SCIENCE ROBOTICS | REVIEW

EMBODIED INTELLIGENCE

Metamaterial robotics

Xiaoyang Zheng[1,2,3]*, **Yuhao Jiang**[1], **Mustafa Mete**[1], **Jingjing Li**[4], **Ikumu Watanabe**[3], **Takayuki Yamada**[2], **Jamie Paik**[1]*

Mechanical metamaterials with customized microstructures are increasingly shaping robotic design and functionality, enabling the integration of sensing, actuation, control, and computation within the robot body. This Review outlines how metamaterial design principles—mechanics-inspired architectures, shape-reconfigurable structures, and material-driven functionality—enhance adaptability and distributed intelligence in robotics. We also discuss how artificial intelligence supports metamaterial robotics in design, modeling, and control, advancing systems with complex sensory feedback, learning capability, and adaptive physical interactions. This Review aims to inspire the community to explore the transformative potential of metamaterial robotics, fostering innovations that bridge the gap between materials engineering and intelligent robotics.

INTRODUCTION

Mechanical metamaterials, known for their periodic building blocks, are architected materials with exceptional properties and functions determined by their microstructures and constituent materials (*1*–*5*). By tailoring the geometries, connections, and spatial distribution of structural elements, metamaterials can outperform their constituent materials, as demonstrated in lattices (*6*, *7*), auxetic metamaterials (*8*, *9*), multistable mechanical metamaterials (*10*, *11*), origami and kirigami metamaterials (*12*, *13*), and stimuli-responsive metamaterials (*2*, *14*). Metamaterial designs enable the customization of structural heterogeneity in the distributed body of a robot. The structural versatility of metamaterials enables the design of robotic systems that are not limited to a single predefined function, allowing diverse applications to emerge from a common metamaterial architecture. For example, a modular chiral origami metamaterial has been demonstrated in robotic transformers, thermoregulation, mechanical memories, energy absorption, and information encryption (*15*).

One emerging direction in materials research focuses on active and adaptive behaviors, where materials are designed to respond dynamically to their environments and potentially contribute to system-level functions such as sensing or control (*2*, *14*). This perspective envisions materials as not merely passive components but as participants in embedded intelligence within larger systems. To this end, we define metamaterial robotics as robotic systems that leverage metamaterial architectures to physically embed one or more core functions—such as sensing, actuation, control, or computation—within the body of a robot, with the goal of enhancing performance, adaptability, or integration.

Mechanical metamaterials have been used in robotics since their emergence in the early 2000s (Fig. 1). In the initial stage, metamaterials were primarily integrated into the bodies of robots—especially in soft robotics (*16*). Their microstructures offered exceptional mechanical advantages, such as light weight yet high stiffness, large deformability, and nonlinear force transmission, enabling lightweight robotic bodies (*17*), shape-changing origami/kirigami-inspired skins (*18*), and compliant soft robotic components (*19*). In the subsequent phase, robotics leveraging responsive metamaterials achieved stimuli-responsiveness, reconfigurability, and multimodal locomotion and actuation. This led to breakthroughs including environment-responsive robots (*20*), modular and swarm robotic systems (*15*, *21*), and mechanical computing with logic gates (*22*). More recently, artificial intelligence (AI) facilitates the design, modeling, and control of metamaterial robotics. Generative AI enables data-driven and physics-informed design of metamaterials with specific robotic functionalities (*23*, *24*). Looking forward, the future vision of metamaterial robotics lies in the convergence of embodied intelligence and reconfigurable matter. Metamaterial robots with real-time adaptivity, onboard learning, and physical intelligence are expected to operate in dynamic, unstructured environments with minimal external computation or human intervention, such as modular reconfigurable robots that can adapt to extreme environments (Fig. 1E) and humanoid robots integrated with metamaterial-based components (Fig. 2).

This Review presents a comprehensive overview of metamaterial robotics. Initially, we identify key challenges in robotics, concentrating on specific aspects that metamaterials can address. Subsequently, we delineate the metamaterial design principles and illustrate how these principles have been harnessed in robotics to enhance performance in sensing, actuation, control, and computation. Furthermore, we highlight the importance of and challenges in designing and modeling metamaterial robots. We conclude by highlighting how integrating AI can advance the intelligence of metamaterial robots.

CHALLENGES IN ROBOTICS

Robotic systems have enabled breakthroughs but accompanied by substantial challenges, including actuation, sensing, control, and computation. Addressing these challenges is critical for the continued evolution of robotic capabilities, especially given that robots are increasingly deployed in dynamic and unstructured environments.

Most robotic systems rely on transmission-based actuators, such as motors and gearboxes, providing high force and efficiency across underwater (*25*), granular (*26*), terrestrial (*27*, *28*), and aerial (*29*, *30*) domains. Although effective, their rigidity and bulk limit use in applications requiring compliance, safety, or miniaturization. Alternative actuators, such as pneumatic and piezoelectric devices, offer improved functionality in wearable robotics and terrain exploration but still face low power density, limited scalability, and integration challenges for high–degree-of-freedom (DoF) motion (*31*–*33*).

---

[1] Reconfigurable Robotics Lab, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland. [2] Institute of Engineering Innovation, Graduate School of Engineering, University of Tokyo, Tokyo 113-8656, Japan. [3] Center for Basic Research on Materials, National Institute for Materials Science, Tsukuba 305-0047, Japan. [4] Institute of Library, Information and Media Science, University of Tsukuba, Tsukuba 305-8550, Japan.
*Corresponding author. Email: xyzheng1995@gmail.com (X.Z.); jamie.paik@epfl.ch (J.P.)

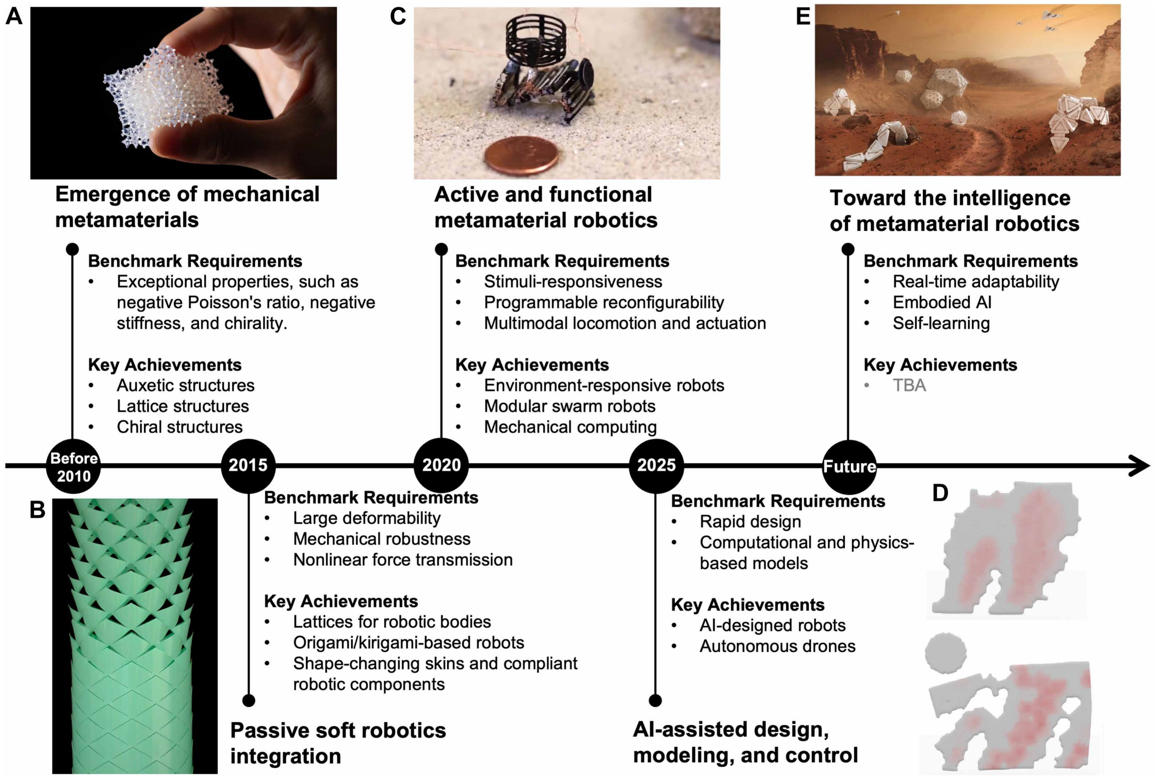


Fig. 1. Development timeline of metamaterials for robotics. (**A**) Auxetic metamaterial (*8*). (**B**) Soft actuator capable of crawling with kirigami skins (*142*). (**C**) Proprioceptive architected robotic metamaterial (*20*). (**D**) AI-designed robots for locomotion and object manipulation (*24*). (**E**) Illustration of a modular, reconfigurable robot swarm transforming into various forms for space missions (*21*).

Sensing is fundamental for robots to perceive their internal states (such as speed, force, and position) and external environments (such as temperature, humidity, and gravity) (*34*). Although high-performance sensors provide precise feedback, they are often bulky, power hungry, and difficult to integrate into compact systems. These challenges intensify in soft robots, which require distributed sensing to capture complex deformations, typically demanding multiple sensors and increasing system complexity and power consumption.

To overcome the limitations of discrete actuators and sensors, research is converging on sensorized actuation, where both functions are integrated within the same material or structure. These self-sensing actuators transduce motion and feedback through changes in electrical, optical, or mechanical properties (*35*, *36*), reducing system size, complexity, and energy use—particularly in soft and miniaturized robots. However, challenges remain in material development, fabrication precision, and holistic system design.

Integrating multifunctional materials and increasing system complexity heighten the demands on control and computation. Because robots incorporate more coupled and nonlinear elements, control systems must handle high-dimensional, dynamic data. Data-driven and learning-based controllers show promise but require extensive computation and rapid data acquisition (*34*, *37*–*39*), whereas model-based approaches depend on accurate physical models, which are often impractical for soft or highly compliant systems. Reliance on central processing units and conventional batteries also limits operation in extreme environments, highlighting the need for decentralized and adaptive computation.

The concept of embodied intelligence has emerged as a transformative framework wherein sensing, actuation, control, and even computation are distributed and embedded within the robot's physical body (*40*–*43*). Harnessing the body's intrinsic structure enables adaptive, efficient, and robust behaviors, especially when traditional control architectures are insufficient. Metamaterials with programmable mechanical and physical properties enable new forms of embodied intelligence in robotics. Unlike conventional materials, metamaterials can be spatially designed at multiple scales to impart behaviors—such as nonlinear stiffness or multistability—directly through their microstructure. This allows robots to achieve complex motions with simple inputs and fewer actuators while providing built-in sensing. By distributing intelligence throughout the body, metamaterials promote adaptive, efficient interactions with the environment and reduce reliance on centralized control.

METAMATERIAL DESIGN PRINCIPLES

A metamaterial typically consists of periodic building blocks, or unit cells, arranged in a specific spatial configuration. In mechanical metamaterials, structural elements deform—through stretching, bending, rotation, buckling, folding, or snapping—under forces, producing collective behaviors and functionalities (*3*). Their constituent materials can be passive (such as polymers, composites, and metals) or active (responsive materials) that respond to stimuli such as temperature, light, or electric and magnetic fields (*2*, *14*). Through tailored material composition and their spatial configuration,

CREDITS: (B) BERTOLDI GROUP/HARVARD UNIVERSITY; (C) RAYNE RESEARCH GROUP/UC BERKELEY.

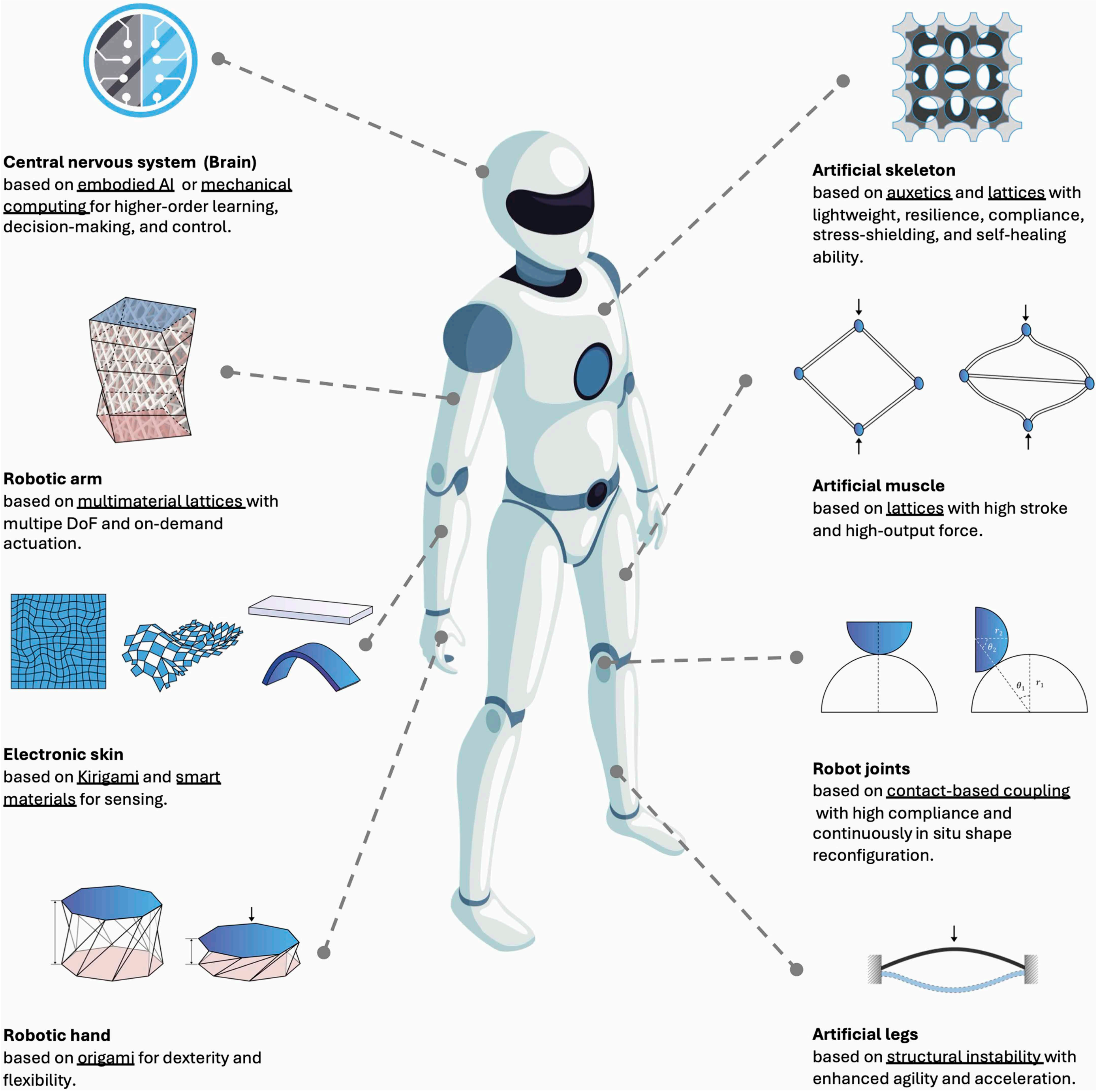
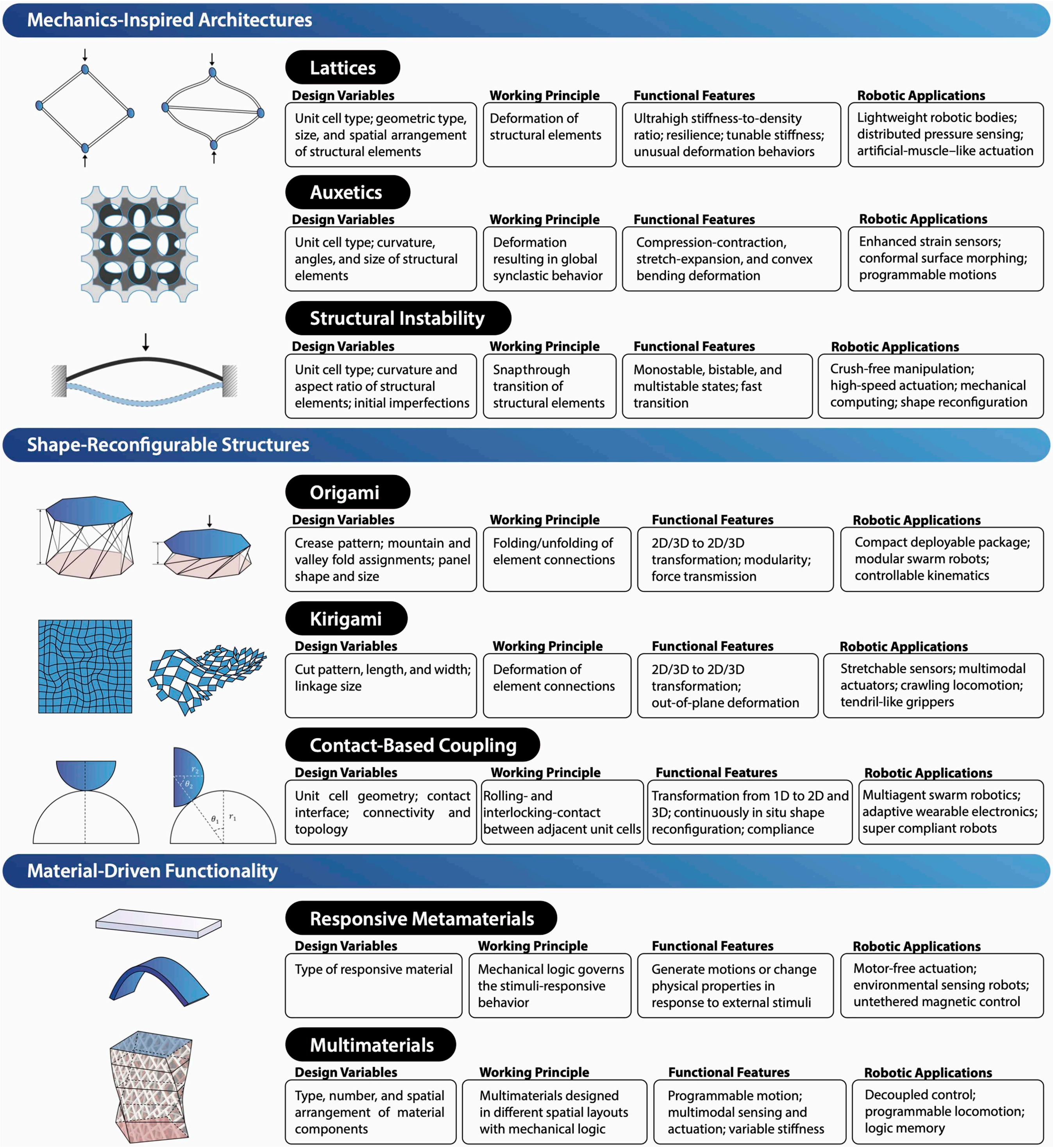


