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Multimodal Soft Robotic Actuation and Locomotion

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Diverse and adaptable modes of complex motion observed at different scales in living creatures are challenging to reproduce in robotic systems. Achieving dexterous movement in conventional robots can be difficult due to the many limitations of applying rigid materials. Robots based on soft materials are inherently deformable, compliant, adaptable, and adjustable, making soft robotics conducive to creating machines with complicated actuation and motion gaits. This review examines the mechanisms and modalities of actuation deformation in materials that respond to various stimuli. Then, strategies based on composite materials are considered to build toward actuators that combine multiple actuation modes for sophisticated movements. Examples across literature illustrate the development of soft actuators as free-moving, entirely soft-bodied robots with multiple locomotion gaits via careful manipulation of external stimuli. The review further highlights how the application of soft functional materials into robots with rigid components further enhances their locomotive abilities. Finally, taking advantage of the shape-morphing properties of soft materials, reconfigurable soft robots have shown the capacity for adaptive gaits that enable transition across environments with different locomotive modes for optimal efficiency. Overall, soft materials enable varied multimodal motion in actuators and robots, positioning soft robotics to make real-world applications for intricate and challenging tasks.

1. Introduction

Nature has evolved creatures with a wide range of sizes, from the micrometer to the meter-scale, that can produce diverse and complex forms of motion with high degrees of freedom.[1] Living organisms have developed robust adaptations that allow them to move in complicated locomotive gaits such as crawling, rolling, running, and jumping on unstructured terrains.[2] Moreover, animals have the ability to seamlessly transition between different environments, including terrestrial, aquatic, and aerial domains.[3] Designing and controlling machines with similarly dexterous locomotive capabilities of those observed in nature is grand aspiration in robotics. However, this goal is challenging using traditional robotic designs, materials, and actuators, which have limited selection and properties.[4] Conventional robots tend to be bulky, expensive, heavy, and difficult to adjust due to the widespread dependency on rigid materials.[5] Additionally, manufacturing and control systems are complicated to implement in these robots.[6,7] Fortunately, the emergence of soft materials in robotics has opened up new possibilities for creating robots that could match the locomotive performance and versatile, adaptable behaviors of living creatures.[8] Using soft materials allows robotics to take inspiration from and mimic nature's design, as it also evidently relies on soft materials to create diverse motion.[9–11] Soft materials have the added benefits of being lightweight, low-cost, easy to fabricate, adjustable, deformable, and have excellent mechanical compliance.[12] All these properties make soft material-based actuators and robots better suited for safe human interaction, and they can also enhance the performance of robotics for applications in exploration, scientific, military, agriculture, and biomedical fields.[13,14] The scope of soft robotics is rapidly advancing, as there are opportunities in novel materials, structural designs, robotic architectures, and fabrication techniques that increase their practicality towards real-world applications.[15] With continued research and development, soft robotics is poised to revolutionize the field of robotics, unlocking new possibilities in the creation of robots that can move and adapt in complex and challenging environments.

Even in the field of conventional robotics, there has been high interest in developing next-generation robots that can adapt to different environments with multimodal locomotion, as reviews have reported extensively on strategies to enable amphibious robots and aerial-terrestrial robots.[16,17] Although some reviews have sparsely noted the importance and progress of multimodal locomotion in soft robots, there has been a lack of an exhaustive report on soft robots with multiple gaits of locomotion and the approaches to accomplish these designs. Previous reviews have comprehensively examined the literature on soft actuators, including actuator materials, performance, design, fabrication, and applications.[18–21] On the other hand, soft robotics reviews have focused on various aspects of directions in the field, such as mechanisms of locomotion, miniature soft robots, untethered soft robots, magnetic soft robots, bioinspired soft robots, and more.[2,3,11,22,23] Hence an analysis on the current state of multimodal soft actuators and robotic locomotion is invaluable. Also, while previous literature has typically focused on either soft

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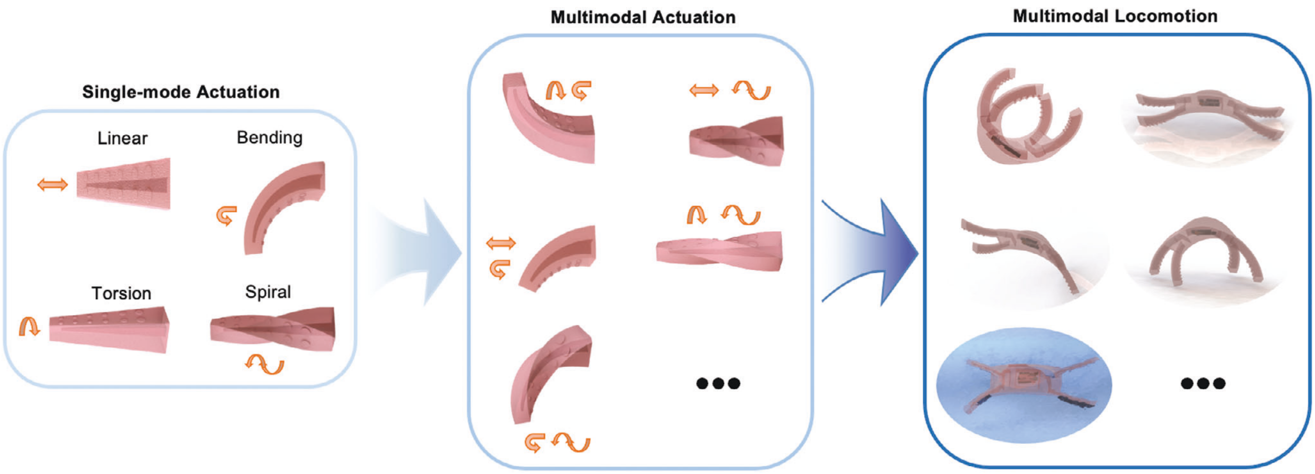

Figure 1. Building toward multiple complex soft robotic locomotive gaits through the combination of single actuation modes and controlling multimodal actuation abilities to produce complicated motion. Left: the basis of unique deformation modes, including linear, bending, torsion, and spiral. Middle: bimodal actuation combining individual modes. Right: multimodal locomotion in a soft robot, including rolling, crawling, jumping, walking, and swimming.

actuators or soft robots, this review aims to further bridge the connection between the complex deformation motions of soft actuators and the complicated locomotion of soft robots.[24] By organizing and outlining the strategies that have been used to achieve multimodal motion in soft actuators and robots, this review aims to inspire the application of these approaches to developing soft machines that are capable of a wider and more diverse range of sophisticated movements that could potentially rival actuation motions observed in biological creatures.

In this review, we explore the development of soft actuators, from basic modes of deformation leading up to multiple modes, and their application into soft robots to enable adaptability and multiple gaits of locomotion (**Figure 1**). First, we provide a brief overview of soft actuators, including smart materials that respond to various stimuli and the simplest actuation motions that they can produce. Then, we discuss strategies to combine different forms of actuation motions in multimodal soft actuators. Finally, we examine how the use of soft actuators enables complex multimodal gaits of locomotion in robots. The range of multimodal soft robots includes fully soft-bodied actuators that are freely moving, engineered robotic systems that apply a combination of functionally soft and rigid structural materials, and robots that use soft materials to actively transform their morphology for locomotion under different environmental conditions. We broadly consider soft robots that are entirely composed of soft materials, as well as robots that consist of soft functional components that are essential to their multi-locomotive abilities. Through these examples in literature, we highlight the importance of soft materials in producing complicated and diverse actuation motions and gaits of robotic locomotion.

2. Background of Soft Actuators

Soft actuators exhibit high flexibility and inherent compliance to arbitrary surfaces while deforming their shape.[25] They have undergone rapid and vigorous development and hold immense potential as vital components in the next generation of robotics.[26] In comparison to traditional rigid robots, mostly powered by electricity, soft actuators are considered highly suitable for a wide range of applications due to their adjustable characteristics, including the materials, types of energy sources, structural designs, and fabrication methods.[27] Despite the relatively recent emergence of this research field, substantial progress has been reported in exploring individual elements and actuation strategies.[20] This review will focus on different types of stimuli and structural designs, revealing a trend towards the emergence of highly versatile soft actuators at a more advanced level.

2.1. Strategies for Soft Actuators

Soft actuators, comprising compliant materials responsive to external stimuli for generating specific motions, rely on various actuation strategies.[28] These soft actuator materials have had a long developmental history spanning decades, and include a broad spectrum of elastic moduli, from pascals to gigapascals.[29] In this review, we define soft actuators as intrinsically deformable materials with comparatively low elastic modulus, exhibiting high flexibility, generating significant strains, and enabling intricate motions with multiple degrees of freedom. Such characteristics are particularly advantageous in the realization of dexterous soft robotics. Among these materials, we will provide an overview of common soft materials that have attracted immense attention in the field, including soft actuation in polymers, elastomers, and gels, based on their actuation mechanisms.

2.1.1. Shape Memory Polymers

Shape memory polymers are distinguished by their ability to exhibit the shape memory effect but within a cross-linked network.[30] Via the shape memory effect, these polymers can undergo temporary deformation with an adjustable stiffness when subjected to specific transitions induced by external stimuli.[31–33]

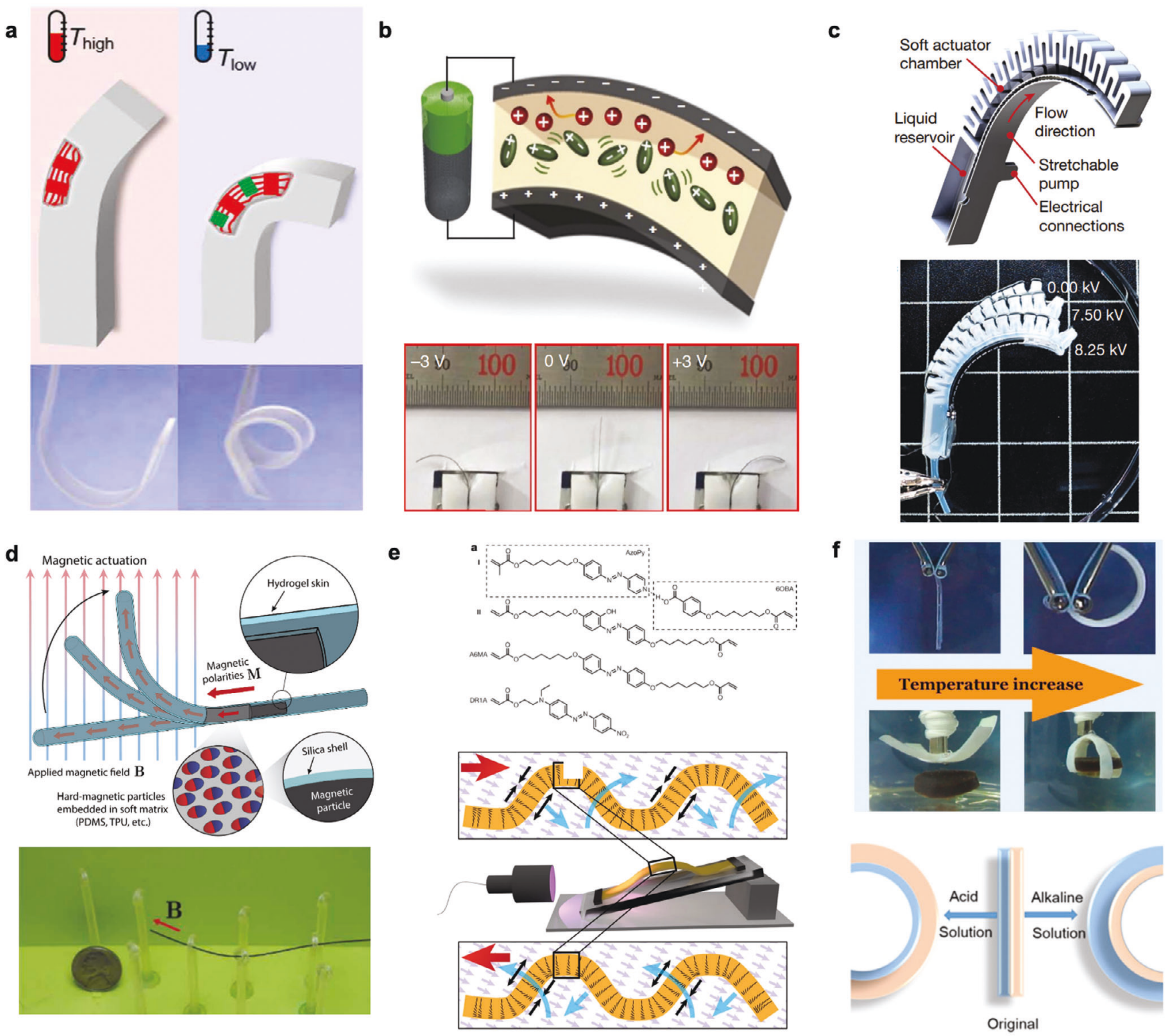

Figure 2. Soft actuators with different soft materials. a) Shape memory polymer actuators with segment chain orientation programming showing shape deformation upon temperature variation. b) Soft actuators made from electroactive polymer composed of cation-conducting block copolymer sandwiched between the electrodes along with the displacement and bending strain at alternating square-wave voltages. c) Stretchable pump, reservoir, and bending chamber made from fluid-driven elastomer. d) Magnetic elastomer with hard magnetic particles embedded in a soft polymer matrix that can navigate through a set of ring obstacles. e) Liquid-crystal networks incorporating azobenzene derivatives that exhibit continuous, directional, macroscopic mechanical waves through photochemical reactions. f) Temperature-responsive hydrogel with tunable mechanical properties, and hydrogels that respond to pH by incorporating chemical groups capable of dissociation. a) Reproduced with permission.[34] Copyright 2018, AAAS. b) Reproduced with permission.[42] Copyright 2016, Nature Publishing Group. c) Reproduced with permission.[65] Copyright 2019, Nature Publishing Group. d) Reproduced with permission.[76] Copyright 2019, AAAS. e) Reproduced with permission.[88] Copyright 2017, Nature Publishing Group. f) Reproduced with permission.[100] Copyright 2015, American Chemical Society. Reproduced with permission.[101] Copyright 2020, American Chemical Society.

