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# From *in vitro* to *in vivo*: Diverse applications of kirigami technology in medical devices

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A B S T R A C T

Kirigami, as a paper-cutting art, has developed into an innovative design and manufacture strategy with the support of material diversity and modern manufacturing technology. Combining the mechanical, electrical, and magnetic properties of materials, carefully designed geometric shapes can significantly improve mechanical flexibility, two-dimensional and three-dimensional reconfiguration, and functionality. This paper focuses on medical devices, and reviews the pattern design, deformation characteristics, function realization and diversified applications of advanced kirigami technology in this field. And the design influencing factors, basic deformation mechanism and various fabrication methods of kirigami are also discussed. Medical devices are mainly classified by *in vitro* and *in vivo* applications, with different functions such as monitoring, power supply, and treatment as sub-categories. At the same time, the application potential of kirigami-based smart devices in medical applications and the auxiliary role of simulation technology in design are discussed. On this basis, the challenges and prospects of the research and development in the field of medical health inspired by kirigami are summarized and prospected.

## 1. Introduction

In recent years, biomedical technology has witnessed rapid development. Innovative medical devices such as wearable health monitoring [1–5] and treatment devices [6–9] for *in vitro* use, drug delivery carriers [10] and stents [11] for *in vivo* use, and intelligent human-computer interaction systems [12,13] have emerged to meet various health needs of human beings. Broadly speaking, medical devices refer to related equipment and consumables used for the prevention, diagnosis, monitoring, treatment or mitigation of disease, covering everything from *in vitro* wearable systems to *in vivo* implantable devices. The research and development of these medical devices invariably involve material selection, structural design, and functional optimization. For instance, when applied to the dynamic surfaces of skin and tissues, materials are required to be deformable, adhesive, and conformable. When the device is implanted into the body, it is required that the biomaterials used have good biocompatibility and controllable degradability. At the same time, as medical devices interact with people, they are also required to have good stability, durability and comfort. In actual design, it is often necessary to meet the above multiple performance requirements through the coordinated regulation of material properties and structural morphology, rather than merely relying on the change of the material's own properties. Traditional rigid materials often fail to meet the aforementioned requirements, and even highly elastic materials such as soft gels cannot singly address these challenges. To address these issues, a technology called kirigami has emerged and has become a highly promising solution at present. Combining modern high-precision manufacturing technologies such as femtosecond laser processing, kirigami structures can be fabricated from the macroscopic to the microscopic and even down to the nanoscale [14–17]. By applying carefully designed geometric cuts to various substrates, novel metamaterials that maintain structural integrity under tension or compression can be prepared. These materials retain their original properties while acquiring additional mechanical and functional characteristics, such as precise shape deformation [18], tunable auxetic behavior [19], super elasticity [20], buckling [21], and multistability [22]. The advantages of this technology are not limited to applications in surface lamination devices for *in vitro* use but can also be extended to the design of implantable devices for *in vivo* use, offering broader and more effective solutions in the medical field.

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Kirigami is an ancient traditional art form, where "kiri" means "cut" and "gami" means "paper", essentially translating to paper cutting. Unlike origami, which typically uses only folding without involving any cutting, kirigami allows for the creation of complex shapes by cutting different patterns into the material, giving it unique advantages such as extreme deformability and the ability to reconstruct in two and three dimensions. For example, a piezoelectric strain sensor patterned with "parallel cutting" [23] can achieve a sensitivity of 9.86 $V/cm^2$ and an ultrahigh stretchability of 320.8 %, and has been successfully applied in tactile gloves for musical instruments [24]. Meanwhile, the deformation forms and mechanisms triggered by different materials and patterns are different, resulting in different mechanical properties. For instance, a piezoelectric strain sensor patterned with "orthogonal cutting" [25] not only exhibits superior stretchability but also possesses excellent auxetic properties, which can minimize the sensor's restriction on structural motion while maintaining the initial stable electrical performance, having successfully achieved human motion monitoring [26]. Meanwhile, the deformability imparted by the cuts enables these laminated composites and other types of composite materials to exhibit excellent stability and conformability [27–29]. Moreover, through specific pattern design [30–33], materials can also achieve reversible and programmable deformation. For example, by combining contour cuts that define structural morphology with self-expanding central fractal cuts, the kirigami design enables implants to naturally form a teardrop shape under their own weight, providing support for the required areas in breast reconstruction [18].

Currently, with the support of modern manufacturing processes such as laser cutting, kirigami technology has achieved universal application of cutting structures ranging from large-scale to micro-nano scales. Meanwhile, the deformation mechanisms involved are constantly being discussed and improved in research [34,35]. With the continuous emergence of Kirigami-based metamaterials with different functions, they have been widely studied in fields such as industry, medicine, and intelligent applications [36–46]. Especially in recent years, the research progress in the medical field has been particularly rapid. However, up to now, there have been few review articles solely on the medical applications inspired by kirigami technology [47]. Moreover, several review articles have summarized recent advances in medical device research from the broader perspective of flexible metamaterials, including applications related to kirigami technology, which provide valuable background for the integration of kirigami structures in biomedical applications [48,49]. Most review articles do not discuss kirigami technology alone but combine it with origami technology or other flexible technologies [50–55]. However, they are quite different in terms of deformation mechanisms and applications [56]. Meanwhile, considering the significant differences in the use environments of medical devices *in vitro* and *in vivo*, kirigami structures assume different functional requirements and performance design goals in different scenarios. Therefore, given the rapid development of kirigami metamaterials in the medical field, timely review and summarization can not only help researchers understand the latest research findings and development trends but also promote further innovation.

In this article, we mainly review the applications of kirigami in medical devices, focusing on the main thread of its use in such equipment, and elaborate it by classifying *in vivo* and *in vitro* medical devices respectively, as well as expanding and supplementing with the latest smart machines. Since the review focuses on the deformation characteristics of different kirigami metamaterial patterns and the experimental results of functional realization, we will dedicate a separate section to the progress of kirigami simulation studies, with a focus on simulation models and output data. Thus, this review is organized into seven sections: (1) Introduction. (2) Introduction to the connection between different factors and deformation forms, focusing on 2D and 3D deformation forms, to elaborate on the basic deformation mechanisms of kirigami and the common fabrication methods currently used for kirigami. Discussion on (3) application of kirigami technology in *in vitro* medical devices and (4) application of kirigami technology in *in vivo* medical devices, which illustrates the progress of kirigami in the field of medical care. (5) Discussion on the application potential of kirigami-based smart devices in medical applications. (6) Research on simulation technology of kirigami metamaterials. (7) Summary and outlook of kirigami-inspired research.

## 2. Deformation forms of kirigami under different induced mechanisms

Kirigami-based multifunctional metamaterials are a novel type of material that achieves special mechanical properties and functionalities by introducing kirigami patterns into the substrate material. The mechanical properties of these metamaterials are influenced by many factors, with pattern design being the most critical. The shape, size, and arrangement of the kirigami cuts significantly affect the deformation behaviors and corresponding functionalities [57]. In this section, we first categorize the deformation of kirigami structures based on the geometric dimensionality of their final configurations: 2D and 3D deformations. This classification reflects distinct functional requirements in medical applications; for example, 2D structures are typically designed for stretchability and skin conformability in wearable systems, while 3D structures are tailored for spatial support, penetration, or controlled shape change in implantable devices. Within each category, we further describe the key deformation mechanisms that enable these structural transformations. Although the deformation mechanisms involved are constantly being discussed and improved. For instance, jin et al. summarized the three basic mechanisms of kirigami, namely 'Out of plane buckling', 'Rotating units' and' Cutting and folding ', and clarified the unique characteristics and applications facilitated by these mechanisms [34]. Finally, to bridge the gap between structural design and functional realization, we summarize commonly used kirigami fabrication methods. These methods allow precise implementation of diverse kirigami patterns across different length scales and substrate materials, thereby ensuring the practical viability of the designs introduced in the earlier sections. Fig. 1 below gives a comprehensive overview of the induced mechanisms under the two reconstruction deformation forms of kirigami, the common fabrication approaches and representative biomedical applications.

### 2.1. 3D deformation of kirigami and corresponding mechanisms

Kirigami is widely applied in various modern engineering applications primarily because it offers greater design freedom and more complex 2D/3D deformation capabilities compared to origami. Among the various deformation behaviors observed in kirigami metamaterials, 3D deformations are particularly notable for their ability to generate spatial configurations. These 3D shapes are typically formed through out-of-plane buckling when the material is stretched or compressed [67,68], or through intentional folding based on predefined cut patterns. The realization of such deformations depends not only on the geometry and distribution of the cutting units, but also on the mechanical properties of the substrate material, which must support structural instability or maintain foldability. In this section, we discuss representative 3D deformation patterns and their underlying mechanisms.