Fig. 2. Concept of a humanoid metamaterial robot. The robot leverages metamaterial designs for core robotic components, with a central nervous system governing high-level functions such as learning, decision-making, and control.

mechanical metamaterials exhibit enhanced performance and tunable properties.

Metamaterial design principles address key challenges in robotics through three main categories depending on the physics of working principles: mechanics-inspired architectures, shape-reconfigurable structures, and material-driven functionalities (Fig. 3). Mechanics-inspired architectures exploit deformation modes of structural elements—such as bending, stretching, and buckling—to tune mechanical response, force transmission, and energy landscapes, enabling programmable motion under actuation forces. Shape-reconfigurable structures focus on the deformation of element connections, facilitating dimensional transformations via origami, kirigami, and rotating or interlocking mechanisms (*44*, *45*). Material-driven functionality leverages responsive and multimaterial systems



Mechanics-Inspired Architectures

	Design Variables	Working Principle	Functional Features	Robotic Applications
Lattices	Unit cell type; geometric type, size, and spatial arrangement of structural elements	Deformation of structural elements	Ultrahigh stiffness-to-density ratio; resilience; tunable stiffness; unusual deformation behaviors	Lightweight robotic bodies; distributed pressure sensing; artificial-muscle–like actuation
Auxetics	Unit cell type; curvature, angles, and size of structural elements	Deformation resulting in global synclastic behavior	Compression-contraction, stretch-expansion, and convex bending deformation	Enhanced strain sensors; conformal surface morphing; programmable motions
Structural Instability	Unit cell type; curvature and aspect ratio of structural elements; initial imperfections	Snapthrough transition of structural elements	Monostable, bistable, and multistable states; fast transition	Crush-free manipulation; high-speed actuation; mechanical computing; shape reconfiguration

Shape-Reconfigurable Structures

	Design Variables	Working Principle	Functional Features	Robotic Applications
Origami	Crease pattern; mountain and valley fold assignments; panel shape and size	Folding/unfolding of element connections	2D/3D to 2D/3D transformation; modularity; force transmission	Compact deployable package; modular swarm robots; controllable kinematics
Kirigami	Cut pattern, length, and width; linkage size	Deformation of element connections	2D/3D to 2D/3D transformation; out-of-plane deformation	Stretchable sensors; multimodal actuators; crawling locomotion; tendril-like grippers
Contact-Based Coupling	Unit cell geometry; contact interface; connectivity and topology	Rolling- and interlocking-contact between adjacent unit cells	Transformation from 1D to 2D and 3D; continuously in situ shape reconfiguration; compliance	Multiagent swarm robotics; adaptive wearable electronics; super compliant robots

Material-Driven Functionality

	Design Variables	Working Principle	Functional Features	Robotic Applications
Responsive Metamaterials	Type of responsive material	Mechanical logic governs the stimuli-responsive behavior	Generate motions or change physical properties in response to external stimuli	Motor-free actuation; environmental sensing robots; untethered magnetic control
Multimaterials	Type, number, and spatial arrangement of material components	Multimaterials designed in different spatial layouts with mechanical logic	Programmable motion; multimodal sensing and actuation; variable stiffness	Decoupled control; programmable locomotion; logic memory

Fig. 3. Metamaterial design principles for robotics. Three main categories are illustrated: mechanics-inspired architectures (lattices, auxetics, and structural instability), shape-reconfigurable structures (origami, kirigami, and contact-based coupling), and material-driven functionality (responsive metamaterials and multimaterials). The design variables, working principles, functional features, and robotic applications of each design principle are highlighted.

to integrate actuation, sensing, and control. Together, these principles provide versatile routes for designing adaptive and multifunctional robotics.

Mechanics-inspired architectures

The body of a robot not only provides structural support but also executes tasks through its motions. Traditional robotic body design primarily emphasizes weight optimization, whereas metamaterial architectures enable the creation of multifunctional robotic bodies. Metamaterial designs use diverse deformation mechanisms, including lattices with optimized topologies, auxetics with counterintuitive deformation behaviors, and structures exploiting instability for snapthrough transitions.

Lattices

Lattices, the primary category of metamaterials, comprise periodic networks of beams or shells (*46*). They exhibit ultrahigh stiffness-to-density ratios (*7*, *47*–*49*), resilience (*50*, *51*), tunable stiffness (*52*–*54*), and unusual deformation behaviors (*55*). Mechanical metamaterials composed of stretch-dominated unit cells demonstrate superior weight efficiency and a higher stiffness-to-weight ratio compared with their bend-dominated counterparts and other foams with disordered microstructures. Conversely, bending-dominated metamaterials offer enhanced compliance and resilience, resulting in superior energy absorption performance (*56*).

An ultrahigh stiffness-to-density ratio enables lightweight yet strong robotic systems (*17*, *57*–*59*). Robots constructed from discrete periodic lattices combine high stiffness with low weight, offering capabilities for swarm assembly, reconfiguration, and versatile locomotion (*17*, *57*, *58*). A representative example is a carbon fiber–reinforced cuboctahedral lattice system that autonomously assembled a 256-unit shelter in 4.2 days using transport and fastening robots, demonstrating large-scale, self-reconfiguring behavior (Fig. 4A) (*17*).

Resilience enables robots to undergo large, recoverable deformation with tunable stiffness (*60*, *61*). Bending-dominated lattices can be elastically compressed and adjusted for stiffness. A robotic arm composed of X-shaped trimmed helicoids demonstrated controllability, sensitivity, and compliance (*60*). Actuated by tendons, it performed compression, bending, and gripping tasks with variable stiffness, enhancing compliance, workspace, and precision compared with conventional soft robotic arms.

Tunable stiffness in robots can be achieved through predesigned geometric design or in situ modulation via deformation (*52*, *62*) or internal pressure (*53*, *54*). This capacity is used in applications such as artificial muscles (*53*), sensing (*54*), and learning (*52*). For instance, a three-dimensional (3D)–printed cubic lattice with air-filled channels demonstrated distributed sensing by measuring pressure changes under deformation (*54*). A soft actuator with tunable internal pressure exhibited predictable kinematics. Mechanical neural networks with adjustable beam stiffness demonstrated learning capabilities analogous to weight adaptation in artificial neural networks (Fig. 4B) (*52*). Tunable edge-localized soft modes and tunable mechanical stability are also found in topological metamaterials (*63*, *64*).

Unusual deformation behaviors, such as compression-twist coupling (*55*) and rigid torque transmission (*65*), can be achieved by strategically designing lattice beam distributions. A chiral-lattice soft robot exemplified this using a saddle-shaped dielectric elastomer actuator and asymmetric feet—one flat, one chiral—to enable diverse, rapid movements (forward, backward, and circular) driven by frequency-dependent voltages (*66*).

Auxetics

Auxetic metamaterials, characterized by a negative Poisson's ratio, exhibit counterintuitive behaviors such as compression-contraction, stretch-expansion, and convex bending. An auxetic metamaterial contracts in all directions when uniaxially compressed and expands in all directions when uniaxially stretched. In contrast, conventional materials, with Poisson's ratios typically in the range of 0.25 to 0.5, laterally expand under uniaxial compression and contract under uniaxial tension. In addition, under a bending load, auxetic plates form convex shapes (positive Gaussian curvature), unlike the saddle shapes of ordinary materials. Typical auxetic designs include reentrant and chiral microstructures: The former deforms through beam bending and deployment, whereas the latter relies on the rotation of chiral nodes (*67*, *68*).

Compression-contraction deformation enables synclastic compressive behavior, enhancing object manipulation and actuation in robotics. This mechanical response facilitates functions such as locomotion with fewer actuators (*69*, *70*), conformal grasping (*71*), multi-DoF legs (*72*), flipper-style locomotion (*73*), and rapid, sustained hopping (*74*). Incorporating auxetic metamaterials in a robot's body simplifies control and actuation. For instance, a soft robot with a single actuator and auxetic and conventional clutches demonstrated inchworm motion through a passage (Fig. 4C) (*69*). The opposing Poisson's ratios of the clutches caused opposite mechanical responses, enabling linear locomotion.

Stretch-expansion deformation predominantly occurs in 2D designs, such as highly sensitive and stretchable strain sensors (*75*–*77*) and multi-DoF hollow-tube actuators (*19*). Integrating chirality into auxetic tubes allows for enhanced force transmission and twisting expansion (*19*). A compliant chiral auxetic actuator with four tubes demonstrated four DoFs, enabling movements in multiple directions (Fig. 4D).

Convex bending deformation enables conformal surface morphing (*78*, *79*) and double curvature in flat sheets (*80*). Double curvature allows for seamless shape displays without aliased edges. An auxetic metamaterial–based shape display demonstrated this by creating a large, continuous surface that responds to hand movements (*80*). The auxetic surface, resistant to easy deformation, provided varying Gaussian curvatures, allowing independent bending in two directions and enhancing the illusion of continuous surface exploration.

Structural instability

Structural instability—such as buckling and crippling—involves sudden failure under minimal force increases. Metamaterials harness such instabilities to create mono-, bi-, and multistable states, as revealed by their elastic energy-force curves (*81*, *82*). Monostable systems exhibit reversible nonlinear large deformations, characterized by an initial linear elastic deformation, followed by a distinct plateau in the stress-strain curve. Bistable systems snap from a high-energy state to a second stable configuration, releasing stored strain energy as kinetic energy and retaining shape after load release. Multistable systems have three or more stable states, enabling complex, programmable deformations.

Monostable systems exhibit reversible nonlinear compression and switchable buckling modes, useful for pneumatic actuation in artificial muscles (*83*), grippers (*84*, *85*), locomotors (*86*, *87*), and valves (*35*). For example, a buckling-dominated metafluid gripper enabled crush-free manipulation by exploiting programmable compressibility and viscosity, showing snapping-induced pressure

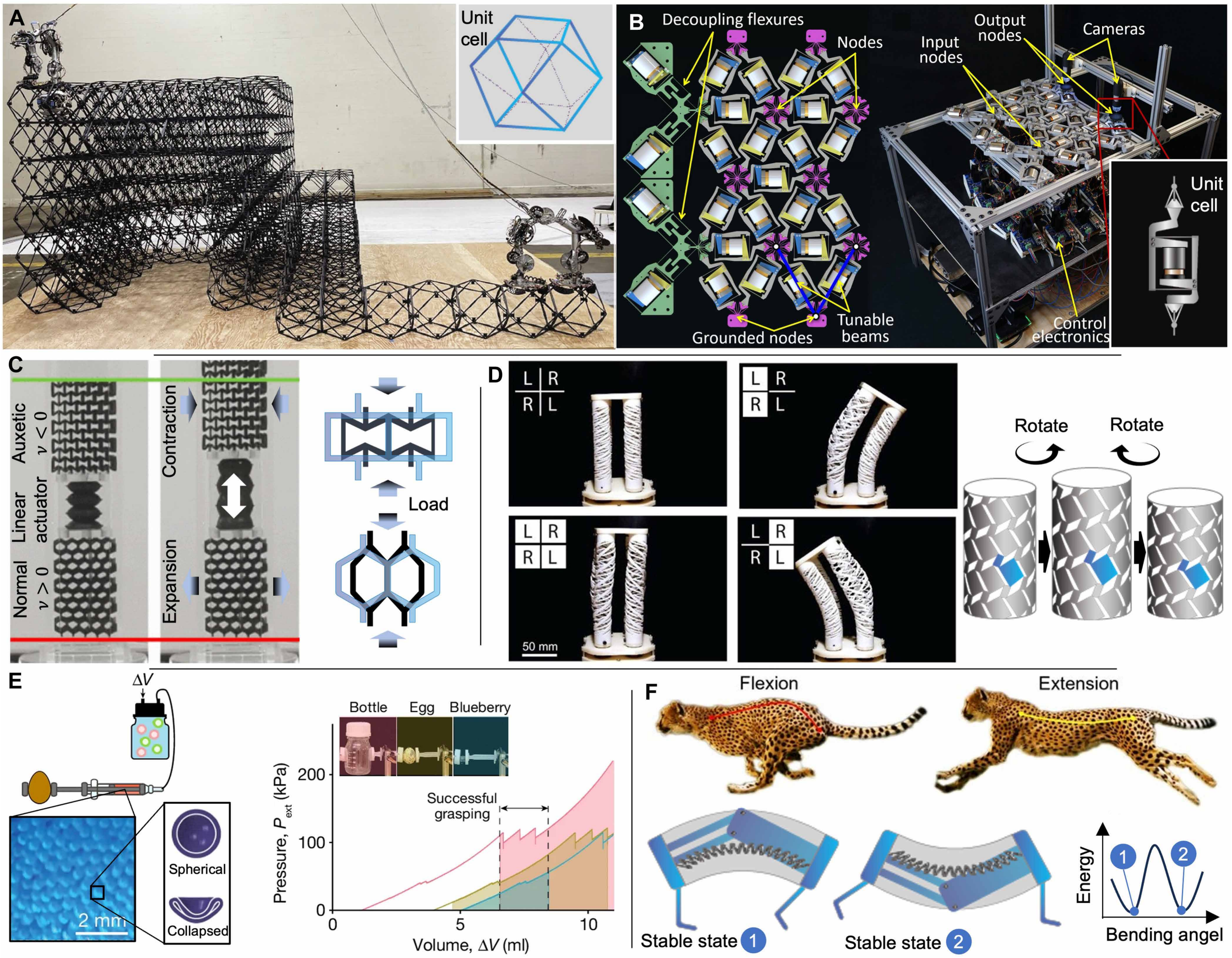


Fig. 4. Metamaterial robotics based on mechanics-inspired architectures. (**A**) Ultralight, strong lattice metamaterial (inset) forms the body of a self-reprogrammable robotic structural system that is assembled and reconfigured by mobile robots (*17*). (**B**) Lattice-based mechanical neural network capable of learning multiple mechanical behaviors by adjusting beam stiffness (*52*). (**C**) Auxetic metamaterials that simplify robot control and reduce actuator requirements in a soft robot. The soft metamaterial robot composed of auxetic and conventional clutches achieves inchworm-like motion using a single actuator. The actuator triggers intrinsic synchronization of the two passive clutches: the auxetic clutch contracts laterally, whereas the normal clutch expands under compression (*69*). (**D**) Auxetic chiral tubes with twist-expansion deformation enhancing a four–degree-of-freedom actuator. By controlling the twist of each tube, the system achieves programmable motion (*19*). (**E**) Shell buckling creating a programmable metafluid composed of micrometer-scale capsules. Nonlinear behavior arising from shell buckling enables an adaptive two-jaw gripper to grasp objects with widely varying sizes and compressive strengths (*85*). (**F**) Snapthrough bistability amplifying actuation speed and force in a locomotive soft robot, enabling rapid energy storage and release within tens of milliseconds between two stable states (*94*).

