross-contamination and leakages. In addition, Lee et al. 51,52,59,60,62,200,215 have developed microfluidic platforms for automated, synchronous, and multiple sample analysis for various biological tests utilising on-chip microvalves and micropumps. Vo et al.53 reported a pneumatically actuated

peristaltic micropump for blood plasma extraction. The pump operated at a flow rate of around 3.5 mL min⁻¹ under 300 kPa pneumatic pressure and 10 Hz operation frequency. The separation efficiency of blood plasma was 97% for a diluted sample. The advantage of this method is the elimination of external pumps. Shin et al. 216 developed a stretchable air filter for adaptive respiratory protection. They used a stretchable elastomer fibre membrane as the air filter layer where micropores of the filter were adjusted using pneumatic control, Fig. 6A. The filter characteristics were changed according to the

air quality and physical activity performed by the wearer via a machine learning algorithm. This work eliminates possible physiological and psychological effects caused by conventional respirators under dynamic environmental conditions.

Mechanical strain-based actuation was used for a straintuneable crack and wrinkle microvalve that can screen particles in the range of 2-20 $\mu m.^{47}$ These valves can screen and perform selective transport of biological cells. Mechanical strain actuation was innovatively applied in an inertial microfluidic device to adjust the cell separation cut-

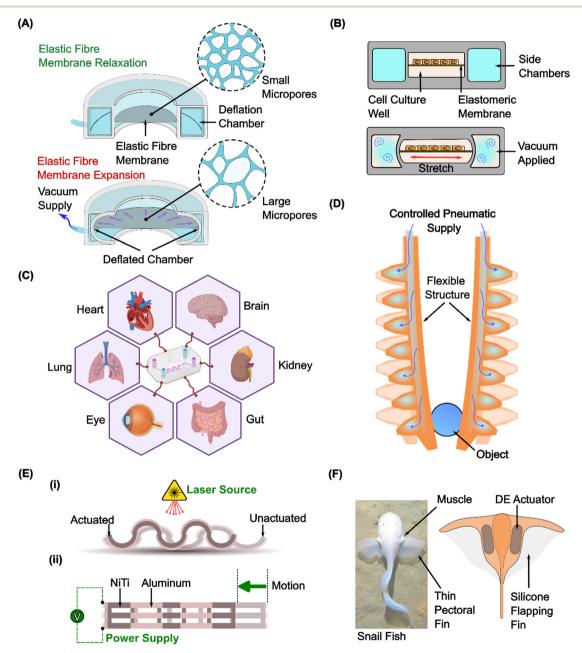


Fig. 6 Applications of flexible and stretchable actuators. (A) Dynamic pore modulation of stretchable elastic fibre membrane for adaptive respiratory protection.²¹⁶ (B) Vacuum-assisted cell-stretching device.²⁰⁵ (C) Current applications of organ on a chip,²²² created with https:// BioRender.com. (D) Soft robotic gripper operated through controlled pneumatic supply to grasp objects.²²³ (E) Multiresponsive inchworm-type microrobot:⁸³ (i) untethered actuation through a laser source for remote operation, (ii) tethered actuation through joule heating for fast operation; (F) bio-inspired swimming robot operated through dielectric elastomer (DE) actuators.²²⁴

off size for the isolation of cancer cells from blood samples. 201,202 Besides, mechanical stretching was used to modify the dimension of microtrappers in real-time and onsite for the on-demand deterministic release of single cells. Recently, mechanical stretching has been employed to regulate an ultra-stretchable viscoelastic microfluidic device for size-tunable sorting of *Haematococcus pluvialis*. 218

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Cell stretching is a tissue engineering technique that stretches cells and tissues to study biological functions in vitro.205 The strain is associated with human body functions such as breathing, blood flow in vessels, intestinal movements, muscle contraction, etc. 203 In addition, cell stretching is also used to enhance medical diagnosis, 219 detecting cell morphological changes for early diagnosis of diseases.²²⁰ Cell stretching devices have been developed to analyse the biological functions of cells under mechanical stretching.221 These devices allow independent control of the magnitude, direction, and frequency of the mechanical strain. Moreover, biocompatible materials such as PDMS and hydrogels are widely used in cell-stretching devices where the cells can grow. Actuating mechanisms based on pneumatic, Fig. 6B, magnetic, and electromagnetic have been utilised to induce mechanical strain of these devices. 204

