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A Review of Trans-Dimensional Kirigami: From Compliant Mechanism to Multifunctional Robot

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Kirigami, or "jianzhi" in Chinese, is an art in paper-cutting. Using simple tools like scissors, artisans transform paper into intricate designs featuring flowers, animals, or characters (e.g., "囍"). Nowadays, kirigami has emerged as a particularly promising design strategy in engineering. This method involves creating systematic cut patterns on thin, planar sheets, which enables complex mechanical responses by changing dimensions, thereby offering innovative solutions for the development of metamaterials, soft actuators, and robotic systems. The concept of the integration of ancient art and modern science and technology has injected vitality into the development of many disciplines and become the forefront of interdisciplinary research. This review provides a systematic review of recent progress on the design of kirigami and applications in diverse robotic prototypes. The kirigami begins by classifying into two categories from a compliant mechanism perspective, and then it examines the distinctive mechanical properties that altered by cut patterns, followed by reviewing the design of the two types of kirigami. Next, the kirigami-inspired kinematic metamaterials is examined. Finally, applications in soft actuators and robotic systems is demonstrated. The integration of design methods, fabrication techniques, materials research, mechanics modeling, and control systems will further advance this emerging field.

1. Introduction

Kirigami, is an art of paper-cut. It has been used throughout the world and has been selected as one of Intangible Cultural Heritages.[1] Kirigami, involves creating patterned cuts on a flat, thin sheet to achieve bending, twisting, contraction as well as extra elongation when an external stimulus is applied on such sheet. With rational design cut patterns, kirigami demonstrates unconventional mechanical properties, including super stretchability, auxetics, bistability/multistability and on-demand buckling.[2,3] Originating from the meticulous practice of cutting 2D paper to intricate 3D forms, kirigami has transcended its artistic boundaries to become a source of inspiration for flexible electronics,[4–8] metamaterials,[9–12] shape-morphing structures,[13–16] and soft robotics.[17–23] Moreover, as a typical periodic structure, the kirigami also can be used to tune wave propagation and filter specific bands of frequencies.[24–26] Recently, several reviews have investigated

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the topic, providing a foundation for understanding kirigami designs. For example, Tao et al.[2] reviewed the kirigami-inspired engineering systems regarding their geometric design, mechanical properties, underlying mechanics, and rich functionalities. Jin et al.[3] outlined the basic mechanisms of kirigami that govern the transformation of kirigami and reviewed a range of promising applications. Brooks et al.[27] explored the progress in the development of kirigami-inspired healthcare applications. Although some literature reviews discuss kirigami designs and kirigami-inspired applications, few systematically classify the categories of kirigami from the perspectives of compliant mechanisms. This classification plays a fundamental role in soft robot development by providing a structured framework for understanding and leveraging the diverse range of compliant mechanisms that can be derived from kirigami principles. This article seeks to address this gap by offering a comprehensive review of progress and future perspectives in this field, which shall enrich the design strategy by expanding kirigami from mechanical design to kinematic motion.

In this review, we first classify the kirigami into two categories from a compliant mechanism perspective and then examine the unique mechanical properties of kirigami induced by cut patterns, including exceptional stretchability, buckling, negative Poisson's ratio (auxetic behavior) and bistability/multistability, which play a pivotal role in designing kirigami-based devices. Then, we will review the pattern in designing of the two types of kirigami. Next, we will review the kirigami-inspired kinematic metamaterials. Then, we will examine the kirigami actuators and robotics regarding designs, actuating strategies, and applications. Finally, we outline future research directions when integrating machine learning into kirigami. By doing so, we hope to provide a valuable resource for researchers, engineers, and potential readers who are interested in this exciting and rapidly evolving field.

Figure 1 illustrates the trans-dimensional nature of kirigami features across multiple scales. At its most fundamental level, kirigami begins with a 1D cut, whether performed manually or automatically. This cutting process inherently involves principles of fracture mechanics, as evidenced by the propagation of cracks along failure frontiers-a phenomenon commonly observed during kirigami manipulation. In the 2D realm, kirigami patterns represent an extensive design space where geometric and topological principles intersect. Through precise modification of these patterns, researchers can systematically

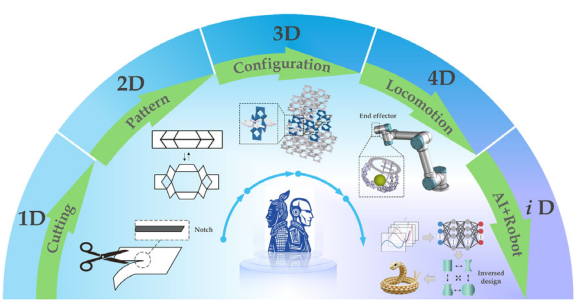

Figure 1. Trans-dimensional feature of kirigami.

alter and even program mechanical properties. The transformation into three dimensions occurs through strategic assembly of kirigami components, incorporating complex kinematic relationships during shape transformation. The integration of actuators and control mechanisms extends kirigami into the fourth dimension, introducing temporal kinetics to its functionality. Recent advances in artificial intelligence have significantly enhanced kirigami design capabilities. AI-driven approaches can now generate comprehensive solutions, translating target shapes into optimized set of cuts, patterns, assembly methods, and actuation sequences. This data-driven, algorithm-enabled inverse design methodology has demonstrated considerable potential across various applications, surely the development of kirigami-based robotic systems can be benefited.

2. Kirigami Design and Mechanical Properties

2.1. Kirigami Patterns in Design

Kirigami involves creating precise patterns of cuts on a thin sheet. Previous reviews have introduced kirigami based on their morphological characteristic, kirigami can be categorized into two primary groups: cut-only kirigami and hybrid fold-cut kirigami. The cut-only category encompasses fractal kirigami,[28–30] kirigami tessellations,[31–33] ribbon kirigami,[34–38] and expansile kirigami.[13,39–44] The hybrid category includes lattice kirigami,[45–48] zigzag kirigami,[49–51] and pop-up orikirigami.[52–59] Here, from a compliant mechanism perspective, kirigami can be classified into two distinct categories based on the compliance distribution characteristics during deformation: one is lumped compliance kirigami, exhibiting deformation concentration at flexure hinges while maintaining facets rigidity, and the other is distributed compliance kirigami, demonstrating relatively uniform deformation profiles throughout the entire structural framework, as illustrated in **Figure 2**a.

Figure 2b illustrates the cut patterns from the perspective of compliant mechanism. The lumped compliance kirigami include fractal kirigami, kirigami tessellation, pop-up kirigami, zigzag kirigami, and lattice kirigami. The distributed compliance kirigami include ribbon kirigami, perforated kirigami, expansile kirigami, and so on. Among the various cut patterns of kirigami proposed in previous literature, there are two fundamental cut patterns, as depicted in Figure 2a, one is named as "orthometric-cuts" and the other named as "parallel-cuts". In addition to the two fundamental cut patterns, many cut patterns have been rationally proposed to achieve intended functions. For example, Yang et al.[60] developed a new class of electro-mechanical metamaterials inspired by transformable kirigami patterns for multiple electromagnetic applications. Tang et al.[61] demonstrated a universal design that integrates origami (the art of paper folding) into kirigami. This integration involves implementing folds that release the constrained degrees of freedom (DOFs) at the planar hinges located at the cut tips. As a result, these hinges can rotate both in-plane and out-of-plane, which not only enriches the structural reconfiguration but also enables more DOFs in actuating the kirigami sheets.

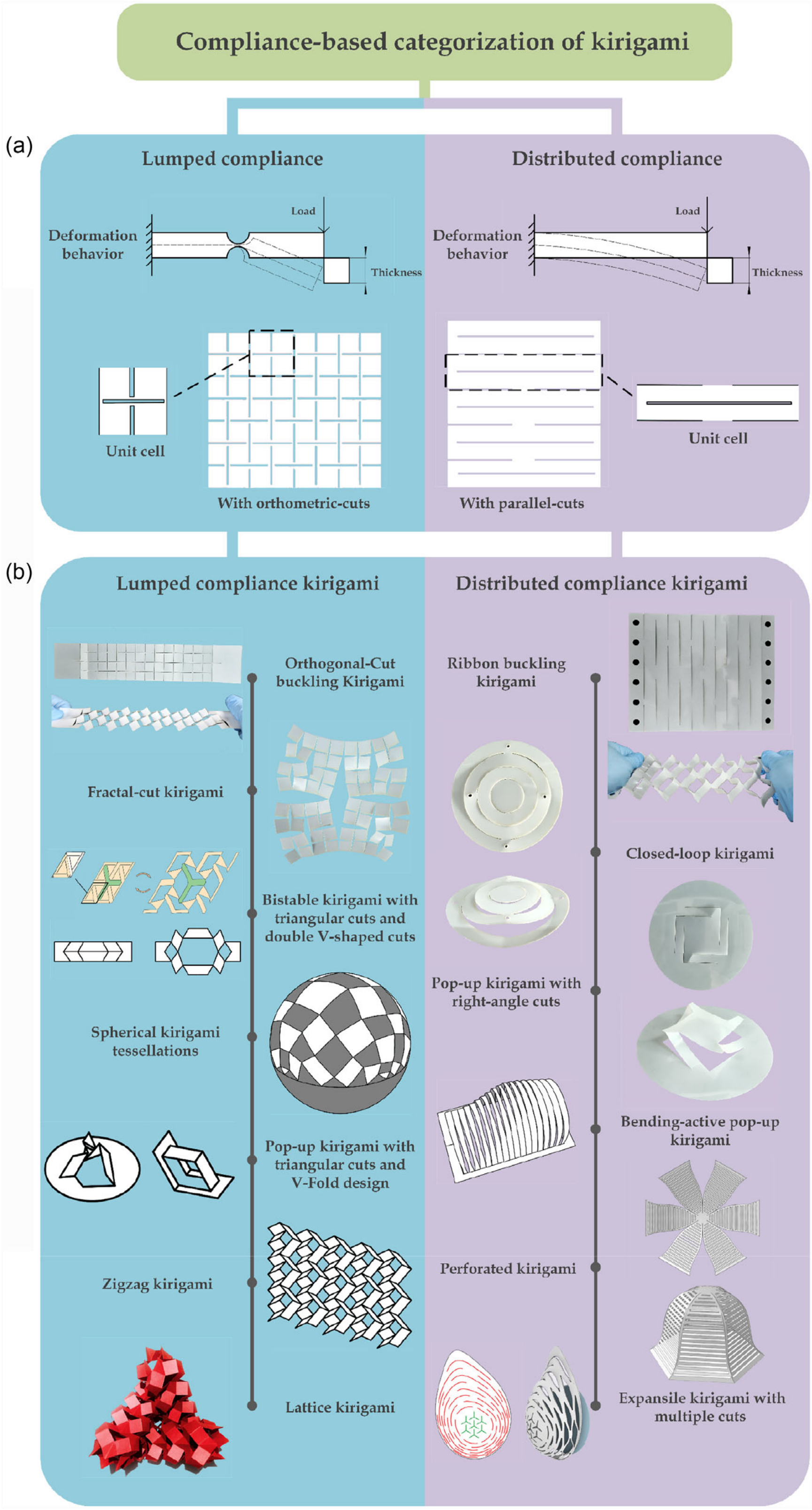

Figure 2. a) Schematic of compliance distribution characteristics in mechanism and two fundamental cut patterns. b) Compliant mechanism-based categorizations of typical kirigami. Adapted with permission.[43] Copyright 2023, Wiley-VCH. Adapted with permission.[44] Copyright 2022, Elsevier. Adapted with permission.[93] Copyright 2024, Wiley-VCH.