The most common 3D deformation of kirigami is the buckling deformation produced by stretching after introducing parallel interlocking linear cut patterns [69,70]. When the material is stretched in the direction perpendicular to the cutting lines, in-plane and out-of-plane deformation energies are generated. When a small amount of stretching is applied, the in-plane deformation plays a dominant role, causing the structure to deform primarily within the plane, which occurs only under the condition of very small tensile strain. As the degree of stretching increases, out-of-plane deformation gradually comes into play. When the two energies become equal, out-of-plane deformation (i.e., buckling) begins, resulting in the formation of the desired tilted


**Fig. 1. The Overview of the induced mechanisms, pattern preparation methods and applications of kirigami metamaterials.** Inner circle: 2D/3D induced deformation mechanisms of kirigami. **Middle circle**: preparation methods of different kirigami patterns, including tool cutting, mold casting, 3D printing, photolithography, laser cutting. etc. Reproduced with permission [58]. Copyright 2020, IEEE. Reproduced with permission [59]. Copyright 2023, The Authors. Reproduced with permission [60]. Copyright 2023, AIP Publishing. Reproduced with permission [61]. Copyright 2023, Wiley. Reproduced with permission [62]. Copyright 2020, American Chemical Society. Reproduced with permission [63]. Copyright 2019, American Chemical Society. **Outer circle**: current and potential applications of different kirigami shapes in the medical field, including protection, monitoring, curing, soft robots, etc. Reproduced with permission [21]. Copyright 2020, Springer Nature. Reproduced with permission [64]. Copyright 2024, Elsevier. Reproduced with permission [26]. Copyright 2024, Elsevier. Reproduced with permission [65]. Copyright 2024, The Authors. Reproduced with permission [18]. Copyright 2022, Wiley. Reproduced with permission [66]. Copyright 2019, The Authors.

small-plane 3D structure. For instance, when the polyethylene terephthalate (PET) composite film is processed with the laser to create parallel linear cutting, it can form a wavy 3D structure upon buckling, similar to the way a pangolin extends its scales. Combined with the shear-hardening effect, this can effectively dissipate impact forces [64]. When GaAs films are cut into this structure using carbon dioxide ($CO_2$) laser cutting, they can be used to track the position of the sun and maximize solar power generation [71]. The characteristic angle $\theta$ between the tilted small plane and the reference plane is correlated with the transverse strain $\varepsilon_T$ (i.e., reduction in width) and the axial strain $\varepsilon_A$ (i.e., increase in length) (Fig. 2a), and the deformation relationship is shown in Eqs. (1) and (2) [71]:

$$\theta = \cos^{-1}(\varepsilon_A + 1)^{-1} \quad (1)$$

$$\varepsilon_T = \frac{R_1 - 1}{R_1 + 1}\left[\cos\left(\sin^{-1}\frac{2R_1 \tan\theta}{R_1 R_2 - R_2}\right) - 1\right] \quad (2)$$

where $\varepsilon_T = (L - L_0)/L_0$, and $\varepsilon_T = (W - W_0)/W_0$. $R_1$, $R_2$ are dimensionless parameters that define the cut pattern in that $R_1 = l_c/\, d$ and $R_2 = l_c/h$. And kirigami cut designs involve the cut length ($l_c$) and the spacing between cuts in the transverse ($d$) and longitudinal ($h$) directions.

In terms of the parallel cutting method, many studies have shown that the 3D deformation effect [57,72,73] of kirigami is greatly influenced by the cutting size [74] and arrangement [62]. On the one hand, increasing the incision length will soften the material, thereby reducing the critical buckling load and increasing the maximum elongation rate. On the other hand, increasing the spacing between each row of cuts will lead to the formation of larger peaks and valleys in the material, and since the material between the spacings is relatively wide, the critical buckling load of the metamaterial will increase, resulting in a decrease in the elongation rate and deformation ability (Fig. 2b). For example, the kirigami-inspired environmentally adaptive facade component is created using parallel cutting. By increasing the relative cutting size and the number of holes in the longitudinal direction, and reducing the number of holes in the transverse direction, the rotational angle and relative opening area of the 3D structure are increased, which in turn affects solar irradiance and ventilation capacity [75]. In addition to the size and arrangement of the pattern, local optimizations, such as adding small cuts near the ends of each incision [76], can also yield unexpected 3D structures and reduce stress concentration at the cuts, resulting in better performance. Furthermore, by implementing a double-slot pattern cutting between each row of cuts [77], each row of units can form a connected structure resembling folded walls after stretching [78], which significantly enhances energy absorption and volume expansion compared to a single parallel cutting pattern (Fig. 2c).

As a derivative of the kirigami parallel linear cutting pattern, replacing the linear pattern with other patterns will also affect the 3D deformation effect. As shown in Fig. 2d, if all the linear cuts in the parallel cutting pattern are replaced with V-shaped cuts [79], the

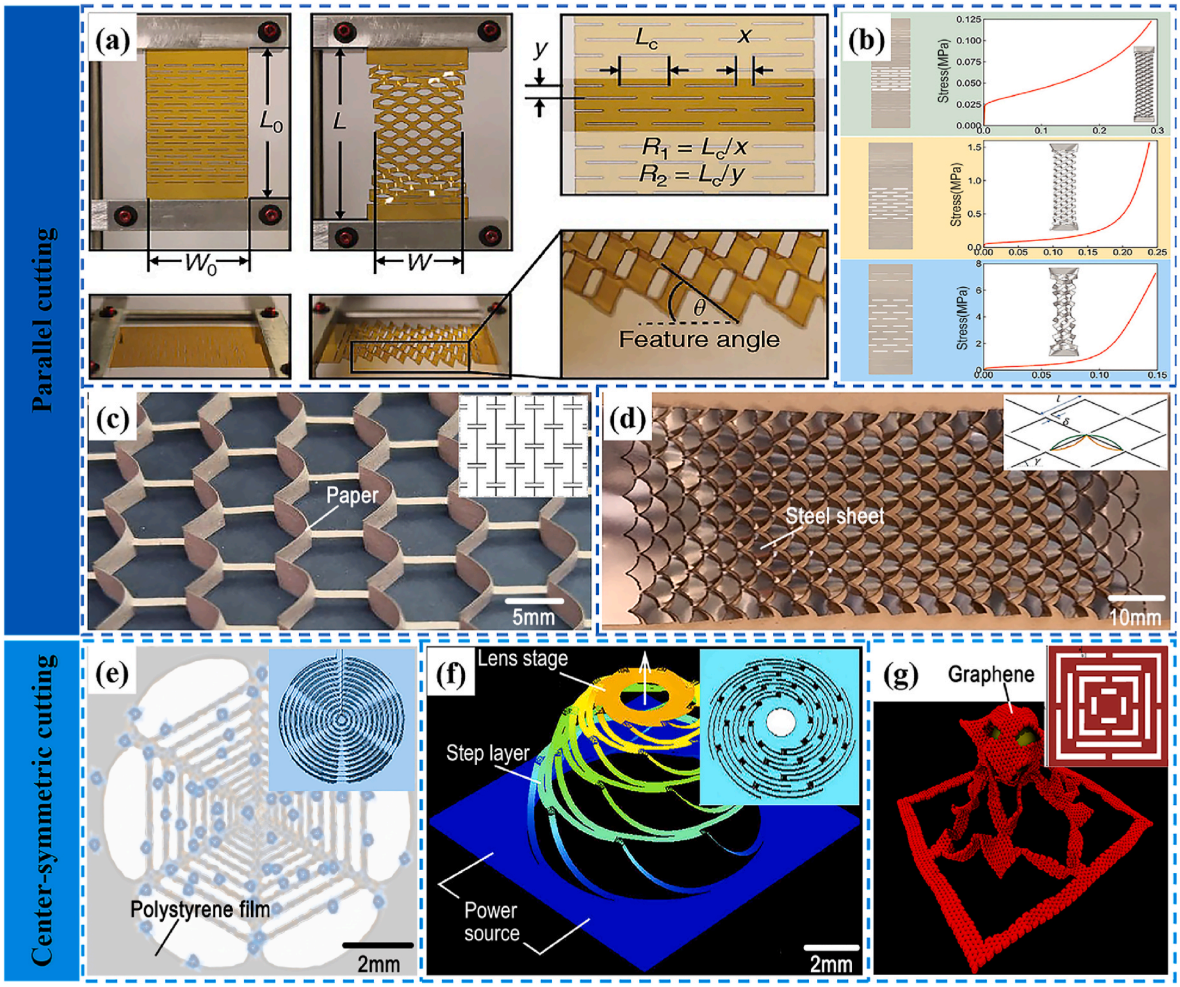


**Fig. 2. Kirigami-based 3D deformations formed by stretching buckling from parallel cutting and center-symmetric cutting patterns.** (a) 3D structures formed by the stretching buckling of linear pattern. Reproduced with permission [71]. Copyright 2015, The Authors. (b) The effect of different sizes and arrangements of linear cuts on the 3D reconstruction outcome. Reproduced with permission [57]. Copyright 2024, Elsevier. (c) Folded wall structures formed after adding small cuts at the ends of incisions and subsequent reconstruction. Reproduced with permission [78]. Copyright 2023, The Authors. (d) Pop-up angle structures formed by replacing linear cuts with V-shaped cuts during reconstruction. Reproduced with permission [21]. Copyright 2020, Springer Nature. (e) Concentric circular arc patterns, (f) spiral line patterns, and (g) circumferential arrays of linear patterns forming 3D pyramidal structures through stretching-induced buckling. Reproduced with permission [93]. Copyright 2021, Wiley. Reproduced with permission [94]. Copyright 2020, Optical Society of America. Reproduced with permission [95] Copyright 2023, Elsevier.

inclined facets generated by the buckling mentioned above will be replaced by triangular pop-up angles. As the degree of stretching increases, the pop-up effect of these pop-up angles becomes more obvious. Besides V-shaped cuts, there are also semi-circular, trapezoidal, and other types of cuts [21,80–82], and the shapes of their pop-up angles also change from triangular to circular and trapezoidal accordingly. Thanks to these 3D pop-up angle structures, kirigami metamaterials possess unique frictional properties and anchoring effects, greatly promoting the application and development of the kirigami technique in biomimetic soft robots [83–85] as well as medical stents [86].