Organ-on-a-chip (OoCs) is an emerging technology where tissue engineering is combined with microfluidics to mimic tissue-specific functions and to mimic key aspects of human physiology. 210 The flexible membranes located in OoCs can be actuated to mimic organ tissue motions, Fig. 6C. Huh et al. 207 developed a lung-on-a-chip reconstituting critical functions of the alveolar-capillary interface of the human lung. In their work, the cells adhered to a PDMS membrane were cyclically stretched and released using a vacuum source to exert physiologically relevant mechanical forces. This process allowed studies of the effect of stretching forces on physiological and pathological lung functions. In addition, Kamei et al. 61 developed an integrated heart/cancer-on-a-chip that uses pneumatically actuated microvalves. Here, the device performed both valving and peristaltic pumping to deliver samples. The results verified the recapitulation of the side effects and the cardiotoxicity of anti-cancer drugs in vitro.

5.2. Soft robotics

Soft robotics is a branch of robotics, where the components of the robots are fully or partially manufactured by mechanically compliant materials. Soft robots are primarily inspired by the behaviour and structures of living organisms. Moreover, a comprehensive study on bioinspired materials for soft robotics can be found in the recent work reported by Roh *et al.* Soft robotics enables safer interactions in collaborative tasks and adaptability to unpredictable environments. Flexible and stretchable materials and suitable actuation mechanisms are paramount in soft robotics. The actuation should provide the intended dexterity to achieve motions such as extension, contraction, twisting, and bending. Actuation mechanisms

such as fluid-driven, ^{68,233,234} thermal, ^{72,88} electrical, ^{225,235,236} and magnetic ^{113,237,238} have been widely used for soft robotics. In addition, chemical actuation ²³⁹ was also applied in tactile soft robotics. The recent works highlighted the application of programmable surfaces, ¹¹¹ grippers, ^{113,117,233} and shape-morphing structures ¹¹⁸ in soft robotics. More importantly, combustion-powered soft actuators shift the capabilities of mobile microrobots into a new dimension. ¹⁴⁷

Fluid-driven actuation is frequently applied in soft robotics, where a liquid flow⁷⁰ or compressed air^{233,240} is used as the working medium, Fig. 6D. However, one significant limitation of fluid-driven actuation is the requirement for external reservoirs and pressure sources to activate the device, making the whole soft robotic system too complex and bulky. Recent studies addressed the above limitation by operating the soft robotic systems through untethered actuation sources,^{68,234} designed as a part of the soft robotic device with a pre-filled actuating medium. Mechanically compliant structures made from flexible materials were used to store the working fluid, transferring the chemical energy to mechanical deformation to perform actuation tasks.

In addition, thermal actuation has been used in soft robotics where the actuator structures can be heated in untethered, ⁸³ Fig. 6E(i), or tethered Fig. 6E(ii)⁷² manners. Tethered actuation results from the deformations of the actuator material by joule heating. Untethered actuation works with incident thermal radiation *via* sources such as lasers that locally heat the actuator materials. Thermally actuated soft robots have a lower actuation speed ⁸⁸ compared to their fluid-driven counterparts.

Moreover, mechanical strain-based actuation has been found in soft robotics, where highly stretchable materials such as dielectric elastomers 241 responsive to electric fields were used as the actuator structures. 136 The dielectric elastomer actuators operate under a high voltage in the kilovoltage range. For example, Li $et\ al.\ ^{224}$ developed a deepsea swimming soft robot using dielectric elastomer muscle actuators where pre-stretched muscles facilitated the flapping motion, Fig. 6F. The soft robot swam at a speed of 2.76 cm s $^{-1}$ under 110 MPa when a 7 kV actuation voltage was applied at a 1 Hz frequency.