For instance, by programming spatial anisotropy within the structure of shape memory polymers, subsequent heating triggers the transition of molecular chain orientations, leading to heterogeneous deformation and subsequent notable actuation output (**Figure** 2a).[34] Moreover, the shape memory effect in polymers is not solely limited to temperature-induced transitions as alternative strategies have leveraged supramolecular interactions to impart shape memory behavior.[35] These actuation mechanism also hinges on entropy change, in which the initially rigid active material softens in response to stimuli such as photochemical interactions, stress, humidity, or pH, activating molecular chains and causing shape deformations.[36] Despite the inherent advantages of shape memory polymers, challenges persist, notably in addressing poor response times and difficulties in precisely localizing heating for specific actuation sites.

2.1.2. Electroactive Polymers

Electroactive polymer actuators consist of a variety of polymers that deform in response to an applied voltage or electric field.[37] While polymers are well-known for their insulating properties, conjugated polymers can become electrical conductive through molecular arrangements that facilitate alternating single and double bonds in the polymer chain, enabling enables sharing of electrons among atoms.[38,39] When a voltage is applied to oxidize or reduce the conductive polymer in solution, large deformations occur at low voltages, thereby converting electrical energy into mechanical work. Another type of electroactive polymer is ionic polymer–metal composites, which consist of an ionic polymer layer between two metal electrodes and demonstrate rapid electromechanical responsiveness (Figure 2b).[40–42] By applying a voltage across the metal electrodes, positively charged cations migrate towards the negative cathode causing an asymmetric distribution that bends the actuator.[42] The actuation performances, such as strain rate, bending radius, and ion transport efficiency, can be tailored based on the structure design and fabrication techniques.[43,44] Rather than an ionic polymer sandwiched between two metal electrodes, dielectric elastomer actuators contain an insulating elastomer between electrodes.[45–48] Functioning as an electric capacitor, the elastomers serve as a deformable dielectric, and an electric potential generates an electrostatic attraction force induced by Maxwell stress that compresses the structure.[49,50] Lastly, piezoelectric polymers are a group of electronic electroactive polymers that exhibit the piezoelectric effect, including poly(vinylidene fluoride).[51,52] Via the piezoelectric effect, polar groups in the polymer align to the direction of an electric field and experience a force that causes deformation and displacement of the polymer for actuation.[53] Despite the efficiency of electrical stimuli in terms of controllability and high electrochemical performance, these methods still heavily rely on a wired tether for power, and they may suffer from instability caused by electrical breakdown defects during operation.

2.1.3. Fluid-driven Elastomers

Actuation through inflation is a widely employed strategy, often referred to as pneumatic and hydraulic actuators, which primarily depend on pressurized gas or liquid within flexible elastomers.[54–57] Fluid-driven elastomers include silicone elastomers, like polydimethylsiloxane, with hydraulic or pneumatic channels patterned into them, or inflatable rubber membranes with a braided sleeve to confine the actuation.[58–60] Not only are these actuators able to perform contraction and expansion by controlling fluidic mediums in confined spaces designed with inflatable materials, but they also offer diverse locomotion options varying the stiffness of flexible materials or creating multiple actuators in series.[61,62] Fluidic actuators gained popularity in the early stages of soft robotic applications due to their high energy efficiency, significant deformation capability, and safe operation.[63,64] For instance, wearable pneumatic actuators that incorporate stretchable bidirectional solid-state pumps have functioned as a highly deforming fluidic muscle with a high bending angle (Figure 2c).[65] Moreover, 3D-printed modular pneumatic grippers, in conjunction with mechanical metamaterials, have demonstrated excellent conformal grasping of soft objects in various dynamic conditions.[66] Additionally, hydraulically amplified self-healing electrostatic artificial muscles, consisting of a fluid within an elastomer, can be pressurized by the electrostatic attraction of electrodes, and have shown specific power output exceeding those of natural muscles.[67–69] However, it should be noted that these actuation strategies often lack precise controllability and necessitate the use of wires and auxiliary equipment.

2.1.4. Magnetic Elastomers

Elastomers controlled by magnetic fields have the unique ability to selectively generate additional torques or forces based on the interaction between an external magnetic field and the magnetic properties of the actuator.[70–72] Magnetically responsive materials are of high interest in soft robotics as the ferromagnetic properties in a material can be programmed into complex structures, and the externally applied magnetic field can be quickly tuned by electromagnetic coils or moving permanent magnets to adjust the direction and magnitude of the field.[23] These actuators have undergone intensive development due to their sophisticated operation, owing to the ability to vary the applied magnetic field with different intensities, directions, and gradients.[73] Since the interaction between magnetic field and ferromagnetic materials is nearly instantaneous, magnet-based actuation results in high actuation power.[74] This versatility plays a crucial role in enabling multimodal locomotion for soft robotics particularly suitable in medical applications. One remarkable example is the use of magnetic nanoparticle-embedded silicone elastomers, which serve as untethered millimeter-scale soft robots capable of various sophisticated locomotion modes by control of external magnetic fields in different terrains.[75] Furthermore, the incorporation of programmed ferromagnetic domains in the homogeneous magnetic nanoparticle and soft matrix enabled omnidirectional steering, facilitating effective navigation tasks even in constrained cerebrovascular phantoms (Figure 2d).[76] Aside from magnetic elastomers, magnetically responsive robots have relied on flexible hinges and springs between magnetic materials, such as in shape-morphing nanomagnet micromachines.[77] While magnetic actuation has strong advantages and a broad design space, magnetic fields have a limited range as the field magnitude exponentially decays with distance from the source.[78] This constrains the working volume that can be controlled with a magnetic field source or limits the actuation force.

2.1.5. Liquid Crystal Elastomers

Similar to shape memory polymers, liquid crystal elastomers undergo significant shape deformations beyond material-specific phase transition temperatures with reliable intermolecular transition characteristics.[79,80] Anisotropic alignment of liquid crystal enables reversible actuation with high strain values, based on thermodynamic phase transition upon the application of external heat.[81] In this system, techniques of programming units of liquid crystal mesogens before crosslinking play a crucial role in their properties and shape deformation characteristics.[82,83]

Alignment of mesogens in desired directions has been demonstrated using mechanical stretching, surface forces, polarized light, and photomasks for patterning, structured films as well as magnetic and electric fields.[84–86] Precise and scalable programming of mesogen domains was realized by exploiting the high operating temperature-direct ink writing technique.[87] Apart from thermal actuation, light-based actuation can be enabled in liquid crystal elastomers through two different working principles, primarily stemming from the photothermal effect and photochemical reactions.[88,89] Photothermal actuation involves macroscopic shape deformation resulting from the conversion of light energy into thermal energy by photothermal components embedded within the material matrix, which in turn triggers temperature-based mechanical actuation. For example, incorporating carbonaceous fillers into a liquid crystal elastomer matrix enabled precise actuation via controlling the light source and enhanced actuation performance.[90,91] On the other hand, photochemical reactions involve initiating shape deformation of the entire matrix through chemical processes within the polymer matrix, resulting from alterations in molecular crosslinking or ordering (Figure 2e).[88,92,93] These versatile actuators have shown promise for a wide range of real-world applications owing to their outstanding actuation performances, which can be achieved by delicate fabrication techniques that tune molecular alignment. However, they typically suffer from challenges similar to shape memory polymers, including slow response time, poor mechanical properties in the isotropic phase after heating, non-localized heating, and others.

2.1.6. Gels and Hydrogels

Gel-based soft actuators utilize gels, swollen polymer networks, as the primary material for actuation.[94] Gels can be categorized based on the type of solvent within their structure, including hydrogels, organogels, and ionogels.[79,95] These actuators have the ability to react to alterations under environmental influences, such as temperature, humidity, and pH, undergoing either swelling or deswelling processes as a response. This leads to a transformation in volume and shape, determined by the equilibrium between the elastic deformation of chains and the mixing energy. Ionogels possess benefits in actuation, including recyclability, nonflammability, nonvolatility, and high ion conductivity.[96] Of all gel actuators, hydrogels are the most extensively used for soft actuators, owing to their abundant, non-toxic, and non-irritating characteristics.[97] While many hydrogel actuators respond to water through osmosis, pressurized water in hydraulic hydrogel actuators overcomes limitations of low actuation speed and force by swelling.[98,99] Another type of hydrogel actuator is temperature-responsive, as hydrogel-based actuators and grippers consisting of alginate and poly(N-isopropylacrylamide) have been demonstrated with tunable mechanical properties (Figure 2f).[100] On the other hand, hydrogels that respond to pH and ionic strength, are engineered by incorporating chemical groups capable of dissociation/ionization into the polymer structure.[101,102] Several studies have aimed to enhance the response time through the use of new composites, geometries, or a combination of stimuli.[103] Gel-based actuators display high biocompatibility with living systems and straightforward fabrication, making them promising for biomedical applications.[104,105] However, challenges persist in integrating them into complex device systems due to limited controllability and work density arising from issues such as breakage at moderate elongation, attributed to a high degree of stretching of polymer chains caused by their interactions with solvent molecules.

Crucially, the type of soft actuator material determines the external stimuli that can trigger deformation based on the actuation mechanism, including temperature, electrical field, pneumatic forces, magnetic field, and chemical solvents.[106] Strategies employed to convert energy into the necessary stimuli for actuation have significantly enhanced the convenience of this process. For example, resistive materials can be used for localized heating in temperature-responsive materials, as running electrical currents in the resistive material generate heat via Joule heating.[107] Photothermal materials can absorb broad spectrums of photons, such as those from a laser, to generate vibration on the molecular scale that results in the heating of the temperature-responsive materials.[89] Heat can be generated from alternating magnetic fields that cause temperature to increase in ferromagnetic magnetothermal particles.[108] Furthermore, magnetothermal particles were reported to heat a liquid-to-gas phase transition temperature, generating a gas that actuated pneumatic artificial muscles.[109] Alternatively, compact electrically powered soft pneumatic pumps have been reported that can responsively power pneumatic soft robots to replace large and bulky conventional air pumps as power supplies, conveniently converting electrical power to a pneumatic source.[65,110] Electromagnets are widely used to convert alternating electrical current into magnetic fields that can be used to manipulate soft magnetic robots.[111] Combinations of stimuli can also enhance the performance of soft actuator materials, as photothermal stimulation on dielectric elastomers has been shown to lower the driving electric fields, which can have dielectric breakdown at high voltages.[112] Applying an electric field on hydrogels in an electrolyte-rich solution can also increase the rate of swelling.[113] Furthermore, these soft materials have proven useful across different actuator architectures, such as hydrogels being used as the ionic polymer in ionic polymer-metal composites, ionically conductive hydrogel electrodes in dielectric elastomers, and liquid crystal elastomers being applied as the insulator in dielectric elastomers to function as electroactive polymers.[114–116]

2.2. Modes of Deformation

While living creatures move in complex and agile manners, the coordinated contraction of many individual muscle fibers is the basis of creating such diverse motion.[117] Periodic movement of muscle fibers and interactions between muscles and other components to create asymmetrical forces are the key principles of creating different forms of movement.[118] Unlike biological muscles that address many microscopic actuators for fine motor movements, soft actuators rely on a few stimuli applied across large macroscopic volumes to trigger specific modes of deformations in a monolithic actuator.[119] While intricate and sophisticated motions produced by biological organisms appear to be complex, they can be broken down into elementary motions.[106] Breaking down the basic types of motion modalities that are