In addition to parallel cutting patterns (linear, V-shaped, semi-circular, trapezoidal, etc.), kirigami also encompasses a series of central symmetry cutting patterns [65,87–92]. The deformation mechanisms of these patterns are similar to those of the parallel linear cutting, which is buckling caused by in-plane and out-of-plane deformation energy when stretching in the direction perpendicular to the cutting lines. However, the stretching methods are slightly different from the former. For parallel cutting, the substrates are typically rectangular, and stretching is applied to two opposite edges. In contrast, central symmetry cutting is mostly performed on circular or polygonal substrates. The periphery of the substrate is fixed, while an out-of-plane force is applied to the center, either through mechanical pushing, pulling, or other external stimuli (e.g., thermal or electrical actuation). This results in pyramid-like 3D structures due to the buckling induced by the competition between in-plane and out-of-plane deformation energy. As shown in Fig. 2e, inspired by spider webs, concentric circular arc slit patterns are cut into the shape memory polymer (SMP) substrate. Upon heating, the substrate undergoes buckling deformation, enabling the collection of water droplets by leveraging their own gravitational force [93]. When materials such as W/NiCr are etched into multiple sets of discontinuous spiral line patterns (Fig. 2f), they undergo buckling deformation into a 3D structure under electrothermal driving, which can be used for endoscopic scanning [94]. At the atomic nanoscale of graphene, the introduction of centrosymmetric kirigami cutting patterns (Fig. 2g) results in exceptional kinetic energy absorption capabilities due to buckling deformation induced by out-of-plane forces, effectively mitigating impact forces. This enhancement in performance can be attributed to a multi-step dissipation mechanism that effectively hinders crack propagation [95]. The existing theoretical models mainly focus on the deformation mechanism of linear parallel structures. By simplifying the geometric relationship between structural parameters and deformation variables, the corresponding mathematical models have been established. However, for more complex kirigami patterns or cases involving the coupling of materials and structures, there is currently a lack of a unified theoretical modeling framework. This also indicates that there is still room for expansion in mechanism modeling in the future.

Contrary to the way of stretching, compressing kirigami metamaterials to a certain strain will also lead to out-of-plane 3D deformation. The 3D reconstructed structure under this mechanism similarly depends on the geometry of the kirigami pattern and the applied boundary conditions. Generally, in order to precisely apply the compression boundary conditions, a layer of pre-stretched elastomer substrate is usually used to generate compressive stress on the metamaterials. The cutting patterns under this deformation mechanism are diverse [96–98], including single-helix, multi-helix, annular, and conical spirals, as well as patterns resembling spherical baskets, flowers, and fences. After compressive buckling, these patterns form highly complex 3D structures (Fig. 3a–d), and they are applicable across micro to macro length scales, spanning materials from soft polymers to brittle inorganic semiconductors and plastic metals [99]. And it has been widely applied in biomedical fields such as cell growth and detection on micro-nano scale 3D scaffolds nowadays. Additionally, by combining different materials, multi-stable structures [100–102] can be achieved, enabling functions such as rapid detection and object grasping [22].

Beyond the 3D deformation caused by stretching or compressive buckling after kirigami cutting, the metamaterials can also be transformed into more complex 3D structures [103–111] through folding after cutting. As everyone knows, origami technology transforms substrate materials into 3D structures through folding, typically requiring pre-designed creases as shown in Fig. 3e and f. It can be observed from the figures that, although the substrates are identical, different crease designs result in a cube and an octahedron, respectively, with the latter requiring significantly higher computational difficulty for crease design than the former. This demonstrates that relying solely on bending or folding to achieve complex 3D target shapes demands substantial computational effort, primarily due to the geometric complexity involved in precisely determining crease positions and angles, the nonlinear nature of deformations, and the need to solve non-convex optimization problems to achieve the desired shapes. In contrast, combining kirigami technology can provide the metamaterials with additional degrees of freedom, and folding after cutting can significantly reduce the complexity of the design process (Fig. 3g). Although this design process remains more intricate compared to patterns such as parallel cutting, this mechanism enables kirigami metamaterials to form more complex 3D structures (Fig. 3h) that cannot be achieved through buckling alone, thereby diversifying the 3D deformation structures. Kirigami metamaterials based on this mechanism have already been widely applied in fields such as drug delivery [10] (Fig. 3i) and robotics [112].

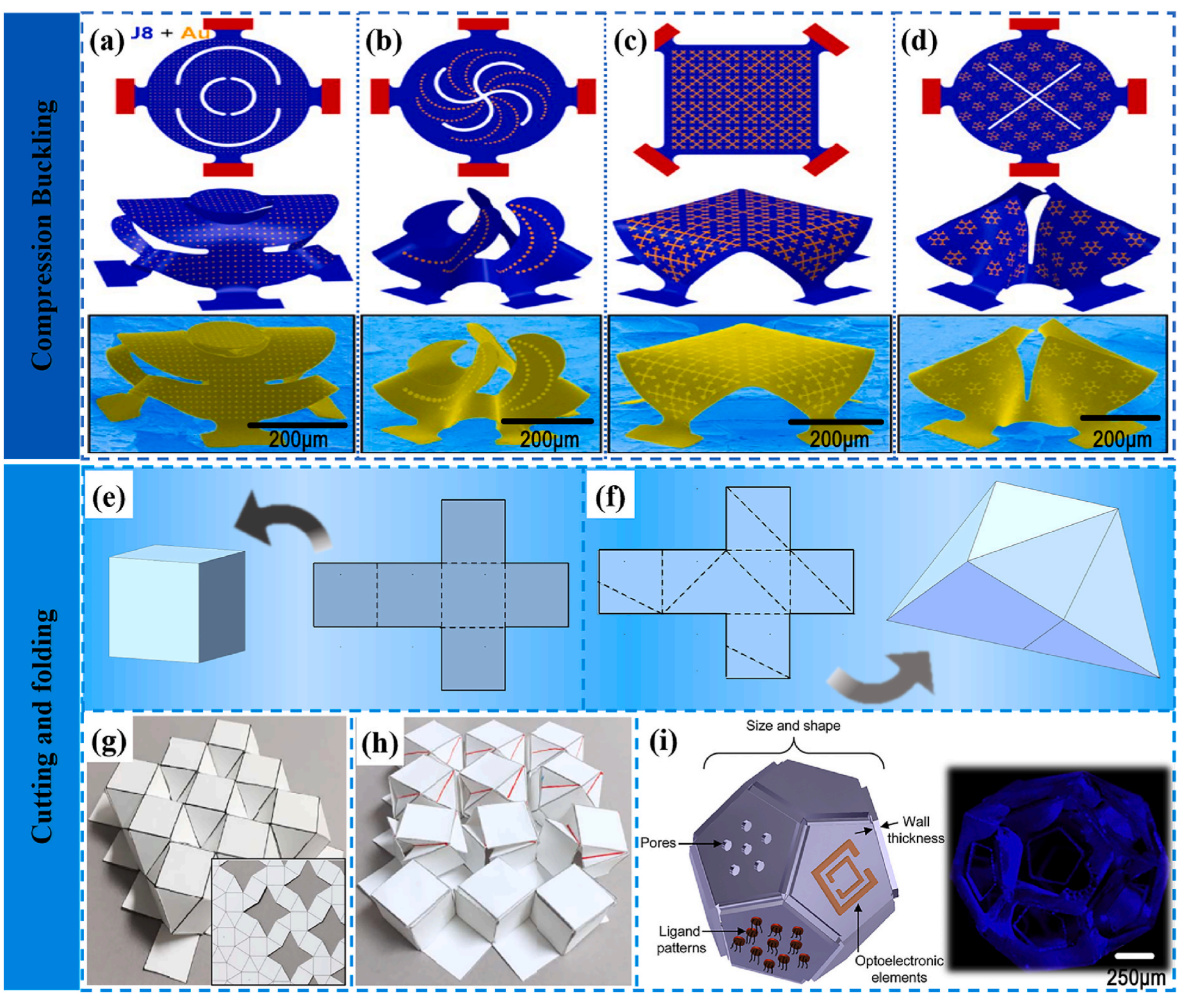


**Fig. 3. Kirigami-based 3D deformations under the mechanisms of compressive buckling and combined folding.** (a–d) Micro-nano scale kirigami patterns and their 3D structures formed by compressive buckling. Reproduced with permission [96]. Copyright 2015, National Academy of Sciences. (e, f) The design of different creases on the same specimen and the resulting 3D structures from deformation. (g, h) 3D structures formed by adding pre-creased patterns and folding based on kirigami technology. Reproduced with permission [107]. Copyright 2016, The Authors. (i) Application of kirigami metamaterials combined with folding techniques in drug delivery. Reproduced with permission [10]. Copyright 2012, Elsevier.

### 2.2. 2D deformation of kirigami and corresponding mechanisms

Unlike the 3D deformation mechanism, 2D deformations typically occur within the plane of the substrate. Many 2D kirigami structures rely on the rotation of cut units to achieve in-plane stretching [113–120], but the mechanical properties of the material also play an important role. In this section, we introduce representative 2D kirigami patterns and explore how geometric design and material characteristics influence their deformation behavior.