Furthermore, magnetic actuation plays a vital role in soft robotic actuation, benefiting from untethered operation and the ability to compact the structures that are difficult to achieve in other actuation principles. Magnetic soft materials are critical for soft magnetic actuators.²³⁸ For example, McDonald *et al.*¹¹³ developed a magnetorheological fluidembedded elastomeric material soft actuator for multidegree-of-freedom soft robotic applications, where they could achieve untethered and localised deformations. Moreover, Ren *et al.*³⁷ reported a magnetic composite elastomer-based jellyfish-inspired millirobot, which was actuated by oscillating magnetic fields.

Chemical fuel-based combustion technology has shown promising performance in mobile robotics because of the

high energy densities compared to other actuation mechanisms. Most actuation mechanisms face one or more limitations regarding energy densities, manufacturability, and scaling laws hindering the miniaturisation capabilities. Chemical combustion-based microactuation facilitates unwavering opportunities to address those drawbacks in micro-mobile robotics. A pioneering work reported a lightweight, high-frequency, power-dense microactuator operated through the combustion of methane and oxygen mixture. 143 The microactuator showed a power-to-weight ratio of 277.2 kW kg⁻¹ per stroke and can produce forces over 9 N and an operating frequency above 100 Hz.

6. Discussion and future perspectives

In this review paper, we first discussed five actuation mechanisms for flexible and stretchable microdevices: fluiddriven, electro-thermal, magnetic, mechanical strain-based, and chemical. We elaborated the design parameters and performance related to each actuation concept. After that, we discussed device materials and fabrication technologies for flexible devices and actuators. Finally, we summarised the main applications of flexible and stretchable microactuators in biomedicine and soft robotics. Although the actuation for flexible microdevices has been extensively studied and significant progress has been made, there are still some challenges and limitations regarding the system complexity, device materials, and fabrication that need to be tackled to unravel the full potential of the devices.

One of the main challenges of actuation on a small scale is the bulky size and complexity of the overall system. Compact actuation schemes are necessary on the microscale to reduce system complexity. For example, the working fluids and pumping pressure for hydraulic and pneumatic microactuators are often externally supplied, and the electrothermal actuators use tethered power sources, making the whole system complicated and less portable. To eliminate these issues, self-containing working fluids and untethered power sources are promising solutions. A few pioneering works have been reported to develop a micro hydraulic actuator where the working fluid can be stored within the device⁶⁸ and an untethered thermal actuation with materials locally heated by an incident laser. 83 Besides, chemical combustion methods can achieve untethered, highforce, and rapid-response actuators. However, quantifying actuator forces remains a challenge due to the complex and dynamic nature of the combustion process, and further work is needed to understand the dynamics process of combustion and its interaction with microdevices during actuation. Moreover, the safety of chemical combustion actuation is another issue since it involves high temperature and pressure in a dynamic and chemically hazardous environment. Also, enhancing the reusability and recyclability of this actuation mechanism rather than single usage will maximise the lifespan and reduce the usage costs of devices.

Another limitation in developing flexible and stretchable devices is the material for fabricating devices. The device materials should have the required flexibility and stretchability without premature failure while in operation. PDMS has been the prominent material for microfluidic devices over the last 20 years. However, PDMS has limited stretchability (maximum strain ~120%)157 and is prone to rupture at a high strain. Therefore, flexible materials with higher stretchability are silicone needed. Thus, commercial elastomers thermoplastic elastomers such as EcoflexTM and FlexdymTM have been used in flexible microdevices. These flexible materials have a much better stretchability with maximum strains of 700-900%, 156,163 However, these materials cannot be covalently bonded through plasma treatment as that of PDMS. The device fabrication techniques developed based on PDMS cannot be directly translated into these materials, and this drawback constrains their wide application in microdevices with microscale channels and ducts. Therefore, additional endeavours should be directed towards utilising these materials in the fabrication of microdevices.