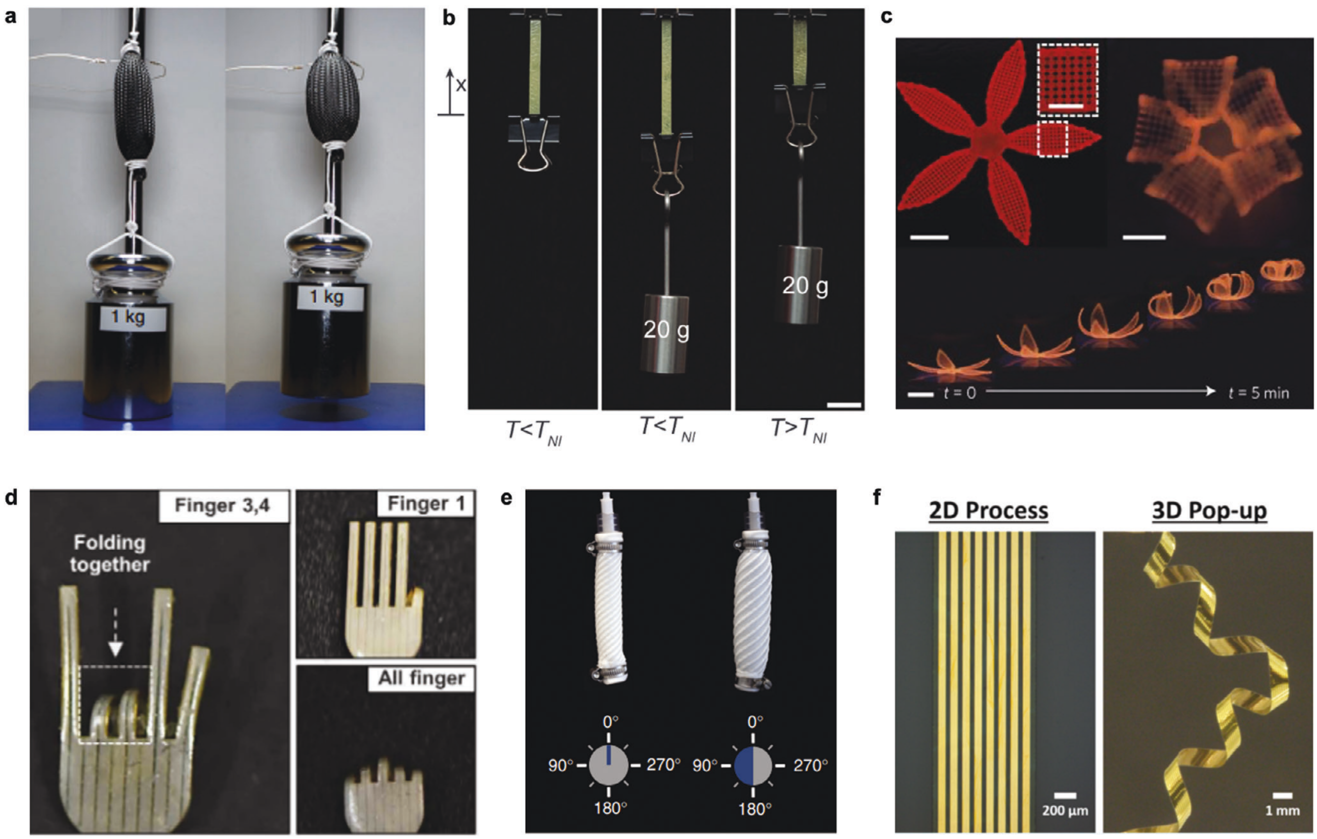

Figure 3. Examples of different motions of soft actuators. a) Mckibben-type fluidic artificial muscle, composed of soft material and braided mesh sleeving, lifting weight of 1 kg through linear motion. b) Linear contractive motion by a unidirectional printed liquid crystal elastomer actuator upon heating. c) 4D printing of anisotropic hydrogels for bending actuation after swelling in water. d) Millimeter-scale soft gripper, constructed from shape memory polymer, achieving distinct finger positions through selective folding using silver nanowire Joule heaters. e) Fabricated through multimaterial 3D printing of silicones, the soft actuator exhibits a torsion motion produced by coiling stripes around the inner soft tube, set at a lead angle of 45° relative to the elongated axis. f) Liquid crystal elastomer actuator patterned with twisted nematic orientation within the substrate, undergoes controlled morphing into 3D structures, resulting from spiral motions. a) Reproduced with permission.[123] Copyright 2017, Nature Publishing Group. b) Reproduced with permission.[87] Copyright 2018, John Wiley & Sons. c) Reproduced with permission.[131] Copyright 2016, Nature Publishing Group. d) Reproduced with permission.[132] Copyright 2021, AAAS. e) Reproduced with permission.[120] Copyright 2018, Nature Publishing Group. f) Reproduced with permission.[138] Copyright 2019, American Chemical Society.

possible in actuators, these include linear, bending, torsional, and spiral motion.[106,120,121]

2.2.1. Linear Motion

Soft actuators capable of achieving linear motions are of significant importance in various applications that demand precise and continuous movements along a straight path. One such application is artificial muscle systems, where the ability to generate linear motion is highly desirable. The initial McKibben artificial muscle served as a pioneering example, demonstrating linear motion through fluidic volume expansion within an inflatable material.[122] To enhance linear contraction in soft actuators, efforts were directed toward designing compliant structures that imitate the flexibility of biological muscle aiming for substantial output force density (**Figure 3**a).[123] Alternatively, employing multiple actuators in series has been explored as a means to amplify deformations and improve performance.[124] Despite the impressive strength of fluidic-driven soft actuators, it still lacks practical adaptability as it can be difficult to adjust the actuation properties of the material. Currently, stimuli-responsive smart materials like highly aligned liquid crystal elastomers can be programmed to have spatial variation in the internal structure for more versatile applications. During actuation, these materials exhibit reversible linear contraction along the axial direction and are capable of lifting heavy weights relative to their own mass (Figure 3b).[87] Consequently, such materials are considered an efficient and promising strategy for achieving soft actuation with the added potential for tailoring contraction properties and incorporating new functionalities through composite structures. Additionally, in a recent development, linear contraction was successfully achieved in a highly aligned fiber-type actuator through the utilization of a nanostructured block copolymer with alternating crystalline and amorphous domains.[125] This unique shape deformation mechanism was based on the transformation of self-assembly and strain-programmed crystallization of the solution-phase block copolymer, leading to reversible macroscopic length variation when exposed to various stimuli.

2.2.2. Bending Motion

Bending motion plays a crucial role in various soft actuators to move and interact effectively with their surroundings. Functional bending motions are especially useful in soft grippers for delicate objects, and are also essential for creating walking or crawling motions in soft robotics.[126,127] Strategies employed in soft actuators to achieve bending motion primarily involve designing heterogeneous structures that vary in material or material properties, resulting in uneven actuation. For instance, integrating constraints at specific positions along flexible gas chambers induces highly bent structures by limiting elongation on one side of the actuator.[57] Precise control of the bending angle can be achieved by adjusting the input gas pressure. Moreover, by incorporating and manipulating azobenzene moieties in the liquid crystalline network, reversible transformation could be achieved through ultraviolet light exposure.[128,129] In the pursuit of versatile actuation, bending angles are controllable by the light intensity or thickness ratio of bilayer structures. Additionally, a hygroscopic soft actuator was engineered to perform as a gripper, utilizing heterogeneous surface chemistry of aligned liquid crystal elastomer films.[130] Treating one side of the film activated with an acidic solution affected the wettability asymmetrically, enabling bending motion in a programmed direction. An alternative hygroscopic actuator was 4D printed with aligned cellulose fibers in a hydrogel to program anisotropic swelling in water to cause bending, much like the anisotropy of swellable cell walls in plants (Figure 3c).[131] Another intriguing approach involved the construction of a millimeter-scale soft gripper based on a composite structure of shape memory polymer film with a subsequent coating layer as a strain-limiting layer of different stiffness (Figure 3d).[132] The actuator deformed towards the side with greater force due to an unbalanced force resulting from the structural configuration. This allowed a natural human finger-like bending motion for delicately gripping objects such as snail eggs without causing damage. The versatility and control offered by bending motion in soft actuators hold promising diverse applications in soft robotics and other fields requiring delicate and precise interactions with objects and environments.

2.2.3. Torsional Motion

Considerable progress has been made in advancing torsional motion in soft actuators, particularly in twisted and coiled configurations of fibers, which have demonstrated improved performance compared to linear actuation with limited strain. Post-treatment processes involving twisting flexible polymer fibers, followed by thermal volume expansion, resulted in significantly increased actuation strokes and superior output force.[133] During thermal actuation, helically oriented single chains in twisted configurations were subjected to transition into random coil configurations, enabling overall shape deformation. In addition, strain-programmable twisted fiber actuators have been demonstrated to achieve reversible actuation based on the mismatch in thermal, mechanical properties within a bimorph structure.[134] Fiber-type actuators with twisting motion have been actively developed as a concept of artificial muscle fiber, employing various material combinations and actuation strategies to take advantage of their high-performance features, including long-life cycles, torsional strokes, actuation speed, and response time. More intuitively, torsional motion was demonstrated in a soft actuator by using an asymmetric constraint introduced in a pneumatic preprogrammed structure (Figure 3e).[120] By adding spiral stripes to the outer surface of an elastic body with both ends fixed, a substantial torsional angle could be achieved upon inflation of the structure, without inducing any bending or extensions. Future directions in developing torsional actuators should focus on preventing tensile movements that are coupled in torsional actuation for some mechanisms.

2.2.4. Spiral Motion

Similar to bending motion, spiral shape deformation can be achieved through non-uniform shrinkage, especially in bilayer structures. However, spiral-shaped actuation occurs when there is a significant degree of geometrical mismatch arising from non-uniform shape deformation larger than the bending motion.[135] By fabricating a bilayer film in a shape-morphing material, different stresses in the two layers generated from variations of printing patterns result in helical structures when subsequently heated above the glass transition temperature. This fabrication approach enables tailored actuation modes, ranging from bending to spiral motions. Interestingly, spiral motion could also be attained through a coupling effect by combining two different bending and torsional motions within a composite structure.[136] The structural design involves the torsional extension of the core actuator part through pressurized fluid, while the strain-limited side of the fabric sleeve undergoes a bending motion, causing the entire structure to accomplish a spiral motion that effectively winds around objects, serving as a gripper. Furthermore, spiral motion can also be realized using liquid crystal elastomer actuators, as macroscopic shape changes are strongly dependent on the direction of self-assembled molecular order. Various approaches can be employed to achieve spiral motion, such as inducing helical alignment at different angles with respect to the director orientation during the fabrication step and creating ribbon structures from the pattern using photolithography after cross-linking can bring a dramatic spiral deformation upon heating (Figure 3f).[137,138]

3. Multimodal Soft Actuators

In contrast to the previously discussed soft actuators that are limited to one type of specific movement in response to a stimulus, recent attention has shifted towards advanced multimodal actuators. This novel concept allows actuators to execute various actions in reaction to external stimuli, making them highly suitable for intricate tasks as versatile soft robots across a broader spectrum of applications. Achieving multimodal functionality in soft actuators with diverse actuation modes, including shape deformations and responsiveness to various stimuli, is attained by careful structural design or by combining multiple actuation modules. Here, we categorize two distinct strategies for enabling multimodal actuation, namely single-stimuli-responsive multimodal actuators and multi-stimuli-responsive multimodal actuators. While single-stimuli-responsive multimodal actuators exploit different ways to heterogeneously apply a single type of stimulus for varied modes of deformation, multi-stimuli-responsive multimodal actuators rely on applying different types of stimuli, separately or together, to achieve various deformation patterns.

3.1. Single-Stimuli-Responsive Multimodal Actuators

Multimodal actuators responsive to single stimuli exhibit their versatility through structural design, material composition, and the manipulation of stimulus direction to achieve a range of shape deformation modes. For instance, integration of electrical heating wires within a liquid crystal elastomer matrix resulted in a tubular soft actuator with different deformation modes (**Figure 4a**).[139] The structural design grants the actuator the ability to execute diverse forms of deformations, including omnidirectional bending and linear contraction, all of which are controlled by electrical inputs. Remarkably, by strategically regulating the electrical heating across distinct regions of the aligned matrix, the actuator was shown in applications as a functional soft gripper and for an untethered soft robot in an integrated system.

Furthermore, silicone-based soft actuators were digitally programmed and 3D-printed into complex architectures, incorporating different materials to yield desired structural deformations by pneumatic force.[120] Inspired by the mechanisms observed in plant systems and muscular hydrostats, various shape deformations such as contraction, expansion, and twisting modes were demonstrated. This was achieved through meticulous control of the lead angle of the stiffer component relative to the elongated axis of the soft cylindrical segment, manipulation of the density of stiffer segments, adjustment of the elastic modulus ratio between the stiff and soft components, and tuning the aspect ratio of the cylinder.

Multimodal actuation can be also achieved by incorporating single material actuators in series. Elaborate configurations of individual pneumatic actuators, capable of reversible contraction and elongation, exhibited a diverse range of motions including bending, flexing, and extending.[140] Notably, these functional movements were achieved even without the strain-limiting elements within the system. Bimorph-actuating electronics were developed with a sensory system to enable perceiving and responding to the surroundings, and the shape adaptability arose from the configuration of heaters innervated in the system (Figure 4b).[107] Through a process of sequential electrothermal actuation for each independent part, complex shapes were achieved.

Moreover, another report showed reconfigurable magnetization within soft composite materials, allowing programmable distribution of local magnetization with remarkably fast response and high precision (Figure 4c).[141] By altering the relative positioning between the soft robot and the field shaper, a dynamic interplay between local static and dynamic motion modes can be cooperated. Such manipulation results in a variety of shape deformation modes, contributing to the accomplishment of specific tasks facilitated by the exceptional performance exhibited by these sophisticated soft robots.

3.2. Multi-Stimuli-Responsive Multimodal Actuators

Varying structural design and material composition allows soft actuators to have multiple responses with a singular stimulus, but a limited range of motions is achievable. Conversely, the adoption of multi-stimuli-responsive actuators presents a paradigm that imparts an elevated level of autonomy in configuring shape deformation modes, thereby increasing the level of versatility and enhanced adaptability. The two main strategies for creating multi-stimuli-responsive materials are either composites with particles mixed into a scaffold to add functionality, or a multilayer structure with each layer responding to different stimuli that induce a type of motion modality.