CREDITS: (C) REPRINTED WITH PERMISSION FROM IEEE PROCEEDINGS; (D) AND (F) REPRODUCED WITH PERMISSION FROM (19, 94), AAAS; (E) REPRODUCED WITH PERMISSION FROM (85), SPRINGER NATURE.

plateaus for effective object handling (Fig. 4E) (*85*). Tunable buckling modes also enable digital logic gates (*88*, *89*) and mechanical information encoding (*90*).

Bistable systems enable rapid transitions between two stable states, providing high-speed, high-force actuation for propulsion (*91*), jumping (*92*, *93*), galloping (*94*), and oscillatory locomotion (*95*). A cheetah-like crawler achieved speeds of 2.68 body lengths/s using a bistable spine actuator that combined springs and pneumatic bending, offering 20 times faster response and three times higher force than conventional actuators (Fig. 4F) (*94*). Bistable mechanisms also enable mechanical logic (*96*–*98*), information encoding and storage (*99*, *100*), and shape reconfiguration (*101*).

Multistable systems, capable of maintaining multiple stable states, enable multimodal transformations (*102*), ternary logic operation (*103*), and multistate shape morphing (*104*). 3D mesostructures exploiting multistable buckling achieved programmable shape reconfiguration through mechanically guided assembly, accomplished by sequentially releasing prestrained elastomers and stabilizing various buckling modes (*104*).

Shape-reconfigurable structures

Robotic systems often require large shape transformations, constrained by bending, stretching, and buckling of structural elements. Shape-reconfigurable structures—drawing from origami, kirigami, and contact-based coupling—enable transformations between 2D and 3D configurations through deformation at element connections. Origami and kirigami use flexible creases and stiff panels for versatile reconfiguration, whereas contact-based coupling relies on rolling or interlocking blocks for modular adaptability. These principles enhance robotic flexibility, force transmission, and control simplicity.

Origami

Origami metamaterials are created by introducing folding creases into flat sheets, reducing elastic energy and facilitating folding and unfolding (*105*, *106*). In rigid origami, elastic energy is localized at creases, yielding predictable kinetics and tunable DoFs. In deformable origami, energy is stored in both the creases and panels, producing more complex mechanical responses. Origami designs allow shape transformations and enhanced force transmission.

Transformations that are 2D to 2D allow folded sheets to deploy into large flat surfaces, enabling compact structures such as gliders (*107*), programmable matter (*108*), and fluid-driven artificial muscles (*109*). An origami-based glider mimicking ladybird beetle wing veins demonstrated compact folding, rapid deployment (466 ms), and effective aerodynamic support with a 35-g mass and a 660-mm wingspan (Fig. 5A) (*107*).

Transformations that are 2D to 3D enable flat sheets to bend, twist, and fold under minimal loads, creating untethered robots responsive to external stimuli (*95*, *110–114*). These stimuli-driven designs allow versatile manipulation and locomotion, including soft grippers actuated by external physical fields (*112*, *114*) and locomotors with controllable gaits (*110*). Origami millirobots can even operate untethered with minimal electronics (*115*).

Transformations that are 3D to 3D enable reconfigurable robotic architectures with programmable functions (*116–119*). Reconfigurability can be achieved through mechanisms such as self-folding chains activated by elastic and magnetic energies (*116*), soft hinges powered by acoustic waves (*117*), pneumatic power-driven extruded cubes (*118*), transformable wheels with hydraulic actuators (*119*), and origami-based breathable air pouches activated by pneumatic pressure (*120*). For instance, an origami-based transformable wheel switched between large and small configurations with high load capacity (>10 kN), payload-to-weight ratio (>50), and shape variation ratio (~1.7) (Fig. 5B) (*119*). This wheel, based on a waterbomb tessellation pattern, showed perpendicularity in driving and supporting directions.

Modularity derived from origami patterns enables reconfigurable and swarm robotics reminiscent of insect behavior (*21*, *121*, *122*). Compared with fixed-shape modules, origami modules offer greater compactness and deployability. Our group developed the Mori robot, which can move, self-connect, and fold into various 3D configurations (*121*, *123*). We later enhanced its versatility using physical polygon meshing, allowing each triangular module to independently extend its edges by up to 7.5%. This supports diverse applications in interaction, manipulation, and multimodal locomotion (Fig. 5C) (*21*).

Force transmission through origami designs enables programmable kinematics in robotics (*124*). Two notable mechanisms are Kresling origami (*15*, *125–129*) and Canfield joint origami (*130–132*). Kresling origami, characterized by its cylindrical shape with triangulated unit cells, features compression-twist coupling motion. Its mechanical properties, ranging from stiff to flexible based on geometric parameters, allow for on-demand deployability and tunable dynamic behaviors, supporting applications such as digital logic gates (*128*), robotic arms (*125*, *127*), and mechanical memory operation via bistability (*126*). A magnetically controlled Kresling arm demonstrated untethered multimodal deformations—stretching, folding, omnidirectional bending, and twisting—for object grasping and manipulation (Fig. 5D) (*127*). Canfield joint origami, a compact three-DoF mechanism, enables haptics, force feedback, and reconfigurable surfaces (*131*, *132*).

Kirigami

Kirigami metamaterials, created by cutting flat sheets to form linkages between panels, enable large shape transformations and nonlinear mechanical responses (*105*). Rigid kirigami, where undeformable panels rotate around small linkages, allows predictable, programmable transformations (*133*). Deformable kirigami, where both panels and linkages deform under tension or compression, exhibits nonlinear behavior such as buckling (*134*). Depending on the motif, kirigami can deploy into 2D or 3D shapes with high stretchability (*135*) and multistability (*136*).

Transformations that are 2D to 2D enable kirigami to stretch under tension or contract under compression. Integrating kirigami with auxetic designs enhances flexible electronics for soft robotics, improving perception and autonomy (*137*, *138*). In addition, 2D-to-2D transformations under compressive loads have applications in surface information encoding and storage (*100*), logic operations (*103*), and adaptive locomotion via soft wheels (*139*). A kirigami-wheeled robot, powered by environmental flow, navigated pipelines using soft wheels that provided support and mobility (*139*).

Transformations that are 2D to 3D in kirigami arise from snap-through buckling under tension or compression, enabling complex 3D surface formation. Two primary transformation modes are stretch buckling, where tensile loads bend panels out of plane to form programmable 3D shapes (*133*, *140*), and compression buckling, where compression induces out-of-plane deformation (*141*). By strategically designing the kirigami's linkages and motifs, stretch buckling allows programmable control of the buckling process, including multiple stages (*142*), buckling direction (*143*), localized mechanical responses (*144*), and the inverse design of desired target shapes (*133*), and supports actuators with diverse linear actuation modes (roll, pitch, yaw, and lift) (*145*) and object grasping (*146*). Compression buckling can be controlled via prestress (*141*), loading sequence (*147*), substrate properties (*104*), and the presence of defects in the kirigami structure (*148*) and is applied in morphable mesostructures (*133*, *141*) and microelectronic devices (*104*). Responsive-material–based kirigami further enables untethered soft millirobots with stimulus-responsive 3D shape changes (*149–152*).

Transformations that are 3D to 3D involve reconfiguring structures entirely within 3D space, seen in kirigami-based tubes (*18*, *142*), lattices (*153*), and baskets (*154*). In tube forms, snap-induced buckling creates textured surfaces that enhance soft actuator locomotion via directional friction (Fig. 5E) (*18*, *155*). Kirigami lattices with Miura folds offer programmable anisotropic bending stiffness for morphing wings and tentacles (*153*). Basket-shaped kirigami grippers use stretch-induced buckling to achieve tendril-like motions, enabling grasping of ultrasoft to ultraheavy objects—up to 16,000 times their own weight (Fig. 5F) (*154*).

Contact-based coupling

Contact-based coupling in metamaterials involves interactions between building blocks to create two main systems: discretely rolling contact and continuously interlocking contact (*156*). Rolling-contact systems use flexure straps (*157*), gears (*44*), hinges (*158*), or magnets

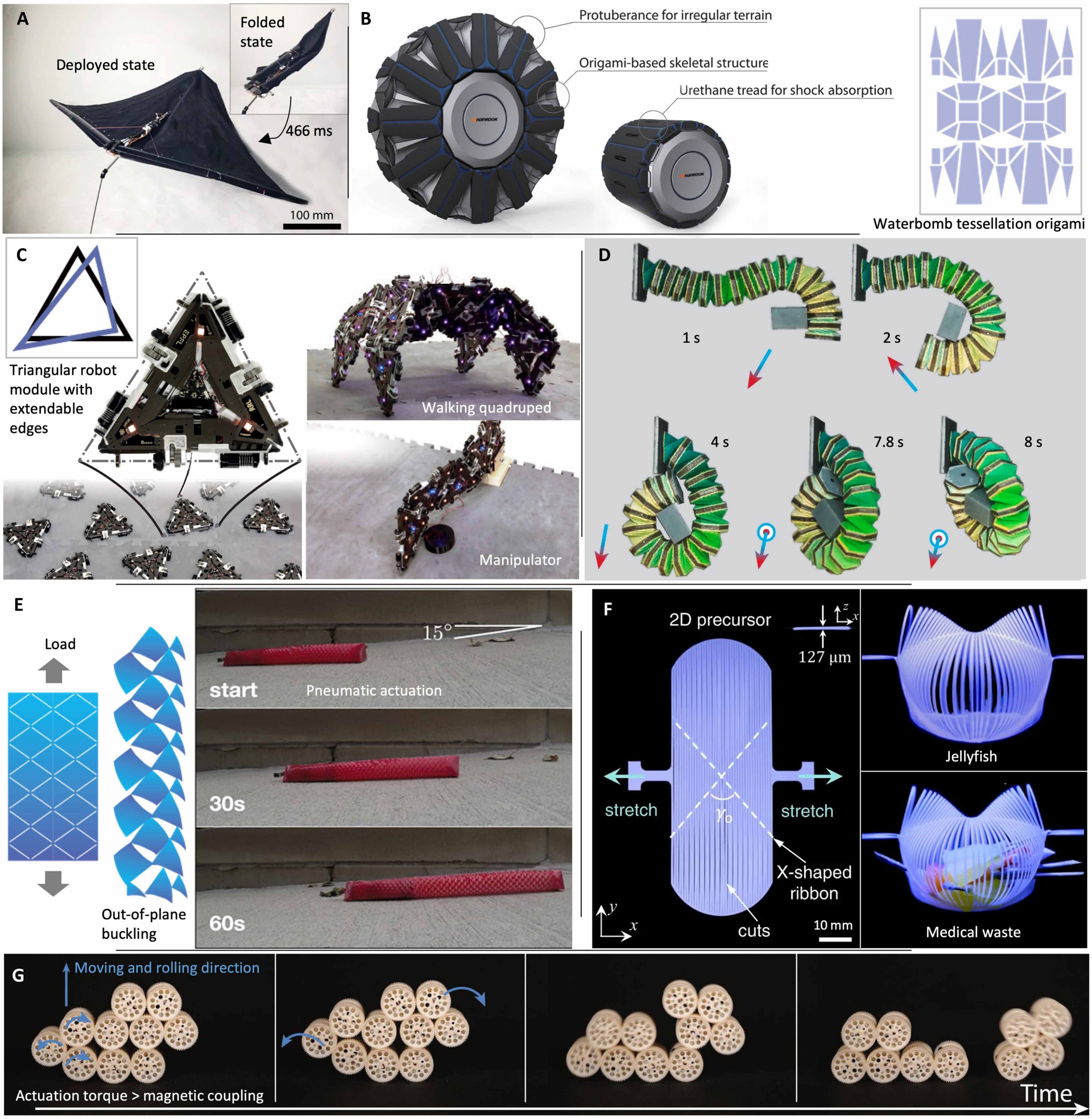


Fig. 5. Metamaterial robotics based on shape-reconfigurable structures. (**A**) Compliant origami frame forming a deployable glider that expands by releasing stored energy (*107*). (**B**) Waterbomb tessellation origami forming a transformable wheel capable of switching between two configurations (*119*). (**C**) Modular origami robot made of triangular shape-changing modules, reconfigurable into diverse 3D configurations (*21*). (**D**) Kresling origami modules forming an octopus-like robotic arm with omnidirectional bending and object-grasping functionality (*127*). (**E**) Kirigami skin enhancing the crawling capability of a soft crawler through buckling-induced pop-up textures (*18*). (**F**) Kirigami-based gripper enabling angle-programmed, tendril-like grasping trajectories for handling diverse objects (*154*). (**G**) Magnetic rolling-contact coupling enabling a self-organizing robotic aggregate capable of autonomously splitting and forming (*159*).

(*159–161*) to enable flexible, in situ reconfiguration. This design enables adaptive robot swarms that can be rearranged within their environment, allowing dramatic dimensional transformations from 1D to 2D and 3D. Interlocking contact systems—built from chainmail, knots, or yarns—achieve tunable mechanics through loosely topological connections such as chaining (*162–164*), weaving (*165*), knotting (*166*), or knitting (*167*), offering continuous control over deformation (*165*, *166*).

In situ reconfiguration, achieved through the relative rotation and motion of rolling contact building blocks, enables continuous tuning of elastic properties without substantial increases in strain energy or internal stress (*44*, *157*). Incorporating motorized units in place of passive building blocks unlocks possibilities for autonomous locomotion and extreme shape morphing versatility. This approach represents a robust design principle for modular, multiagent swarm robotics with decentralized control, such as global signals (*159*, *168*), mechanical feedback (*159*), spatiotemporal modulation (*160*), and mechanical compression or thermal stimuli (*169*). A compelling example is a self-organizing robotic aggregate with magnetically coupled, motor-driven gear units that switch between solid-like and fluid-like states for adaptable movement (Fig. 5G) (*159*). This approach highlights the potential for robotic swarms to dynamically adapt their forms in diverse environments through in situ reconfiguration.

Continuously interlocking contact systems exploit compliance to enable adaptive functionalities. In textiles, interlocking patterns allow fabrics to dynamically adjust softness and shape for wearable adaptability (*162*, *167*, *170*). These structures also support body-conforming textile electronics for physiological monitoring (*165*). Beyond textiles, integrating stimuli-responsive materials such as liquid crystal elastomers (LCEs) enables knotted artificial muscles with rapid thermal actuation (*166*). Interlocking designs also drive microrobotic locomotion, such as corkscrew and tumbling motions via magnetically actuated multimaterial microswimmers (*171*).

Material-driven functionality

Traditionally, robots separate electronics for sensing, actuation, control, and computation from their physical bodies, creating a divide between the "brain" and the "body" (*172*). However, integrating intelligence directly into materials blurs this boundary, enabling robots whose bodies contribute to sensorized actuation and computation in response to external control. Stimuli-responsive (smart) materials can sense and react to external cues—such as temperature, light, moisture, pH, magnetic fields, electric currents, or electromagnetic fields—by generating motions (such as expanding, contracting, bending, twisting, squeezing, and stretching) or altering their physical properties (such as stiffness, phase, and surface texture). This dual sensing-actuation capability allows for direct, material-level control of robotic behavior. However, their use is limited by slow response, low durability, and insufficient mechanical strength in dynamic tasks. Combining responsive and passive materials into metamaterial architectures enables programmable mechanical responses and multifunctional robotic bodies with adaptive, autonomous capabilities. Multimaterial metamaterials further allow spatially distributed functions but face fabrication challenges related to resolution, material compatibility, and process complexity (*2*, *14*, *173*).

Responsive metamaterials for actuation, sensing, and control

Unlike traditional stimuli-responsive materials that react monotonically to stimuli, responsive metamaterials integrate these materials with mechanical logic networks. In such systems, mechanical logic governs the response of the materials, creating a programmable stimuli-responsive behavior that translates environmental inputs into shape and property changes within the network itself. This material-based perception embeds sensing functions directly into the robot's body, offering an alternative or complement to conventional sensors. Unlike discrete electronic sensors, this approach enables distributed, structurally integrated mechanical responses to external stimuli, potentially enhancing robustness, spatial resolution, and functional density. Consequently, stimuli responsiveness enables sensorized actuation, where the same structure both senses and responds, allowing direct control of the robot's behavior using external physical fields.