Under the rotation mechanism, 2D deformation is commonly seen in staggered Y-shaped cutting patterns [121–123]. After stretching and rotation, triangular units are formed, where each unit is connected to other units through its respective tips. These units are usually rigid, and the materials connected at the tips become hinges that can rotate freely. For example, in Fig. 4a, a composite material mainly composed of polylactic acid was processed and successfully applied to medical electronic skin sensors. This kirigami structure maintains good compliance and adhesion with 2D planes or even 2D curved surfaces under pressing, stretching, and compression [124]. The deformation of the Y-shaped cutting structure is determined by the kinematic relationship between the units [34] (Fig. 4c), where the strain of the structure can be calculated from the rotation angle θ of the triangular elements. The strains in the x and y directions are expressed by Eqs. (3) and (4), respectively:

$$\varepsilon_x = \begin{cases} \frac{1}{2}\left[\cos\left(\frac{\theta}{2}\right) + 2\cos\left(\frac{\pi}{3} - \frac{\theta}{2}\right)\right] - 1 & \left(0 \le \frac{\theta}{2} < \frac{\pi}{6}\right) \\ \frac{1}{2}\left[\cos\left(\frac{2\pi}{3} - \frac{\theta}{2}\right) + \cos\left(\frac{\theta}{2}\right) + 2\cos\left(\frac{\pi}{3} - \frac{\theta}{2}\right)\right] - 1 & \left(\frac{\pi}{6} \le \frac{\theta}{2} \le \frac{\pi}{3}\right) \end{cases} \tag{3}$$

$$\varepsilon_y = \frac{2}{\sqrt{3}}\left[\sin\left(\frac{\theta}{2}\right) + \sin\left(\frac{\theta}{2} + \frac{\pi}{3}\right)\right] - 1 \tag{4}$$

Except for the staggered Y-shaped cutting pattern, orthogonal staggered linear cutting [125,126] is also commonly found in 2D deformation patterns. After stretching and rotation, this structure can form square units [127], and its deformation mechanism is similar to that of the Y-shaped pattern. For example, in Fig. 4b, a soft battery made from a carbon cloth-based composite material can withstand stretching, bending, twisting, and other deformations, showing excellent stability and biocompatibility [128]. This makes it highly suitable for wearable and implantable bioelectronic products. As shown in Fig. 4d, the strain of the orthogonal cutting structure is expressed by Eq. (5) [34]:

$$\varepsilon_x = \varepsilon_y = \sin\left(\frac{\theta}{2}\right) + \cos\left(\frac{\theta}{2}\right) - 1 \tag{5}$$

where $\theta$ represents the rotation angle of the square element.

Furthermore, numerous studies have demonstrated that patterns such as Y-shaped and orthogonal staggered configurations, when applied in a hierarchical structure (i.e., replicating the same cutting

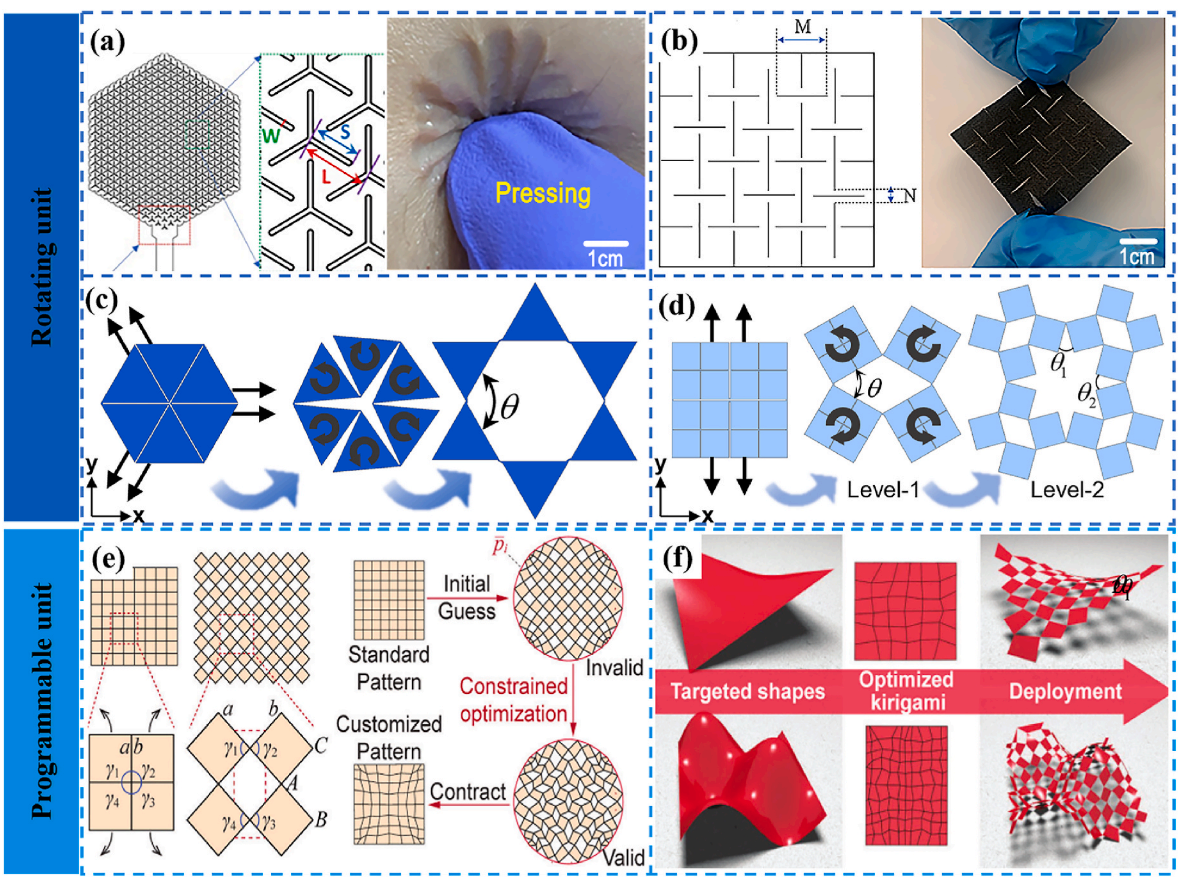


**Fig. 4. Kirigami-based 2D deformation formed by the rotation of common units and programmable units.** (a) The design of the Y-shaped cutting pattern and its reconfigured structure maintaining good compliance and adhesion under pressing. Reproduced with permission [124]. Copyright 2021, American Chemical Society. (b) The design of the orthogonal cutting pattern and experimental photos of reconfigured deformation under negative Poisson's ratio performance. Reproduced with permission [128]. Copyright 2023, Elsevier. (c) Kinematic relationships between triangular cells under Y-shaped cutting. (d) Kinematic relations between square cells under orthogonal cutting. (e) The design of programmable rotating unit based on the orthogonal cutting pattern. (f) 2D surface structure formed by rotating the programmable kirigami pattern. Reproduced with permission [30]. Copyright 2023, Springer Nature.

pattern multiple times on the primary unit) [25,34,129,130], can introduce additional degrees of freedom into the structure. This enables highly complex shape transformations and facilitates the accommodation of larger strains. As illustrated in Fig. 4d, the strain of the level-2 structure with orthogonal cutting patterns can be expressed in terms of the rotation angles $\theta_1$ and $\theta_2$, where the strains in the x and y directions are given by Eqs. (6) and (7), respectively:

$$\varepsilon_x = \cos\left(\frac{\theta_1}{2}\right) + \frac{1}{2}\sin\left(\frac{\theta_1}{2}\right) + \frac{1}{2}\cos\left(\frac{\theta_2}{2}\right) - 1 \quad (6)$$

$$\varepsilon_y = \cos\left(\frac{\theta_2}{2}\right) + \frac{1}{2}\cos\left(\frac{\theta_2}{2}\right) + \frac{1}{2}\cos\left(\frac{\theta_1}{2}\right) - 1 \quad (7)$$

At the same time, for each group of four units in the level-1 structure (Fig. 4e), research has revealed that their four internal angles ($\gamma_i$) and adjacent sides ($a$, $b$) exhibit the following 2D deformation relationship, as expressed by Eqs. (8) and (9) [30]:

$$\gamma_1 + \gamma_2 + \gamma_3 + \gamma_4 = 2\pi \quad (8)$$

$$a^2 - b^2 = 0 \quad (9)$$

Therefore, based on this deformation relationship, a series of optimization and deployments can be employed to design a non-periodic programmable kirigami pattern [131–138], distinct from the simple orthogonal cutting, as illustrated on the right side of Fig. 4e. Owing to the localized buckling generated at the angular connections of each rotating unit during the stretching process, they are indirectly endowed with sufficient degrees of freedom to rotate both in-plane and out-of-plane, but the rotating units themselves deform little in this process. Leveraging this characteristic, kirigami metamaterials, through the rotation of cut units, can approximate the transformation into anticipated complex surfaces with non-zero Gaussian curvature (Fig. 4f). Jiang et al. studied rigid polyimide (PI) sheets integrated with electronic modules, which, after being orthogonally cut to form electronic surface armor, exhibit excellent stretchability, conformability, and protective properties on dynamic 2D curved surfaces, such as adapting well to an expanding balloon, simulating the swallowing of an egg [139]. Silva et al. prepared soft robots by incorporating magnetic particles into elastic rubber and then performing orthogonal cutting, enabling the robots to move on arbitrary 2D curved surfaces [140]. Similarly, for in-plane deformation, current analytical models are primarily based on regular orthogonal or Y-shaped patterns. While these offer simplified geometric representations, theoretical frameworks that incorporate more complex cut geometries or material and structure interactions are still under development.