3.2.1. Particulate Composites for Multimodal Actuators

One example of a heterogeneous composite material actuator involves incorporating magnetic microparticles into an liquid crystal elastomer matrix to leverage their respective advantages for distinct motion while maintaining their independent functionality as a single module (**Figure 5a**).[142] Notably, this actuator demonstrated its functionality by executing a complex task. It could respond with torsional actuation according to a rotating magnetic field. Then, upon contact with a heated needle brought into proximity, the liquid crystal elastomer component responded by spiraling actuation to curl and grasp around the hot needle.

Another particulate composite consisting of mixing liquid metal droplets into a liquid crystal elastomer matrix was fabricated via 3D printing. This actuator could respond to various stimuli and actuation modes based on the concentration of filler content.[143] For instance, at certain liquid metal concentrations, the actuator exhibits reversible bending motion due to photothermal response, while at other concentrations, electrothermal response through Joule heating enables linear motion after the formation of a percolated network.

A composite consisting of hard magnetic particles and shape memory polymers was also 3D printed to form multimodal shape transformation abilities.[144] While this device does not respond to stimuli according to the four basic types of actuation motion modalities, printed structures had five different states depending on whether temperature and magnetic fields are applied, and the direction of the magnetic field. The tunability of these materials ensures precise control over the transformation process, facilitating various mechanical behaviors.

3.2.2. Bilayer Composites for Multimodal Actuators

Rather than composites created by mixing a scaffold and particles, a multi-stimuli responsive actuator was realized by integrating a thin layer of moisture-sensitive conductive polymer with another layer of passive silicone elastomer (Figure 5b).[145,146] This arrangement led to flexible bidirectional bending motions, where

Figure 4. Multimodal actuators that are responsive to a single stimulus. a) By selectively applying electrical potential, the tubular actuator made of liquid crystal elastomer demonstrates both bending and uniform contraction modes. b) Utilizing a carbon black-doped liquid crystal elastomer nanocomposite, complex shape manipulation is achieved, resulting in diverse actuation motions through the strategic placement of Kapton film in different positions. c) Through the combination of hard magnetic particles and stretchable silicone rubber, a reconfigurable actuator exhibited a range of magnetization patterns and undergoes multimodal shape transformations when subjected to a magnetic field. a) Reproduced with permission.[139] Copyright 2019, AAAS. b) Reproduced with permission.[107] Copyright 2018, John Wiley & Sons. c) Reproduced with permission.[141] Copyright 2021, Elsevier.

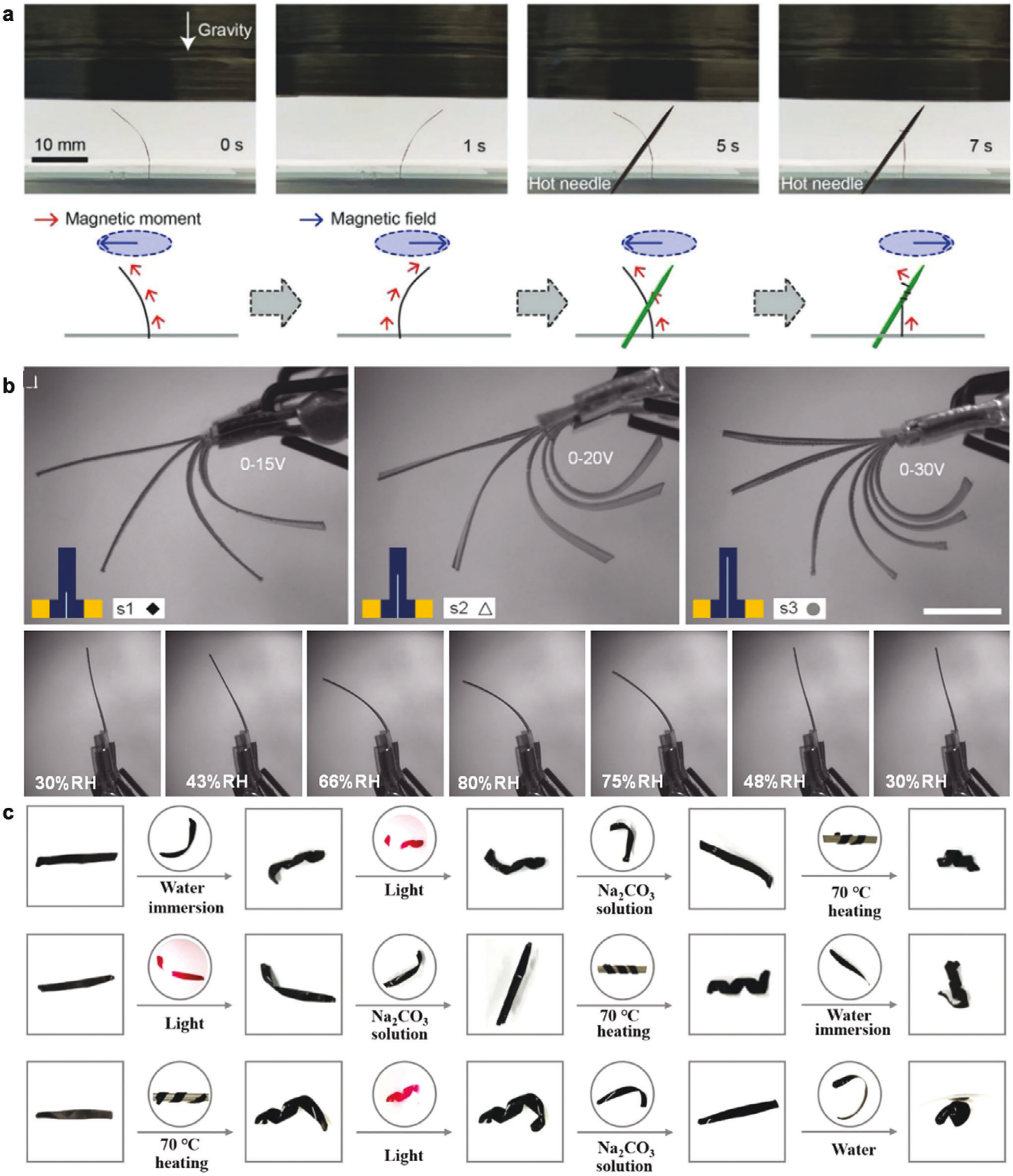

Figure 5. Multimodal actuators that are responsive to multiple stimuli. a) Magnetic microparticles embedded into liquid crystal elastomer film showing different shape deformations with torsional actuation to specific rotations by manipulating a magnetic field, followed by spiraling actuation once in contact with a hot needle. b) Hygromorphic soft composite actuator with distinctive bending motions in varying directions, arising from water desorption driven by Joule heating (upper) and water absorption triggered by variation in relative humidity levels (lower). c) Multimodal soft actuator assembled with three distinct polymer components for an energy transduction network that enables diverse actuation modes in response to six different types of stimuli. a) Reproduced with permission.[142] Copyright 2021, John Wiley & Sons. b) Reproduced with permission.[145] Copyright 2015, John Wiley & Sons. c) Reproduced with permission.[153] Copyright 2022, American Chemical Society.

increasing humidity induces water absorption and bending in one direction, while applying current causes water desorption and bending in the opposite direction. Interestingly, this design also exhibited sensitivity to touch, with the active layer undergoing deformation due to changes in electric resistance induced by mechanical pressure. Many other two-layered composite materials that respond to different stimuli have been used to achieve bidirectional bending, where typically a layer of water-responsive polymer gel induces bending in one direction due to swelling in water.[147–150]

A programmable patterned actuator with a bilayer structure exhibited multiple stimuli-responsive behavior and demonstrated functional adaptive movement.[151,152] A facile fabrication method for precise patterning on a flexible graphene oxide film using hydrogel microstamping allowed the actuator to achieve different motions in response to stimuli such as temperature, light, or humidity. Not only could this bilayer made of graphene oxide and polypyrrole show bidirectional bending, but the film with alternating sequence of graphene oxide and polypyrrole portions could also exhibit spiraling deformation when exposed to high humidity. As a result, this versatile small-sized actuator could perform various tasks, including grabbing objects, crawling, and twining, by exploiting different multimodal actuation modes.

Another dual-layer material consisted of a polysiloxane-based liquid crystal soft actuator to mimic a plant tendril. This actuator was capable of performing bending and chiral twisting through modulation of light sources with different wavelengths.[129] The underlying key mechanism of this functional actuation was the chemical compositions of hierarchical layers of soft actuators, which are capable of responding to different stimuli, enabling multiple shape deformations. Specifically, one layer was responsive to ultraviolet light and caused bending, while the other layer triggered twisting motion via near-infrared light. Likewise, a liquid crystal elastomer and magnetically responsive elastomer bimorph showed bending under a magnetic field and spiraling in response to high temperature above 80 °C.[153]

Additionally, a programmable composite polymer structure was reported that responded to several stimuli and exhibiting various modes of motion. While this composite was also a bilayer structure, its ability to respond to many different stimuli was made possible by using a passive elastomer layer along with a conductive polymer layer that consisted of an interpenetrating network of multiple responsive polymers. By controlling diverse stimuli, such as temperature, light, electricity, humidity, ions, and even organic solvents, the actuator showed diverse and programmable motions (Figure 5c).[154] This versatile and responsive actuator holds potential for applications in functional soft robotics, as it could serve as an adaptive gripper for thin objects and a self-regulating switch to maintain humidity.

Compared to previous proof-of-concept demonstrations in relevant research fields, these multimodal soft actuators, combining various multi-stimuli responsive actuation strategies in multimaterial structures, are expected to have promising implications for more practical applications in soft robotics, biomedical devices, and other fields. Soft actuators are notably essential in soft grippers that typically consist of several bending actuators.[126] However, recent progress has shown pneumatic grippers that use active entanglement, simultaneously combining spiraling, linear contraction, bending, and torsional motion, from multiple pneumatic actuators for topological grasping, which shows the importance of combined deformation motions to better manipulate and conform to objects.[155,156] Further directions in developing multimodal soft actuators may include incorporating actuators that respond to different combinations of stimuli and increasing the number of stimuli that an actuator can respond to, thereby increasing the complexity of actuation modalities. For example, a liquid crystal elastomer-based composite containing both magnetic nanoparticles and photothermal filler could be a sophisticated soft actuator. Magnetic and photonic stimuli are compatible since they can be both applied wirelessly. Moreover, this composite could enable all basic modes of deformation, as photothermal actuation enables linear contraction and bending modes, while magnetic actuation can trigger torsional and spiraling actuation, in addition to other possible deformation modes depending on the magnetization profile of the magnetic nanoparticles.[157,158] Furthermore, independently controlling each stimuli-sources and simultaneously actuating with both optical and magnetic stimuli can result in mixed modes of deformation. While engineering multilayered materials could also enable composites that respond to many stimuli for multifaceted deformations, a major limitation is that any layer that is not actuated instead serves as a passive layer that constrains the deformation modes of other layers.[159,160]

4. Multimodal Locomotion of Soft Robots

Robots composed of soft materials and actuators provide a pathway for machines that can employ various gaits of movement or that can travel across multiple environments.[161] By incorporating different modes of actuation, more complex locomotion can be achieved.[162] Hence, using soft multimodal actuators with a variety of shape-changing abilities is conducive to soft robots that are similarly capable of multiple locomotive modes. This is especially apparent for soft-bodied robots consisting of a single monolithic actuator which can deform to asymmetrically interact with an environment and drive translational motion.[163] Although this technique is feasible in simple small-scale smart materials, larger complex robotic systems instead need to be designed with considerations that allow multimodal locomotion, such as with multiple actuating limbs, functional components, or a chassis that permits complicated motions and adaptability.[164] Moreover, the advantages of soft materials for multimodal robotics are notably evident when these materials are applied to facilitate active reconfiguration and transformative shape deformation that further enhance or enable additional modes of locomotion and adaptable behaviors.[165] In contrast with conventional robots that are composed of rigid materials that are limited by a finite number of joints, soft materials that deform with high degrees of freedom governed by continuum mechanics significantly simplify the ability for time-varying shape morphing.[166] These strategies for accomplishing multimodal locomotion in soft robots are centered around the utilization of a diverse variety of soft materials that are versatile, tunable, and responsive.[167]

4.1. Multimodal Locomotion by Soft Actuators as Robots

While the aforementioned actuators are fixed in position to prevent translational displacements, soft responsive materials that