Thermoresponsive metamaterials, typically based on LCEs and shape memory polymers (SMPs), use thermal expansion, phase transitions, and the shape memory effect to produce programmable mechanical responses. Heating can be applied via the Joule effect (*174*–*178*) or enviromental temperature changes (*91*, *111*, *179*–*181*). Deformations can be tuned by strain mismatch of bilayered films with different thermal expansion coefficients (*111*, *181*, *182*) or with active-passive material combinations (*174*, *183*). Snapthrough instability accelerates actuation speed (*176*), and localized heating enables programmable nonlinear motions (*87*, *180*). Beyond polymers, thermostatic metal strips enhance actuation capacity, thermal strain, and bandgap tunability in temperature-responsive metamaterial actuators (Fig. 6A) (*181*).

Photoresponsive metamaterials operate at both the molecular and composite levels. Photoactive molecules such as azobenzene undergo light-induced isomerization, enabling reversible bending, folding, contraction, and wave propagation for light-driven functions such as light tracking and gripping (*95*, *114*, *184*). A kirigami-based rolling robot made of photoresponsive LCEs demonstrated light-directed versatile locomotion (Fig. 6B) (*185*). Localized photoresponses can create strain mismatches, as seen in hydrogel films bending via light-induced hydrophobicity changes (*184*). At the composite level, embedding photoabsorbers into thermoresponsive matrices enables photothermal actuation and reprogrammable soft robotics (*87*, *186*). Combining photoresponsive polymers with metamaterial architectures yields nonreciprocal, self-regulated motion, such as LCE microactuators tracking light via opto-chemo-mechanical feedback (*187*).

Chemistry-responsive metamaterials, often based on hydrogels and liquid-crystalline polymers (LCPs), react to liquids, pH, or ion concentration through swelling or shrinking, enabling reversible topological and bending transformations. For instance, LCP microstructures can shift from triangular to hexagonal lattices via liquid-induced swelling (*188*), and layered LCPs bend in response to moisture (*189*). A 3D-printable pH-responsive hydrogel enables 3D-to-3D shape morphing in a single-material, single-step mode (*190*), and xerogels integrating graphene and magnetic elastomers support multifunctional, logic-driven soft robotics (*149*).

Electric-responsive metamaterials—based on electroactive hydrogels (*191*, *192*), dielectric elastomers (*66*, *193*), LCEs (*177*, *194*), and piezoelectric composites (*20*, *163*, *195*)—deform under applied voltages. Hydrogels bend via ion-induced osmotic pressure, elastomers expand through electrostatic forces, LCEs contract by Joule heating, and piezoelectrics enable two-way conversion between electric and mechanical signals. Integrating these materials into metamaterial architectures enables programing mechanical strains in response to electrical fields, supporting applications in sensing and feedback-driven actuation (*20*, *163*, *196*). A robotic metamaterial combining conductive, piezoactive, and structural elements achieved electric-field–driven shape changes and decision-making via self-sensing (Fig. 6C) (*20*).

Magnetic-responsive metamaterials—typically composites embedded with magnetic particles—enable rapid reconfiguration and actuation in soft robotics (*116*, *122*, *159*, *197*). Although early designs exhibited limited response modes (*146*, *151*), recent advances in constitutive material (*112*), structural integration (*150*, *198*), and postprocessing design (*152*) have expanded their capabilities. Metamaterial designs can break the undesired chain-like assembly of magnetic dipole-dipole interactions because of the low-energy

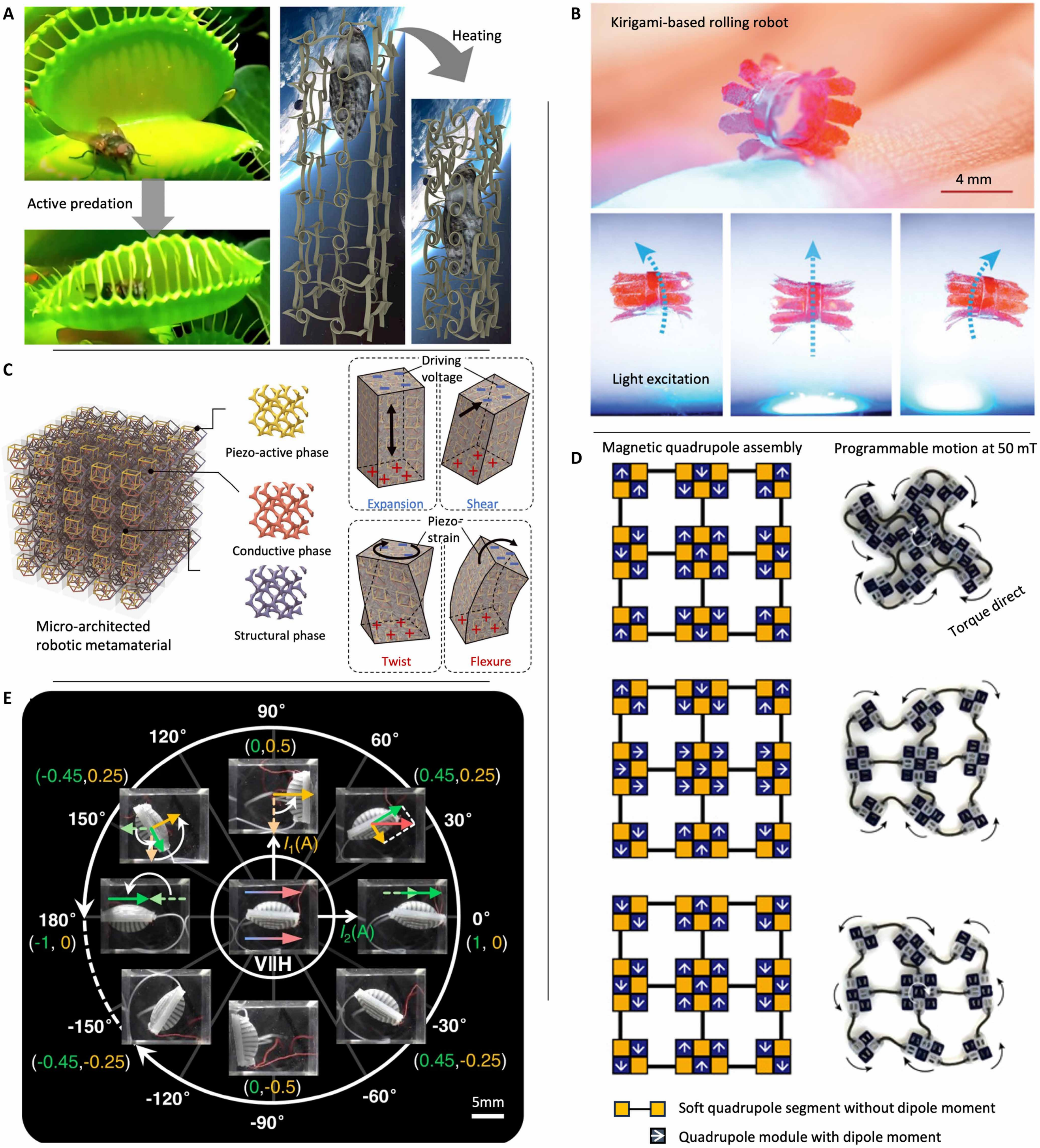


Fig. 6. Metamaterial robotics based on responsive metamaterials. (**A**) Temperature-responsive metamaterials composed of thermostatic metal strips, demonstrating active predation behavior in extreme temperature environments (*181*). (**B**) Photoresponsive kirigami forming a millimeter-scale rolling robot, with locomotion controlled by light excitation direction (*185*). (**C**) Piezoelectric metamaterial with various strain modes and a piezoelectric strain matrix (*20*). (**D**) Magnetically responsive lattice forming programmable actuators composed of passive and active (with dipole moment) quadrupoles, with programmable motions controlled by magnetization direction (*199*). (**E**) Electromagnetic soft actuator module with self-vectoring control and high-dimensional operation, capable of forming modular robots with multimodal locomotion (*201*).

CREDIT: (A) REPRODUCED WITH PERMISSION FROM (181), AAAS.

configurations of dipole symmetry. For example, a lattice design forming magnetic quadrupole modules alters magnetic particle-particle interactions in both symmetry and strength, enabling the formation of stable, frustration-free magnetic assemblies with arbitrary 2D shapes (Fig. 6D) (*199*). In addition, magneto-origami structures allow foldable deployment under magnetic fields (*198*). Programmable magnetization further supports multimodal locomotion and sensing (*150*), although real-time customization via localized magnetization remains challenging (*152*).

Electromagnetic-responsive materials overcome the localized magnetization limit by leveraging Lorentz forces from magnetic fields and electric currents for fast, reprogrammable actuation. Embedding liquid-metal coils in soft enclosures enables highly stretchable, ultrafast actuators (*113*, *200*). Configurations such as planar spirals and 3D helices allow control of electromagnetic vector orientation and magnitude (*201*). Assembling these modules in parallel permits arbitrary in-plane actuation via magnetic torque and force (Fig. 6E).

Multimaterial metamaterials for programmable functions

Responsive metamaterials integrate actuation, sensing, and control, but single-material systems constrain design flexibility. Combining responsive with passive or other responsive materials enables versatile architectures—bilayer, multilayer, surface-patterned, doped, interpenetrating, tensegrity, and assembled forms (Fig. 7A). In these multimaterial metamaterial systems, materials with distinct physical properties are subjected to a load or external stimulus, generating strain mismatch that leads to internal stress and results in intentional deformation behavior. These designs, coupled with metamaterial logic networks, are supported by advanced multimaterial additive manufacturing (*202*). These multimaterial metamaterials allow decoupled sensing, actuation, and control through various external stimuli and bring about versatile responses such as programmable motion, shape transformation, and variable stiffness.

Metamaterials made from multiple responsive materials can decouple sensing, actuation, and control via diverse external stimuli. Often realized in 2D origami or kirigami architectures (*149*, *203*, *204*), these systems adapt their shapes or properties through spatially tuned component arrangements. For example, a soft millirobot with a hydrogel–elastomer–magnetic nanoparticle sandwich structure responded to six stimuli, enabling autonomous motion (*203*). Another kirigami-inspired robot used modular materials to sense and react to light, heat, and solvents, adjusting its trajectory autonomously (Fig. 7B) (*204*).

Metamaterials built from materials with varying stiffness enable programmable motions. Bimaterial systems combining responsive and passive materials allow untethered actuation via magnetic fields

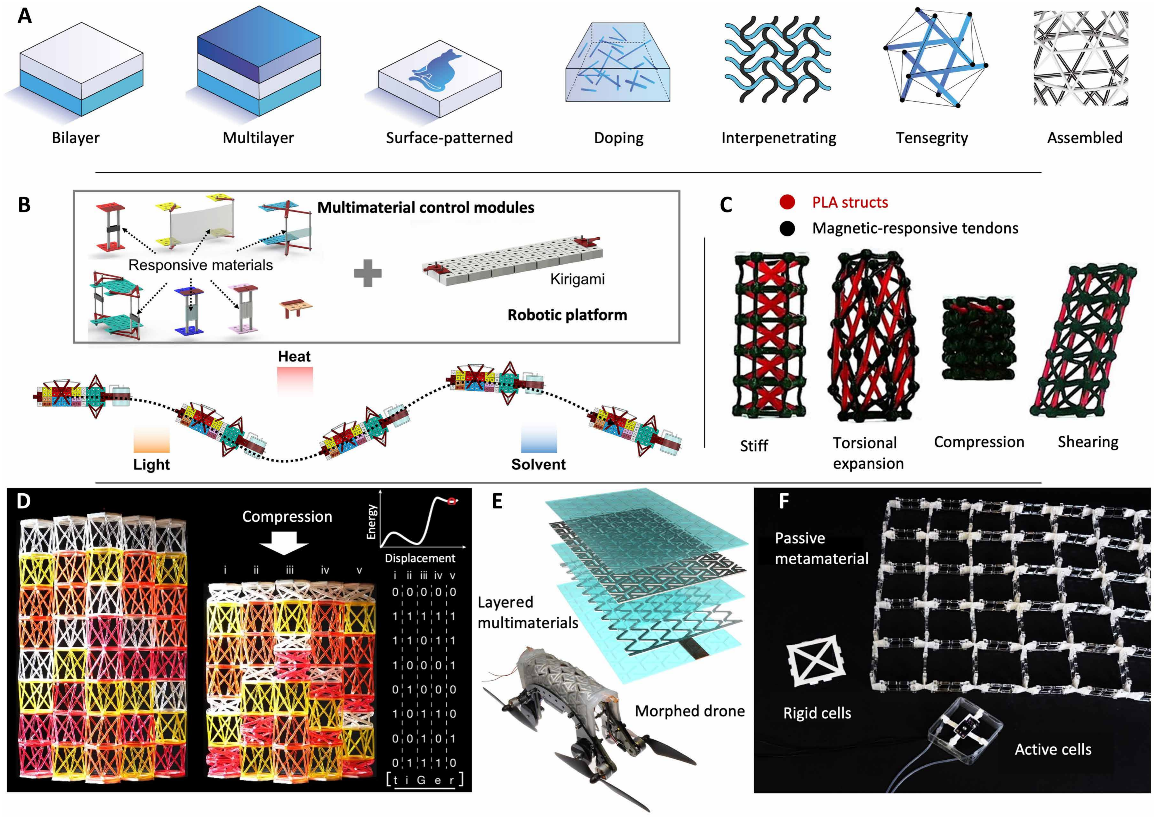


Fig. 7. Metamaterials robotics based on multimaterial metamaterials. (**A**) Various multimaterial layouts that can be integrated with metamaterial designs. (**B**) Multimaterials with diverse stimulus responsiveness, creating a modular robot actuated by decoupled multiple stimuli (*204*). (**C**) Bimaterials composed of magnetic-responsive tendons and passive struts architected in a tensegrity structure, creating magnetically controlled programmable actuation (*205*). (**D**) Multimaterials with varying stiffness assembled into a modular metamaterial, allowing programmable information storage and/or encryption based on the folding and deploying sequence of origami cells (*15*). (**E**) Multilayered multimaterial metamaterial with a phase-transition auxetic endoskeleton used to construct an autonomously morphing drone (*78*). (**F**) Unit cell–level multimaterial system composed of a passive metamaterial framework and locally inserted passive and active unit cells, enabling pneumatically actuated, reconfigurable robotic function (*211*).

CREDITS: (B) REPRODUCED WITH PERMISSION FROM (204), AAAS; (D) REPRODUCED WITH PERMISSION FROM (15), SPRINGER NATURE.

(*205*), light (*186*), or heat (*111*, *179*). For example, tensegrity structures, consisting of rigid struts and flexible tendons held together by tensile and compressive forces, offer a high stiffness-to-mass ratio, structural flexibility, and broad deployability. Using magnetic-responsive tendons and optimized node configurations enables programmable actuation (Fig. 7C) (*205*). Bimaterial pneumatic systems use soft components for deformation and stiff ones for guidance, achieving stretch, contraction, twist, and bend (*202*, *206*, *207*). Multimaterial systems using prestretch techniques demonstrated rapid high-energy release in jumping robots (*208*). Modular chiral origami metamaterials consisting of Kresling origami unit cells with different stiffness exhibited programmable information storage/encryption (Fig. 7D) (*15*).

Multimaterial metamaterials also offer distinct advantages, such as reversible shape transformation, variable stiffness, and reduced reliance on actuators. Embedding phase-transition materials—such as SMPs (soft-rigid switching) and low–melting-point alloys (liquid-solid switching)—into passive materials enables shape morphing (*78*), conformal gripping (*209*), shape reconfiguration (*210*), and high-load object manipulation (*174*, *183*). These phase-change materials are often arranged in auxetics (*78*), kirigami (*78*), or origami layouts (*210*). For example, a multimaterial auxetic kirigami achieved large deformability and high load capacity, enabling a morphing drone to transition autonomously between ground and aerial configurations (Fig. 7E) (*78*). Reversible shape transformation can also arise from the structural design level, such as through Maxwell lattices—an example of topological metamaterials (*11*). Beyond material-level design, unit cell–level strategies—such as locally embedding active units into passive metamaterials—allow for dynamic shape changes and robotic functions (Fig. 7F) (*211*). This approach minimizes actuator requirements because passive rigid cells redistribute forces to produce complex motions with fewer active components.

DESIGN AND MODELING OF METAMATERIAL ROBOTS

Achieving integrated functionalities and enhanced performance heavily depends on the design of metamaterial robots. Traditionally, human-guided heuristic design has led to the discovery of a wide range of metamaterials and robotics. However, this approach relies heavily on designers' intuition and inspiration from nature, often involving trial and error. Investigating mechanical properties and responses typically requires laborious experiments or computationally expensive simulations, and design complexity soon exceeds human capacity. Computational methods—such as topology optimization and deep generative models—help overcome these limitations by automating the design process, enabling optimal structure generation (*1*, *212*) and inverse design with targeted robotic functionalities (*23*, *24*). For a comprehensive overview of recent advancements, challenges, and opportunities in computational models for metamaterial design, see (*213*).