2.2. Kirigami-Tuned Mechanical Properties

With periodic cut patterns, the kirigami demonstrate distinctive mechanical properties, including exceptional stretchability, controlled buckling responses, negative Poisson's ratio (auxetic behavior), and bistability/multistability.

2.2.1. Exceptional Stretchability and Buckling

Exceptional stretchability refers to the ability to achieve substantial deformation when an external load is applied and return to its original shape after removing the external load. Usually, large stretchability mainly rely on the hyper-elastic deformation in rubbery materials. However, rubber's stretchability is determined by its molecular structure. Kirigami provides a scalable and easily fabricated method to significantly enhance the stretchability that are not limited to rubbery materials.[62–64] **Figure 3**a demonstrates that a kirigami with parallel cuts can achieve a large strain, exceeding 500%, under uniaxial stretching. The deformation mechanism of kirigami primarily involves two origins. One is local rotation, and the other is buckling-induced deformation. The local rotation mechanism discretizes sheets into interconnected unit cells, such as squares or triangles, joined at their vertices. As shown in Figure 3b, the unit cells separated by cuts behave as rigid facets, with connecting ligaments acting as flexible rotating hinges. When subjected to tensile force, the connecting ligaments bend even buckle. When examining buckling-induced deformation in kirigami, a fundamental competition emerges between in-plane deformation energy and out-of-plane deformation energy during stretching.[65,66] As shown in Figure 3c,d, initially, under minimal applied stretch, the structure primarily deforms within the plane as the in-plane strain energy remains lower than the out-of-plane bending energy. As the stretching intensity increases, the system reaches a critical point where in-plane and out-of-plane energies equilibrate, triggering out-of-plane deformation. This out-of-plane deformation manifests significantly lower stiffness compared to in-plane deformation, primarily because thin sheets exhibit a substantially lower bending modulus relative to their in-plane stretching modulus, resulting in a transition from a conventional linear response in its planar state to a nonlinear response characterized by reduced mechanical stiffness, primarily due to buckling phenomena. Nevertheless, the system's stiffness experiences a renewed increase as the applied strain approaches the kirigami's

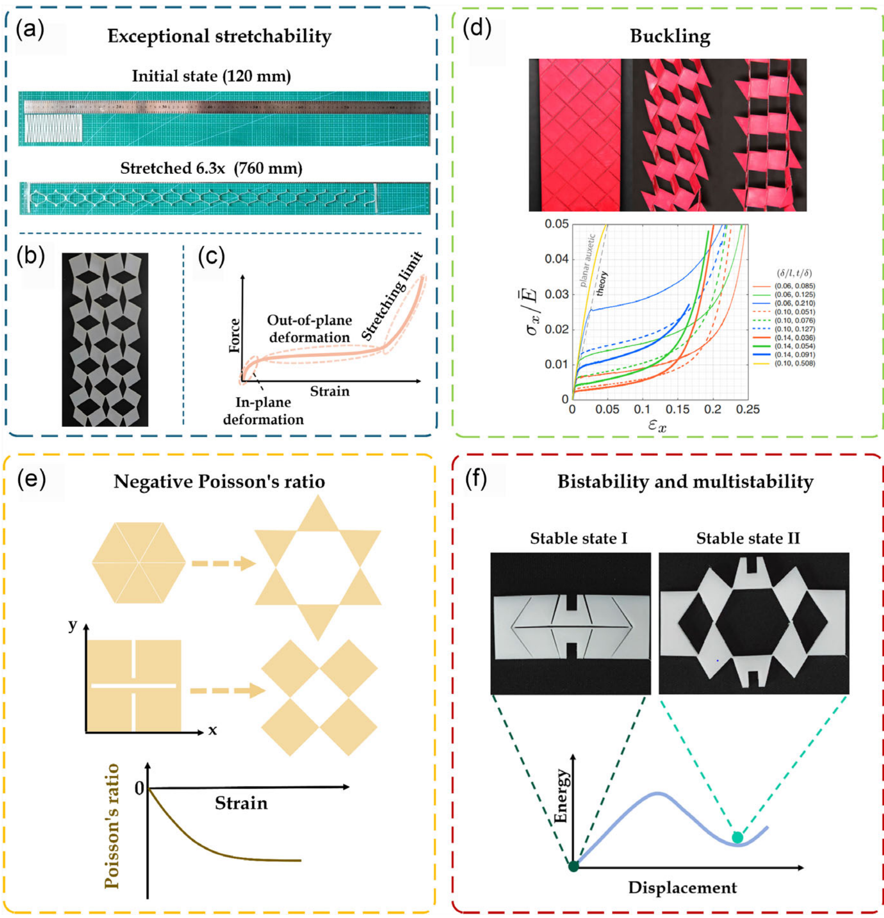

Figure 3. a) A ribbon kirigami was initially in a relaxed state and then stretched to 6.3 times its original length. b) A kirigami featured orthometric-cuts. c) The strain–stress curve of a kirigami under uniaxial stretch. d) Kirigami exhibit a three-stage nonlinear response and out-of-plane buckling. Adapted with permission.[65] Copyright 2017, American Physical Society. e) Kirigami enables negative Poisson's ratio. f) A bistable kirigami enabled by carefully designed cut pattern.

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stretching limit. Furthermore, the mechanical properties can be precisely tailored through systematic manipulation of cut parameters, including their geometric configuration, quantity, dimensional attributes, and distribution.[67–70]

2.2.2. Negative Poisson's Ratio

Negative Poisson's ratio (auxetic behavior), is a distinctive mechanical property where a material expands, rather than contracts, in the direction perpendicular to an applied tensile load. The negative Poisson's ratio behavior has shown great potentials in metamaterials,[71–74] logic gates,[75] actuators and robotics,[76,77] flexible electronics,[78,79] and architecture.[80] The negative Poisson's ratio behavior of kirigami typically arises from the local rotation of facets. As shown in Figure 3e, the individual facets may vary in shape and size, but they can exhibit complex rotations when subjected to an in-plane stretch.[81–83]

2.2.3. Bistability and Multistability

Bistability and multistability refer to the property of a certain system that possess two or more local minimum energy, corresponding to stable equilibrium states, and it can switch between these stable states upon external perturbation. The unique characteristics have been leveraged in actuator,[84] metamaterials,[85,86] logic gates,[87–89] and energy absorber.[90] Kirigami offers a promising design method for constructing multistable structures. As demonstrated in Figure 3f, a carefully designed cut pattern in a kirigami enables simultaneous bistability and negative Poisson's ratio.

3. Compliant Mechanism in Kirigami

3.1. Lumped Compliance Kirigami

Fractal kirigami and kirigami tessellation, which can be regarded as the evolution of the orthometric-cuts, are two prominent types of lumped compliance kirigami, where the sheets are patterned with polygonal units connected by flexible hinges. Inspired by stem cell differentiation, Cho et al.[30] pioneered the introduction of hierarchical fractal cutting patterns in 2D sheet, enabling expansion into various predesigned complex shapes and patterns with precise mechanical property control. Experimental validation demonstrated that this hierarchical fractal cutting approach could achieve material area expansion exceeding 800% of the original size, thereby significantly expanding the design space for engineering materials. Extending beyond planar cutting patterns, Dang et al.[31] investigated cutting patterns on nonEuclidean geometric surfaces, specifically focusing on spherical quadrilateral kirigami as illustrated in **Figure 4**a. A compatibility theorem is proposed and proved for the deployment of kirigami tessellations restricted on a spherical surface, demonstrating that appropriate cut designs could yield bistable spherical quadrilateral configurations.

The rotation of rigid facets enables kirigami to transform into shape-morphing surfaces through programed cut patterns. Wang et al.[32] presented a differentiable inverse design framework for developing magnetic active fractal kirigami. This framework incorporates the physical interactions among geometry, material properties, and stimuli when magnetic particles are embedded in soft materials and achieving targeted shape transformations under magnetic actuation. Figure 4b demonstrates the optimized magnetic kirigami's capability to achieve specified geometric shape transformations (e.g., dog-like, egg-like, and goblet-like deployed configurations) through the inverse design framework. Jin et al.[13] advanced this concept by embedding cut kirigami sheets within inflatable elastic membranes. As shown in Figure 4c, The inflation of chamber is constrained by the kirigami patterns, allowing target surface fitting through strategic modification of key geometric parameters.

Specific kirigami exhibiting bistable characteristics achieve deployment and contraction between two equilibrium states through nonlinear deformation and instability of flexure hinges at panel connections, combining negative Poisson's ratio with configuration-switching capabilities. These bistable unit cells can be arranged through periodic tessellation, rotation, mirroring, serial and parallel connections to form multistable kirigami. The ability to switch between different stable states enables diverse mechanical properties, providing a foundation for developing adaptive structures. As shown in Figure 4d, building upon triangular-cut bistable cells, Cho et al.[91] implemented spatially varying hinges to control structural stiffness, ensuring shape retention and stability in deployed configurations. Meng et al.[92] developed a multistep programable mechanical metamaterial by integrating orthogonal-cut bistable square kirigami with thermally-driven materials. This innovative material demonstrates programable, multistep transformations between various stable configurations, enabling tunable stiffness and achieving reversible mode bifurcation through temperature-responsive behavior, as illustrated in Figure 4e. Qiao et al.[93] investigated symmetry breaking in triangular-cut bistable kirigami to achieve geometric frustration and anisotropic deformation, enabling arbitrary scaling within planar and spatial bistable domains. Yin et al.[94,95] introduced a bistable cell based on double V-shaped kirigami topology, successfully decoupling energy barriers from force/displacement characteristics by a machine learning-genetic algorithm inverse design framework. Then a unified double V-shaped kirigami configuration is proposed and the resulting arrays of bistable kirigami cells exhibit Poisson's ratios spanning both positive and negative values while enabling stretch-driven bending and shear deformation. Chen et al.[40] established an inverse design methodology and parametric unit library based on bistable triangular-cut kirigami cells and their topological variability. This approach enables diverse surface fitting through controlled manipulation of longitudinal and transverse strain variations, with the deformed stable states exhibiting notable load-bearing capacity.