As seen above, the formation of 2D curved surfaces and the rotation of cutting units do indeed play a key role in many structures. However, the 2D deformation mechanism does not rely entirely on rotational drive; it can also be jointly induced by other geometric arrangements and the mechanical properties of the material itself. As shown in Fig. 5, the 2D tensile deformation exhibited by the simple parallel kirigami structure is not the 3D structure described in Section 2.1, nor does it rely on the rotation of elements, but is achieved through the synergy of the arrangement of notches along the tensile direction and the ductility of the material itself. This type of mechanism usually occurs in highly ductile materials and can generate significant tensile capacity while maintaining the stability of the structure within the plane. According to Hooke's Law $\sigma = E{\cdot}\varepsilon$, it is clear that the lower the Young's modulus, the more easily the material deforms, achieving greater deformation. Due to their relatively high Young's modulus, traditional materials have limited deformation capabilities when subjected to forces. Therefore, as mentioned in the previous section, after reaching a certain amount of in-plane deformation, they will turn into out-of-plane 3D buckling deformation. For many elastic materials, they have relatively large elastic

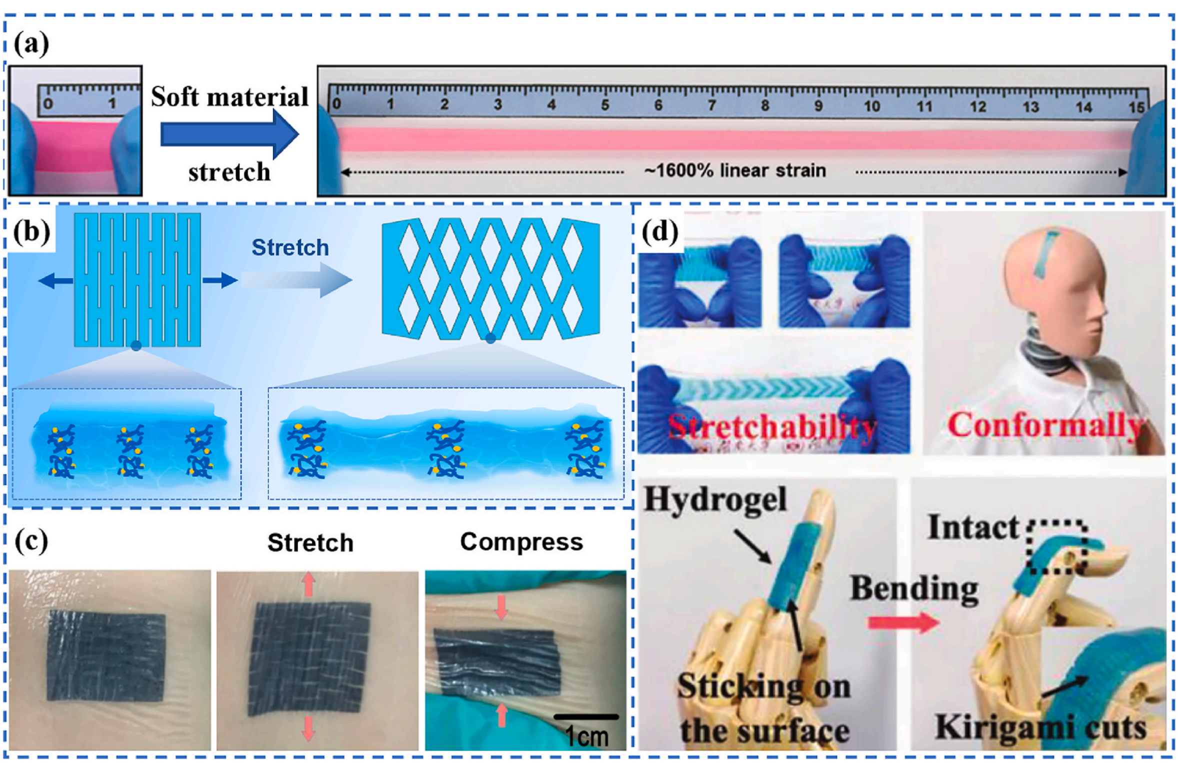


**Fig. 5. The effect of material mechanical properties on 2D deformation.** (a) PLCL polymer material with a self-achievable ultra-high stretch of 1600 %. Reproduced with permission [143]. Copyright 2023, The Authors. (b) Schematic illustration of the tensile deformation of an elastic material with parallel cutting patterns. (c) 2D deformation of parallel-cut PVA composite soft material under stretching and compression on the skin surface. Reproduced with permission [59]. Copyright 2023, The Authors. (d) 2D deformation of parallel-cut hydrogel with good 2D surface performance under skin and joint bending. Reproduced with permission [61]. Copyright 2023, Wiley.

deformation ability and high ductility, and can largely maintain in-plane deformation without turning into buckling after being subjected to forces [141,142]. They usually have a low elastic modulus and can disperse loads through large elastic deformations when subjected to stretching or compression, avoiding buckling instability caused by stress concentration. For example, the poly(l-lactide-co-ε-caprolactone) (PLCL) in Fig. 5a can achieve a 2D linear strain of 1600 % of its own without buckling [143]. Therefore, in a certain sense, 3D deformation patterns achieved through stretching buckling can reduce Young's modulus to enable in-plane 2D deformation (Fig. 5b). Taking the most common parallel cutting pattern for 3D deformation as an example, softer composite materials such as those composed of polyvinyl alcohol (PVA) [59] exhibit excellent skin conformability and stretchability (>100 %) after parallel cutting, suitable for monitoring medical electrical signals (Fig. 5c). Additionally, soft electronic medical devices made from conductive hydrogels [61] show good sensitivity and remarkable stretchability (>5000 %) after being subjected to parallel cutting patterns, maintaining excellent conformability even on the 2D curved surfaces formed by bending finger joints (Fig. 5d). Thus, it can be said that the deformation mechanisms of kirigami result from the combined effects of material properties and pattern design. When engineering applications, the appropriate materials and cutting units should be determined based on functional requirements.

### 2.3. Kirigami cutting shapes and preparation methods

Through the discussion of various deformation forms and mechanisms of kirigami, it is clear that the cutting patterns and the mechanical properties of the substrates play a crucial role in the deformation of kirigami metamaterials. Different patterns and materials require different fabrication techniques, each with its own advantages. By utilizing modern fabrication technologies such as subtractive methods (e.g., tool cutting [1], ultraviolet (UV) laser cutting [144,145], $CO_2$ laser cutting [146], photolithography [62]) and additive methods (e.g., 3D printing [147], deposition [148]), macroscale and microscale kirigami metamaterial structures can be produced. This section will be briefly discussed the fabrication methods of different materials according to the cutting patterns. Table 1 lists some preparation methods, materials, and medical applications by shape category.

Parallel cutting patterns are widely applied to various substrate materials due to their excellent deformability. Using sharp tools for cutting is the simplest and most convenient fabrication method. Composite films primarily made of polymer materials, such as polyvinylidene fluoride (PVDF), are parallel cut with blades. This not only enhances the piezoelectric effect but also significantly increases flexibility and adaptability, making it applicable in energy harvesters [149]. Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) films, due to their mechanical properties and limited stretchability, can be simply cut with a blade and used as epidermal electrodes for monitoring human movement and physiological signals [124]. However, tool cutting is more suitable for harder materials and often results in patterns on the millimeter scale. For high-precision applications, laser cutting is often selected as a fast and low-cost fabrication method, with precision reaching the micrometer level. For light-absorbing materials, such as polyimide (PI) blended with polymer nanoparticles [150], paper coated with graphite [151], and elastomeric rubber coated with eutectic gallium-indium alloy [146], all can be precisely cut by laser and applied in the core components of health monitoring devices [158]. Regarding the photolithography technology for sub-micron patterns, parallel cutting can be formed through photo-mask exposure and cross-linking, generating patterns in silk fibroin [62]. In addition to subtractive preparation methods, based on hydrogels [61], a kind of integrated glove has been developed by using 3D printing technology, which has already achieved underwater human-machine interaction.

The aforementioned preparation methods are equally applicable to orthogonal cutting patterns. By shearing carbon cloth with a tool, a carbon cloth current collector can be obtained [128]. Elastic polymer polydimethylsiloxane (PDMS), after being patterned with femtosecond laser cutting to achieve 1 mm precision, has broad application prospects in flexible, waterproof biological label packaging [152]. Currently, to enhance the control of soft robots, it is common to add magnetic materials to elastomeric silicone rubber and introduce kirigami structures.