Modeling plays a crucial role in the design and optimization of metamaterial robots. Analytical models, numerical simulations [such as finite element analysis and physics-based simulations (*214*)], and reduced-order models enable the prediction and optimization of metamaterial robots across scales, from unit-cell mechanics to system-level functionality. These approaches support rational mechanical design, physically consistent state estimation, optimal control, and system identification in complex dynamical systems with contact-rich behaviors. Furthermore, AI (such as physics-informed machine learning and data-driven modeling) helps bridge the gap between theoretical predictions and real-world material behavior, accelerating the iterative design process for robotic sensing, actuation, and control (*215*).

Undoubtedly, many challenges remain in the effective design and modeling of metamaterial robots. Physics-based models, although accurate, are often computationally expensive, whereas AI-based models face limitations from data scarcity, low data quality, and physically implausible outputs. In particular, the design and modeling of responsive and multimaterial systems are particularly difficult because of their nonlinear and coupled behaviors under multiple stimuli and extreme conditions. Capturing these interactions in real time remains an open problem for control and prediction. A promising direction lies in the integration of AI with high-fidelity physical simulations to bridge data-driven learning and physical accuracy.

OUTLOOK

Although metamaterial design principles have substantially enhanced robotic designs, current state-of-the-art metamaterial robots still lack full integration of sensing, actuation, computation, communication, locomotion, and manipulation. Some prototypes demonstrate partial integration, such as piezoelectric metamaterial robots capable of movement, sensing, and feedback control (*20*), and nonreciprocity metamaterial robots incorporating local sensing, computation, communication, and actuation (*216*). Achieving fully functional integration in metamaterial robotics can be pursued through various strategies, including the partial or full combination of responsive materials, metamaterial designs, embodied intelligence, advanced fabrication techniques, and high-fidelity simulation and control techniques.

Looking ahead, there remain critical research gaps in achieving the full potential of metamaterial robotics. First, unified design frameworks are needed to seamlessly integrate material properties, geometry, and functionality across scales; progress is hindered by the lack of standardized datasets and benchmarks. Second, achieving robust, scalable manufacturing remains an open challenge, particularly in fabricating structures with spatially varying heterogeneity and properties. Third, the modeling of dynamic interactions between metamaterial robots and environments—especially in unstructured, real-world settings—requires more efficient hybrid modeling tools. Last, this long-term vision requires having a platform of metamaterial robots that go beyond online models: robotic systems capable of autonomous learning, adaptation, and reconfiguration through the coevolution of material, morphology, and control. Advancing toward this goal will require interdisciplinary collaboration across robotics, materials science, computer science, and manufacturing, alongside a sustained effort to develop open-access tools and shared platforms for community-wide innovation.

Recent advances in AI have expanded the capabilities of metamaterial robotics. Beyond design and modeling, AI, such as reinforcement learning, supports autonomous control (*39*, *217*, *218*), real-world humanoid locomotion (*219*), dynamic robotic tracking (*220*), and agile soccer skills (*221*). Embedding these AI models into metamaterial robotic systems can improve robotic control, enabling robots to perform complex tasks, adapt to changing environments, and learn over time (*222*). With hierarchical architectures inspired by biological systems, metamaterial robotics holds the potential to achieve embodied intelligence across scales, from individual robotics with embedded intelligence to swarm robotics with the ability to communicate and collaborate.

We define the intelligence in the context of metamaterial robotics as the capacity to autonomously sense, process, and respond to environmental stimuli and to learn, adapt, and update behavior on the basis of memory. To move beyond subjective interpretation, intelligence can be evaluated using six objective criteria: (i) sensorimotor responsiveness, the ability to detect external stimuli and generate a physical response within defined latency thresholds; (ii) adaptability, the capacity to modify behavior or performance in response to varying environmental or task conditions; (iii) task generalization, the ability to perform multiple tasks or operate across different conditions without manual intervention; (iv) energy efficiency, the amount of energy required for perception, actuation, or decision-making relative to task complexity; (v) autonomy, the degree to which the system operates without external control, including local feedback control loops or embedded computational decision-making; and (vi) onboard learning, the capacity to store past experiences or states and use them to guide future decisions.

Individual metamaterial robotics

Integrating metamaterials into robotic components can address key challenges in actuation, sensing, control, and computation, advancing toward embodied intelligence. At a lower level of intelligence, metamaterial robots resemble simple organisms, such as Western Pacific hexactinellid sponges, which thrive in extreme deep-sea environments through hierarchical cylindrical lattice structures that provide mechanical robustness across scales (*223*). This hierarchical architecture inspires mechanical computing systems, where information processing and storage emerge as inherent material properties (*22*). These mechanical computing systems have been realized in logic computing (*88*, *96*), information storage (*99*, *100*), and mechanical neural networks (*52*). By leveraging hierarchical architectures and mechanical computing, metamaterial robots could blur the boundary between body and brain, potentially enabling autonomous adaptation to extreme environments (*224*).

At a higher level of intelligence, metamaterial robotics may mirror complex organisms such as humans. Drawing inspiration from biological systems, vertebrates have sophisticated sensory systems that enable them to perceive their environment through vision, touch, and other senses. They also have brains that learn, compute, reason, and make decisions; muscle systems that contract and relax to generate forces; and compliant bones and soft tissues that achieve dynamic gaits by storing elastic energy. Embodied AI follows this principle, enabling robots to interact with the physical world with agility, dexterity, and understanding. Furthermore, emerging technologies—including quantum machine learning (*225*), quantum materials (*226*), nanoelectromechanical systems (*227*), and neuromorphic computing (*228*)—further promise miniaturized "brains" within robotic bodies. We envision metamaterial robots that integrate such computing units with decentralized sensing networks, artificial muscles, and compliant skeletal structures (Fig. 2). This system-level intelligence emerges from a combination of a centralized computing system (for higher-order learning, decision-making, and control) and distributed, material-embedded sensing and actuation units (for local responsiveness and adaptation). In this sense, the brain captures the collective functionality of mechanical responses and embedded sensing networks, enabling the robot to perceive, interpret, and interact with its environment.

Swarm metamaterial robotics

Beyond individual robotics, swarm robotics involves groups of robots that coordinate and cooperate to solve problems or perform tasks collectively. Self-organized swarms of simple robots can function as a robotic society that is more robust to individual failures, more resilient to environmental changes, and capable of performing complex tasks and constructing sophisticated structures (*229*). Traditional robot swarms are typically homogeneous in physical designs and control algorithms, limiting emergent diversity and task flexibility. Metamaterials offer a pathway toward heterogeneous swarms composed of robots with specialized perception, actuation, and control capabilities, adaptable to varied environments. For example, metamaterial robots based on multistable structures can reconfigure their shapes (*82*), whereas those incorporating multiple smart materials can sense and respond to various external stimuli (*2*). Crucially, the contact-based coupling of metamaterial building blocks provides a mechanism for physical interaction and coordination across robots of different sizes and forms, enabling the creation of robotic aggregates and collectives (*159*, *160*, *168*).

Looking ahead, for robotic systems to perform increasingly complex tasks, they must—similar to many organisms on Earth—evolve from operating as isolated individuals or under centralized control to functioning as self-organizing, loosely coupled teams. Inspired by natural collectives—such as insect colonies or fish schools—swarm metamaterial robotics aims to generate emergent collective behaviors through simple local interaction rules. With the integration of embodied AI, these swarms could achieve higher levels of intelligence, enabling learning, communication, and collaboration across scales. These systems could range from microscale robot swarms for biomedical applications, such as targeted drug delivery, to meter-scale robot swarms for space exploration missions (Fig. 1E).

CONCLUSION

Metamaterial robotics represents a rapidly emerging frontier that unites materials, mechanics, and robotics to create systems capable of integrated sensing, actuation, control, and computation. Design principles—mechanics-inspired architectures, shape-reconfigurable structures, and material-driven functionality—enable tunable mechanical responses that underpin embodied intelligence, fostering adaptive, reconfigurable, and functionally distributed robotic systems. Modeling and simulation—ranging from physics-based to AI-driven and hybrid approaches—are key to predicting performance, optimizing structure, and bridging the gap between material behavior and robotic function.

Despite substantial progress, challenges remain in scalable manufacturing, accurate modeling of nonlinear and stimuli-responsive behaviors, and seamless integration of decentralized sensing and control. Addressing these gaps will require interdisciplinary collaboration across materials science, mechanical engineering, robotics, and computer science. Looking forward, metamaterial robotics has the potential to reshape how robotic systems interact with their environments—evolving from rigid, centralized machines to adaptive, intelligent collectives capable of self-organization, learning, and autonomous evolution, embedding intelligence not only in algorithms but also within their very materials and microstructures.

REFERENCES AND NOTES

1. X. Zheng, X. Zhang, T. T. Chen, I. Watanabe, Deep learning in mechanical metamaterials: From prediction and generation to inverse design. *Adv. Mater.* **35**, e2302530 (2023).
2. X. Xia, C. M. Spadaccini, J. R. Greer, Responsive materials architected in space and time. *Nat. Rev. Mater.* **7**, 683–701 (2022).
3. K. Bertoldi, V. Vitelli, J. Christensen, M. Van Hecke, Flexible mechanical metamaterials. *Nat. Rev. Mater.* **2**, 1–11 (2017).
4. P. Jiao, J. Mueller, J. R. Raney, X. Zheng, A. H. Alavi, Mechanical metamaterials and beyond. *Nat. Commun.* **14**, 6004 (2023).
5. P. Sinha, T. Mukhopadhyay, Programmable multi-physical mechanics of mechanical metamaterials. *Mater. Sci. Eng. R Rep.* **155**, 100745 (2023).
6. T. A. Schaedler, A. J. Jacobsen, A. Torrents, A. E. Sorensen, J. Lian, J. R. Greer, L. Valdevit, W. B. Carter, Ultralight metallic microlattices. *Science* **334**, 962–965 (2011).
7. X. Zheng, H. Lee, T. H. Weisgraber, M. Shusteff, J. DeOtte, E. B. Duoss, J. D. Kuntz, M. M. Biener, Q. Ge, J. A. Jackson, S. O. Kucheyev, N. X. Fang, C. M. Spadaccini, Ultralight, ultrastiff mechanical metamaterials. *Science* **344**, 1373–1377 (2014).
8. X. Zheng, X. Guo, I. Watanabe, A mathematically defined 3D auxetic metamaterial with tunable mechanical and conduction properties. *Mater. Des.* **198**, 109313 (2021).
9. S. Babaee, J. Shim, J. C. Weaver, E. R. Chen, N. Patel, K. Bertoldi, 3D soft metamaterials with negative Poisson's ratio. *Adv. Mater.* **25**, 5044–5049 (2013).
10. L. Jin, R. Khajehtourian, J. Mueller, A. Rafsanjani, V. Tournat, K. Bertoldi, D. M. Kochmann, Guided transition waves in multistable mechanical metamaterials. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 2319–2325 (2020).
11. H. Xiu, H. Liu, A. Poli, G. Wan, K. Sun, E. M. Arruda, X. Mao, Z. Chen, Topological transformability and reprogrammability of multistable mechanical metamaterials. *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2211725119 (2022).
12. B. Liu, J. L. Silverberg, A. A. Evans, C. D. Santangelo, R. J. Lang, T. C. Hull, I. Cohen, Topological kinematics of origami metamaterials. *Nat. Phys.* **14**, 811–815 (2018).
13. J. L. Silverberg, A. A. Evans, L. McLeod, R. C. Hayward, T. Hull, C. D. Santangelo, I. Cohen, Using origami design principles to fold reprogrammable mechanical metamaterials. *Science* **345**, 647–650 (2014).
14. J. Qi, Z. Chen, P. Jiang, H. Wenxia, Y. Wang, Z. Zhao, X. Cao, S. Zhang, R. Tao, Y. Li, D. Fang, Recent progress in active mechanical metamaterials and construction principles. *Adv. Sci.* **9**, e2102662 (2022).
15. T. Zhao, X. Dang, K. Manos, S. Zang, J. Mandal, M. Chen, G. H. Paulino, Modular chiral origami metamaterials. *Nature* **640**, 931–940 (2025).
16. A. Rafsanjani, K. Bertoldi, A. R. Studart, Programming soft robots with flexible mechanical metamaterials. *Sci. Robot.* **4**, eaav7874 (2019).
17. C. E. Gregg, D. Catanoso, B. Olivia Irene, I. K. Formoso, M. E. Ochalek, T. J. Olatunde, I. W. Park, F. M. Sebastianelli, E. M. Taylor, G. T. Trinh, K. C. Cheung, Ultralight, strong, and self-reprogrammable mechanical metamaterials. *Sci. Robot.* **9**, eadi2746 (2024).
18. A. Rafsanjani, Y. Zhang, B. Liu, S. M. Rubinstein, K. Bertoldi, Kirigami skins make a simple soft actuator crawl. *Sci. Robot.* **3**, eaar7555 (2018).
19. J. I. Lipton, R. MacCurdy, Z. Manchester, L. Chin, D. Cellucci, D. Rus, Handedness in shearing auxetics creates rigid and compliant structures. *Science* **360**, 632–635 (2018).
20. H. Cui, D. Yao, R. Hensleigh, L. Haotian, A. Calderon, X. Zhenpeng, S. Davaria, Z. Wang, P. Mercier, P. Tarazaga, X. R. Zheng, Design and printing of proprioceptive three-dimensional architected robotic metamaterials. *Science* **376**, 1287–1293 (2022).
21. C. H. Belke, K. Holdcroft, A. Sigrist, J. Paik, Morphological flexibility in robotic systems through physical polygon meshing. *Nat. Mach. Int.* **5**, 669–675 (2023).
22. H. Yasuda, P. R. Buskohl, A. Gillman, T. D. Murphey, S. Stepney, R. A. Vaia, J. R. Raney, Mechanical computing. *Nature* **598**, 39–48 (2021).
23. S. Bonfanti, R. Guerra, F. Font-Clos, D. Rayneau-Kirkhope, S. Zapperi, Automatic design of mechanical metamaterial actuators. *Nat. Commun.* **11**, 4162 (2020).
24. D. Matthews, A. Spielberg, D. Rus, S. Kriegman, J. Bongard, Efficient automatic design of robots. *Proc. Natl. Acad. Sci. U.S.A.* **120**, e2305180120 (2023).
25. O. Khatib, X. Yeh, G. Brantner, B. Soe, B. Kim, S. Ganguly, H. Stuart, S. Wang, M. Cutkosky, A. Edsinger, P. Mullins, M. Barham, C. R. Voolstra, K. N. Salama, M. L'Hour, V. Creuze, Ocean one: A robotic avatar for oceanic discovery. *IEEE Robot. Autom. Mag.* **23**, 20–29 (2016).
26. T. S. Vaquero, G. Daddi, R. Thakker, M. Paton, A. Jasour, M. P. Strub, R. M. Swan, R. Royce, M. Gildner, P. Tosi, M. Veismann, P. Gavrilov, E. Marteau, J. Bowkett, D. L. de Mola Lemus, Y. Nakka, B. Hockman, A. Orekhov, T. D. Hasseler, C. Leake, B. Nuernberger, P. Proença, W. Reid, W. Talbot, N. Georgiev, T. Pailevanian, A. Archanian, E. Ambrose, J. Jasper, R. Etheredge, C. Roman, D. Levine, K. Otsu, S. Yearicks, H. Melikyan, R. R. Rieber, K. Carpenter, J. Nash, A. Jain, L. Shiraishi, M. Robinson, M. Travers, H. Choset, J. Burdick, A. Gardner, M. Cable, M. Ingham, M. Ono, EELS: Autonomous snake-like robot with task and motion planning capabilities for ice world exploration. *Sci. Robot.* **9**, eadh8332 (2024).
27. D. J. Hyun, S. Seok, J. Lee, S. Kim, High speed trot-running: Implementation of a hierarchical controller using proprioceptive impedance control on the MIT Cheetah. *Int. J. Robot. Res.* **33**, 1417–1445 (2014).
28. A. Badri-Spröwitz, A. A. Sarvestani, M. Sitti, M. A. Daley, BirdBot achieves energy-efficient gait with minimal control using avian-inspired leg clutching. *Sci. Robot.* **7**, eabg4055 (2022).
29. P. Sareh, P. Chermprayong, M. Emmanuelli, H. Nadeem, M. Kovac, Rotorigami: A rotary origami protective system for robotic rotorcraft. *Sci. Robot.* **3**, eaah5228 (2018).
30. K. Kim, P. Spieler, E.-S. Lupu, A. Ramezani, S.-J. Chung, A bipedal walking robot that can fly, slackline, and skateboard. *Sci. Robot.* **6**, eabf8136 (2021).
31. Y. Ding, M. Kim, S. Kuindersma, C. J. Walsh, Human-in-the-loop optimization of hip assistance with a soft exosuit during walking. *Sci. Robot.* **3**, eaar5438 (2018).
32. M. Mete, H. Jeong, W. D. Wang, J. Paik, Sori: A softness-rendering interface to unravel the nature of softness perception. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2314901121 (2024).
33. R. Baines, S. K. Patiballa, J. Booth, L. Ramirez, T. Sipple, A. Garcia, F. Fish, R. Kramer-Bottiglio, Multi-environment robotic transitions through adaptive morphogenesis. *Nature* **610**, 283–289 (2022).
34. X. Zhou, X. Wen, Z. Wang, Y. Gao, H. Li, Q. Wang, T. Yang, L. Haojian, Y. Cao, X. Chao, F. Gao, Swarm of micro flying robots in the wild. *Sci. Robot.* **7**, eabm5954 (2022).
35. J. K. Choe, J. Kim, H. Song, J. Bae, J. Kim, A soft, self-sensing tensile valve for perceptive soft robots. *Nat. Commun.* **14**, 3942 (2023).
36. S. P. M. Babu, F. Visentin, A. Sadeghi, A. Mondini, F. Meder, B. Mazzolai, Sensorized foam actuator with intrinsic proprioception and tunable stiffness behavior for soft robots. *Adv. Intell. Syst.* **3**, 2100022 (2021).
37. D. Hoeller, N. Rudin, D. Sako, M. Hutter, ANYmal parkour: Learning agile navigation for quadrupedal robots. *Sci. Robot.* **9**, eadi7566 (2024).
38. L. Li, S. Wang, Y. Zhang, S. Song, C. Wang, S. Tan, W. Zhao, G. Wang, W. Sun, F. Yang, J. Liu, B. Chen, X. Haoyuan, P. Nguyen, M. Kovac, L. Wen, Aerial-aquatic robots capable of crossing the air-water boundary and hitchhiking on surfaces. *Sci. Robot.* **7**, eabm6695 (2022).
39. Y. Song, A. Romero, M. Müller, V. Koltun, D. Scaramuzza, Reaching the limit in autonomous racing: Optimal control versus reinforcement learning. *Sci. Robot.* **8**, eadg1462 (2023).
40. A. Gupta, S. Savarese, S. Ganguli, L. Fei-Fei, Embodied intelligence via learning and evolution. *Nat. Commun.* **12**, 5721 (2021).
41. V. A. Baulin, A. Giacometti, D. A. Fedosov, S. Ebbens, N. R. Varela-Rosales, N. Feliu, M. Chowdhury, M. Hu, R. Füchslin, M. Dijkstra, M. Mussel, R. van Roij, D. Xie, V. Tzanov, M. Zu, S. Hidalgo-Caballero, Y. Yuan, L. Cocconi, C.-M. Ghim, C. Cottin-Bizonne, M. C. Miguel, M. J. Esplandiu, J. Simmchen, W. J. Parak, M. Werner, G. Gompper, M. M. Hanczyc, Intelligent soft matter: Towards embodied intelligence. *Soft Matter* **21**, 4129–4145 (2025).
42. D. S. Polat, Z. Chen, S. A. M. Weima, S. Aya, D. Liu, An autonomous snapper featuring adaptive actuation and embodied intelligence. *Sci. Adv.* **11**, eadu4268 (2025).
43. A. Comoretto, H. A. H. Schomaker, J. T. B. Overvelde, Physical synchronization of soft self-oscillating limbs for fast and autonomous locomotion. *Science* **388**, 610–615 (2025).
44. X. Fang, J. Wen, L. Cheng, Y. Dianlong, H. Zhang, P. Gumbsch, Programmable gear-based mechanical metamaterials. *Nat. Mater.* **21**, 869–876 (2022).
45. K. K. Dudek, M. Kadic, C. Coulais, K. Bertoldi, Shape-morphing metamaterials. *Nat. Rev. Mater.* **10**, 783–798 (2025).
46. J. Bauer, L. R. Meza, T. A. Schaedler, R. Schwaiger, X. Zheng, L. Valdevit, Nanolattices: An emerging class of mechanical metamaterials. *Adv. Mater.* **29**, 1701850 (2017).
47. J. B. Berger, H. N. G. Wadley, R. M. McMeeking, Mechanical metamaterials at the theoretical limit of isotropic elastic stiffness. *Nature* **543**, 533–537 (2017).
48. C. Crook, J. Bauer, A. G. Izard, C. Santos, J. de Oliveira, J. M. de Souza e Silva, J. B. Berger, L. Valdevit, Plate-nanolattices at the theoretical limit of stiffness and strength. *Nat. Commun.* **11**, 1579 (2020).
49. X. Zheng, F. Zhibing, D. Kai, C. Wang, Y. Yi, Minimal surface designs for porous materials: From microstructures to mechanical properties. *J. Mater. Sci.* **53**, 10194–10208 (2018).
50. X. Zheng, W. Smith, J. Jackson, B. Moran, H. Cui, D. Chen, J. Ye, N. Fang, N. Rodriguez, T. Weisgraber, C. M. Spadaccini, Multiscale metallic metamaterials. *Nat. Mater.* **15**, 1100–1106 (2016).
51. Y. Jiang, Q. Wang, Highly-stretchable 3D-architected mechanical metamaterials. *Sci. Rep.* **6**, 34147 (2016).
52. R. H. Lee, E. A. B. Mulder, J. B. Hopkins, Mechanical neural networks: Architected materials that learn behaviors. *Sci. Robot.* **7**, eabq7278 (2022).
53. D. Yang, M. Feng, G. Guoying, High-stroke, high-output-force, fabric-lattice artificial muscles for soft robots. *Adv. Mater.* **36**, e2306928 (2024).
54. R. L. Truby, L. Chin, A. Zhang, D. Rus, Fluidic innervation sensorizes structures from a single build material. *Sci. Adv.* **8**, eabq4385 (2022).
55. T. Frenzel, M. Kadic, M. Wegener, Three-dimensional mechanical metamaterials with a twist. *Science* **358**, 1072–1074 (2017).
56. V. S. Deshpande, M. F. Ashby, N. A. Fleck, Foam topology: Bending versus stretching dominated architectures. *Acta Mater.* **49**, 1035–1040 (2001).
57. A. Abdel-Rahman, C. Cameron, B. Jenett, M. Smith, N. Gershenfeld, Self-replicating hierarchical modular robotic swarms. *Commun. Eng.* **1**, 35 (2022).