Furthermore, hybrid fold-cut kirigami, including lattice kirigami,[46,47,96–98] zigzag kirigami,[49–51] and pop-up kirigami,[56–58] can be viewed as lumped compliance kirigami due to their deformation concentration along creases while maintaining panel rigidity during deployment. Notably, a triangular-cut pop-up ori-kirigami variant[57] exhibits bistable characteristics, where arm elastic deformation occurs during rotational deployment but recovers upon transitioning to another stable state, as illustrated in Figure 4f. Throughout the ori-kirigami deployment process, deformation primarily

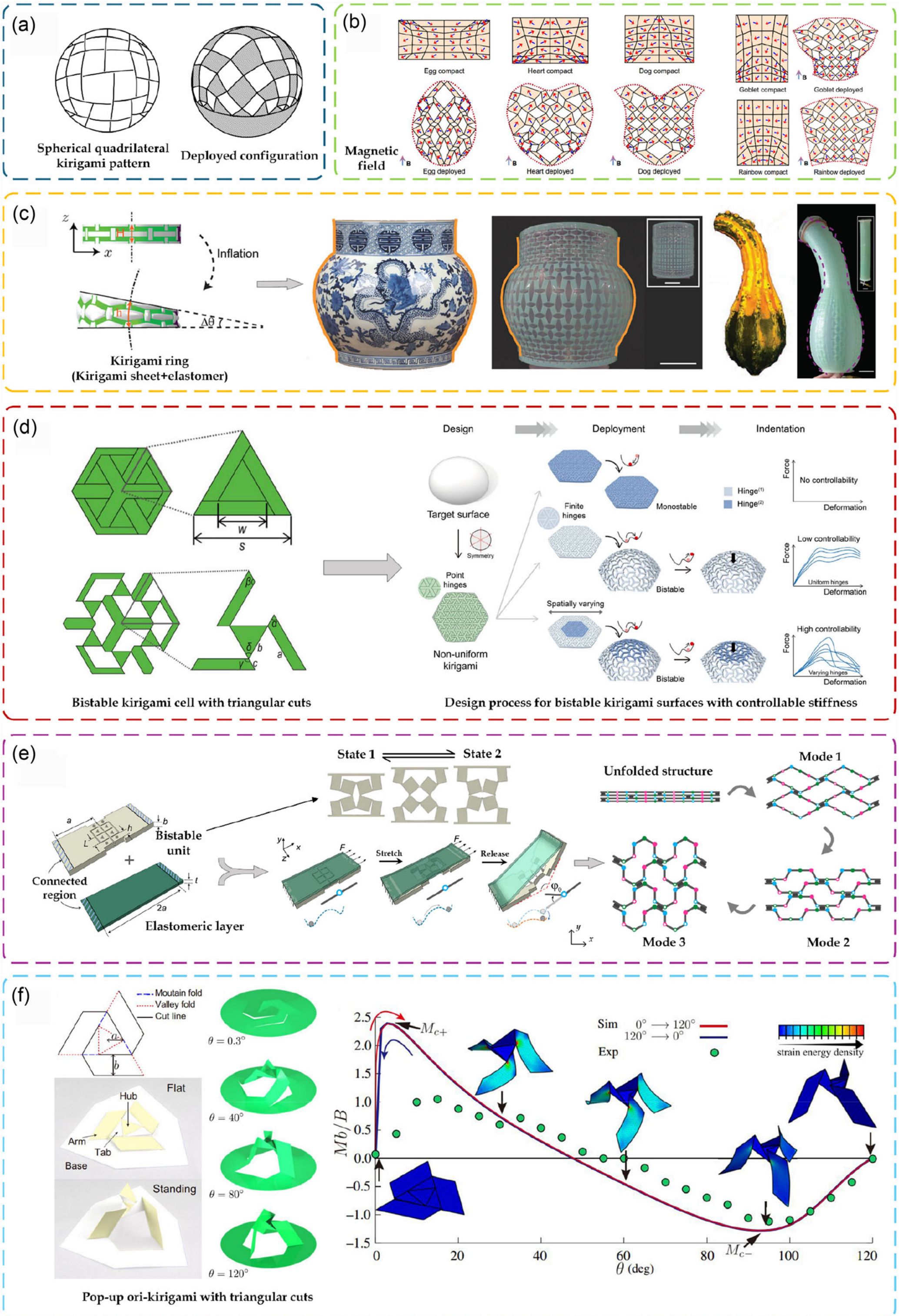

Figure 4. Typical lumped compliance kirigami. a) Reconfigurable spherical quadrilateral kirigami tessellations. b) Physics-aware differentiable design of magnetically actuated kirigami to achieve different target shapes. Adapted under the terms of the Creative Commons CC-BY license.[32] Copyright 2023, The Authors. Published by Springer Nature. c) Inflatable kirigami with programmable shape like a jar and a squash. Adapted with permission.[13] Copyright 2020, Wiley-VCH. d) Bistable kirigami cell with triangular cuts and the design process for bistable kirigami surfaces with controllable stiffness. Adapted under the terms of the Creative Commons CC-BY license.[91] Copyright 2022, The Authors. AAAS. e) A multistep multimodal mechanical metamaterial enabled by bistable self-folding kirigami cells. Adapted with permission.[92] Copyright 2024, Wiley-VCH. f) Pop-up ori-kirigami with triangular cuts and its torque profile during the bistable transition. Adapted with permission.[57] Copyright 2022, American Physical Society.

concentrates at creases, with arm bending serving as a "virtual crease" that bridges the motion path between flat and standing configurations.

3.2. Distributed Compliance Kirigami

A representative form of distributed compliance kirigami is ribbon kirigami, initially developed for enhancing the stretchability of graphene materials through strategic cutting patterns.[34] This technique involves creating periodic parallel cuts in planar sheets to form highly flexible ribbon-like structures. Under uniaxial stretching, these compliant ribbons undergo bending, twisting, and even buckling. Remarkably, this approach demonstrates scalable applicability across diverse length scales, from micrometer-level implementations (10^{-6} meters)[34,99] to macroscopic applications.[18,100–104] Due to their wide range of potential applications, understanding and exploiting the deformation mechanism and mechanical response of ribbon kirigami has attracted significant research interest in recent years. Chen et al.[38] conducted a comprehensive study on the deformation mechanisms and stretchability of ribbon kirigami, identifying a critical transition threshold that determines the deformation behavior. Below this threshold, structural deformation is primarily governed by geometric design parameters, while material properties dominate beyond this critical point. Han at al.[105] developed a prediction model for critical force by incorporating beam deflection theory and a force concentration parameter to estimate the ultimate nominal force in kirigami metallic glasses. Moshe at al.[106] introduced a geometric method for analyzing perforated elastic sheets and developed a kirigami-based approach to control stress distribution in elastic materials. Wang et al.[36] investigated the thermal effects on the mechanical response of ribbon kirigami, developing a closed-form analytical model based on thermal considerations and large deflection beam theory. This model accurately predicts the stretchability and stiffness of ribbon kirigami under thermal loading, demonstrating the significant influence of thermal effects in practical applications.

Moreover, various cut patterns enrich the mechanical properties of kirigami. Hong et al.[107] introduced a novel 3D deformation design methodology utilizing boundary curvature, which significantly simplifies inverse design of 3D deformations and dynamic deformation control, thereby creating new strategies for curvature-based shape programming in kirigami metamaterials. Yu et al.[37] achieved remarkable multistable reconfiguration characteristics by strategically widening one cut in the ribbon kirigami. As shown in **Figure 5**a, this modification enabled nonsequential transitions between any four stable configurations and facilitated dynamic configuration propagation between kirigami cells, resulting in reprogramable functionality.

Ribbon kirigami, characterized by its simple fabrication process and remarkable enhancement of material stretchability, demonstrates significant potential in flexible sensors and health monitoring. Gao et al.[108] developed a paper-based wearable sensor inspired by fish scale and kirigami pattern, integrating microfluidic and electronic systems for sweat collection, biochemical detection, and motion monitoring. This innovative design exhibits its superior stretchability, breathability, and esthetic appeal. As shown in Figure 5b, Yu et al.[109] investigated a supramolecular hydrogel with integrated ribbon kirigami architecture, incorporating liquid metal template printing. The resulting flexible electronic membrane demonstrates excellent conformability to curved surfaces and high sensitivity in detecting human motion. Liu et al.[110] advanced the field by creating wearable ribbon kirigami electronic devices based on a composite nano-fiber framework (CNFF). As illustrated in Figure 5c, through multiscale simulations, they elucidated the framework's exceptional fracture resistance and successfully integrated various microelectronic sensors and electroactive polymers into the CNFF platform, enabling comprehensive physiological monitoring including electrocardiogram, electromyogram, skin temperature, and other vital parameters.

Distinct from ribbon kirigami, Zhang et al.[44] introduced a novel shape-morphing design methodology based on perforated kirigami. Perforated kirigami exhibits distributed compliance through strategically designed pores, enabling localized bending stiffness modulation while preserving material thickness, independent of intrinsic material properties. This approach achieves 2D to 3D shape transformations by creating specific hole patterns in planar materials and controlling bending stiffness through localized porosity adjustment. Furthermore, expansile kirigami and pop-up kirigami with specialized cuts can undergo deployment, bending, and twisting upon external stimulation. These kirigami variants, exhibiting deformation distribution throughout the entire structure, are classified as distributed compliance kirigami. Customizable expansile kirigami with tailored cuts can be inversely designed to deploy into specific configurations on demand. As shown in Figure 5d, Lee et al.[43] developed an inverse design strategy for acellular dermal matrix (ADM) sheets using expansile kirigami technology. Through contour cuts and fractal patterns on ADM surfaces, it can expand and conform to implant contours, achieving more natural and precise breast reconstruction outcomes.

Moreover, the integration of responsive materials with kirigami enables active shape transformation from 2D planar structures to 3D configurations. As shown in Figure 5e, Liu et al.[53] designed a reconfigurable 3D metasurface based on light-activated pop-up kirigami at the microscale, exploring its optical properties. As shown in Figure 5f, Tabassian et al.[54] created an electro-active and photo-active actuator using vanadium oxide nanowire (VONW) hybrid films integrated with pop-up kirigami, demonstrating exceptional actuation performance.