**Table 1**
Preparation methods, corresponding materials and medical applications based on kirigami shapes.

| Shapes | Methods | Materials | Applications | Ref. |
|---|---|---|---|---|
| Parallel linear | Knife cutting | PEDOT:PSS/PVA/AgNWs/PU | Health monitoring;<br>Human–machine interactions. | [59] |
| | Blade cutting | P(VDF-TrFE) | Flexible energy harvesters. | [149] |
| | Laser cutting | Modified PI | Multifunctional sensors. | [150] |
| | $CO_2$ laser cutting | Silicone | Health monitoring. | [146] |
| | $CO_2$ laser cutting | Modified paper | Temperature sensor;<br>Inflammation/infection treatment;<br>Health monitoring. | [151] |
| | Photolithographic | Silk protein | Substrates for cell culture. | [62] |
| | 3D printing | Organic hydrogel | Human–machine interactions. | [61] |
| Orthogonal linear | Scissor cutting | Carbon cloth | Lithiumion soft battery. | [128] |
| | Laser cutting | AgNWs-PDMS | Health monitoring. | [29] |
| | Laser cutting | PDMS | Bioelectronic tag. | [152] |
| | $CO_2$ laser cutting | Magnetized rubber | A smart soft robot. | [140] |
| | Casting with 3D printed mold | Magnetized rubber | A smart soft robot. | [60] |
| Cross/Lotus-shaped | Scissor cutting | Pre-stretched flexible composites | Fast grasping and stable manipulation for objects. | [22] |
| Combination of triangles and stars | Laser cutting | Rubber sheet coated by conductive material | Reconfigurable electromagnetic systems. | [153] |
| Rectangular/rhombic/elliptical | Laser cutting | Superhydrophobic shape memory complexes | Smart morphing materials with anti-wetting performance. | [154] |
| Y-shaped | Laser cutting | PEDOT:PSS coated by PLA | Physiological signal monitoring;<br>Electrical equipment controlling. | [124] |
| Serpentine | Laser cutting | PET-PI-Ti/Pt-PI multilayer film | Temperature, humidity and movement monitoring. | [155] |
| | $CO_2$ laser cutting | Modified rubber | Rubber-based supercapacitor. | [156] |
| Pinwheel-shaped | Plasma chemical vapor deposition | Functional film of Cr/Au | A tunable 3D architecture;<br>3D THz Biosensor. | [148] |
| Snake-Skin-Like | Magnetron sputtering | AgPdCu alloy | Stretchable electrodes;<br>Wearable temperature sensor. | [157] |
| Cross/I-beam/Rice-shaped | Photolithographic polymerization | Composite hydrogel sheets | Multi-contact switches. | [102] |

At this stage, there are two common preparation methods: one involves mixing magnetic nanoparticles with part A of the silicone rubber, followed by adding part B and crosslinking the mixture in a mold to form a film, which is then laser-cut into a kirigami structure [140]. The other method involves directly casting the silicone rubber through a 3D-printed mold to form the kirigami structure, which is then assembled with pre-prepared magnetic disks [60]. Apart from the commonly used parallel and orthogonal cutting patterns, other structures can be fabricated using the aforementioned methods. For instance, pre-stretched flexible composites can be cut into cross and lotus patterns [22] using a blade. Rubber coated with a conductive layer [153] and multilayer composite films consisting of metal and polymer [124] can be laser-processed into Y-shaped and other patterns. Furthermore, for certain materials, physical/chemical vapor deposition methods [148] may be chosen. For example, an AgPdCu target can be sputtered onto a PU substrate via magnetron sputtering technology to form snake-skin patterns [157]. Such preparation methods are often combined with photolithography techniques [102].

In summary, based on advanced modern subtractive and additive manufacturing techniques, various kirigami micro/nano unit structures for different materials are not constrained. It is only necessary to choose appropriate processing methods for the selected materials to achieve the purpose of saving time and manufacturing costs.

## 3. *In vitro* medical device applications based on kirigami designs

The diverse cutting patterns have engendered rich functionalities in kirigami metamaterials. Owing to their unique properties such as super stretchability, tunable surface morphology, and two-to-three-dimensional reconfigurability, an increasing number of kirigami metamaterials are being applied in the healthcare sector. This provides new solutions to the limitations of traditional medical devices in terms of flexibility, extensibility, and compliance, significantly promoting the innovative development of medical equipment. It is worth emphasizing that in most *in vitro* applications, kirigami not only serves as a structural aid, but is also a key factor in achieving a leap in the functional performance of devices, such as enhancing skin fit in wearable sensors and deformation adaptation in therapeutic patches. In this section, we will focus on discussing the applications of kirigami technology involved in *in vitro* medical devices, such as wearable health monitoring, power supply and treatment devices. These applications are of great significance for improving healthcare standards and enhancing patient experience.

### 3.1. Wearable health monitoring devices

The function of wearable monitoring devices mainly relies on the core component, the sensor, whose performance directly affects the accuracy of the health diagnostic monitoring system [159–162]. Sensors designed based on kirigami [163–167] achieve their specific shapes and functionalities through precise cutting and folding of materials. This kirigami-based design can effectively enhance the sensitivity, stability, and adaptability of sensors, providing more accurate and reliable data support for health diagnostic monitoring systems.

Wearable health monitoring devices mainly involve the monitoring of physiological signals to complete assessment, feedback, and diagnosis. Fig. 6 shows some representative applications of wearable monitoring devices, in which the substrates are primarily selected from

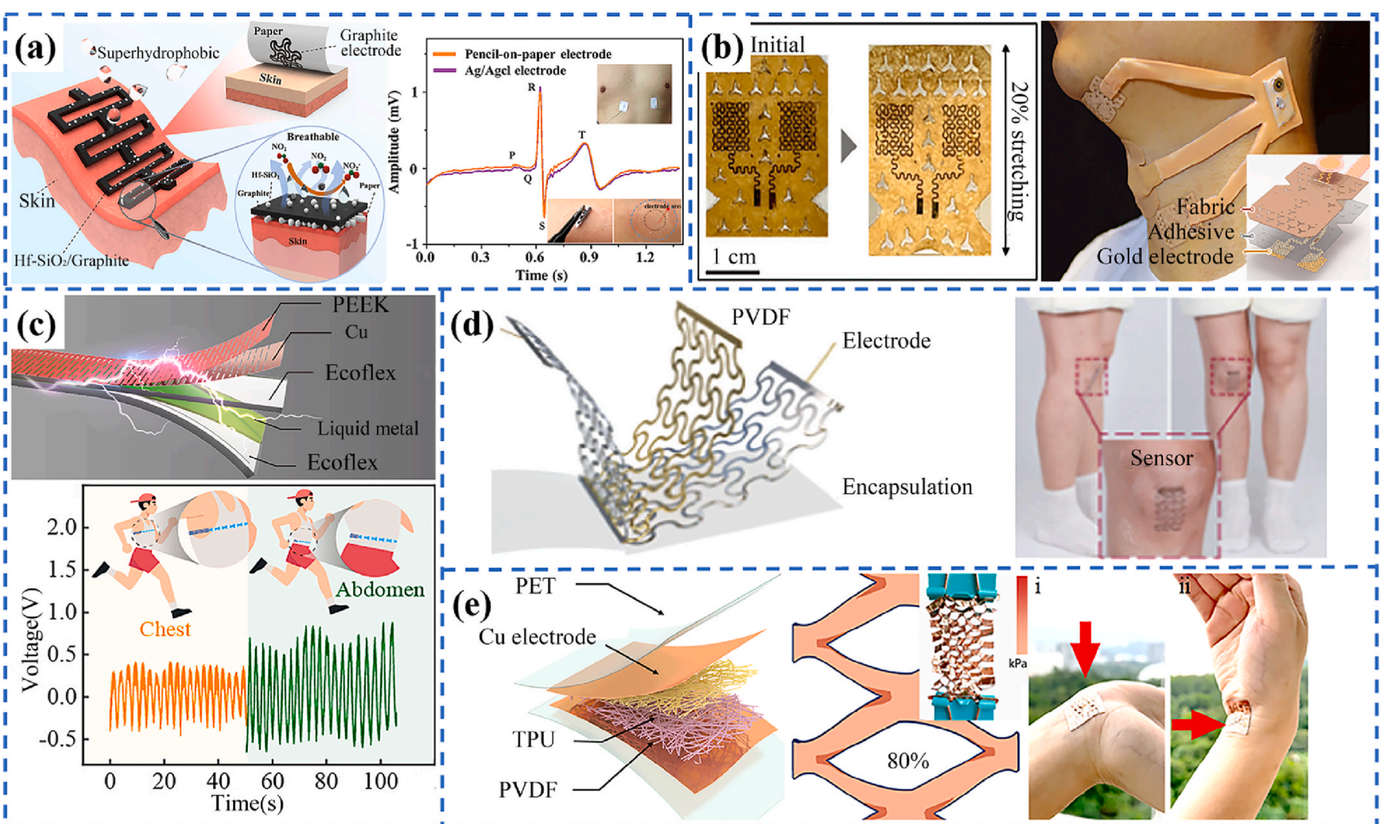


**Fig. 6. Kirigami-based wearable health monitoring devices.** (a) Modified paper-based sensor with parallel linear cutting patterns for real-time, continuous monitoring of physiological signals. Reproduced with permission [151]. Copyright 2023, Elsevier. (b) Fabric patch with Y-shaped cutting patterns to maintain conformal contact between the electrodes and skin for monitoring EMG signals. Reproduced with permission [168]. Copyright 2024, The Authors. (c) Stretchable BS made from Cu foil and PEEK film, along with a high-sensitivity compression BS for monitoring respiratory depth. Reproduced with permission [169]. Copyright 2024, Elsevier. (d, e) PVDF composites with different kirigami patterns for monitoring repetitive joint motion, effectively addressing the bending issues of joints. Reproduced with permission [170,171]. Copyright 2024, The Authors.