58. B. Jenett, D. Cellucci, "A mobile robot for locomotion through a 3D periodic lattice environment" in *2017 IEEE International Conference on Robotics and Automation (ICRA)* (IEEE, 2017), pp. 5474–5479.
59. J. Jeong, J. Yang, G. H. G. Christmann, J. Baltes, Lightweight mechatronic system for humanoid robot. *Knowl. Eng. Rev.* **38**, e5 (2023).
60. Q. Guan, F. Stella, C. D. Santina, J. Leng, J. Hughes, Trimmed helicoids: An architectured soft structure yielding soft robots with high precision, large workspace, and compliant interactions. *Npj Robot.* **1**, 4 (2023).
61. D. Wang, C. Jiang, G. Guoying, Modeling and design of lattice-reinforced pneumatic soft robots. *IEEE Trans. Robot.* **40**, 606–623 (2024).
62. Q. Guan, B. Dai, H. H. Cheng, J. Hughes, Lattice structure musculoskeletal robots: Harnessing programmable geometric topology and anisotropy. *Sci. Adv.* **11**, eadu9856 (2025).
63. C. L. Kane, T. C. Lubensky, Topological boundary modes in isostatic lattices. *Nat. Phys.* **10**, 39–45 (2014).
64. A. S. Meeussen, J. Paulose, V. Vitelli, Geared topological metamaterials with tunable mechanical stability. *Phys. Rev. X* **6**, 041029 (2016).
65. M. Carton, J. F. Kowalewski, J. Guo, J. F. Alpert, A. Garg, D. Revier, J. I. Lipton, Bridging hard and soft: Mechanical metamaterials enable rigid torque transmission in soft robots. *Sci. Robot.* **10**, eads0548 (2025).
66. D. Wang, B. Zhao, X. Li, L. Dong, M. Zhang, J. Zou, G. Guoying, Dexterous electrical-driven soft robots with reconfigurable chiral-lattice foot design. *Nat. Commun.* **14**, 5067 (2023).
67. X. Ren, R. Das, P. Tran, T. D. Ngo, Y. M. Xie, Auxetic metamaterials and structures: A review. *Smart Mater. Struct.* **27**, 023001 (2018).
68. W. Wenwang, H. Wenxia, G. Qian, H. Liao, X. Xiaoying, F. Berto, Mechanical design and multifunctional applications of chiral mechanical metamaterials: A review. *Mater. Des.* **180**, 107950 (2019).
69. A. G. Mark, S. Palagi, T. Qiu, P. Fischer, "Auxetic metamaterial simplifies soft robot design" in *2016 IEEE International Conference on Robotics and Automation (ICRA)* (IEEE, 2016), pp. 4951–4956.
70. B. Liu, J. Feng, Y. Kang, J. Li, H. Qirui, Z. Lin, F. Jianzhong, Three-dimensional auxetic structure design methods based on bulking-induced deformation and the application in soft crawling robot. *Compos. Part B Eng.* **244**, 110146 (2022).
71. C. Tawk, R. Mutlu, G. Alici, A 3D printed modular soft gripper integrated with metamaterials for conformal grasping. *Front. Robot. AI* **8**, 799230 (2022).
72. P. Kaarthik, F. L. Sanchez, J. Avtges, R. L. Truby, Motorized, untethered soft robots via 3D printed auxetics. *Soft Matter* **18**, 8229–8237 (2022).
73. L. Chin, M. Burns, G. Xie, D. Rus, Flipper-style locomotion through strong expanding modular robots. *IEEE Robot. Autom. Lett.* **8**, 528–535 (2023).
74. Y.-J. Lee, S. Misra, W.-H. Chen, D. E. Koditschek, C. Sung, S. Yang, Tendon-driven auxetic tubular springs for resilient hopping robots. *Adv. Intell. Syst.* **4**, 2100152 (2022).
75. Y. Jiang, Z. Liu, N. Matsuhisa, D. Qi, W. R. Leow, H. Yang, Y. Jiancan, G. Chen, Y. Liu, C. Wan, Z. Liu, X. Chen, Auxetic mechanical metamaterials to enhance sensitivity of stretchable strain sensors. *Adv. Mater.* **30**, e1706589 (2018).
76. A. Ahmadpour, A. K. Yetisen, S. Tasoglu, Piezoelectric metamaterial blood pressure sensor. *ACS Appl. Electron. Mater.* **5**, 3280–3290 (2023).
77. H. Taiqi, T. Pan, D. Guo, Y. Xiao, F. Li, M. Gao, Z. Huang, J. Zhu, T. Cheng, Y. Lin, Omnidirectional configuration of stretchable strain sensor enabled by the strain engineering with chiral auxetic metamaterial. *ACS Nano* **17**, 22035–22045 (2023).
78. D. Hwang, E. J. Barron III, A. B. M. Tahidul Haque, M. D. Bartlett, Shape morphing mechanical metamaterials through reversible plasticity. *Sci. Robot.* **7**, eabg2171 (2022).
79. C. Jiang, F. Rist, H. Wang, J. Wallner, H. Pottmann, Shape-morphing mechanical metamaterials. *Comput. Aided Des.* **143**, 103146 (2022).
80. A. Steed, E. Ofek, M. Sinclair, M. Gonzalez-Franco, A mechatronic shape display based on auxetic materials. *Nat. Commun.* **12**, 4758 (2021).
81. A. Pal, V. Restrepo, D. Goswami, R. V. Martinez, Exploiting mechanical instabilities in soft robotics: Control, sensing, and actuation. *Adv. Mater.* **33**, e2006939 (2021).
82. Y. Chi, Y. Li, Y. Zhao, Y. Hong, Y. Tang, J. Yin, Bistable and multistable actuators for soft robots: Structures, materials, and functionalities. *Adv. Mater.* **34**, e2110384 (2022).
83. D. Yang, M. S. Verma, J.-H. So, B. Mosadegh, C. Keplinger, B. Lee, F. Khashai, E. Lossner, Z. Suo, G. M. Whitesides, Buckling pneumatic linear actuators inspired by muscle. *Adv. Mater. Technol.* **1**, (2016).
84. D. Yang, B. Mosadegh, A. Ainla, B. C. G. Lee, F. Khashai, Z. Suo, K. Bertoldi, G. M. C. Whitesides, Buckling of elastomeric beams enables actuation of soft machines. *Adv. Mater.* **27**, 6323–6327 (2015).
85. A. Djellouli, B. Van Raemdonck, Y. Wang, Y. Yang, A. Caillaud, D. Weitz, S. Rubinstein, B. Gorissen, K. Bertoldi, Shell buckling for programmable metafluids. *Nature* **628**, 545–550 (2024).
86. H. Bruno Grossi, J. C. Z. Palza, C. Falcón, G. During, Metarpillar: Soft robotic locomotion based on buckling-driven elastomeric metamaterials. *Mater. Des.* **212**, 110285 (2021).
87. X. Zheng, K. Uto, H. Wei-Hsun, T.-T. Chen, M. Naito, I. Watanabe, Reprogrammable flexible mechanical metamaterials. *Appl. Mater. Today* **29**, 101662 (2022).
88. C. El Helou, P. R. Buskohl, C. E. Tabor, R. L. Harne, Digital logic gates in soft, conductive mechanical metamaterials. *Nat. Commun.* **12**, 1633 (2021).
89. C. El Helou, B. Grossmann, Mechanical integrated circuit materials. *Nature* **608**, 699–703 (2022).
90. J. K. Choe, J. Yi, H. Jang, H. Won, S. Lee, H. Lee, Y. Jang, H. Song, J. Kim, Digital mechanical metamaterial: Encoding mechanical information with graphical stiffness pattern for adaptive soft machines. *Adv. Mater.* **36**, e2304302 (2024).
91. T. Chen, O. R. Bilal, K. Shea, C. Daraio, Harnessing bistability for directional propulsion of soft, untethered robots. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 5698–5702 (2018).
92. B. Gorissen, D. Melancon, N. Vasios, M. Torbati, K. Bertoldi, Inflatable soft jumper inspired by shell snapping. *Sci. Robot.* **5**, eabb1967 (2020).
93. A. F. Minori, S. Jadhav, H. Chen, S. Fong, M. T. Tolley, Power amplification for jumping soft robots actuated by artificial muscles. *Front. Robot. AI* **9**, 844282 (2022).
94. Y. Tang, Y. Chi, J. Sun, T.-H. Huang, O. H. Maghsoudi, A. Spence, J. Zhao, S. Hao, J. Yin, Leveraging elastic instabilities for amplified performance: Spine-inspired high-speed and high-force soft robots. *Sci. Adv.* **6**, eaaz6912 (2020).
95. A. H. Gelebart, D. J. Mulder, M. Varga, A. Konya, G. Vantomme, E. W. Meijer, R. L. B. Selinger, D. J. Broer, Making waves in a photoactive polymer film. *Nature* **546**, 632–636 (2017).
96. T. Mei, Z. Meng, K. Zhao, C. Q. Chen, A mechanical metamaterial with reprogrammable logical functions. *Nat. Commun.* **12**, 7234 (2021).
97. J. Daniel, P. R. Preston, H. J. Jiang, M. P. Nemitz, J. Rawson, Z. Suo, G. M. Whitesides, Digital logic for soft devices. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 7750–7759 (2019).
98. J. Byun, A. Pal, J. Ko, M. Sitti, Integrated mechanical computing for autonomous soft machines. *Nat. Commun.* **15**, 2933 (2024).
99. T. Chen, M. Pauly, P. M. Reis, A reprogrammable mechanical metamaterial with stable memory. *Nature* **589**, 386–390 (2021).
100. Z. Meng, H. Yan, M. Liu, W. Qin, G. M. Genin, C. Q. Chen, Encoding and storage of information in mechanical metamaterials. *Adv. Sci.* **10**, e2301581 (2023).
101. A. Zareei, B. Deng, K. Bertoldi, Harnessing transition waves to realize deployable structures. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 4015–4020 (2020).
102. N. Xia, D. Jin, C. Pan, J. Zhang, Z. Yang, S. Lin, J. Zhao, L. Wang, L. Zhang, Dynamic morphological transformations in soft architected materials via buckling instability encoded heterogeneous magnetization. *Nat. Commun.* **13**, 7514 (2022).
103. H. Zhang, W. Jun, D. Fang, Y. Zhang, Hierarchical mechanical metamaterials built with scalable tristable elements for ternary logic operation and amplitude modulation. *Sci. Adv.* **7**, eabf1966 (2021).
104. H. Fu, K. Nan, W. Bai, W. Huang, K. Bai, L. Lu, C. Zhou, Y. Liu, F. Liu, J. Wang, M. Han, Z. Yan, H. Luan, Y. Zhang, Y. Zhang, J. Zhao, X. Cheng, M. Li, J. W. Lee, Y. Liu, D. Fang, X. Li, Y. Huang, Y. Zhang, J. A. Rogers, Morphable 3D mesostructures and microelectronic devices by multistable buckling mechanics. *Nat. Mater.* **17**, 268–276 (2018).
105. Z. Zhai, W. Lingling, H. Jiang, Mechanical metamaterials based on origami and kirigami. *Appl. Phys. Rev.* **8**, (2021).
106. M. Meloni, J. Cai, Q. Zhang, D. S.-H. Lee, M. Li, R. Ma, T. E. Parashkevov, J. Feng, Engineering origami: A comprehensive review of recent applications, design methods, and tools. *Adv. Sci.* **8**, 2000636 (2021).
107. S.-M. Baek, S. Yim, S.-H. Chae, D.-Y. Lee, K.-J. Cho, Ladybird beetle–inspired compliant origami. *Sci. Robot.* **5**, (2020).
108. B. Elliot Hawkes, N. M. An, H. T. Benbernou, S. Kim, E. D. Demaine, D. Rus, R. J. Wood, Programmable matter by folding. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 12441–12445 (2010).
109. S. Li, D. M. Vogt, D. Rus, R. J. Wood, Fluid-driven origami-inspired artificial muscles. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 13132–13137 (2017).
110. S. Zhang, X. Ke, Q. Jiang, H. Ding, W. Zhigang, Programmable and reprocessable multifunctional elastomeric sheets for soft origami robots. *Sci. Robot.* **6**, eabd6107 (2021).
111. S. Wang, Y. Gao, A. Wei, P. Xiao, Y. Liang, L. Wei, C. Chen, C. Zhang, G. Yang, H. Yao, T. Chen, Asymmetric elastoplasticity of stacked graphene assembly actualizes programmable untethered soft robotics. *Nat. Commun.* **11**, 4359 (2020).
112. Q. Ze, X. Kuang, W. Shuai, S. Janet Wong, M. Montgomery, R. Zhang, J. M. Kovitz, H. Fengyuan Yang, J. Qi, R. Zhao, Magnetic shape memory polymers with integrated multifunctional shape manipulation. *Adv. Mater.* **32**, e1906657 (2020).
113. G. Mao, D. Schiller, D. Danninger, B. Hailegnaw, F. Hartmann, T. Stockinger, M. Drack, N. Arnold, M. Kaltenbrunner, Ultrafast small-scale soft electromagnetic robots. *Nat. Commun.* **13**, 4456 (2022).
114. O. M. Wani, H. Zeng, A. Priimagi, A light-driven artificial flytrap. *Nat. Commun.* **8**, 15546 (2017).
115. Z. Zhakypov, K. Mori, K. Hosoda, J. Paik, Designing minimal and scalable insect-inspired multi-locomotion millirobots. *Nature* **571**, 381–386 (2019).
116. G. Hongri, M. Möckli, C. Ehmke, M. Kim, M. Wieland, S. Moser, C. Bechinger, Q. Boehler, B. J. Nelson, Self-folding soft-robotic chains with reconfigurable shapes and functionalities. *Nat. Commun.* **14**, 1263 (2023).
117. Z. Zhang, Z. Shi, D. Ahmed, Sonotransformers: Transformable acoustically activated wireless microscale machines. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2314661121 (2024).