4. Kirigami-Inspired Kinematic Metamaterials

Metamaterials are a class of novel artificial composite structures. By rationally designing their shapes, structures, and arrangements without violating fundamental physical laws, they can exhibit extraordinary physical properties that are unattainable in natural or conventional synthetic materials.[111] These unique properties are not primarily determined by the intrinsic characteristics of the constituent materials but rather by the topological and deformational features of their internal artificial structures.[112,113] As a powerful design strategy, kirigami principle has been inspired new mechanical metamaterials,[28,114] thermal metamaterials,[115] acoustic metasurfaces,[116] and optical

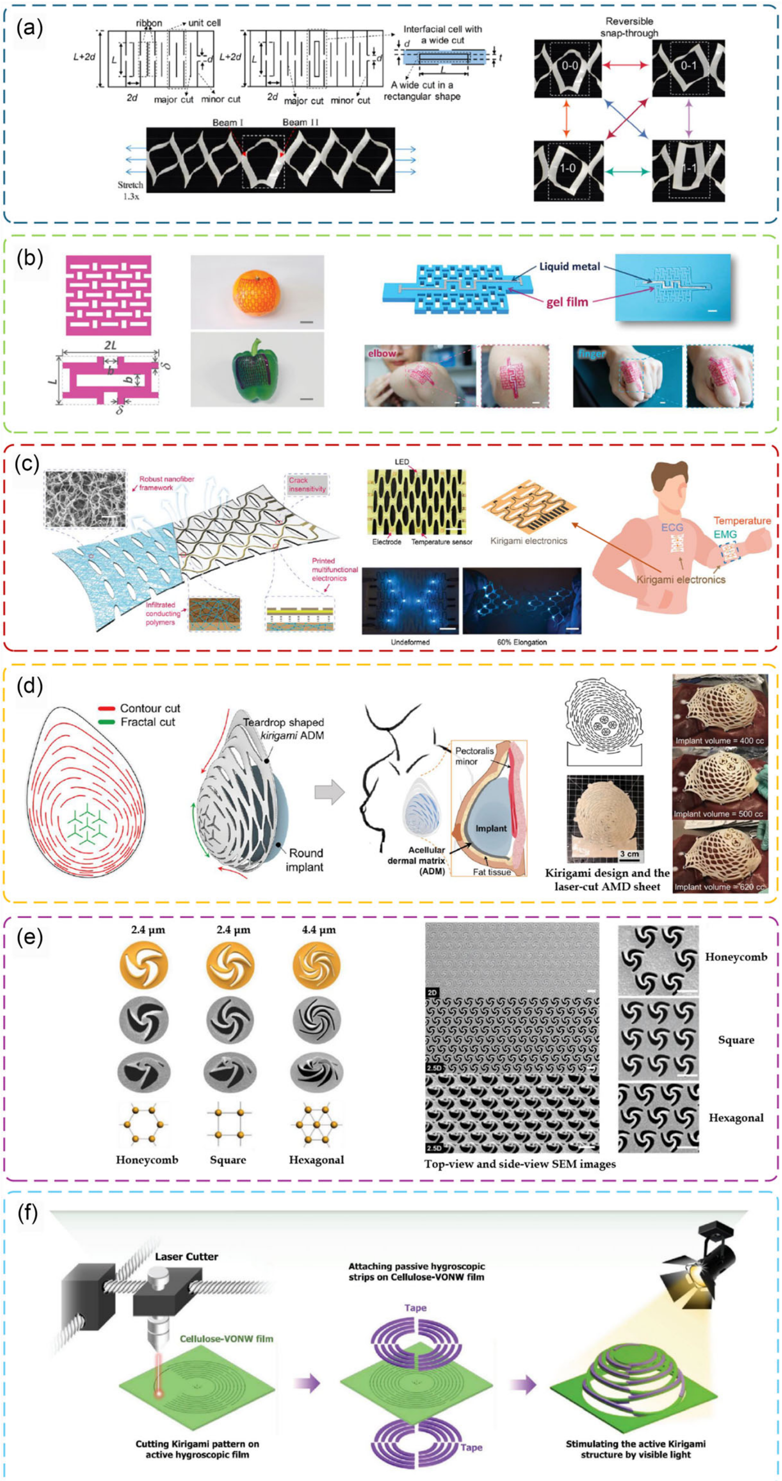

Figure 5. Typical distributed compliance kirigami. a) Reprogramable multistable ribbon kirigami with a wide cut. Adapted under the terms of the Creative Commons CC-BY license.[37] Copyright 2023, The Authors. Published by AIP Publishing. b) Soft electronics fabricated by stencil printing liquid metal on hydrogel films with ribbon kirigami demonstrate excellent compliance Adapted with permission.[109] Copyright 2021, Wiley-VCH. c) Robust and multifunctional ribbon kirigami electronics based on CNFF and its capability for sensing various biological signals. Adapted with permission.[110] Copyright 2022, Wiley-VCH. d) Natural shaping and precise conformability of ADM sheets for implant-based breast reconstruction through expansile kirigami. Adapted with permission.[43] Copyright 2023, Wiley-VCH. e) Kirigami-inspired chiral metamolecules with different rotational symmetries and the SEM images of nano-kirigami enabled stereo metasurfaces. Adapted with permission.[53] Copyright 2020, Wiley-VCH. f) Fabrication of stimuli-responsive pop-up kirigami by cellulose-VONW film for active shape transformation from 2D state to 3D configuration. Adapted with permission.[54] Copyright 2021, Wiley-VCH.

metasurfaces domains[117] through geometric nonlinearity, material heterogeneity, and multiphysical coupling. In kirigami-inspired metamaterials, the local deformation offers rich kinematic relations, yet extending the programmability in mechanical responses. Therefore, such kirigami metamaterials are also a subcategory of kinematic metamaterials. In the field of mechanics, metamaterials exhibit unconventional properties such as negative Poisson's ratio,[118] negative stiffness,[119] and negative compressibility,[120] demonstrating broad application prospects in aerospace engineering,[121,122] marine engineering,[123,124] flexible electronics,[5,125] and biomedical fields.[126,127] Among these, auxetic metamaterials with negative Poisson's ratio exhibit unique mass concentration effects under compressive loading, demonstrating superior performance in acoustic damping, energy absorption, and impact resistance applications.[128,129] Negative stiffness metamaterials achieve their distinctive properties through sophisticated structural control mechanisms, including buckling-induced compressive bending, postbuckling large deformation, and snap-through transitions between high-energy critical equilibrium states and low-energy stable configurations. The characteristic negative stiffness behavior observed in their force-displacement constitutive relationships during steady-state snapping processes makes them particularly valuable for advanced vibration control systems.[119,130,131] Furthermore, negative compressibility metamaterials exhibit negative expansion in one or more orthogonal directions under uniaxial compression. This counterintuitive behavior has led to innovative applications in deep-sea exploration equipment and high-precision sensing devices, where their unique mechanical properties can be effectively utilized.[120,132,133]

Concurrently, tunability is achieved through either intrinsic structural reconfiguration or responsive adaptation to external stimuli, necessitating enhanced material intelligence in responding to environmental variations and external excitations.[134] The pursuit of advanced tunability has driven significant research focus toward kinematic metamaterials capable of substantial deformation. The development of these kinematic metamaterials has concurrently established foundational design paradigms at the microscale for motion structures, enabling unprecedented programmability over flexible deformation and dynamic performance modulation.[135]

As shown in **Figure 6**, kinematic metamaterials can be systematically classified into five primary categories based on their deformation mechanisms: 1) lattice metamaterials, 2) multistable metamaterials, 3) origami/kirigami-inspired metamaterials, 4) smart material-based metamaterials, and 5) bio-inspired metamaterials. Elastic large-deformation metamaterials, typically represented by lattice and honeycomb structures, consist of cells comprising beams, trusses, plates, and shells. These structures enable the amplification of local elastic microdeformations into global large deformations through coordinated cell interactions.[129,136–138] Multistable metamaterials utilize bistable or multistable configurations, where input energy exceeding a stability threshold triggers rapid transitions between stable states, enabling pronounced and responsive deformations.[139–141] This principle has been extensively employed in the design of programable metamaterials.[142–144] Origami-inspired metamaterials achieve specific 3D deformations through strategically designed crease patterns in planar structures,[145–149] while kirigami-inspired metamaterials utilize precisely engineered cut arrays in thin sheets to achieve large deformations through controlled extension and stability mechanisms.[30,65,96,150] Smart material-based metamaterials integrate functional materials that respond to external stimuli, including temperature-responsive,[92,151,152] light-responsive,[153,154] and magnetically actuated variants.[155–158] Bio-inspired metamaterials employ multiscale design strategies derived from natural biological structures and their deformation mechanisms.[108,159–162]

5. Kirigami Actuators

Soft actuator is a crucial element of a soft robot, enabling the system's deformable body to interact with the environment and achieve desired actuation patterns, such as locomotion, manipulation, gripping, human-machine interaction, and more.[163] Kirigami offers a versatile design framework that enables enhanced programmability through the adjustment of various parameters, such as kirigami patterns, material properties, and actuation strategies. Such capabilities position kirigami actuators as promising tools for navigating unstructured terrains and accessing confined spaces that are beyond the reach of conventional rigid actuators. These unique features open up a wide range of applications, including environmental monitoring, space exploration, medical diagnostics, and robotic-assisted surgery. The key to translating paper-cutting art into kirigami actuators is to accurately manipulate the synergistic relationship between material properties, cutting patterns design and the appropriate external actuation.

As shown in **Figure 7**a, Wang et al[102] proposed a kirigami/origami-based soft linear actuator. Dias et al.[96–99] introduced a range of kirigami actuators capable of performing four primary types of linear actuation: roll, pitch, yaw, and lift, by applying a uniaxial extension. As shown in Figure 7b, Belding et al.[164] demonstrated a new class of pneumatic kirigami actuators (PKA) capable of producing a variety of motions, including bending, twisting, contraction and elongation. The actuators comprise an outer frame featuring cut patterns, and an inner inflatable balloon. When pressurized, the balloon expands with a nonlinear pressure–volume relation, and the cuts enable nonsymmetric deformation upon pressure for different motion modes. The required actuation pressure depends on the cut length, enabling sequential actuation through pressure control. Zhou et al.[165] introduced a novel planar PKA capable of actively controlling bidirectional bending deformation, enabling it to mimic various curved surfaces with different Gaussian curvatures. An application showcasing the enhancement of a sucker gripper's performance using PKA as its orientation driver illustrates PKA's potential industrial applications.

Though multimotion modes such as bending, twisting, contraction, and elongation have been achieved through programable design, a limitation of the current design is that the geometric parameters cannot be altered once the actuator is fabricated, making reprogramable functionality challenging to achieve. Reprogrammable actuators, which can perform new motion modes without requiring the creation of a new one, offer substantial potential for cost reduction and expanded