modified paper-based materials, composite polymer-based materials, highly elastic body-based materials and so on [29]. In a study, an 8B pencil was used to uniformly coat graphite on cellulose paper, which was then cut into kirigami parallel patterns using $CO_2$ laser and prepared a superhydrophobic coating [151]. The modified paper-based sensor exhibits high sensitivity, low detection limits, and rapid response/recovery times for $NO_2$ gas and temperature, with strong resistance to environmental temperature and relative humidity interference. Additionally, by connecting the sensor to a data acquisition system with copper wires coated in silver paste, it enables real-time, continuous, and high-fidelity monitoring of electrophysiological signals (Fig. 6a), such as electrocardiograms (ECG), electromyograms (EMG), and electroencephalograms (EEG). The kirigami structure minimized the impact of mechanical deformations, such as bending and stretching, on signal monitoring. By adjusting the applied voltage, it was possible to effectively increase the skin surface temperature, which can be used for thermotherapy to treat joint injuries, improve blood circulation, disinfect medical dressings, and promote wound healing. In the monitoring of muscle signals, Shin et al. fabricated serpentine electrodes by laser processing a PI film coated with an Au layer, which was then embedded into a fabric patch with a kirigami Y-shaped pattern [168]. When the kirigami patch is stretched, the edges of the Y-shaped pattern deform first, preventing strain from propagating to the electrode region. Compared to the 0.1 % strain applied to electrodes by non-patterned patches, the Y-shaped pattern exhibited only 0.05 % strain. Furthermore, when subjected to repeated 25 % tensile strain, the Y-shaped pattern demonstrated 0.1 % less resistance variation than non-patterned ones. And the kirigami patch demonstrated significantly better adhesion performance, rarely exhibiting the peeling phenomenon observed in non-patterned patches even with increasing curvature. This allows the patch to maintain conformal contact with the skin under various complex curvatures, enabling stable EMG signal measurement during movements such as swallowing. By measuring the EMG signals and sound signals of related muscles (Fig. 6b), it can determine whether swallowing is normal, with an overall accuracy rate of 89.47 %. In another study, by combining kirigami structures with the principle of triboelectric nanogenerators (TENG), the highly effective, accurate, and high-resolution stretching/compressive buckling sensor (BS) was designed by bonding a stretchable substrate with kirigami electrodes [169]. The kirigami electrodes were formed by bonding Cu foil and PEEK film, and the stretch/compression kirigami pattern was cut out using a laser. The potential difference between electrodes changes with the bending angle of the kirigami electrodes, thereby generating a current in the external circuit. The stretch BS can perceive the size of an object being grasped during the soft gripper's grab-and-release process, with an identification accuracy of 93.75 %. And the compression BS demonstrated a sensitivity of 1.3307 V/mm when monitoring the deformation of a 2D surface, which can be used to monitor the deformation amplitude of the chest and abdomen during breathing to assess respiratory depth (Fig. 6c), as well as changes in the limbs during movement.

Wearable stretchable sensors can conform to the human skin, providing various comfortable, accurate, and continuous health monitoring and diagnostics. However, in applications involving large strains, such as joint motion monitoring, they face issues with bending. Rigid materials can lead to a decrease in the reliability and repeatability of the sensor after repeated bending [172,173]. Therefore, selecting the appropriate material is crucial. PVDF, which is often used as a triboelectric functional layer, can take advantage of its piezoelectric effect and low modulus properties. Combined with the kirigami design, its adhesion and comfort can be greatly increased, and it can be applied in the qualitative assessment and monitoring devices for knee joints. PVDF was endowed with an irregular serpentine mesh kirigami pattern, and copper layers were deposited on both sides to serve as electrodes, forming an anti-buckling, stretchable, and wearable sensor for capturing knee joint motion [170] (Fig. 6d). Finally, by encapsulating PDMS, the sensor obtained a higher critical strain and meanwhile the influence of humidity changes caused by sweat was reduced, making the monitoring portable, continuous and accurate. The sensor with low area ratio patterns can withstand approximately 21 times the strain of non-patterned sensors, and its effective modulus is only 11.8 % that of sensors with high area ratio patterns. In addition to the aforementioned design, PVDF and thermoplastic polyurethane (TPU) can be electro spun into mesh-like fibrous functional films that provide enhanced triboelectric charging. By encapsulating the electrodes with an ultrathin PET layer, a new type of pressure sensor is formed [171]. The introduction of kirigami parallel patterns confers stretchable and conformal properties to the sensor, meeting the demands of uneven surfaces such as human joints (Fig. 6e). Through the piezoelectric signal feedback, this sensor enables monitor of minute joint movements with an accuracy sufficient to detect the slight motion of a finger tapping a balloon.

In the development of soft, deformable biosensors, some highly elastic materials, such as PDMS blended with metal ions, have been chosen as kirigami substrates to achieve multi-signal sensing, and Fig. 7 lists several applications of kirigami-based elastomers in health monitoring. By spraying the multiwalled-carbon-nanotube (MWCNT) solution on a PDMS thin film using a shadow mask, and using mechanical cutting to form kirigami rectangular patterns followed by the deposition of silver nanowire (AgNW) conductive layers, a stretchable bionic multimodal receptor (SBMR) was designed [174]. Through stretching and recovery of the receptor, the kirigami structure enables the sensor to switch between 2D and 3D modes. In the 2D mode, the SBMR can perceive in-plane signals as an electronic skin, including pressure and bending; in the 3D mode, the SBMR can perceive out-of-plane signals (Fig. 7a), such as force, airflow, temperature, and humidity. Furthermore, it exhibits high stability and durability in cyclic reliability tests. The repeated mechanical cycling of kirigami sensors could lead to local strain accumulation or fatigue-induced microcracks at stress concentration sites, especially around sharp cut tips. However, the design employed here effectively distributes strain across the patterned structure, which helps to mitigate crack initiation and extend operational life. In another study, $CO_2$ laser direct writing and transfer processes were utilized to integrate LIG (laser-induced graphene) electrodes on PDMS, followed by UV laser cutting to create parallel linear kirigami patterns, resulting in the design of a tunable and ultra-sensitive piezoresistive strain sensor [175]. The sensor is highly sensitive to small skin deformations caused by tendon movements. By employing a pre-tensioning strategy, the strain sensor can obtain high-amplitude and distinguishable signals generated by different gestures, jumping methods, and loads (Fig. 7b). In addition, a rubber composite film blended with lead zirconate titanate and barium titanate was processed with a cutting machine to create a centrosymmetric L-shaped kirigami structure [91], resulting in an ultra-stretchable piezoelectric sensor. This sensor can achieve coupled large deformations with strains up to 200 % and demonstrates strong temperature stability and durability, maintaining piezoelectric performance over a wide temperature range. As deformation increases, the maximum electrical response reaches 24.6 V, enabling precise human posture monitoring (Fig. 7c).

### 3.2. Wearable power supply devices

In recent years, flexible electronics incorporating kirigami technology have made significant advancements in wearable applications, achieving a series of functions such as health monitoring. And power supply and energy storage devices, as the guarantee for the normal operation of these devices, their stability and high efficiency are crucial for application performance. Traditional power sources, due to their large size and high rigidity, are limited in their use for wearable devices. Therefore, miniaturized, flexible, and highly deformable power supply and energy storage devices have been rapidly developed [176]. By integrating kirigami technology through ingenious cutting and layout, the mechanical and electrical properties of materials can be precisely