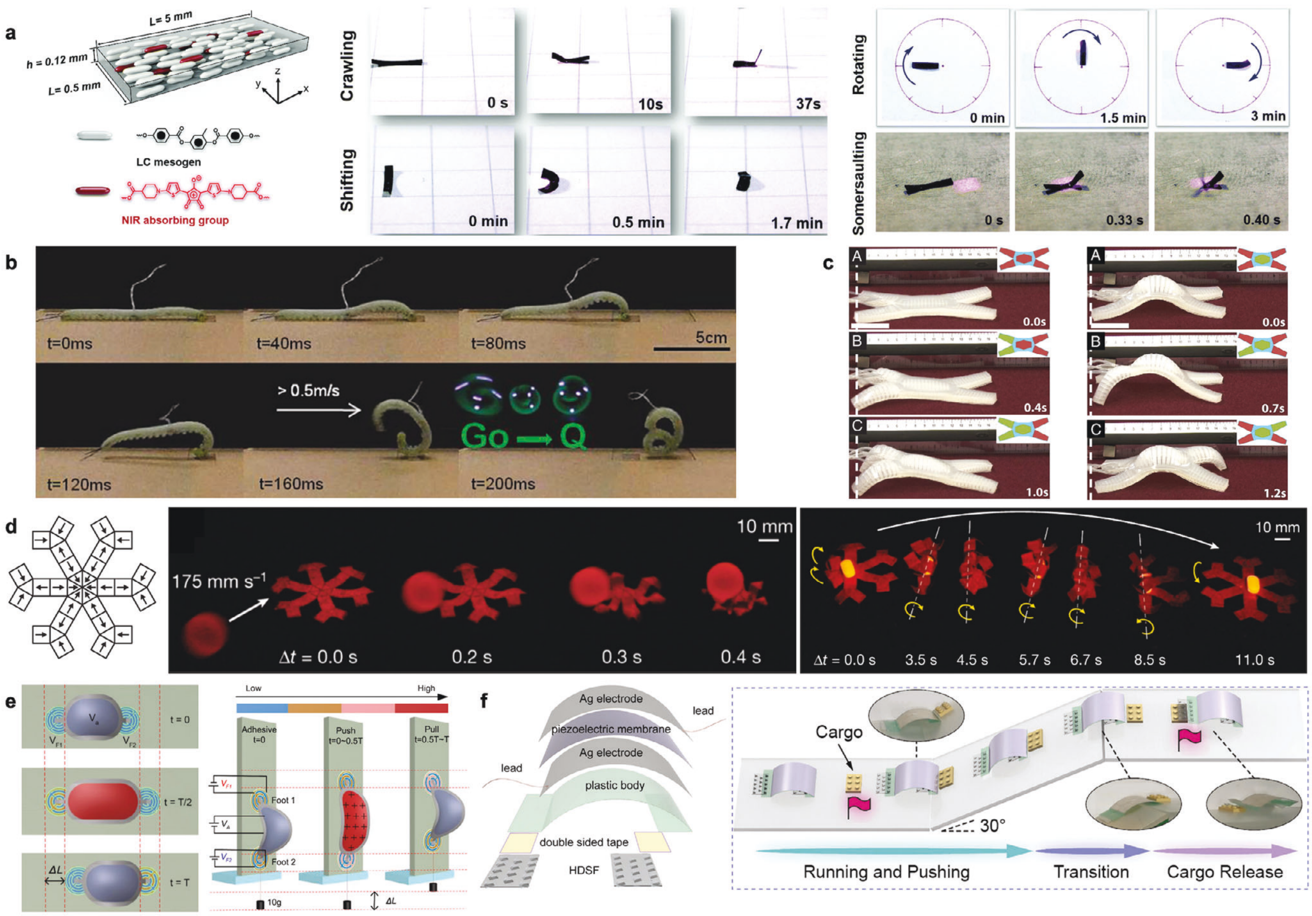

Figure 6. Multimodal locomotion gaits by soft actuators acting as free-moving soft-bodied robots on terrestrial environments. a) Near infrared-sensitive liquid crystal elastomer that can crawl, shift laterally, rotate, roll, somersault jump, and more. b) A caterpillar-inspired robot that uses shape memory alloy for crawling and rolling locomotion. c) Multigait soft robot that has two distinct crawling gaits based on the sequence of pneumatically actuated portions. d) 3D printed ferromagnetic domains for locally programmed magnetization in a centimeter-scale hexapedal magnetic robot that could walk and roll. e) Dielectric elastomer-based crawling and wall climbing robot with switchable electroadhesive feet. f) Piezoelectric driven robot that has highly directional footpads for running on flat ground and passively adapting to climbing on slopes. a) Reproduced with permission.[170] Copyright 2022, Royal Society of Chemistry. b) Reproduced with permission.[182] Copyright 2011, IOP Publishing. c) Reproduced with permission.[56] Copyright 2011, National Academy of Sciences. d) Reproduced with permission.[179] Copyright 2018, Nature Publishing Group. e) Reproduced with permission.[183] Copyright 2023, John Wiley & Sons. f) Reproduced with permission.[181] Copyright 2018, AAAS.

are instead unfastened can be actuated against their surrounding environment, such as the ground, to generate locomotive forces that propel an actuator forward and act as soft-bodied agents.[168,169] Moreover, multimodal locomotive gaits can be realized in small-scale freely moving soft actuators by applying different external stimuli to produce an assortment of geometric deformations that correspond to a desired gait.

4.1.1. Multi-Gait Locomotion by Soft-Bodied Robots in Terrestrial Environments

Powered without the need for a wired tethered, a millimeter-scale robot was controlled by a laser to manipulate photothermal liquid crystal elastomer (**Figure 6**a).[170] This achieved multimodal locomotive behaviors that included crawling, rotating, somersault jumping, and rolling, among others. The soft-bodied robot simply consisted of liquid crystal elastomer with mesogens aligned along the length of the robot so that it contracts when actuated and included near-infrared active materials that converted light into heat for reversible actuation. The authors varied the position of incident laser light along the rectangular body of the robot and the incident angle of light to demonstrate a wide variety of shape morphing. To make use of this shape-morphing ability for different robotic locomotion, the position of the laser source was applied as a function of time in different manners. For crawling, the laser was swept along the length of the body to generate contraction and bending while one end of the robot was anchored to the ground. Rotating was shown by sweeping the laser across the tip of the robot to steer it towards that direction of the laser motion. Scanning the laser longitudinally at a faster rate than used for crawling, the robot rapidly curves to drive a forward rolling motion that creates a somersault jumping motion. Alternatively, scanning the laser laterally along the width of the liquid crystal elastomer generates a rolling motion. Combining these different modes, the liquid crystal elastomer-based robot was shown to move in different directions across a two-dimensional plane, crawl on a surface underwater, and crawl in an oil-filled glass cylindrical tube. While other liquid crystal polymers and photo-responsive materials have been similarly manipulated to perform many of the same locomotion modes, this work has notably demonstrated the widest variety of gaits, owing to a responsive near infrared-responsive monomer in the liquid crystal elastomer, careful control of the laser stimuli, and a rigorous exploration of possible modes of locomotion.[171–177]

Similarly capable of crawling and rolling gaits, a caterpillar-inspired robot was designed to study the kinematics of caterpillar locomotion (Figure 6b).[178] The caterpillar-based robot was built from a silicone rubber body with two coiled nitinol shape memory alloy actuators to separately control the motion of the posterior and anterior halves of the body. For crawling locomotion, retractable adhesion pads help to anchor parts of the body, as displacement initiates from the posterior half and actuation propagates to the anterior half, while the posterior relaxes. To achieve rolling locomotion, the authors found that high electrical stimulation intensity for fast Joule heating of the shape memory alloy is needed to generate large 1G acceleration and high angular momentum, up to 200 revolutions per minute.

Notably, the pioneering work in the field of soft robotics also employed multiple gaits to showcase the versatility of soft actuator-based robotics.[56] Using soft lithography, a tetrapod was fabricated with independently addressable pneumatic actuators made of siloxane elastomers, including four pneumatic limbs and one pneumatic channel in the spine of the robot (Figure 6c).[56] In the 16 cm long robot soft pneumatic tetrapod, the undulation gait involved propagating pressure from the rear limbs to the center, and then the front pair of limbs to drive the robot forward at a speed of ≈93 body lengths per hour. The crawling mode instead required constantly pressurizing the spine, such that the robot was arched about 5 cm high, and then alternating actuation between each of the opposing back and front legs to move at a pace of approximately 192 body lengths per hour. Combining both gaits of locomotion, the tetrapod was shown to maneuver underneath an obstacle by undulation, and then continue crawling.

While many distinct gaits of locomotion have been reported in millimeter-scale magnetic soft robots, it is challenging to reproduce multimodal locomotion in larger-scale systems due to the costly necessity to also increase the magnet size used to manipulate the system.[74] Centimeter-scale magnetic soft robots were reported by locally programming the magnetization in a 3D printing method that could precisely orient printed ferromagnetic domains at larger scales (Figure 6d).[179] The robot was 3D printed with an electromagnet mounted at the tip of the nozzle to program the polarity of magnetic particles in an elastomer scaffolded composite as it is extruded and cured. Although a planar hexapedal structure was printed, applying magnetic fields actuates the ferromagnetic domains causing complex folding that transforms the design into popped-up 3D structures. By cyclically applying magnetic fields by bringing a permanent magnet into close proximity and then removing it, a walking modality in the hexapedal robot was demonstrated. Alternatively, rolling a permanent magnet in proximity caused the hexapod to roll, which was shown to wrap and transport an oblong pharmaceutical pill. This method of intricately designing ferromagnetic domains via 3D printing shows promise for enabling additional multimodal robots. For example, in a 3D auxetic structure printed with this technique, sudden reversal of a magnetic field triggers horizontal leaping by the structure, albeit only with this single mode of locomotion for this design. Regardless, the ability to pattern complex magnetization profiles in complicated 3D structures opens the avenue for creating more diverse gaits of locomotion for soft magnetic robots at larger scales. While vat polymerization-based 3D printing has similarly produced magnetic soft millirobots, they are limited in size.[180]

Although the previous examples have demonstrated robots moving across flat terrains, an electrically powered soft robot made of a curved dielectric elastomer actuator and two electroadhesive feet was reported for crawling and climbing vertically up a 90° wall at 0.75 body lengths per second (Figure 6e).[181] The electroadhesive feet were essential to crawling, as one foot provided adhesion when a voltage was applied while the other foot was not electrically active so that it was free to move off the ground during actuation. Similarly, the electroadhesive feet were necessary to oppose gravitational forces to enable vertical climbing. In climbing mode, both electroadhesive feet were active at all times such that the robot stayed attached against the wall, but the voltage applied, and therefore the strength of the adhesion, alternated between each foot so the dielectric elastomer could overcome friction for the foot with weaker adhesion to climb upward. Although a two-legged robot could only move along one axis, coupling two robots joined side-by-side into a four-legged robot allowed the robot to steer by controlling the actuation of either side at a time, or move forward by crawling simultaneously on both sides.

Although the soft dielectric elastomer-based robot could crawl on flat ground and climb on vertical walls, it did not demonstrate the ability to transition between flat and sloped ground. Another crawler-type robot bioinspired by inchworms instead used a three-segment pneumatic actuator to power crawling on a flat surface, as well as to achieve climbing on a slope with angles as steep as a 75-degrees.[182] The robot was created from Ecoflex elastomers molded with air channels and the elastomers were surrounded by strain strain-limiting fiber outer layer to confine the actuation to linear contraction. Pneumatic lines are separated for the front and back suction feet that allow the robot to adhere to sloped surfaces against gravitational force, and channels for the head-body actuator and tail actuator segments that provide two degrees of freedom. Specific sequences of pressure control are applied to the front sucker, back sucker, head-body actuator, and tail actuator for the different modes of locomotion, including crawling, transition between crawling to climbing a slope, and slope climbing only.

However, both of these crawling and climbing robots required active control of functional feet to enable adhesion while climbing. To simplify climbing capabilities, a piezoelectric-driven soft robot used passive footpads to enable self-transitioning in challenging climbing tasks (Figure 6f).[183] The robot consisted of curved polyvinylidene fluoride piezoelectric membrane sandwiched between two sheets of silver electrodes to make the body. Of special importance, the highly direction sliding-tuned footpads consisted of inclined photolithography patterned micropillars that are angled. The anisotropic angle of the micropillars makes it so that sliding the footpads in one direction has low friction, allowing the robot to climb on sloped surfaces, while high