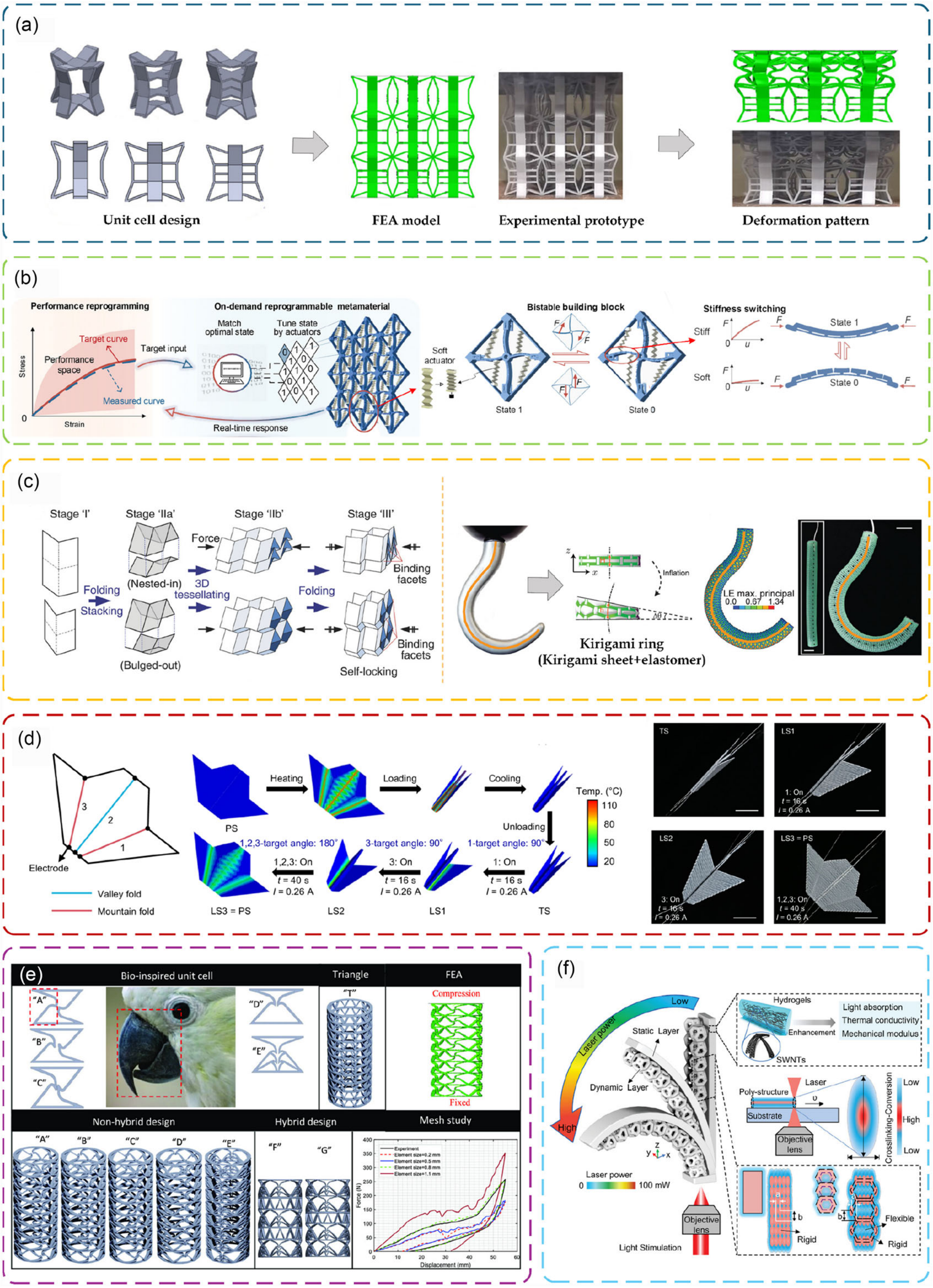

Figure 6. Typical kinematic metamaterials. a) 3D zero Poisson's ratio deformable metamaterial for energy absorption. Adapted with permission.[136] Copyright 2023, Wiley-VCH. b) On-demand reprogramable bistable cellular deformable metamaterial driven by structure performance relations. Adapted with permission.[210] Copyright 2024, Wiley-VCH. c) Programable self-locking origami mechanical metamaterials. Adapted with permission.[146] Copyright 2018, Wiley-VCH. and inflatable kirigami metamaterials with programable shapes. Adapted with permission.[13] Copyright 2020, Wiley-VCH. d) Electrothermally controlled deployable origami metamaterial fabricated by 4D printing of continuous fiber-reinforced composites. Adapted under the terms of the Creative Commons CC-BY license.[152] Copyright 2024, The Authors. Published by Springer Nature. e) Parrot beak-inspired metamaterials deformable metamaterial for supreme energy absorption/dissipation. Adapted with permission.[160] Copyright 2023, Wiley-VCH. f) Femtosecond laser 4D printing of light-driven intelligent micromechanical metamaterial. Adapted with permission.[154] Copyright 2023, Wiley-VCH.

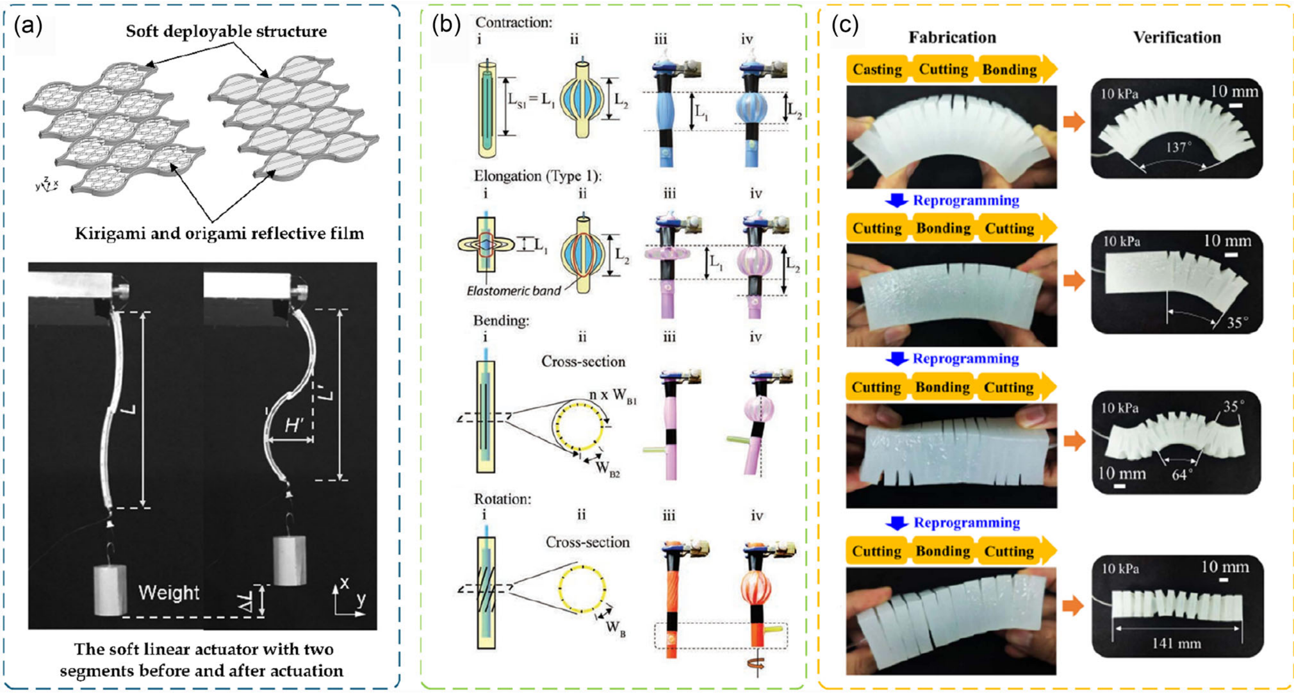

Figure 7. a) A kirigami/origami-based soft linear actuator. Adapted with permission.[102] Copyright 2017, Wiley-VCH. b) The schematic diagram and experimental results of actuators with vertical slits that produce localized contraction, elongation, bending, or rotation upon inflation. Adapted with permission.[164] Copyright 2017, Wiley-VCH. c) The reprogramable design concept verified by four scenarios. Adapted with permission.[166] Copyright 2024, IEEE.

applications. As shown in Figure 7c, Wang et al.[166] proposed a straightforward design strategy for reprogramable soft pneumatic actuators using volume-preserving cutting and bonding of solid silicone materials. The motion mode can be modified by adjusting the cutting and bonding procedures.

In addition to the programmable and reprogramable motion modes, the kinematic analysis is also crucial for understanding an actuator's characteristics, providing a foundation for its design and optimization. Khosravi et al.[167] developed and experimentally validated a novel kinematics model aimed at elucidating the relationship between kirigami cutting pattern designs and the motion characteristics of actuators. The model employs a virtual fold and rigid-facet assumption, which simplifies the motion analysis while maintaining a high degree of accuracy. The kirigami principle has not only been used directly in actuator structures but has also inspired many actuator designs. For example, taking inspiration from kirigami, Guo et al.[168] proposed a new soft pneumatic actuator capable of producing bending, stretching, contraction, and combined motions of bending with either stretching or contraction.

Besides the actuator's structural design, the actuation principle is crucial for actuator design. Pneumatic soft actuators have garnered considerable attention for their simple and human-friendly interaction.[169] The predominant fabrication techniques for these pneumatic soft actuators are 3D printing,[168,170,171] and molding.[172–174] However, these methods are often time consuming and costly, as they involve constructing complex air channel or multiple casting steps. Recently, some planar fabrication technologies have been employed for pneumatic soft actuators and robots. For instance, Chung et al.[175] proposed a straightforward three-step method for manufacturing inflatable kirigami actuators. Using this process, three innovative designs of inflatable kirigami actuators are introduced. The cut patterns enable kirigami actuators achieve substantial deformation with a load attached. Upon inflation, the actuators' stiffness increases rapidly, resulting in contraction of the actuators and lift of the load. The proposed parallel kirigami actuators to achieves a contraction ratio of 78.5% at 200 kPa with a 100 g weight attached.

6. Kirigami Robots

For a long time, robotics has been at the forefront of technological innovation, continuously evolving to meet the diverse needs of human society. From the early days of industrial automation, where rigid robotic arms were used for repetitive manufacturing tasks, to the development of sophisticated humanoid robots[176] providing complex locomotion and interaction,[177] the field has witnessed remarkable progress in industry and medical.[178,179] However, traditional rigid robots often face limitations when they have to operate in unstructured and dynamic environments, interacting with humans in a safe and natural manner, and mimicking the complex and adaptable behaviors of living organisms. Soft robots represent a paradigm shift in robotics, drawing inspiration from the natural world to create machines that are more flexible, adaptable, and compliant. The concept of soft robots bases in the idea of using materials that can deform and change shape in response to external stimuli, much like the muscles, tendons, and tissues of living beings.[180–182] This unique property allows soft robots to navigate through complex and confined spaces, conform to irregular surfaces, and interact with humans and the environment in a more gentle and natural way.

In recent years, there is a growing interest in incorporating kirigami as functional components within soft robotic systems. Kirigami, with its programable kinematics and tunable mechanical properties, emerges as an ideal candidate for the structural framework of soft robots. Additionally, kirigami facilitates the seamless integration of electronic components, as well as sensors and actuators, further enhancing the functionality and adaptability of soft robotic systems.

6.1. Kirigami-Enabled Soft Grippers

The two essential tasks for soft robots are object manipulation and locomotion. Soft robotic manipulators excel in the manipulation due to their exceptional adaptability, enabling them to autonomously grasp and handle objects with irregular shapes. Engineers have used kirigami to design simple, robust soft grippers that enable precise and rapid grasping. For example, Yang et al.[100] developed a kirigami gripper with a shell-like structure using a straightforward material system. As shown in **Figure 8**a, the gripper is actuated through simple stretching of the kirigami shell, which induces out-of-plane bending deformation, enabling effective gripping motion. This design allows the gripper to pick up a diverse array of objects, such as hydrogel spheres, raspberries, wallets, and even grains of sand. Additionally, the gripper can be miniaturized and modularized, facilitating its integration with existing robotic platforms.