118. J. T. B. Overvelde, T. A. De Jong, Y. Shevchenko, S. A. Becerra, G. M. Whitesides, J. C. Weaver, C. Hoberman, K. Bertoldi, A three-dimensional actuated origami-inspired transformable metamaterial with multiple degrees of freedom. *Nat. Commun.* **7**, 10929 (2016).
119. D.-Y. Lee, J.-K. Kim, C.-Y. Sohn, J.-M. Heo, K.-J. Cho, High–load capacity origami transformable wheel. *Sci. Robot.* **6**, eabe0201 (2021).
120. B. Seyidoğlu, A. Rafsanjani, A textile origami snake robot for rectilinear locomotion. *Device* **2**, 100226 (2024).
121. C. H. Belke, J. Paik, Mori: A modular origami robot. *IEEE/ASME Trans. Mech.* **22**, 2153–2164 (2017).
122. W. Wang, N.-G. Kim, H. Rodrigue, S.-H. Ahn, Modular assembly of soft deployable structures and robots. *Mater. Horiz.* **4**, 367–376 (2017).
123. A. Bolotnikova, K. Holdcroft, H. Cerbone, C. Belke, A. Ijspeert, J. Paik, Optimized user-guided motion control of modular robots. *Nat. Commun.* **16**, 8675 (2025).
124. S. Mintchev, J. Shintake, D. Floreano, Bioinspired dual-stiffness origami. *Sci. Robot.* **3**, eaau0275 (2018).
125. C. Zhang, Z. Zhang, Y. Peng, Y. Zhang, S. An, Y. Wang, Z. Zhai, X. Yan, H. Jiang, Plug & play origami modules with all-purpose deformation modes. *Nat. Commun.* **14**, 4329 (2023).
126. S. Larissa, Q. Z. Novelino, W. Shuai, G. H. Paulino, R. Zhao, Untethered control of functional origami microrobots with distributed actuation. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 24096–24101 (2020).
127. W. Shuai, Q. Ze, J. Dai, N. Udipi, G. H. Paulino, R. Zhao, Stretchable origami robotic arm with omnidirectional bending and twisting. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2110023118 (2021).
128. Q. Zhang, K. Barri, P. Jiao, L. Wenyun, J. Luo, W. Meng, J. Wang, L. Hong, J. Mueller, Z. L. Wang, A. H. Alavi, Meta-mechanotronics for self-powered computation. *Mater. Today* **65**, 78–89 (2023).
129. W. Shuang, T. Zhao, Y. Zhu, G. H. Paulino, Modular multi-degree-of-freedom soft origami robots with reprogrammable electrothermal actuation. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2322625121 (2024).
130. R. Baines, F. Zuliani, N. Chennoufi, S. Joshi, R. Kramer-Bottiglio, J. Paik, Multi-modal deformation and temperature sensing for context-sensitive machines. *Nat. Commun.* **14**, 7499 (2023).
131. S. Mintchev, M. Salerno, A. Cherpillod, S. Scaduto, J. Paik, A portable three-degrees-of-freedom force feedback origami robot for human–robot interactions. *Nat. Mach. Int.* **1**, 584–593 (2019).
132. M. Salerno, J. Paik, S. Mintchev, Ori-pixel, a multi-dofs origami pixel for modular reconfigurable surfaces. *IEEE Robot. Autom. Lett.* **5**, 6988–6995 (2020).
133. G. P. T. Choi, L. H. Dudte, L. Mahadevan, Programming shape using kirigami tessellations. *Nat. Mater.* **18**, 999–1004 (2019).
134. S. Xu, Z. Yan, K.-I. Jang, W. Huang, H. Fu, J. Kim, Z. Wei, M. Flavin, J. M. Cracken, R. Wang, A. Badea, Y. Liu, D. Xiao, G. Zhou, J. Lee, H. U. Chung, H. Cheng, W. Ren, A. Banks, X. Li, U. Paik, R. G. Nuzzo, Y. Huang, Y. Zhang, J. A. Rogers, Assembly of micro/nanomaterials into complex, three-dimensional architectures by compressive buckling. *Science* **347**, 154–159 (2015).
135. Y. Tang, J. Yin, Design of cut unit geometry in hierarchical kirigami-based auxetic metamaterials for high stretchability and compressibility. *Extreme Mech. Lett.* **12**, 77–85 (2017).
136. L. Xiao Shang, A. R. Liu, D. Pasini, Durable bistable auxetics made of rigid solids. *J. Mater. Res.* **33**, 300–308 (2018).
137. H. Yang, S. Ding, J. Wang, S. Sun, R. Swaminathan, S. W. L. Ng, X. Pan, G. W. Ho, Computational design of ultra-robust strain sensors for soft robot perception and autonomy. *Nat. Commun.* **15**, 1636 (2024).
138. D. T. Nguyen, Q. Zeng, X. Tian, P. Chia, W. Changsheng, Y. Liu, J. S. Ho, Ambient health sensing on passive surfaces using metamaterials. *Sci. Adv.* **10**, eadj6613 (2024).
139. C. Hong, W. Yingdan, C. Wang, Z. Ren, C. Wang, Z. Liu, H. Wenqi, M. Sitti, Wireless flow-powered miniature robot capable of traversing tubular structures. *Sci. Robot.* **9**, eadi5155 (2024).
140. X. Zhang, L. Medina, H. Cai, V. Aksyuk, H. D. Espinosa, D. Lopez, Kirigami engineering—nanoscale structures exhibiting a range of controllable 3D configurations. *Adv. Mater.* **33**, e2005275 (2021).
141. Y. Zhang, Z. Yan, K. Nan, D. Xiao, Y. Liu, H. Luan, F. Haoran, X. Wang, Q. Yang, J. Wang, Y. Huang, J. A. Rogers, A mechanically driven form of kirigami as a route to 3D mesostructures in micro/nanomembranes. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 11757–11764 (2015).
142. A. Rafsanjani, L. Jin, B. Deng, K. Bertoldi, Propagation of pop ups in kirigami shells. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 8200–8205 (2019).
143. Y. Tang, G. Lin, S. Yang, Y. K. Yi, R. D. Kamien, J. Yin, Programmable kiri-kirigami metamaterials. *Adv. Mater.* **29**, 1604262 (2017).
144. D.-G. Hwang, M. D. Bartlett, Tunable mechanical metamaterials through hybrid kirigami structures. *Sci. Rep.* **8**, 3378 (2018).
145. M. A. Dias, M. P. McCarron, D. Rayneau-Kirkhope, P. Z. Hanakata, D. K. Campbell, H. S. Park, D. P. Holmes, Kirigami actuators. *Soft Matter* **13**, 9087–9092 (2017).
146. Y. Yang, K. Vella, D. P. Holmes, Grasping with kirigami shells. *Sci. Robot.* **6**, eabd6426 (2021).
147. H. Luan, X. Cheng, A. Wang, S. Zhao, K. Bai, H. Wang, W. Pang, Z. Xie, K. Li, F. Zhang, Y. Xue, Y. Huang, Y. Zhang, Design and fabrication of heterogeneous, deformable substrates for the mechanically guided 3D assembly. *ACS Appl. Mater. Interfaces* **11**, 3482–3492 (2019).
148. K. Bashandeh, M. Humood, J. Lee, M. Han, Y. Cui, Y. Shi, Y. Huang, J. A. Rogers, A. A. Polycarpou, The effect of defects on the cyclic behavior of polymeric 3D kirigami structures. *Extreme Mech. Lett.* **36**, 100650 (2020).
149. Z. Zheng, J. Han, Q. Shi, S. O. Demir, W. Jiang, M. Sitti, Single-step precision programming of decoupled multiresponsive soft millirobots. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2320386121 (2024).
150. L. Yue Dong, N. X. Wang, Z. Yang, C. Zhang, C. Pan, D. Jin, J. Zhang, C. Majidi, L. Zhang, Untethered small-scale magnetic soft robot with programmable magnetization and integrated multifunctional modules. *Sci. Adv.* **8**, eabn8932 (2022).
151. Z. Ren, H. Wenqi, X. Dong, M. Sitti, Multi-functional soft-bodied jellyfish-like swimming. *Nat. Commun.* **10**, 2703 (2019).
152. J. Yuwei, H. Run, Y. Xie, J. Yao, X. Li, Y. Lv, X. Han, Q. Cao, L. Li, Reconfigurable magnetic soft robots with multimodal locomotion. *Nano Energy* **87**, 106169 (2021).
153. A. P. Rubio, K. Mundilova, D. Preiss, E. D. Demaine, N. Gershenfeld, "Kirigami corrugations: Strong, modular, and programmable plate lattices" in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (American Society of Mechanical Engineers, 2023), vol. 87363, p. V008T08A049.
154. Y. Hong, Y. Zhao, J. Berman, Y. Chi, Y. Li, H. Huang, J. Yin, Angle-programmed tendril-like trajectories enable a multifunctional gripper with ultradelicacy, ultrastrength, and ultraprecision. *Nat. Commun.* **14**, 4625 (2023).
155. C. Branyan, R. L. Hatton, Y. Mengüç, Snake-inspired kirigami skin for lateral undulation of a soft snake robot. *IEEE Robot. Autom. Lett.* **5**, 1728–1733 (2020).
156. M. Mirkhalaf, A. Rafsanjani, Harnessing machine mechanisms to continuously reprogram metamaterials. *Matter* **6**, 3719–3731 (2023).
157. L. A. Shaw, S. Chizari, M. Dotson, Y. Song, J. B. Hopkins, Compliant rolling-contact architected materials for shape reconfigurability. *Nat. Commun.* **9**, 4594 (2018).
158. T. Wang, C. Pierce, V. Kojouharov, B. Chong, K. Diaz, L. Hang, D. I. Goldman, Mechanical intelligence simplifies control in terrestrial limbless locomotion. *Sci. Robot.* **8**, eadi2243 (2023).
159. B. Saintyves, M. Spenko, H. M. Jaeger, A self-organizing robotic aggregate using solid and liquid-like collective states. *Sci. Robot.* **9**, eadh4130 (2024).
160. M. R. Devlin, S. Kim, O. Campàs, E. W. Hawkes, Material-like robotic collectives with spatiotemporal control of strength and shape. *Science* **387**, 880–885 (2025).
161. D. Zhao, H. Luo, T. Yuxiao, C. Meng, T. L. Lam, Snail-inspired robotic swarms: A hybrid connector drives collective adaptation in unstructured outdoor environments. *Nat. Commun.* **15**, 3647 (2024).
162. Y. Wang, L. Li, D. Hofmann, J. E. Andrade, C. Daraio, Structured fabrics with tunable mechanical properties. *Nature* **596**, 238–243 (2021).
163. R. Hensleigh, H. Cui, X. Zhenpeng, J. Massman, D. Yao, J. Berrigan, X. Zheng, Charge-programmed three-dimensional printing for multi-material electronic devices. *Nat. Electron.* **3**, 216–224 (2020).
164. X. Zheng, I. Watanabe, S. Wang, T.-T. Chen, M. Naito, Minimal-surface-based multiphase metamaterials with highly variable stiffness. *Mater. Des.* **237**, 112548 (2024).
165. W. Fan, Q. He, K. Meng, X. Tan, Z. Zhou, G. Zhang, J. Yang, Z. L. Wang, Machine-knitted washable sensor array textile for precise epidermal physiological signal monitoring. *Sci. Adv.* **6**, eaay2840 (2020).
166. W. Chen, D. Tong, L. Meng, B. Tan, R. Lan, Q. Zhang, H. Yang, C. Wang, K. Liu, Knotted artificial muscles for bio-mimetic actuation under deepwater. *Adv. Mater.* **36**, e2400763 (2024).
167. K. Singal, M. S. Dimitriyev, S. E. Gonzalez, A. Patrick Cachine, S. Quinn, E. A. Matsumoto, Programming mechanics in knitted materials, stitch by stitch. *Nat. Commun.* **15**, 2622 (2024).
168. S. Li, R. Batra, D. Brown, H.-D. Chang, N. Ranganathan, C. Hoberman, D. Rus, H. Lipson, Particle robotics based on statistical mechanics of loosely coupled components. *Nature* **567**, 361–365 (2019).
169. Z. Meng, H. Yan, Y. Wang, Granular metamaterials with dynamic bond reconfiguration. *Sci. Adv.* **10**, eadq7933 (2024).
170. W. Zhou, S. Nadarajah, L. Li, A. G. Izard, H. Yan, A. K. Prachet, P. Patel, X. Xia, C. Daraio, 3D polycatenated architected materials. *Science* **387**, 269–277 (2025).
171. C. C. J. Alcântara, F. C. Landers, S. Kim, C. De Marco, D. Ahmed, B. J. Nelson, S. Pané, Mechanically interlocked 3D multi-material micromachines. *Nat. Commun.* **11**, 5957 (2020).
172. M. A. McEvoy, N. Correll, Materials that couple sensing, actuation, computation, and communication. *Science* **347**, 1261689 (2015).