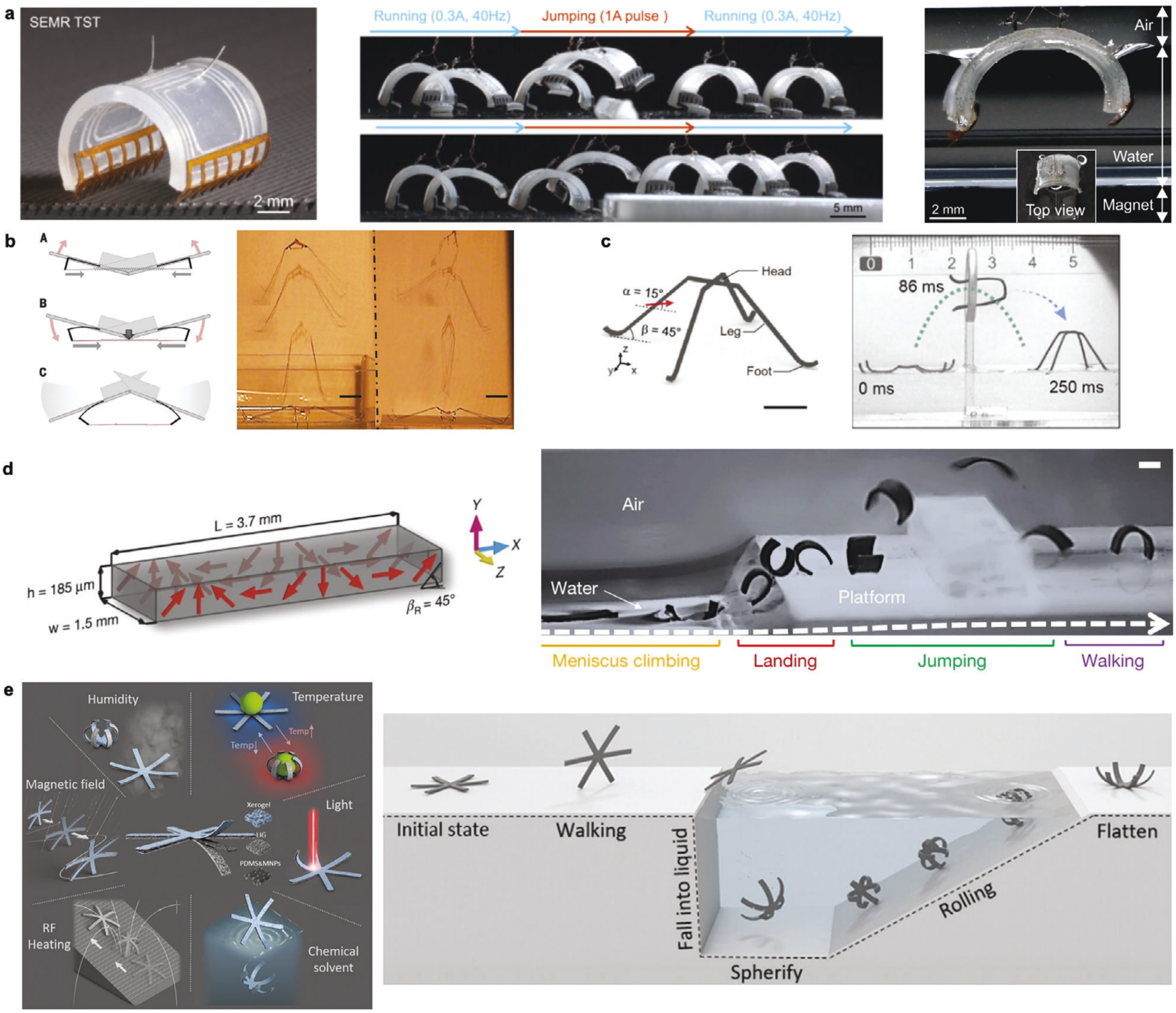

Figure 7. Multimodal locomotion by soft bodied robots across different environments. a) A soft electromagnetic actuator with liquid metal coils that can run, jump, and swim. b) Water strider-inspired jumping robotic insect that uses shape memory alloys. c) Four-legged magnetic robot that can jump from the surface of the water and delicately maneuver through obstacles in the air. d) Magnetoelastic robot with a programmed magnetization profile that enables multimodal locomotion, including crawling, rolling, walking, rolling, jumping, and others. e) Multi-stimuli-response hexapod robot that can walk and roll. a) Reproduced with permission.[184] Copyright 2022, Nature Publishing Group. b) Reproduced with permission.[185] Copyright 2015, AAAS. c) Reproduced with permission.[186] Copyright 2023, John Wiley & Sons. d) Reproduced with permission.[75] Copyright 2018, Nature Publishing Group. e) Reproduced with permission.[192] Copyright 2023, John Wiley & Sons.

frictional forces in the opposite direction prevent the robot from sliding on the slope. Not only could the robot transition from flat ground to slopes as steep as 60°, but the robot could also run on 90° vertical walls at 1.4 body lengths per second, as well as upside down at 180° due to triboelectricity and electrostatic induction improving adhesion of the footpads onto a steel plate.

4.1.2. *Multi-Gait Locomotion by Soft-Bodied Robots in Different Environments*

Although electrically responsive dielectric elastomer-based robots respond at kilohertz range frequencies, they require high voltages on the scale of kilovolts to operate. A soft electromagnetic robot composed of printed liquid metal coils embedded in an elastomeric bilayer was demonstrated to operate under several volts via Lorentz forces (**Figure** 7a).[184] Alternating the direction of the currents changes the direction of the Lorentz forces to drive bending the curved body inward or outward, rapidly deforming the elastomeric body as it pushes off the ground. Controlling the magnitude of the current and frequency allowed the small-scale electromagnet robot to move from walking to running at up to an impressive speed of 70 body lengths per second. Pulsing the robot with square waves of 1A current even triggered the actuator to leap a few millimeters off the substrate. Furthermore, the robot could swim along the surface of the water by quickly generating forces that push water to convert into forward propelling momentum, allowing the robot to swim up to 4.8 body lengths per second. Additionally, the electromagnetic robot was demonstrated in an application to transport cargo and with an onboard battery to run and swim without a tethered wire.

While the soft electromagnetic robot could only leap a few millimeters off the ground, studying the jumping motion of water striders led to the development of a robot that could jump up to 142 mm off the surface of the water and ground (Figure 7b).[185] Importantly, using soft materials allowed the design of a light 68 mg robot, which is a weight of only 6% of the maximum surface tension of water, to allow it to float. The water strider robot employed shape memory alloy legs with a curved tip that rotate inward to generate a sudden impulse of up to 13.8 *g* acceleration and maximize the momentum transfer for leaping. Additionally, the robotic water striders had a low descending velocity to avoid breaking the surface of the water. Similarly, a magnetically actuated robot inspired by water striders has been reported that could jump up to 3 cm high from not only the ground but also from the surface of water. The amphibious robot, composed of neodymium particles in an elastomer, employed the four-legged structure of arthropods and could even maneuver in mid-air after jumping (Figure 7c).[186] The bioinspired design was notably lightweight with a mass of 33 mg and density of 1.8 g cm^{-3}, allowing it to jump not only from the ground, but also from the surface of the water into air and to land without breaking the water surface. Furthermore, the pose and motion of the robot in the air were modeled and well-controlled enough to navigate aerial obstacles, like jumping over a wall or through a ring. This insect-scale robot could also walk on the ground, paddle across the surface of water, and swim underwater.

In a millimeter-scale magneto-elastic robot, manipulating the applied magnetic field led to a wide variety of modes of locomotion, including crawling, walking, rolling, jumping, and swimming (Figure 7d).[75] To create a robot with such mobility, strong magnetic microparticles were placed in an elastomer scaffold to construct the rectangular body, and the direction of the magnetization vector was programmed to vary along the length of the body. While the magnetization profile of the robot body is fixed, time-varying magnetic fields are applied to control the shape of the robot for a specific gait as well as to steer it. The soft robot could perform jellyfish-like swimming by alternating between a “C” and “V” body shape under periodically changing magnetic fields. It could roll forward according to a high-magnitude rotating magnetic field. Walking was shown by tilting a magnetic field back and forth at a small angle to cause the robot to teeter from one foot to the other cyclically. Oscillatory longitudinal traveling waves propagating through the body allow the robot to crawl on land or produce undulating swimming. Directional jumping to overcome obstacles was possible by taking advantage of the rigid-body motion and shape change to accelerate the robot into the air. Additionally, the robot was shown to climb between the underwater and air interface of a meniscus, dive to submerge underwater, and transition between water and land environments. While this report only touted the promising biomedical applications of this robot by controlling it to traverse through ex vivo chicken tissue, further work demonstrated its potential to operate in confined fluid-filled environments, namely filled cylindrical tubes to mimic blood vessels in the body. Not only were previous modes of locomotion shown by this robot in cylindrical tubes of varying diameter, but an additional mode of helical surface crawling, spiraling helically along the inner diameter of a tube, was demonstrated as this could be useful for moving against the direction of fluid flow to maintain friction along the walls the tube.[187] Further building on the seminal work, hydrogel bioadhesives were attached to the robot for sensing the physiological properties of biological tissue.[188] This included the use of a pH-sensitive hydrogel whose adhesion strength depended on the environmental pH, and another bioadhesive that could measure viscoelasticity by examining the detachment time as the magnitude of magnetic fields were varied while X-ray or ultrasound monitors the adherence to tissue. Additionally, microspikes placed on the feet of this robot enabled a peeling-and-loading mechanism for climbing 3D surfaces.[189] The preliminary ex vivo and in situ demonstrations with this robot show the feasibility of applying miniature agents for minimally invasive surgeries, drug delivery, and biosensing. And soft magnetic miniature robot inspired work has further demonstrated up to six degrees of freedom of control.[190,191]

Like multi-stimuli-responsive actuators that can perform multimodal deformations, soft robots can be designed to respond to multiple stimuli for multimodal locomotion. A multi-stimuli-responsive soft robot was developed to respond to six different stimuli structures, including humidity, temperature, light, radiofrequency heating, magnetic fields, and chemical solvents (Figure 7e).[192] The three-layer hexapod robot consisted of a magnetic elastomer layer, laser-induced graphene layer, and electrodeposited hydrogel layer, allowing it to respond to several stimuli. While six stimuli were demonstrated, in essence, the robot deformed based on water absorption in high humidity or in water to cause the hydrogel to swell, while heating that desiccates the hydrogel into a xerogel. Hence, laser-based photothermal heating of the graphene, radiofrequency-based heating of magnetothermal particles, and adjusting environmental temperature produced similar shape-morphing effects. Then, by manipulating the magnetic field the robot can be steered, such as walking on two legs when in a flattened snowflake shape. Alternatively, the hydrogel layer swells in water, causing the robot to curl into a ball, so that controlling the magnetic field can manipulate the robot to roll underwater.

While completely soft-bodied robots have high degrees of freedom, it can be difficult to decouple motion in different portions of an entirely soft robot that is mechanically homogenous. This is especially challenging in miniature machines that most commonly locomote via crawling along with other gaits.[2,193] While a monolithic soft actuator can be exploited as a freely moving soft robot, these are typically limited to miniature systems as it can be challenging to scale the materials and stimuli that are required to control these soft robots. Hence, the applications of small singular soft actuator-based robots are best suited for biomedical applications, including drug delivery, minimally invasive surgery, tissue scaffold assembly, cellular manipulation, and biosensing.[194] Such soft biomedical robots are low cost, easy to fabricate, simple to control, minimally invasive, and have soft mechanical properties that match body tissue making them safer for operation. Even though our discussion has focused on soft robots on the millimeter-scale and larger, soft microswimmers have similarly employed multi-stimuli approaches to modulating locomotion for biomedical microrobots.[195,196] Besides this, strategies to scale up fully soft-bodied robots include distributing individually addressable soft actuators to mechanically decouple their motion in a wholly soft robotic system. Other soft components like compliant joints with differing mechanical properties could divide a soft robot to uncouple the actuation of different actuators for precise control of various limbs or forms of the robot body. For example, an entirely soft robotic octopus[197] and deep-sea fish for exploration[198] with multiple separated soft actuators have been developed, albeit with single modes of locomotion. However, certain types of stimuli are better suited to accommodate the ability to address actuators in a channel-specific manner, such as pneumatics, electric, and heating, as compared to magnetic stimuli that act across large volumes or photonic stimuli that can be too localized.

4.2. Multimodal Locomotion in Robots with Soft Functional Components

Aside from fully soft-bodied creatures, nature has evolved a diverse range of animals that rely on rigid bones for complex adaptations and locomotion.[199] The skeletal system in mammals is crucial for structural support to stand and move, for locomotion as anchor points are necessary for contracting muscles, and for maintaining body shape.[200] Applying soft materials and actuators to robots with rigid components, such as joints, links, fixtures, mounts, and frames, can further enable complicated robotic designs, enhance performance, and improve locomotive abilities.[201]

Rather than placing magnetic nanoparticles into elastomeric scaffolds like the previously discussed magnetic robots, an origami Kresling sphere was sandwiched between two permanent magnetic plates to enhance its abilities (**Figure 8a**).[202] In addition to being able to roll, flip, jump, and spin to propel swimming, the magnetically controlled amphibious origami millirobot could fold and unfold to pump a stored drug for potential medical applications. The origami folds acted as fins to propel swimming as the robot spirals in water with a rotating magnetic field. Furthermore, a pulsed strong magnetic field can cause the origami structure to collapse momentarily for a pumping action, as the magnetic plates torque in opposite directions in response to the magnetic field. The amphibious locomotion was demonstrated by traveling through an obstacle course to highlight the ground locomotion, jumping into water, swimming, and cargo capture and release.

Multimodal actuators responsive to single stimuli exhibit their versatility through structural design, material composition, and the manipulation of stimulus direction to achieve a range of shape deformation modes. For instance, integration of electrical heating wires within a liquid crystal elastomer matrix resulted in a tubular soft actuator with different deformation modes (Figure 4a).[139] The structural design grants the actuator the ability to execute diverse forms of deformations, including omnidirectional bending and linear contraction, all of which are controlled by electrical inputs. Remarkably, by strategically regulating the electrical heating across distinct regions of the aligned matrix, the actuator was shown in applications as a functional soft gripper and for an untethered soft robot in an integrated system.

Many insect-scale flying robots have been reported that employ soft materials including flexible flapping wings that store elastic potential energy that quickly convert to lift forces and high kinetic energy that is needed to oppose gravity for flying.[204] Furthermore, using soft actuators like piezoelectric or dielectric elastomers allows these flying robots to remain small and lightweight.[205] However, increasing the functionality beyond taking off into flight from the ground requires careful design considerations. A hybrid microrobot driven by piezoelectric actuators also integrated many additional components to enable the transition between aquatic and aerial environments (Figure 8c).[206] Specifically, this required balance beams, a buoyant outrigger, electrolytic plates to decompose water into hydrogen and oxygen gas, a gas collection chamber, and a sparker for ignition of the gases to break from the water surface and take off. While the wing flapping frequency needed to be high to fly in the air at 140 Hz, the frequency was at 5 Hz for stable swimming due to the difference in density between air and water. The insect-inspired robot employed separate piezoelectric actuators for each wing, allowing it to control the body yaw, pitch, and roll for directional flight. A similar micro aerial vehicle included a switchable electroadhesive device for a perching mode that allowed it to hang from landing sites that were above ground level (Figure 8d).[207] Importantly, this allowed the robotic insect to not only fly but also hang in the air on a wide variety of materials, including a leaf, wood, and glass, which significantly conserves three orders of magnitude of power usage that would otherwise be needed to sustain flight, hovering at a constant height above the ground. The electroadhesive consisted of parylene C and polyimide as insulation for two copper electrodes, and a polyurethane foam damper to reduce impact, making it light and conformable to attach onto structures with curved surfaces.