As shown in Figure 8b, Hong et al.[107] introduced a versatile and durable kirigami hand with dynamically programmable shape morphing, capable of gently encapsulating gelatinous and delicate organisms in unstructured environments through simple uniaxial stretching. Furthermore, leveraging the precise control of shape and trajectory through cut boundaries, Hong et al.[183] have advanced this concept to develop a universal, adaptable, multifunctional, and robust kirigami gripper. This innovative gripper is capable of performing ultradelicate, ultrarobust, and ultraprecise grasping tasks. As illustrated in Figure 8c, it can handle fragile liquids with minimal contact pressure, as low as 0.05 kPa, and lift objects weighing up to 16 000 times its own weight. Additionally, it demonstrates proficiency in grasping extremely thin and flexible items, such as microfibers with a diameter of 2 μm on a flat substrate.

In addition to grasping by using out-of-plane deformation caused by mechanical stretching, the kirigami can be integrated with prestretched substrate to form a bistable gripper. As shown in Figure 8d, Mungekar et al.[184] utilized bistable soft deployable structures to design a soft kirigami gripper actuated by an extending shape memory alloy spring. It is worth noting that the gripper only needs a small amount of energy input to overcome the energy barrier during grasping while no energy is required to maintain the holding state.

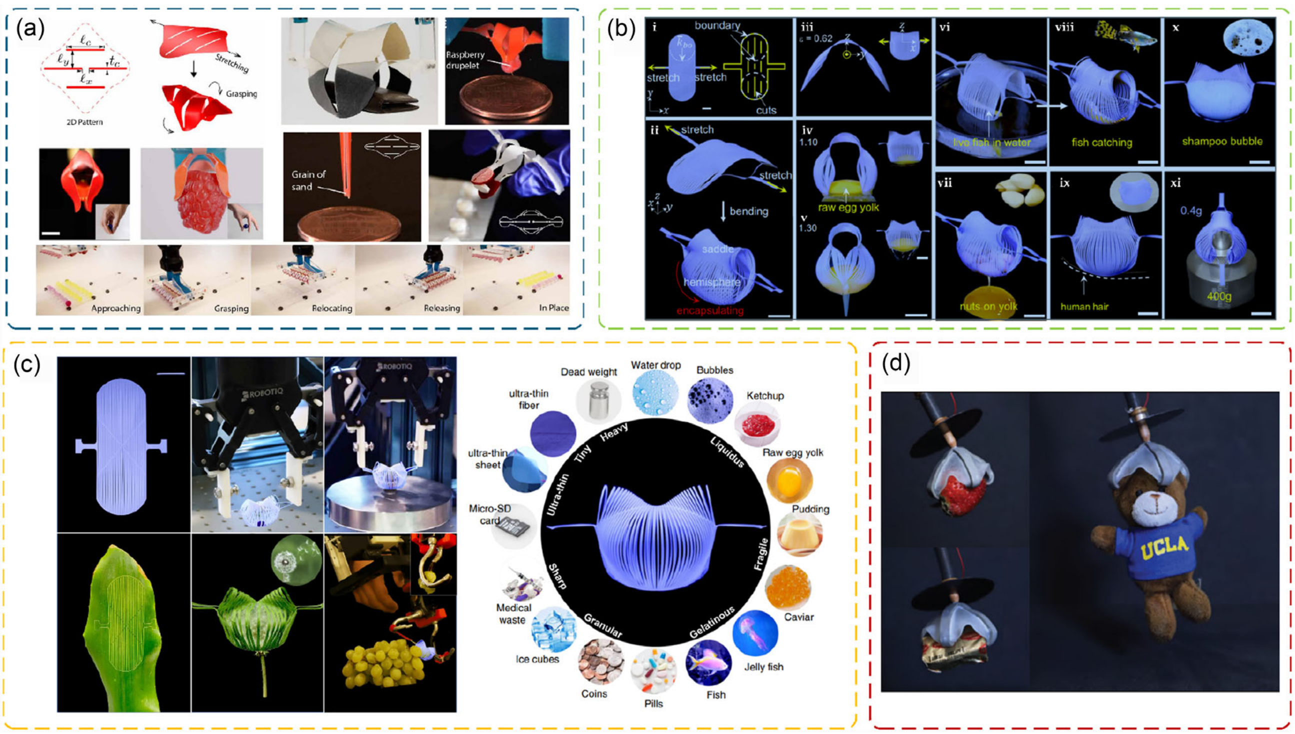

Figure 8. a) A gripper utilizing kirigami shells is engineered to convert mechanical stretching into a grasping motion. Adapted with permission.[100] Copyright 2021, AAAS. b) Shape-morphing kirigami sheets enable the design of a soft gripper. Adapted under the terms of the Creative Commons CC-BY license.[107] Copyright 2022, The Authors. Published by Springer Nature. c) A multifunctional kirigami gripper with ultradelicacy, ultrastrength, and ultraprecision. Adapted under the terms of the Creative Commons CC-BY license.[183] Copyright 2023, The Authors. Published by Springer Nature. d) A bistable kirigami gripper actuated by an extending shape memory alloy spring. Adapted with permission.[184] Copyright 2023, Wiley-VCH.

In addition to grasping objects, the kirigami show great tremendous in transport and manipulation of objects. Janbaz et al.[185] utilized the kirigami to carry a ping-pong ball forward. Chi et al.[186] developed a dynamic spatiotemporal shape-shifting kirigami dome metasheet characterized by its deformability and stiffness. This metasheet exhibits omnidirectional doming and can perform multimodal translational and rotational wave-like shape-shifting.

6.2. Tethered Crawling Robots

Kirigami offers promising opportunities for the development of a new class of soft robots capable of navigating complex environments for applications such as exploration and rescue operations. In recent years, several crawling robots have been designed following a unified paradigm, primarily consisting of a kirigami shell and an inflatable balloon. A notable example of this potential is the work by Rafsanjani et al.[187] who designed a kirigami-based flexible skin. As shown in **Figure 9**a, this innovative skin can be integrated with a fiber-reinforced pneumatic body to facilitate snake-like crawling locomotion. When the pneumatic body inflates, the kirigami skin stretches and buckles, creating directional friction that enables the robot to crawl efficiently. In addition, inspired by the friction-assisted locomotion of snakes, Branyan et al.[188] enhanced lateral-longitudinal frictional anisotropy, which led to improved locomotion capabilities in the subsequent robot. Furthermore, Branyan et al.[189] implemented an enhanced kirigami pattern that increases the lateral-cranial friction ratio on a snake-inspired skin to improve the locomotion of a soft snake robot.

Kirigami robot can be developed with load capacity, which allows for the potential integration of cameras, sensors, and control systems. Shen et al.[190] designed a soft, flat crawling robot, which consists of two components: a piece of skin with scales and a flat balloon. The balloon's expansion ensures the robot contracts, while the scales' anisotropic friction enables it to crawl forward. The robot, weighing just 5 grams, can effectively crawl while carrying a load exceeding 400 times its own weight.

In addition to crawling, kirigami robots is also utilized to achieve legged locomotion. For example, Firouzeh et al.[191] demonstrated that kirigami, beyond its application as a skin to create directional friction for robotic crawling, can also be utilized in various other capacities such as flat springs, stretchable electronics, sensors, and actuators. To illustrate these versatile applications, they designed and developed a foldable composite inchworm robot. The robot incorporates three distinct kirigami layers, each serving a specific function: one shape memory alloy (SMA) kirigami serves as an actuator, electrically conductive

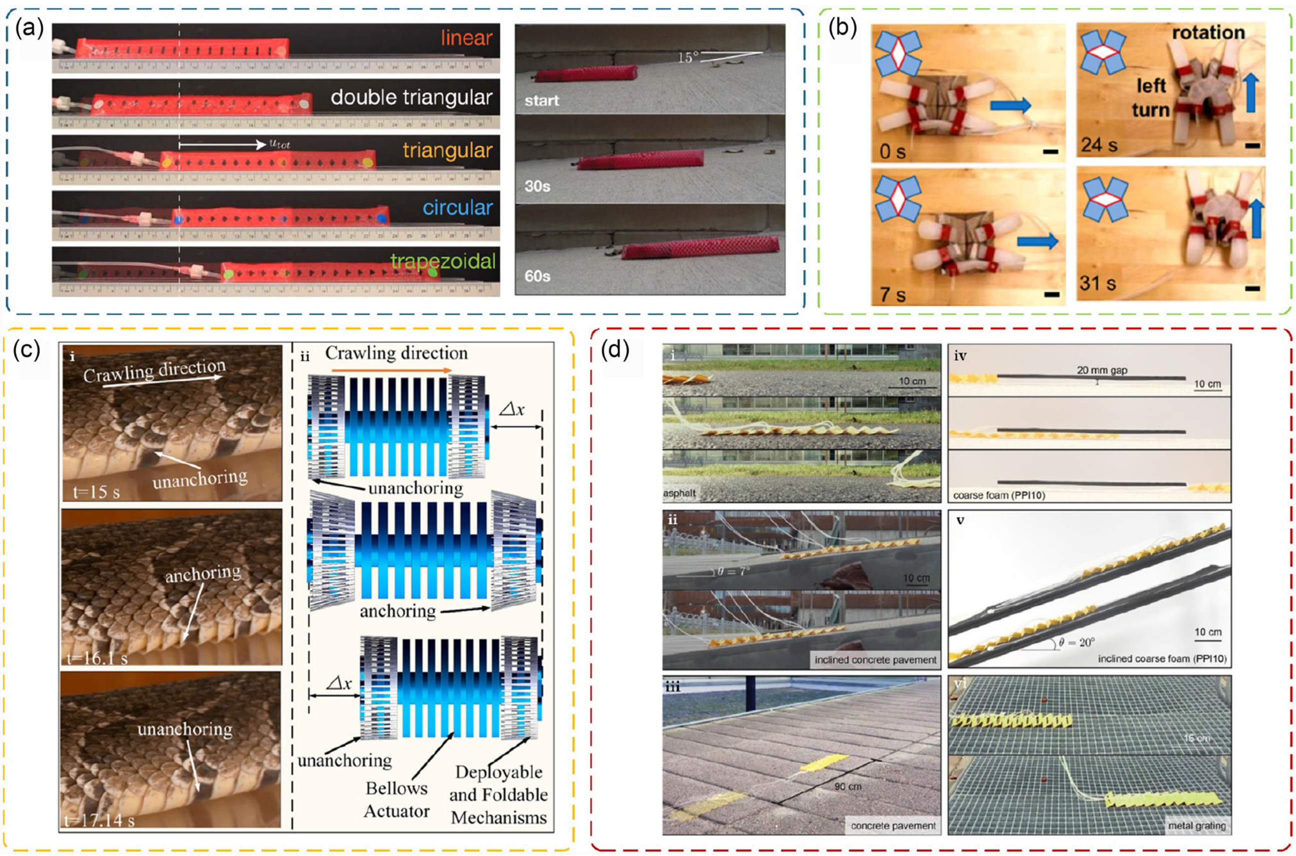

Figure 9. a) Kirigami-skinned soft crawlers consisted of kirigami skins and inflatable balloons. Adapted with permission.[187] Copyright 2018, AAAS. b) A crawler capable of crawling and turning that integrates kirigami and origami. Adapted with permission.[61] Copyright 2019, National Academy of Science. c) A pneumatic soft crawling robot with multimodal locomotion and bionic motion mechanism. Adapted with permission.[192] Copyright 2024, IEEE. d) Locomotion of an inflatable kirigami crawler on diverse terrains. Adapted with permission.[193] Copyright 2025, Wiley-VCH.

kirigami layers with sensitive electrical resistance to elongation serve as a sensor, and the third as a contact pad providing directional friction. These components significantly enhance the design and manufacturing potential of composite robots for a wide range of applications.