173. Q. He, S. Ferracin, J. R. Raney, Programmable responsive metamaterials for mechanical computing and robotics. *Nat. Comput. Sci.* **4**, 567–573 (2024).
174. Y. Roh, M. Kim, S. M. Won, D. Lim, I. Hong, S. Lee, T. Kim, C. Kim, D. Lee, S. Im, G. Lee, D. Kim, D. Shin, D. Gong, B. Kim, S. Kim, S. Kim, H. K. Kim, B.-K. Koo, S. Seo, J.-S. Koh, D. Kang, S. Han, Vital signal sensing and manipulation of a microscale organ with a multifunctional soft gripper. *Sci. Robot.* **6**, eabi6774 (2021).
175. Y. Wang, H. Ye, J. He, Q. Ge, Y. Xiong, Electrothermally controlled origami fabricated by 4d printing of continuous fiber-reinforced composites. *Nat. Commun.* **15**, 2322 (2024).
176. W. Shuang, G. L. Baker, J. Yin, Y. Zhu, Fast thermal actuators for soft robotics. *Soft Robot.* **9**, 1031–1039 (2022).
177. W. Pang, S. Xu, J. Wu, R. Bo, T. Jin, Y. Xiao, Z. Liu, F. Zhang, X. Cheng, K. Bai, H. Song, Z. Xue, L. Wen, Y. Zhang, A soft microrobot with highly deformable 3D actuators for climbing and transitioning complex surfaces. *Proc. Natl. Acad. Sci. U.S.A.* **119**, e2215028119 (2022).
178. X. Shiwei, H. Xiaonan, R. Yang, C. Zang, L. Li, Y. Xiao, W. Liu, B. Tian, W. Pang, R. Bo, Q. Liu, Y. Yang, Y. Lai, J. Wu, H. Zhao, L. Wen, Y. Zhang, Transforming machines capable of continuous 3D shape morphing and locking. *Nat. Mach. Int.* **7**, 703–715 (2025).
179. A. Kotikian, C. McMahan, E. C. Davidson, J. M. Muhammad, R. D. Weeks, C. Daraio, J. A. Lewis, Untethered soft robotic matter with passive control of shape morphing and propulsion. *Sci. Robot.* **4**, eaax7044 (2019).
180. B. Jin, H. Song, R. Jiang, J. Song, Q. Zhao, T. Xie, Programming a crystalline shape memory polymer network with thermo-and photo-reversible bonds toward a single-component soft robot. *Sci. Adv.* **4**, eaao3865 (2018).
181. Y. Zhang, W. Z. Jiang, Y. Pan, X. C. Teng, X. Hang Hang, H. Yan, X. H. Ni, J. Dong, D. Han, W. Q. Chen, J. Yang, Y. M. Xie, Y. Lu, X. Ren, Temperature-responsive metamaterials made of highly sensitive thermostat metal strips. *Sci. Adv.* **10**, eads0892 (2024).
182. L. M. Korpas, R. Yin, H. Yasuda, J. R. Raney, Temperature-responsive multistable metamaterials. *ACS Appl. Mater. Interfaces* **13**, 31163–31170 (2021).
183. Y.-F. Zhang, N. Zhang, H. Hingorani, N. Ding, D. Wang, C. Yuan, B. Zhang, G. Guoying, Q. Ge, Fast-response, stiffness-tunable soft actuator by hybrid multimaterial 3D printing. *Adv. Funct. Mater.* **29**, 1806698 (2019).
184. C. Li, A. Iscen, H. Sai, K. Sato, N. A. Sather, S. M. Chin, Z. Álvarez, L. C. Palmer, G. C. Schatz, S. I. Stupp, Supramolecular–covalent hybrid polymers for light-activated mechanical actuation. *Nat. Mater.* **19**, 900–909 (2020).
185. Y.-C. Cheng, L. Hao-Chuan, X. Lee, H. Zeng, A. Priimagi, Kirigami-based light-induced shape-morphing and locomotion. *Adv. Mater.* **32**, e1906233 (2020).
186. Z. Wang, K. Li, Q. He, S. Cai, A light-powered ultralight tensegrity robot with high deformability and load capacity. *Adv. Mater.* **31**, e1806849 (2019).
187. S. Li, M. M. Lerch, J. T. Waters, B. Deng, R. S. Martens, Y. Yao, D. Y. Kim, K. Bertoldi, A. Grinthal, A. C. Balazs, J. Aizenberg, Self-regulated non-reciprocal motions in single-material microstructures. *Nature* **605**, 76–83 (2022).
188. S. Li, B. Deng, A. Grinthal, A. Schneider-Yamamura, J. Kang, R. S. Martens, C. T. Zhang, J. Li, Y. Siqin, K. Bertoldi, J. Aizenberg, Liquid-induced topological transformations of cellular microstructures. *Nature* **592**, 386–391 (2021).
189. X. Yang, L. Lan, X. Pan, Q. Di, X. Liu, L. Li, P. Naumov, H. Zhang, Bioinspired soft robots based on organic polymer-crystal hybrid materials with response to temperature and humidity. *Nat. Commun.* **14**, 2287 (2023).
190. D. Jin, Q. Chen, T.-Y. Huang, J. Huang, L. Zhang, H. Duan, Four-dimensional direct laser writing of reconfigurable compound micromachines. *Mater. Today* **32**, 19–25 (2020).
191. D. Morales, E. Palleau, M. D. Dickey, O. D. Velev, Electro-actuated hydrogel walkers with dual responsive legs. *Soft Matter* **10**, 1337–1348 (2014).
192. D. Han, C. Farino, C. Yang, T. Scott, D. Browe, W. Choi, J. W. Freeman, H. Lee, Soft robotic manipulation and locomotion with a 3D printed electroactive hydrogel. *ACS Appl. Mater. Interfaces* **10**, 17512–17518 (2018).
193. T. Li, G. Li, Y. Liang, T. Cheng, J. Dai, X. Yang, B. Liu, Z. Zeng, Z. Huang, Y. Luo, T. Xie, W. Yang, Fast-moving soft electronic fish. *Sci. Adv.* **3**, e1602045 (2017).
194. X. Lin, C. Zhu, S. Lamont, X. Zou, Y. Yang, S. Chen, J. Ding, F. J. Vernerey, Programming motion into materials using electricity-driven liquid crystal elastomer actuators. *Soft Robot.* **11**, 464–472 (2024).
195. H. Cui, R. Hensleigh, D. Yao, D. Maurya, P. Kumar, M. G. Kang, S. Priya, X. Zheng, Three-dimensional printing of piezoelectric materials with designed anisotropy and directional response. *Nat. Mater.* **18**, 234–241 (2019).
196. J. Liu, X. Zhang, J. Liu, X. Liu, C. Zhang, 3D printing of anisotropic piezoresistive pressure sensors for directional force perception. *Adv. Sci.* **11**, e2309607 (2024).
197. W. Shuai, Q. Ze, R. Zhang, H. Nan, Y. Cheng, F. Yang, R. Zhao, Symmetry-breaking actuation mechanism for soft robotics and active metamaterials. *ACS Appl. Mater. Interfaces* **11**, 41649–41658 (2019).
198. S. Yi, L. Wang, Z. Chen, J. Wang, X. Song, P. Liu, Y. Zhang, Q. Luo, L. Peng, W. Zhigang, C. F. Guo, L. Jiang, High-throughput fabrication of soft magneto-origami machines. *Nat. Commun.* **13**, 4177 (2022).
199. G. Hongri, Q. Boehler, D. Ahmed, B. J. Nelson, Magnetic quadrupole assemblies with arbitrary shapes and magnetizations. *Sci. Robot.* **4**, eaax8977 (2019).
200. G. Mao, M. Drack, M. Karami-Mosammam, D. Wirthl, T. Stockinger, R. Schwödiauer, M. Kaltenbrunner, Soft electromagnetic actuators. *Sci. Adv.* **6**, eabc0251 (2020).
201. W. Li, H. Chen, Z. Yi, F. Fang, X. Guo, W. Zhiyuan, Q. Gao, L. Shao, X. Jian, G. Meng, W. Zhang, Self-vectoring electromagnetic soft robots with high operational dimensionality. *Nat. Commun.* **14**, 182 (2023).
202. M. A. Skylar-Scott, J. Mueller, C. W. Visser, J. A. Lewis, Voxelated soft matter via multimaterial multinozzle 3D printing. *Nature* **575**, 330–335 (2019).
203. Z. Zheng, J. Han, S. O. Demir, H. Wang, W. Jiang, H. Liu, M. Sitti, Electrodeposited superhydrophilic-superhydrophobic composites for untethered multi-stimuli-responsive soft millirobots. *Adv. Sci.* **10**, e2302409 (2023).
204. Q. He, R. Yin, Y. Hua, W. Jiao, C. Mo, H. Shu, J. R. Raney, A modular strategy for distributed, embodied control of electronics-free soft robots. *Sci. Adv.* **9**, eade9247 (2023).
205. H. Lee, Y. Jang, J. K. Choe, S. Lee, H. Song, J. P. Lee, N. Lone, J. Kim, 3D-printed programmable tensegrity for soft robotics. *Sci. Robot.* **5**, eaay9024 (2020).
206. M. Schaffner, J. A. Faber, L. Pianegonda, P. A. Rühs, F. Coulter, A. R. Studart, 3D printing of robotic soft actuators with programmable bioinspired architectures. *Nat. Commun.* **9**, 878 (2018).
207. Z. Wang, Q. Boyu Zhang, H. C. He, J. Wang, Y. Yao, N. Zhou, W. Cui, Multimaterial embedded 3D printing of composite reinforced soft actuators. *Research* **6**, 0122 (2023).
208. E. W. Hawkes, C. Xiao, R.-A. Peloquin, C. Keeley, M. R. Begley, M. T. Pope, G. Niemeyer, Engineered jumpers overcome biological limits via work multiplication. *Nature* **604**, 657–661 (2022).
209. J. Sun, E. Lerner, B. Tighe, C. Middlemist, J. Zhao, Embedded shape morphing for morphologically adaptive robots. *Nat. Commun.* **14**, 6023 (2023).
210. Q. Liu, W. Wang, M. F. Reynolds, M. C. Cao, M. Z. Miskin, T. A. Arias, D. A. Muller, P. L. McEuen, I. Cohen, Micrometer-sized electrically programmable shape-memory actuators for low-power microrobotics. *Sci. Robot.* **6**, eabe6663 (2021).
211. Z. Cui, S. Wang, V. Y. Han, T. Rae-Grant, W. Y. Yang, A. Zhu, S. E. Hudson, A. Ion, "Robotic metamaterials: A modular system for hands-on configuration of ad-hoc dynamic applications" in *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (ACM, 2024), pp. 1–15.
212. X. Zheng, I. Watanabe, J. Paik, J. Li, X. Guo, M. Naito, Text-to-microstructure generation using generative deep learning. *Small* **20**, e2402685 (2024).
213. S. Bonfanti, S. Hiemer, R. Zulkarnain, R. Guerra, M. Zaiser, S. Zapperi, Computational design of mechanical metamaterials. *Nat. Comput. Sci.* **4**, 574–583 (2024).
214. E. Todorov, T. Erez, Y. Tassa, "Mujoco: A physics engine for model-based control" in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems* (IEEE, 2012), pp. 5026–5033.
215. G. E. Karniadakis, I. G. Kevrekidis, L. Lu, P. Perdikaris, S. Wang, L. Yang, Physics-informed machine learning. *Nat. Rev. Phys.* **3**, 422–440 (2021).
216. M. Brandenbourger, X. Locsin, E. Lerner, C. Coulais, Non-reciprocal robotic metamaterials. *Nat. Commun.* **10**, 4608 (2019).
217. E. Kaufmann, L. Bauersfeld, A. Loquercio, M. Müller, V. Koltun, D. Scaramuzza, Champion-level drone racing using deep reinforcement learning. *Nature* **620**, 982–987 (2023).
218. S. Muiños-Landin, A. Fischer, V. Holubec, F. Cichos, Reinforcement learning with artificial microswimmers. *Sci. Robot.* **6**, eabd9285 (2021).
219. I. Radosavovic, T. Xiao, B. Zhang, T. Darrell, J. Malik, K. Sreenath, Real-world humanoid locomotion with reinforcement learning. *Sci. Robot.* **9**, eadi9579 (2024).
220. I. Masmitja, M. Martin, T. O'Reilly, B. Kieft, N. Palomeras, J. Navarro, K. Katija, Dynamic robotic tracking of underwater targets using reinforcement learning. *Sci. Robot.* **8**, eade7811 (2023).
221. T. Haarnoja, B. Moran, G. Lever, S. H. Huang, D. Tirumala, J. Humplik, M. Wulfmeier, S. Tunyasuvunakool, N. Y. Siegel, R. Hafner, M. Bloesch, K. Hartikainen, A. Byravan, L. Hasenclever, Y. Tassa, F. Sadeghi, N. Batchelor, F. Casarini, S. Saliceti, C. Game, N. Sreendra, K. Patel, M. Gwira, A. Huber, N. Hurley, F. Nori, R. Hadsell, N. Heess, Learning agile soccer skills for a bipedal robot with deep reinforcement learning. *Sci. Robot.* **9**, eadi8022 (2024).
222. R. Mon-Williams, G. Li, R. Long, D. Wenqian, C. G. Lucas, Embodied large language models enable robots to complete complex tasks in unpredictable environments. *Nat. Mach. Int.* **7**, 592–601 (2025).
223. M. C. Fernandes, J. Aizenberg, J. C. Weaver, K. Bertoldi, Mechanically robust lattices inspired by deep-sea glass sponges. *Nat. Mater.* **20**, 237–241 (2021).
224. Y. Mengüç, N. Correll, R. Kramer, J. Paik, Will robots be bodies with brains or brains with bodies? *Sci. Robot.* **2**, eaar4527 (2017).
225. J. Biamonte, P. Wittek, N. Pancotti, P. Rebentrost, N. Wiebe, S. Lloyd, Quantum machine learning. *Nature* **549**, 195–202 (2017).
226. B. Keimer, J. E. Moore, The physics of quantum materials. *Nat. Phys.* **13**, 1045–1055 (2017).
227. A. R. Bin Luo, C. D. Will-Cole, Y. He, X. Liu, H. Lin, R. Huang, X. Shi, M. McConney, M. Page, M. Sanghadasa, R. Ramesh, N. X. Sun, Magnetoelectric microelectromechanical and nanoelectromechanical systems for the iot. *Nat. Rev. Electr. Eng.* **1**, 317–334 (2024).

228. D. Kudithipudi, C. Schuman, C. M. Vineyard, T. Pandit, C. Merkel, R. Kubendran, J. B. Aimone, G. Orchard, C. Mayr, R. B. C. Schuman, C. M. Vineyard, T. Pandit, C. Merkel, R. Kubendran, J. B. Aimone, G. Orchard, C. Mayr, R. Benosman, J. Hays, C. Young, C. Bartolozzi, A. Majumdar, S. G. Cardwell, M. Payvand, S. Buckley, S. Kulkarni, H. A. Gonzalez, G. Cauwenberghs, C. S. Thakur, A. Subramoney, S. Furber, Neuromorphic computing at scale. *Nature* **637**, 801–812 (2025).

229. M. Dorigo, G. Theraulaz, V. Trianni, Reflections on the future of swarm robotics. *Sci. Robot.* **5**, eabe4385 (2020).

Acknowledgments: We thank all members of Reconfigurable Robotics Lab (RRL) for the hospitality during the stay at École Polytechnique Fédérale de Lausanne (EPFL). **Funding:** This research was supported by the Grant-in-Aid for JSPS Fellows PD (grant number 22KJ0407) and the Young Researcher's Exchange Programme—Special 2023 Call Japan of Japanese–Swiss Science and Technology Programme (project no. JP_EG_special_032023_11). **Author contributions:** X.Z. and J.P. conceived the project and outlined the manuscript. X.Z., Y.J., and M.M. wrote the manuscript, with contributions from T.Y., I.W., and J.P. X.Z. and J.L. prepared the figures. All authors reviewed and/or edited the manuscript and figures prior to submission. **Competing interests:** The authors declare that they have no competing interests.

Submitted 2 March 2025
Accepted 21 October 2025
Published 19 November 2025
10.1126/scirobotics.adx1519

Science Robotics

Metamaterial robotics

Xiaoyang Zheng, Yuhao Jiang, Mustafa Mete, Jingjing Li, Ikumu Watanabe, Takayuki Yamada, and Jamie Paik

Sci. Robot. **10** (108), eadx1519. DOI: 10.1126/scirobotics.adx1519

Science Robotics (ISSN 2470-9476) is published by the American Association for the Advancement of Science. 1200 New York Avenue NW, Washington, DC 20005. The title *Science Robotics* is a registered trademark of AAAS.