A major challenge in these insect-scale robots is the need for wires for power, as heavy onboard batteries would make flying prohibitive. Hence, the use of an energy-dense power source would be invaluable in small-scale robotic systems. To address the importance of efficient powering solutions in millirobots, soft robots that use the powerful combustion of energy-dense chemical fuels have been gaining traction.[208] In a recent development, soft combustion actuators with a mass of 325 mg and power density of 277.2 kW kg1 have been reported to generate 9 N of force at over 100 Hz frequencies (Figure 8e).[209] Crucially, the combustion microactuator uses a rigid combustion chamber with an inlet for methane and oxygen fuel, an exhaust port, ignition wires to create a spark, and an elastomer membrane that deforms to provide actuation under combustion. A four-legged robot was made by incorporating four combustion actuators. Then, by controlling the sparking frequency, fuel-to-air equivalence ratio, fuel flow rate, and number of active combustion chambers, different locomotion modes were achieved. Incredibly, this powerful combustion-based robot demonstrated jumping up to 59 cm or 20 body lengths high, and 16 cm or 5.5 body lengths horizontally when using low sparking frequencies of about 1 Hz and high equivalence ratios >0.35. When high sparking frequencies of 20 Hz and a low equivalence ratio of 0.2 was used, the robot could speedily crawl at up to about 4 cm s^{-1}. Although tethers were used here to supply the fuel and ignite the spark, this robot demonstrated the effective use of combustion for high-power gaits of locomotion.

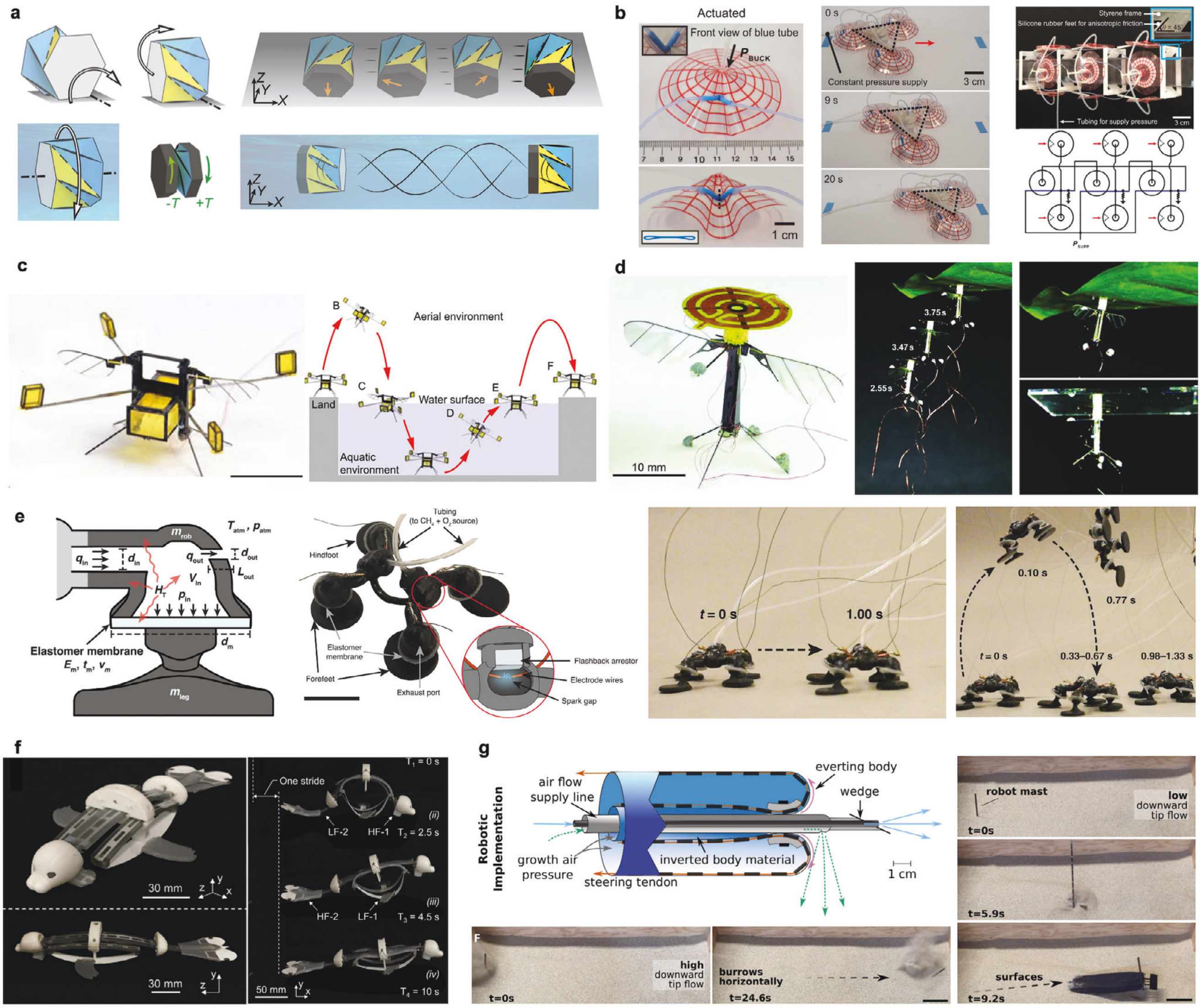

Figure 8. Multimodal locomotion by hybrid robots that use a combination of soft functional materials and rigid supports. a) Magnetically amphibious origami millirobot that can roll, flip, jump, spin, swim, and fold reversibly to pump a carried drug. b) A novel pneumatic buckling-sheet actuator used in robots that can crawl, climb a beam and dive underwater along the beam. c) Insect-scale aerial-aquatic robot that can swim and fly. d) Flying micro aerial vehicle with a switchable electroadhesive head that allows it to perch onto overhanging objects to conserve power. e) Four-legged robot that incorporates combustion microactuators for running and jumping. f) Seal-inspired amphibious robot that uses shape memory alloys to adapt to crawling on land and swimming in water. g) Soft burrowing robot made from an everting body with a pneumatically powered tip that can extend and fluidize granular media. a) Reproduced with permission.[202] Copyright 2022, Nature Publishing Group. b) Reproduced with permission.[206] Copyright 2017, AAAS. c) Reproduced with permission.[207] Copyright 2016, AAAS. d) Reproduced with permission.[203] Copyright 2022, AAAS. e) Reproduced with permission.[209] Copyright 2023, AAAS.

While all of the hybrid robots discussed so far are relatively small in scale and demonstrated in laboratory settings, it remains a challenge to create large-scale soft robots that can go out into the field for exploration, and search and rescue operations, among other applications. To address this, an amphibious seal-inspired robot was designed that could adapt to terrestrial and aquatic environments (Figure 8f).[210] In order to create a seal-size robot, two pairs of shape memory alloys were employed to control the body and tail separately for two degrees of freedom, as shape memory alloys only bend in one direction. Two additional support shape memory actuators mounted on the sides further allowed for asymmetric forces to tilt the locomotive direction. Although these shape memory alloys were encased in an elastomer matrix, rigid 3D printed plastics were used in the robot architecture, including the seal head, body and tail fixtures, side fins, and tail fins that enhance swimming performance. The fixtures also encased wiring and polyfoam blocks required to keep the robot neutrally buoyant at a constant depth in water. This resulted in a large-scale robot with a total length of 257.4 mm, weighing almost 30 grams that could adapt to land and water environments. During undulating two-anchor crawling, both body and tail actuators alternated in opposing bending directions to mimic the galumphing of a seal. On the other hand, only the tail actuator needed to oscillate upwards and downwards to propel swimming while the body actuator remained static.

Although the seal-inspired robot demonstrated crawling in the sand, a pneumatic soft robot demonstrated not only crawling on sand, but also burrowing and traversing through subterranean environments under the sand (Figure 8g).[211] The soft burrowing robot was made from an everting structure of nylon ripstop fabric with silicone and urethane, with the distal end sealed to a 60 mm diameter cylinder providing the air supply line. The supply line consisted of concentric nylon tubes for forward and downward airflow. Four braided steel tendons were equally spaced around the circumference of the body to control the steering as they could shorten. While a solid object traversing through granular media, like soil or sand, is met with strong resistive forces that impede its movement, the soft burrowing robot employed techniques to reduce the drag on the body. Critically, the air supply line tip is first extended into granular media for easy penetration before the everting skin is pneumatically driven to expand around the tip. Another important strategy is using the tip of the supply line tip to rapidly flow air against granular media causing the granular particles to act like a fluid, reducing the resistance. Lastly, using an asymmetrical wedge-shaped tip was used to reduce drag and generate. The synergistic use of a tip extension and pneumatic everting body, tip-based airflow for granular fluidization, and asymmetric wedge tip resulted in a robot that could quickly and effectively burrow into sand, emerge from subterranean environments to crawl on sand, and even navigate around underground obstacles.

Hybrid soft robots that utilize hard components make use of mechanical robustness for practical advantages, such as with advanced modes of locomotion and scaling up to larger robotic systems with fixtures and mounts to accommodate multiple soft actuators for complicated locomotion and robot architectures. This approach to soft robotics encompasses the design of biorobotics inspired by mammals that aim to emulate and study their biomechanics.[8] Additionally, creating biorobots opens the avenue to thoroughly study the neuromechanics of animal locomotion which further includes applying neuroscience to program motor control for agile, efficient, and robust locomotion.[212] The application of neuromechanical principles that incorporate environmental interactions and sensory feedback to inform decision-making could ultimately result in the development of autonomous robotic agents. Mammal-sized robots would be especially useful for search and rescue, exploration, navigation of hazardous environments, inspection, and more. On the other hand, insect-sized robots that use rigid parts like the exoskeleton of an insect could be critical for surveillance and agriculture, as the so-called "Robobees" could be critical for compensating for the decline of natural bee populations.[204] Robobees could assist in pollination for flowering plants that include crops for food production, biodiversity, and, critically, the health of ecosystems. Improving robotic flying insects to have better adaptability and operating modes for power efficiency for wireless operation is therefore critical for their success. Moreover, an aerial additive manufacturing drone that 3D prints materials for construction was introduced and bioinspired by the way in which wasps transport materials to construct hives. These additive-manufacturing drones could also benefit from the application of soft materials for reduced weight, ease of fabrication, and lowered costs.[213] Ideally, the development of this category of soft robots would produce humanoid robots that advance automation in all industries, from military and energy, to services, manufacturing, and construction.

4.3. Multimodal Locomotion in Actively Reconfigurable Soft Robots

The current generation of mobile robots has applications across outdoor field activities, including ecological monitoring and extreme environment exploration, and indoor activities like warehouse management, surveillance, healthcare, and cleaning.[214–217] One of the biggest challenges to performing these tasks involves transitioning between multiple environments.[218,219] One strategy for designing robots that can better adapt to different environments is through biomimetics. Nature offers numerous instances of organisms that employ changes in shape as a strategy for functioning effectively in demanding and ever-changing dynamic environments. Animals that primarily live in one type of environment tend to have unique body shapes and moving strategies after long periods of evolution.[220] On the contrary, cross-environment animals tend to have moderately effective body plans, propulsion mechanisms, and gaits for different environments.[221–224] For example, most turtles can both swim and crawl on land, but are usually slower than terrestrial mammals walking on land or aquatic mammals and fish swimming in water. Conventional robots tend to have a fixed design for body and moving strategies, which is not conducive to environment transiting.[221,225] However, simply adding optimal propulsion features for different environments to one robot can also result in inefficient design.[226–229] Engineers have also developed robots with characteristics reminiscent of caterpillars that can roll,[182] are modular,[230–232] include tensegrity,[233,234] grow like plants,[235] and have origami-inspired designs.[236,237] These robots exhibit a certain level of shape-changing capability. In contrast, robots made entirely or have parts that consist of soft materials and actuators open a pathway for adaptive shape-morphing abilities. While all soft robots undergo time-varying body deformation during locomotion, reconfigurable robots can distinctly rearrange their morphology into different static configurations.[165] Incorporating soft materials with convenient mechanisms for shape transformation, soft robots can maintain different states and body forms that are used for different modes of locomotion. Then, by actively controlled reconfiguration of the robot morphology and behaviors, efficient modes of locomotion to traverse various environments can be realized.