The crawling robots in these designs typically exhibit one motion mode, such as forward movement, because they use a single actuator, restricting their practical applications. Increasing the number of actuators enables the robot to achieve multiple motion modes. As illustrated in Figure 9b, Tang et al.[61] demonstrated a robot capable of crawling and turning using a combination of kirigami and origami. As shown in Figure 9c, Mei et al.[192] presented a pneumatic soft crawling robot with multimodal locomotion. Seyidoğlu et al.[193] proposed an inflatable kirigami crawler capable of achieving multi locomotion on diverse terrains by introducing multiple channels and segments into kirigami, as illustrated in Figure 9d. Seyidoğlu et al.[194] also constructed a triangular actuator frame consisting of three fiber-reinforced extending actuators positioned at each edge. By actuating these in pairs, the frame can elongate symmetrically in three directions. To facilitate omnidirectional planar movement, they enveloped the actuator frame with a reconfigurable kirigami skin, thereby creating a soft crawling robot, allowing the robot to steer and navigate complex paths.

The directional friction from buckled kirigami has inspired other applications. For example, Babaee et al.[159] affixed stretchable, lightweight steel kirigami patches to shoe soles to improve friction with walking or working surfaces, which may reduce the risk of slips and falls in various environments. Liu et al.[195] designed a a soft earthworm robot that simulates earthworm anchoring mechanisms by integrating kirigami skin with radially-expanding pneumatic actuators. The robustness and drag force performance of the kirigami skin were enhanced by combining a silicone layer with a plastic sheet.

6.3. Untethered Kirigami Robots by Remote Actuation

The kirigami robots mentioned above possess inherent advantages in flexibility and adaptability, yet their operational range are often constrained by their power supply with tethers. Some soft robotic systems predominantly rely on external power sources, requiring either bulky pneumatic pumps or intricate electrical wiring networks. The presence of pneumatic tubes or electrical wires particularly compromises the robots' mobility and functionality, especially when navigating confined or tortuous environments inaccessible to humans. These tethered connections exert unwanted tension forces on the robotic structure, thereby restricting their movement and potentially compromising their operational effectiveness. In recent decades, stimuli-responsive soft materials, known for their sensitivity to external stimuli and adaptive responses, have garnered significant interest and made substantial progress. Stimuli-responsive soft materials react to external inputs such as light, heat, and magnetic fields, enabling remote actuation of soft robots without complex wiring for power supply, thus establishing a new paradigm in robot design. This strategy enhances functionality and efficiency by ensuring seamless collaboration between structural components and actuators. Integrating these elements streamlines the design process, resulting in improved performance and reduced complexity of the robots. For example, Cheng et al.[196] proposed a kirigami-based, light-fueled rolling robot by integrating light-responsive sheets with the kirigami technique. As shown in **Figure 10**a, the robot can turn left, roll forward, and turn right by adjusting the direction of light excitation. Moreover, Chen et al.[197] developed a kind of liquid crystal elastomer (LCE) kirigami capable of bending, folding, twisting, and rolling when subjected to light stimuli. As shown in Figure 10b, by integrating a Chinese character "喜" with LCE kirigami, they demonstrated a "喜-shaped" robots capable of locomotion upon light. He et al.[198] proposed several kirigami-patterned reconfigurable structures based on light-responsive material and explored their applications in biomimetic actuators. Liu et al.[199] incorporated kirigami cuts into passive solids, enabling them to morph into a target shape in response to temperature stimulus. Cui et al.[200] developed innovative 3D structures by embedding rigid origami/kirigami skeletons with creases into heat-shrinkable polymer sheets to fabricate composite sheets. As shown in Figure 10c, when heated, the polymer sheets undergo shrinkage; however, this shrinkage is constrained by the embedded origami/kirigami patterns, resulting in laterally nonuniform strain. Consequently, the Gaussian curvature of the composite sheets is altered, transforming the initially flat sheets into curved 3D structures.

In addition to light-responsive and heat-responsive materials, magnetic-responsive materials also show significant potential for advancing soft robotics.[201] For example, Duhr et al.[202] developed an untethered crawling soft robot by incorporating kirigami cuts into a soft magnetic sheet, enabling efficient crawling under a rotating magnetic field. Furthermore, the authors demonstrated that altering the shape of the cuts and the orientation of the magnet allows the robot to be steered. When combined with the translational motion of magnet, enabling the programming of complex crawling paths, as illustrated in Figure 10d. Zhu et al.[203] proposed a method that combines kirigami with magnetic-responsive materials to achieve complex 2D-to-3D and 3D-to-3D shape morphing and precise magnetization programming through cut-guided deformation. As shown in Figure 10e, the out-of-plane deformation induced by the magnetic field created anisotropic friction, allowing the kirigami to crawl forward through repeated application and removal of the field generated by a permanent magnet.

In addition, the kirigami with orthometric-cuts also show great potentials in robotics. As shown in Figure 10f, Wang et al.[204] utilized kirigami with embedded hard-magnetic disks in each facet to design an untethered soft robot. The kirigami robot is constructed using a characteristic cut pattern defined by orthogonal cuts. These kirigami patterns enable both in-plane and out-of-plane shape transformations when exposed to magnetic stimuli, thereby substantially enhancing the robot's kinematic DOF. By precisely manipulating the magnetization arrays and the applied magnetic fields, the proposed robots demonstrate versatile locomotion capabilities, including walking, crawling, flapping, and swinging. In addition, Wang et al.[76] developed an untethered soft robot that demonstrates programmable multimodal motions through the integration of bistable kirigami and hard magnetic actuations. This innovative design

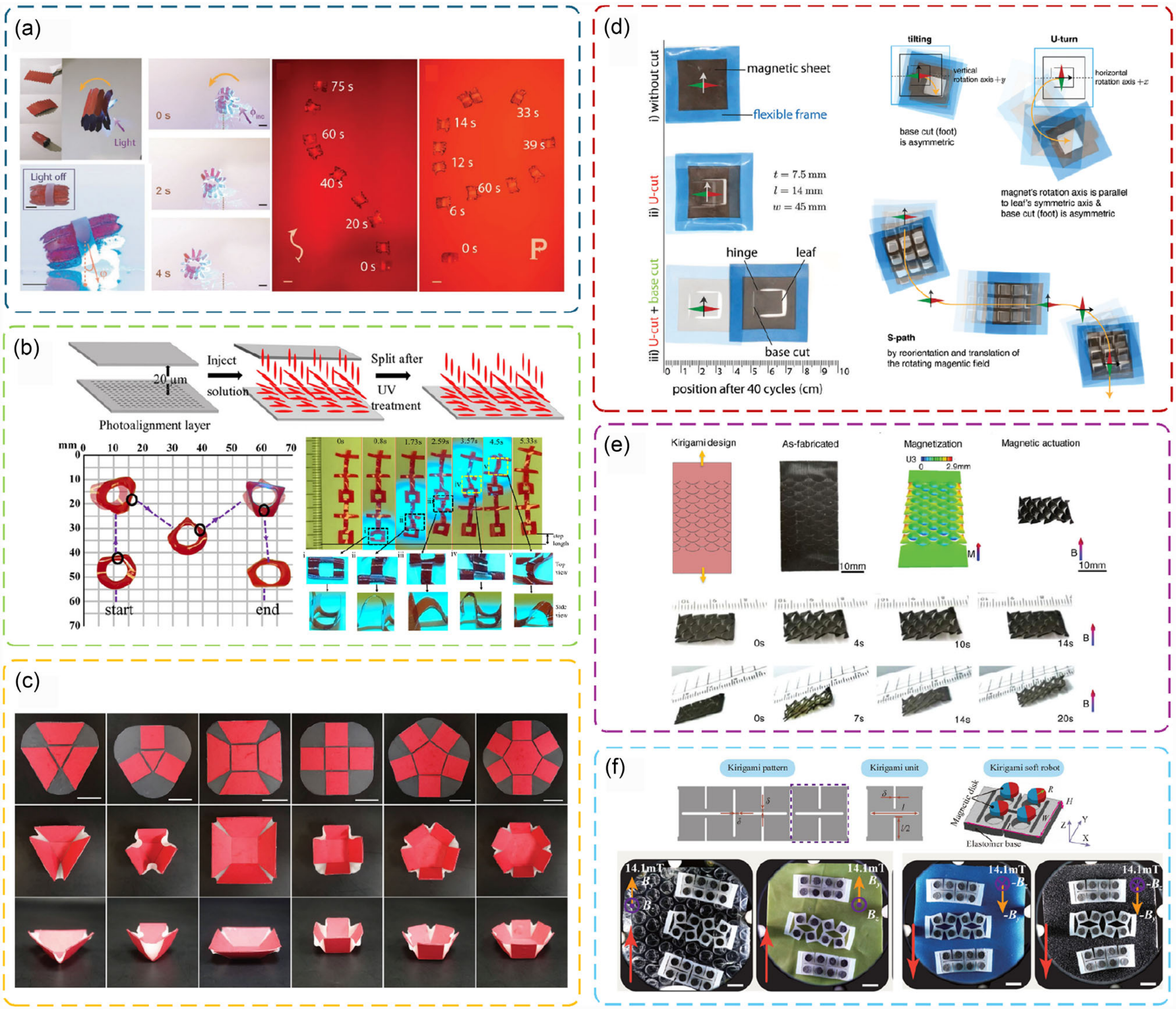

Figure 10. a) A kirigami-based rolling robot capable of turning left, rolling forward, and turning right in response to light input. Adapted with permission.[196] Copyright 2020, Wiley-VCH. b) The kirigami enables the locomotion of a Chinese character "喜" made of liquid crystal elastomer in response to light input. Adapted with permission.[197] Copyright 2022, Wiley-VCH. c) Kirigami/origami-guided morphing in response to heat input. Adapted with permission.[200] Copyright 2018, Wiley-VCH. d) A magnetic kirigami robot capable of programable crawling path. Adapted with permission.[202] Copyright 2023, Wiley-VCH. e) A kirigami-inspired soft crawling robot. Adapted with permission.[203] Copyright 2022, Wiley-VCH. f) Untethered magnetic kirigami soft robots with programable locomotion and environmental adaptability. Adapted with permission.[204] Copyright 2023, AIP Publishing.

allows the soft robot to undergo rapid transitions between two stable states by manipulating the external magnetic field.