Traditional flexible and stretchable microfluidic devices are fabricated mainly by the soft lithography process, where the devices are prone to fail due to the high risk of bonding failure in the layer-by-layer stacking approach, resulting in liquid leakages. Using sacrificial mould manufacturing techniques to develop intricate microdevices eliminates drawbacks associated with the multi-layer fabrication process. However, using 3D printing to manufacture sacrificial moulds has limited material availability for sacrificial moulds, minimum achievable feature size, and poor surface morphology.²⁴² To address this issue, 3D printing methods such as direct ink writing and stereolithography can be used to print flexible microdevices directly without sacrificial moulds. In this case, the printing resolution and development of advanced resins with good stretchability after curing are critical. UV-curable resins are emerging for highly stretchable structure fabrications. Patel et al.243 reported a highly stretchable UV-curable elastomer with Young's modulus ranging from 0.58 to 4.21 MPa and maximum strain up to 1100%. This resin was formulated by combining epoxy aliphatic acrylate and a difunctional crosslinker of aliphatic urethane diacrylate diluted with isobornyl acrylate. Altering the ratios of epoxy aliphatic acrylate and aliphatic urethane diacrylate could tune the mechanical properties of the UV-cured elastomers. Implementing these advanced resins in high-resolution 3D printing techniques such as two-photon polymerisation (2PP) will be a promising method to print the devices directly with precise microscale features. The fabrication cost and printing efficacy of the 3D printing techniques should be optimised so that the fabrication techniques become competitive enough and easy to access for wide usage as that of PDMS fabrication.

In conclusion, as microdevices evolve from being portable to becoming wearable, there is a rising interest in flexible and stretchable devices capable of surmounting dimensional limitations, enhancing adaptability to intricate body surfaces,

and sustaining prolonged performance. Ensuring adequate actuation mechanisms becomes crucial for the optimal functionality of such devices. Selecting suitable materials and implementing precise fabrication techniques emerge as pivotal factors for the successful development and widespread adoption of these devices. Addressing current challenges related to system complexity, device materials, and fabrication techniques requires sustained and substantial efforts to advance actuation technologies for

List of abbreviations

flexible microdevices.

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2D	Two-dimensional
2PP	Two-photon polymerisation
3D	Three-dimensional
4D	Four-dimensional
ABS	Acrylonitrile butadiene styrene
AgNW	Silver nanowire
AMFs	Alternating magnetic fields
Bio-SHARPE	Bioinspired soft and high aspect ratio

pumping element
CTE-poly(PEGDMA) Cellulose nanocrystals assembled

poly(ethylene glycol)dimethacrylate

CNCs Cellulose nanocrystals
CNTs Carbon nanotubes

CTE Coefficient of thermal expansion

DE Dielectric elastomer

DEA Dielectric elastomer actuator

DIW Direct-ink-writing
DNA Deoxyribonucleic acid

EGaIn Eutectic GaIn Electromagnetic

ESCARGOT Embedded scaffold removing

open technology

FDM Fused deposition modeling

GO Graphene oxide

ICP Inductively coupled plasma
LDPE Low density polyethylene
LIG Laser-induced graphene

MEMS Microelectromechanical systems

MGO MXene graphene oxide MR Magnetorheological

MSMM Magnetic shape memory material NiTiNOL Nickel-titanium naval ordnance

laboratory

OoC Organ-on-a-chip

PCB Polydimethylsiloxane encapsulated

carbon black

PDMS Polydimethylsiloxane

PEGDMA Poly(ethylene glycol)dimethacrylate

PI Polyimide PLA Polylactic acid

PMMA Polymethylmethacrylate PNIPAm Poly(*N*-isopropyl acrylamide)

PVC Polyvinyl chloride

PVDF Poly(vinylidene fluoride)
PZT Lead zirconate titanate

RBCs Red blood cells

SCHAM Self-contained hydraulically-actuated

microfluidic

SE Silicone elastomer
SLA Stereolithography
SMA Shape memory alloy
SMM Shape memory material
SMP Shape memory polymer
SOI Silicon-on-insulator

SOIMUMP Silicon-on-insulator multi-user

micromachining process

TCNCs Tunicate cellulose nanocrystals
TPE Thermoplastic elastomer
TPU Thermoplastic polyurethane

UV Ultraviolet

VRS Vinylsilane-rich silicone

Author contributions

N.-T. N. and J. Z. conceptualization, supervision, and project administration. U. R. formal analysis, writing – original draft, visualization. A. M., H. C., and S. H. visualization. J. Z. and N.-T. N. writing – review & editing. N.-T. N., and J. Z. funding acquisition. All the authors provided critical feedback and read and approved the manuscript.

Conflicts of interest

The authors have declared no conflict of interest.

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