To determine if changing the robot's shape could increase its average moving speed across various environments, a robot that actively adjusts its shape to move in two distinct environments—flat and inclined planes—is tested (**Figure 9a**).[238] The robot featured an internal inflatable bladder for shape alteration, along with a single set of external bladders for locomotion. Indeed, adaptive robot design allowed for different locomotion styles, rolling in a cylindrical shape when inflated and inchworm-like crawling motion when flattened. The rolling movement involved inflating the trailing-edge bladder to tip the robot forward and

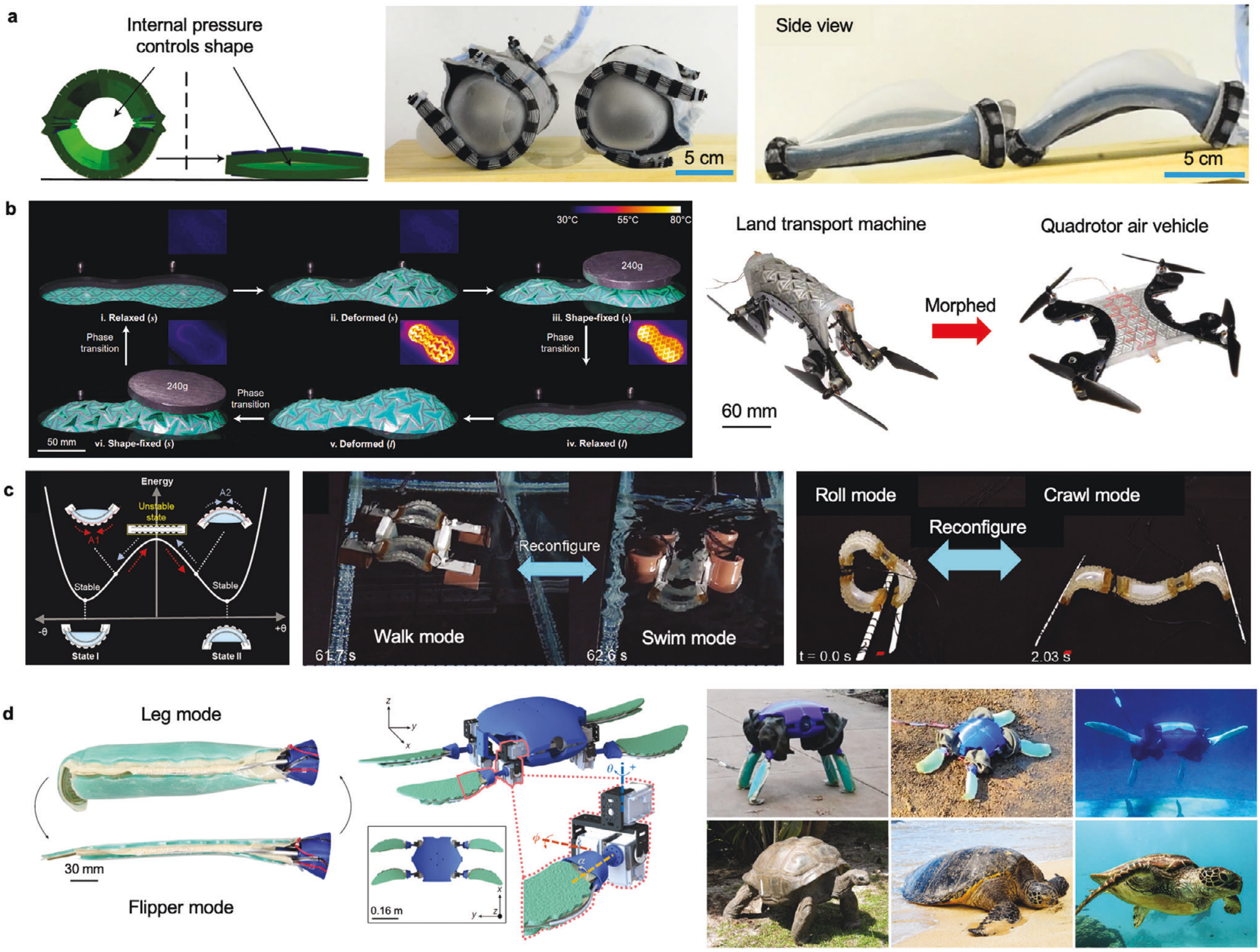

Figure 9. Multimodal locomotion by robots uses actuation of a soft material that reconfigures the morphology of the robot for different gaits of motion. a) Pneumatic shape-changing robot that uses a cylindrical shape for rolling on flat surfaces and a flat shape for crawling on inclined surface. b) A heat-responsive shape morphing metamaterial applied in a drone that enables a land transport machine and a quadrotor air vehicle when flattened. c) Bistable shape memory actuators with two-shape transitions for walking and swimming modes in an amphibious robot, and rolling and crawling modes in a caterpillar robot. d) Turtle-inspired robot with limbs that switch between a leg shape for walking mode and a flipper shape for crawling and swimming modes. a) Reproduced with permission.[238] Copyright 2021, Nature Publishing Group. b) Reproduced with permission.[239] Copyright 2022, AAAS. c) Reproduced with permission.[240] Copyright 2023, John Wiley & Sons. d) Reproduced with permission.[241] Copyright 2022, Nature Publishing Group.

sequentially inflating actuators. The inchworm motion entailed inflating four upward-facing bladders simultaneously to create an arched shape. The findings demonstrated that modifying both the robot's shape and control strategy yielded faster locomotion across changing environments compared to adopting the only control strategy for a static-shaped robot. In simulations, the shape-changing robot outperformed a non-morphing counterpart in traversing test environments. These simulation insights were then employed to design a physical robot, proving that shape alteration is a feasible strategy to enhance its movement speed. Notably, rolling against an incline was difficult and required the robot to morph into a crawler to climb uphill instead.

Not only can shape morphing be used in different conditions in a terrestrial environment, but this also has practical implications for the transition between dissimilar environments. To enable the transition between terrestrial and aerial environments in a drone robot, a multifunctional shape-morphing robotic surface with reversible and rapid polymorphic reconfigurability was applied for the quadcopter body (Figure 9b).[239] The combination of elastomeric kirigami and a unique reversible plasticity mechanism in metal alloys allowed for swift (<0.1 s) transformation of flat sheets into intricate load-bearing shapes. This process incorporates reversibility and self-healing through phase change. This composite material addresses the usual trade-offs between deformability and load-bearing capability, and it eliminates the need for sustained power to maintain reconfigured forms. This innovative robotic surface can be seamlessly integrated with onboard control systems, motors, and power sources. This integration enables the creation of a flexible robotic morphing drone capable of transitioning into a land-based vehicle that rolls on wheels. The transformation from a ground-based machine to an aerial vehicle is achieved autonomously. Hence, incorporating shape-changing soft materials into rigid robots is a pragmatic approach enabling environmental adaptability.

Rather than applying transformative soft materials to conventional robots, a soft robot instead was designed with highly compact and dynamic bistable soft actuators to perform multimodal locomotion in different environments (Figure 9c).[240] These actuators consist of a pre-stretched membrane positioned between two 3D-printed frames that house embedded shape memory alloy coils. Owing to the bistable structure, swiftly switching between two opposing curved states was achieved in these actuators. Driven by shape memory alloys, the compact and rapid-response nature of these pliable bistable actuators is harnessed as artificial muscles for soft robots capable of morphing their shape. This capability is demonstrated through three distinct soft robots. These robots include an adaptable amphibious model capable of both terrestrial walking and aquatic swimming, a caterpillar-inspired robot capable of both crawling and rolling movements, and a similar crawling and jumping robot. Active shape transformation in the amphibious robot was especially important, as the robot needed to stand upright to use its legs for walking. In water, the bistable actuators were then triggered to reconfigure the state of the robot morphology, spreading the actuator legs laterally to act as fins for more effective swimming abilities. Similarly, controlling the pressure in pneumatic actuators enabled the switching between wheels and paddles in another amphibious soft robot.[161]

However, one disadvantage of soft robots is that they lose the advantages of engineering materials and strategies to exceed animal performance. A robot called Amphibious Robotic Turtle (ART) combines stimulus-responsive soft materials with traditional rigid robotics components, greatly improving the shape-changing of its limbs and gait control logistics for multimodal locomotion (Figure 9d).[241] ART is specifically designed for versatile movement across various environments using an approach known as adaptive morphogenesis. This strategy involves achieving adaptable robot morphology and behaviors through a unified combination of structural elements and actuation systems. By incorporating specialized morphogenic characteristics tailored for both aquatic and terrestrial locomotion, ART amalgamates the streamlined flipper shape and swimming patterns of sea turtles with the columnar leg shape and gaits of land-dwelling tortoises. ART's limbs possess the ability to transition between functional hydrodynamic shapes suitable for swimming and sturdy load-bearing configurations. The robot's shoulder joints, equipped with three motors each in a well-defined arrangement, enable a variety of gaits. This comprehensive design empowers ART to carry out a range of activities: from swimming submerged and gliding on water's surface to traversing diverse surfaces on land and transitioning seamlessly between terrestrial and aquatic environments. For aquatic locomotion, ART features a morphing limb design comprising antagonistic pneumatic actuators paired with strain-limiting layers adhered to thermoset polymers. By heating embedded heaters to soften the thermosets and inflating the pneumatic actuators, the robot's limb undergoes adaptable changes in both cross-sectional area (fourfold increase) and stiffness (storage modulus increased by 450 times). These changes enable ART's limbs to dynamically transform from a cylindrical leg shape suitable for walking to a flat flipper shape ideal for swimming. In aquatic trials, when ART's limbs adopt the flipper mode, it engages in paddling motions inspired by observations of freshwater turtles and semi-aquatic mammals. Additionally, a flapping motion akin to sea turtles and fully aquatic mammals is executed. This flapping gait comprises vertical movement patterns involving consecutive upstrokes and downstrokes. In terrestrial scenarios, ART demonstrates creeping, a lateral walking sequence influenced by the upright walking of terrestrial tortoises and other four-legged animals, enabling slow-speed movement. Furthermore, ART exhibits a crawling gait reminiscent of the movements of sea turtles during beaching. During creeping, only one of ART's limbs is off the ground at a given time, while the robot incrementally pivots its body for forward motion. In crawling, ART rests on its belly, employing both fore and aft limbs in tandem to lift slightly and push rearwards simultaneously, propelling it forward. ART proves that in the ever-changing and unpredictable settings like the shift from land to water, adopting a robot design approach that addresses adaptability in both the structure and behavior can lead to improved efficiency.

From all the examples shown above, it is clear that shape-changing techniques are crucial to multimodal locomotion, and therefore multiple environments adaptation.[242] Although traditional rigid robots might excel in specific tasks, they encounter challenges when confronted with diverse environments.[243] Simply incorporating actively shape-changing soft materials into conventional robots significantly enhances their capabilities for multimodal locomotion.[17] Further applying soft actuators for the reconfiguration of entirely soft-bodied robots opens expansive possibilities for innovative robot designs. The advent of soft shape-changing robots significantly broadens this scope by introducing multimodal locomotion adaptive to different environments.[244] These adaptive soft robots expand the diversity of functions, and the working area one robot can have.[245] Not only do reconfigurable robots make operating in different environments and transitioning in between environments possible, but they also substantially improve locomotive efficiency.

5. Conclusion

Developing soft multimodal actuators and robots has the potential of creating machines that can reproduce the vast combinations of dexterous movements observed in living creatures.[3] Soft robots with multiple modes of locomotion have advantages in adaptability to different terrains and environments, improved agility of various gaits, controllable navigation, changing morphology, and overall versatility.[2,246,247] Many opportunities exist as there are various permutations of locomotion modes that have not yet been mixed within a robot. Future directions could explore the design of more complicated robotic systems that incorporate many actuators in a system with compliant joints for more functional soft robots, much like how the coordination of many biological muscles is needed to control living creatures.[248] Alternatively, the approach of applying soft actuators into conventional robots has demonstrated enhanced capabilities, including improving efficiency and enabling additional modes of locomotion. The use of actively shape-reconfiguring robots also holds a wide variety of creative possibilities.[240] While multimodal soft actuators can be exploited as soft-bodied robotic agents, they could also find applications in a variety of devices, including grippers and manipulators,[249,250] haptics,[251] prosthetics,[252] bioelectronic devices,[253] and more.[73] Thus, designing actuators that exhibit a wider range of multimodal behaviors through the incorporation of various thoughtful structural designs or multi-stimuli-responsive materials for mixed actuation would be an interesting direction to explore.

Overall, multimodal soft robotic systems are poised to make an impact on the field of robotics. While huge leaps in robotic control have been made in software with the rise of machine learning and artificial intelligence, hardware has lagged behind due to the limitations of designing machines with conventional robotic materials.[254,255] The difficulty of control is proportional to the complexity of a traditional robot, which must be increased as more motors and components are integrated into advanced robotic systems.[7,164] Applying soft materials into robotics provides pathways for simplified and intuitive robotic control.[203] Creating bioinspired robots not only simulates animals for the study of biomechanics,[8,256] but also bioinspired robot design to improve the robot mechanics also complements the development of neuromechanical control.[212] Hence, the development of bioinspired robots, which often necessarily requires soft materials, can drive the disciplines of neuroscience and robotic control together. Additionally, the use of soft materials lends itself to more advanced methods of manufacturing, such as multimaterial 3D printing.[257–262] Entirely soft robots with an integrated microfluidics controllers and fuel for autonomous robots have been reported, made with creative 3D printing strategies.[197] In addition, novel methods of additive manufacturing have provided the means of producing fully assembled hybrid robots, with rigid structural components, soft actuators, and integrated sensors, fabricated all in one printing round to avoid the need for complicated and time-consuming assembling procedures.[263] Furthermore, soft robots can incorporate sensors for monitoring applications and tactile sensory feedback to better control movements, such as sensors for pressure, strain, hazardous chemicals, pH, temperature and more.[264,265] Altogether, robots with performance that exceed locomotive abilities observed in nature can be engineered.[266] Ultimately, these developments could go toward automation, and the expansive and impactful applications of robotics in society.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

actuation, locomotion, multimodal soft robotics

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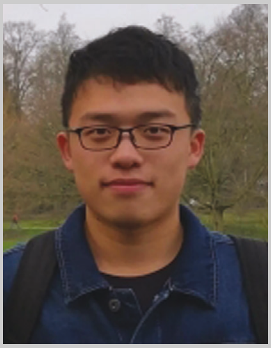

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