7. Kirigami + Artificial Intelligence

A latest research topic of considerable interest is the development of an inverse design methodology specifically tailored to target diverse mechanical properties and multifunctionality in kirigami. This methodology aims to create cut patterns that can encode specific characteristics to the material, such as enhanced flexibility, stiffness, tunable mechanical properties, or even programable shapes. Most cut patterns discussed in this article derive from the two fundamental cut patterns: orthometric-cuts and parallel-cuts, as depicted in Figure 2a. The potential configurations for distributing cuts in a kirigami sheet are virtually limitless, necessitating the development of an inverse design method to generate kirigami cuts that fulfill specific functions. Recent advancements in machine learning have opened up new avenues for addressing this complex design challenge. As illustrated in **Figure 11**a, Kim et al.[205] proposed an auxiliary metamaterial design optimization method based on origami techniques. By designing the geometric parameters of kirigami units, including the cut angle (θ), cut width (w_s), hinge width (w_h), and leg width (w_l), multistability and shape deformation ability were achieved. Specifically, response surface models, as

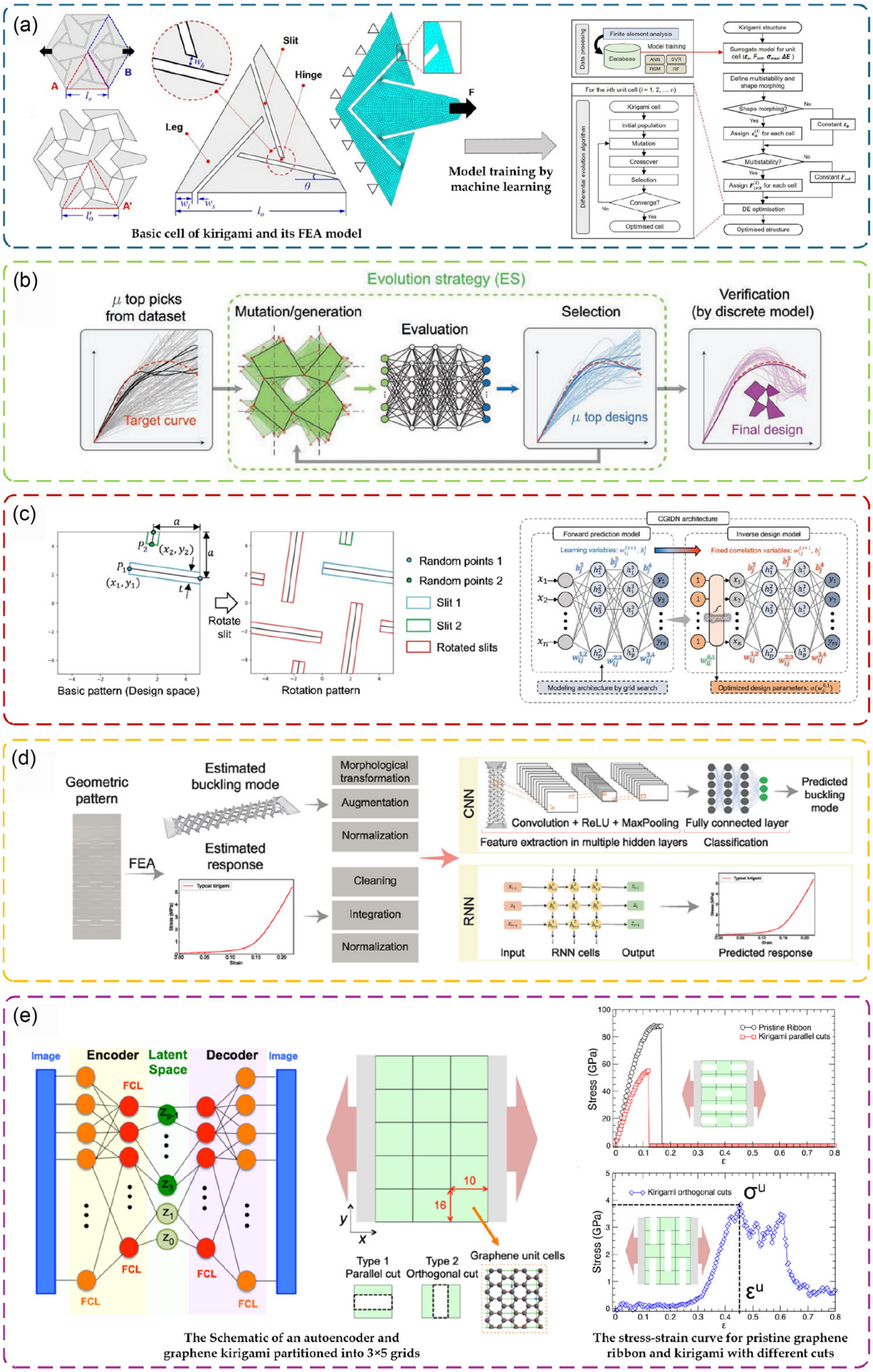

Figure 11. Inverse design based on machine learning. a) Inverse design of auxetic metamaterials based on artificial neural networks (ANN), support vector regression (SVR), and random forests (RF). Adapted under the terms of the Creative Commons CC-BY license.[205] Copyright 2025, The Authors. Published by Taylor & Francis. b) Inverse design of stress–strain curves for 2D mechanical metamaterials via multilayer perceptrons and evolutionary strategies. Adapted with permission.[206] Copyright 2022, Wiley-VCH. c) Design of metamaterial structures with target strain Poisson's ratio achieved via CGIDN. Adapted with permission.[207] Copyright 2024, Elsevier. d) Classification of buckling modes and inverse design of target stress–strain curves in kirigami based via CNN and RNN. Adapted with permission.[208] Copyright 2024, Elsevier. e) Forward prediction and inverse design of mechanical properties in kirigami based via SAE. Adapted with permission.[209] Copyright 2020, American Physical Society.

well as machine learning models such as artificial neural networks, support vector regression, and random forest, were constructed to approximate the complex design parameter-performance relationships. Meanwhile, differential evolution algorithm was combined with surrogate models for design optimization, effectively improving computational efficiency. Ultimately, multistable deformation behaviors under different critical forces were realized, and the target shapes could exhibit deformation effects such as conical or curved shapes. Deng et al.[206] on the other hand, generated different unit cells by randomly perturbing the vertex positions of quadrilaterals, thereby influencing the mechanical response of metamaterials. As depicted in Figure 11b, they introduced a multilayer perceptron model to learn the relationship between geometric parameters and stress–strain responses. By combining this method with evolutionary strategies, geometric configurations with expected nonlinear mechanical responses were effectively achieved and applied to the design of energy absorption systems, soft robots, and deformable structures. This type of ML-based inverse design method establishes the correspondence between known shape design parameters and mechanical properties to realize inverse design for target properties. Its advantages lie in significantly reducing optimization complexity and improving computational efficiency by predefining the topological constraint design space dimensions. However, its design freedom is limited by parameterized templates, making it difficult to yield new configurations, and the prediction accuracy for strongly nonlinear or abrupt responses still needs improvement.

Besides, different mechanical properties are attained through different cutting patterns. As shown in Figure 11c, Kang et al.[207] proposed six independent parameters for kirigami cuts (boundary distance a, coordinates of two random points (x_1, y_1), (x_2, y_2) and cut thickness t) and used a machine learning method called constrained generative inverse design network (CGIDN) to successfully design metamaterial structures with specific strain-dependent Poisson's ratios. CGIDN effectively navigates complex design spaces through backpropagation and active learning, reducing the need for datasets and iterative experiments. The geometric parameters of the designed unit structures can precisely match the target mechanical behavior. Moreover, Zhang et al.[208] studied incision parameters such as slit length (l_{slit}), slit spacing (l_{sp}), slit width (l_{w}), distance from slit to left boundary (l_{sll}), and distance from spacing to left boundary (l_{spl}), and used two machine learning methods, convolutional neural networks (CNN) and recurrent neural networks (RNN), to predict and classify the buckling modes and constitutive relationships of kirigami structures, as illustrated in Figure 11d. By extracting the stress–strain curves of kirigami structures, the RNN model uses history-dependent hidden states to efficiently process sequential data and establish the connection between geometry and constitutive relationships. An RNN model configured with 3 layers of gated recurrent units (GRU) and 500 neurons achieved the best performance. Given a target stress–strain curve, the RNN model trained through multiple iterations continuously optimizes geometric parameters to find the combination most matching the target curve. This method can effectively expand the design space of kirigami patterns, accurately predict complex nonlinear constitutive relationships and buckling modes, and thus realize target-oriented kirigami structure design to meet various functional requirements. As shown in Figure 11e, Hanakata et al.[209] designed parameters such as cutting directions (parallel and orthogonal cuts) and the number of cuts and adopted a machine learning method of supervised autoencoders (SAE) for design. Different from traditional variational autoencoders (VAE), SAE can not only reconstruct cutting configurations but also predict mechanical properties such as ultimate stress and strain. By interpolating in the latent space, SAE can generate hybrid designs containing both parallel and vertical cuts, even though the training samples only include parallel or vertical cuts. This approach helps identify alternative designs and predict their mechanical properties with reasonable accuracy, thus expanding the search space for material design. This type of method establishes the correspondence between cutting patterns and mechanical properties through machine learning to achieve inverse design. It aviods predefined topological constraints, while directly maps the deep relationship between cutting patterns and mechanical properties, and can generate novel structures beyond experience (such as hybrid cuts and gradient patterns).

By leveraging the power of machine learning algorithms, researchers can now potentially automate the inverse design process, enabling the rapid generation and optimization of kirigami cut patterns tailored to meet specific mechanical and functional criteria. This represents a significant step forward in the field of kirigami design and has the potential to unlock a wide range of innovative applications. However, the structural variability leads to difficulties in modeling and simulation, as well as high costs in acquiring training datasets. It is worth noting that current research is mostly limited to linear cutting configurations. Expanding the design space to complex curved paths (such as spline curves and custom contours) can further unleash topological innovation potential and may enrich mechanical responses, but it will drastically increase the complexity of geometric structure, mechanical modeling, and simulation calculations. This is another challenge that shall be addressed in the future.

8. Conclusion

Kirigami's artistic elegance has found practical applications in metamaterials and robotic engineering. This review outlines recent advancements in the geometric design and mechanical properties of kirigami, highlighting their applications in metamaterials and robotic systems. Introducing cuts provides a novel way to modulate mechanical behavior, significantly enriching the design space and enabling distinctive mechanical properties. Kirigami have been developed by integrating principles in compliant mechanisms, offering performances in different dimensions. Through the integration of design, materials, fabrication, and control systems, kirigami gain unprecedented functional capabilities. Utilizing the kirigami with advanced manufacturing, measurement, and intelligent diagnosis techniques, it is promising to apply the kirigami from laboratory prototypes to large-scale production and commercialization. The ancient art of paper cutting will undoubtedly continue to inspire innovative engineering research.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

actuators and robots, compliant mechanism, kirigami, metamaterials

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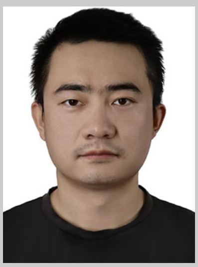

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