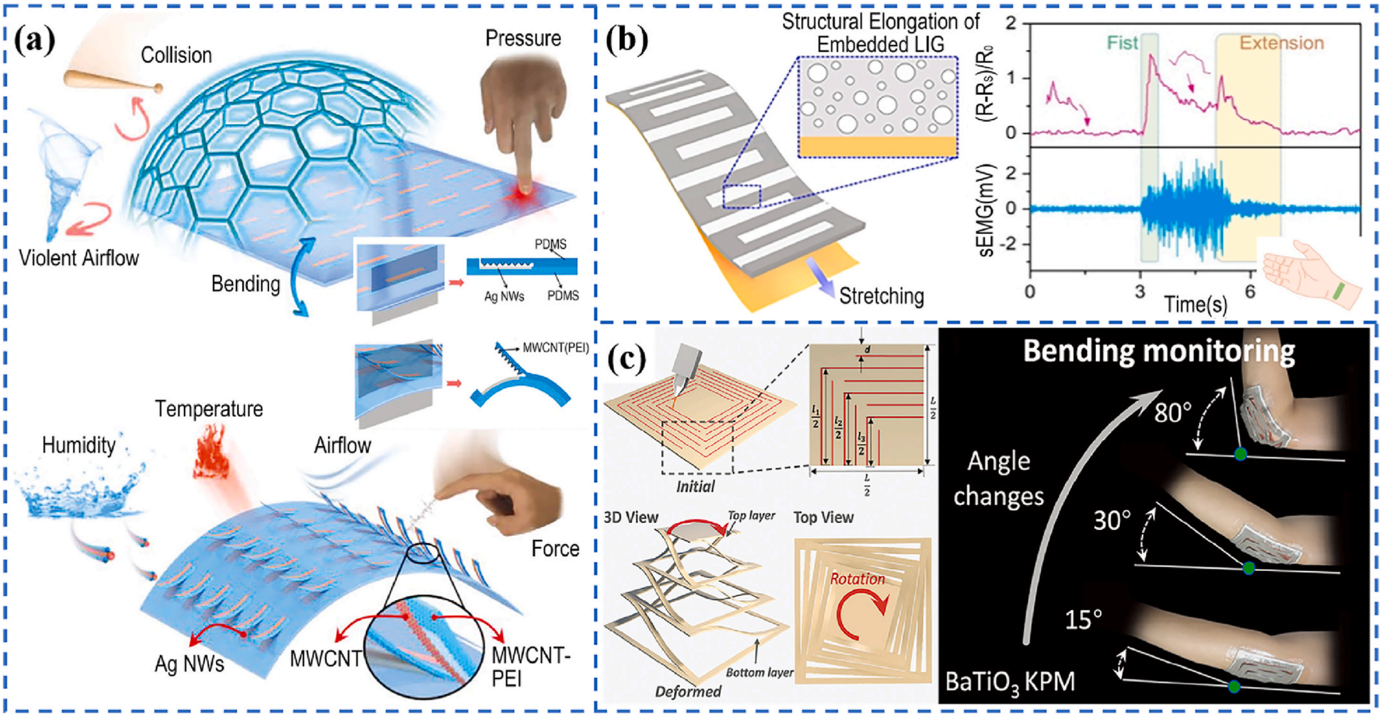


**Fig. 7. Kirigami-based monitoring devices with highly elastic materials.** (a) SBMR on a PDMS substrate sensing different signals in 2D and 3D modes, demonstrating high stability and durability. Reproduced with permission [174]. Copyright 2024, Wiley. (b) PDMS integrated with LIG electrodes is highly sensitive to small skin deformations, capable of monitoring signals during various movements. Reproduced with permission [175]. Copyright 2024, American Chemical Society. (c) Rubber composite film with a centrosymmetric L-shaped pattern, exhibiting a maximum electrical response of 24.6V and enabling precise human posture monitoring. Reproduced with permission [91]. Copyright 2023, The Authors.

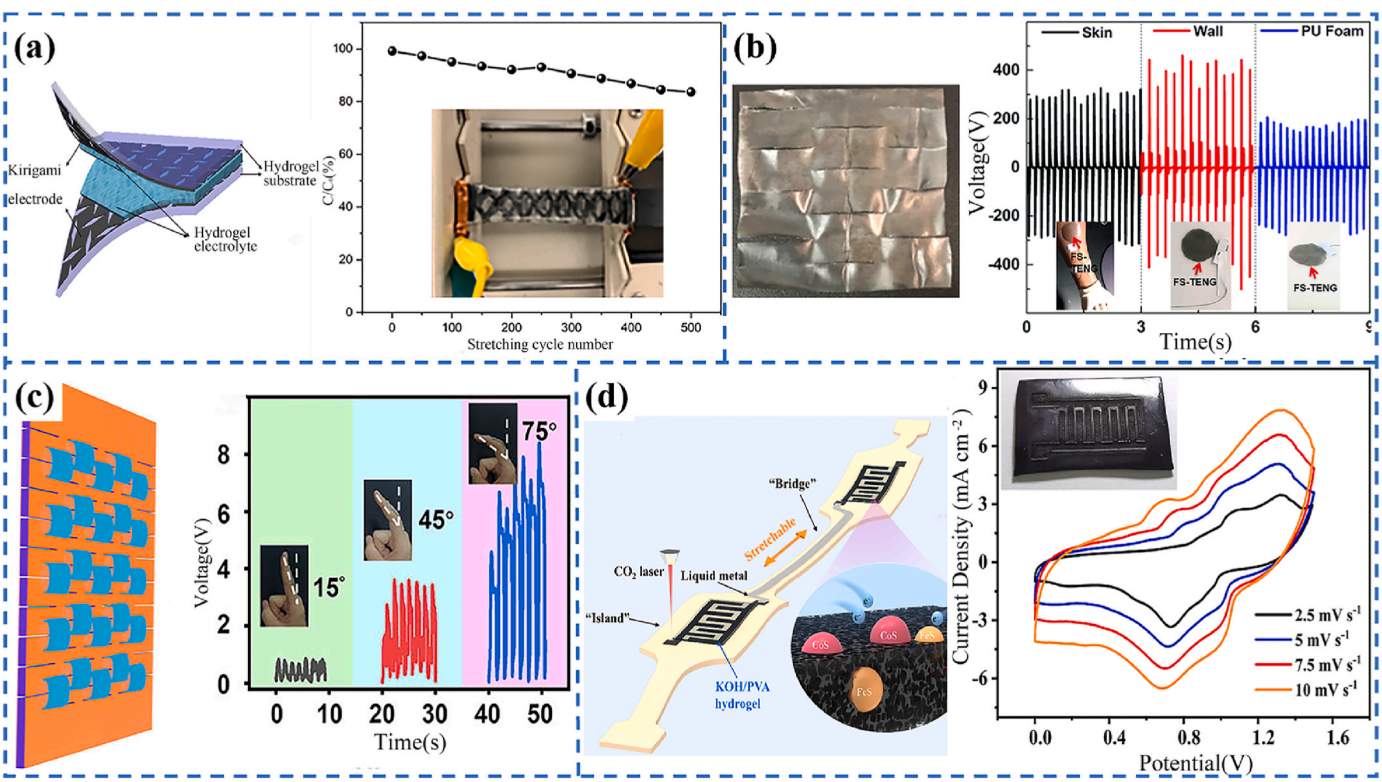


**Fig. 8. Kirigami-based wearable power supply devices.** (a) The design of the battery with the orthogonal cutting pattern, and capacitance retention after cyclic stretching of the battery with the parallel cutting pattern. Reproduced with permission [128]. Copyright 2023, Elsevier. (b) FS-TENG design with parallel cutting pattern and its energy output. Reproduced with permission [184]. Copyright 2021, American Chemical Society. (c) K-HENG design with parallel cutting pattern and its power transmission performance. Reproduced with permission [185]. Copyright 2022, Wiley. (d) Kirigami capacitor design with serpentine pattern and its excellent electromechanical stability. Reproduced with permission [156]. Copyright 2024, Elsevier.

controlled, thereby enhancing the functionality and adaptability of wearable electronics [177–183]. Fig. 8 showcases several different wearable power supply devices developed in recent years.

Chemical batteries, as devices that convert chemical energy into electrical energy, generate current through chemical reactions. And the application scenarios for wearable devices require the batteries to be stretchable and even reconfigurable. Gao et al. used a cutting tool to perform parallel/orthogonal cutting on carbon cloth to obtain the Kirigami patterned carbon cloth current collector. Then, chemical slurry and lithium manganese oxide were respectively coated on the kirigami current collector to prepare the anode and cathode, ultimately fusing the two electrodes to form a fully reconfigurable film-like soft battery [128]. In this study, the parallel cutting significantly enhanced the soft battery's compliance, and kirigami electrodes exhibited minimal resistance change during uniaxial stretching and small out-of-plane deformation. The soft battery exhibited a Young's modulus of 64.1 kPa. Meanwhile, when stretched by 100 %, the soft battery demonstrated a high specific capacity of 83.5 mAh/g at a current density of 0.5 A/g. And the orthogonal cutting kirigami electrodes were used for the first time to provide multi-dimensional stretchability for the reconfigurable soft battery. This soft battery can be bent up to 180° and twisted up to 90° without significant capacity attenuation, demonstrating multi-dimensional stretchability, long-term stability, and biocompatibility (Fig. 8a).

TENG is a device that harvests mechanical energy and converts it into electrical energy based on the principles of triboelectrification and electrostatic induction, which can provide power for the aforementioned wearable devices [186]. Through kirigami cutting, many power generation materials with insufficient elasticity can be endowed with a certain degree of flexibility and deformability. For instance, by depositing graphene electrodes on $[PEO/PAA]_{100}$ films and cutting into various kirigami patterns according to deformation requirements, a free-standing skin-like TENG (FS-TENG) is created [184]. Compared to traditional generators, this device exhibits approximately 100 % ultra-transparency, around 900 % super stretchability, and high foldability, with a folding contraction rate of up to 1/32 of its original size. This enables it to shape-adaptively adhere to complex surfaces and harvest energy from mechanical movements such as those found in skin, jackets, and shoe insoles, where FS-TENG demonstrates significant output performance (Fig. 8b).

The piezoelectric nanogenerator (PENG) can utilize the piezoelectric effect of some materials to generate electric energy. Flexible PDMS blended barium titanate composite film is laser-cut into linear patterns, obtaining a PENG based on kirigami. And flexible PTFE composite film is cut into equally wide strips as triboelectric layers, alternately inserted into the PENG to form a K-HENG (Kirigami-Based Flexible, High-Performance Piezoelectric/Triboelectric Hybrid Nanogenerator) with an interlocking structure [185]. It can be stretched up to 100 %, and harvests energy under compression, stretching, and twisting conditions. Compared with individual PENG and TENG, K-HENG can capture kinetic energy from different directions and forms, and has higher energy density, so significantly improving the power transmission performance (Fig. 8c). In addition, its piezoelectric properties can also be used as a sensor to monitor human motion. For example, when placed near the throat, it can monitor the loudness and frequency of human voice based on the voltage signal generated by vocal cord vibration. When connected to fingers, it can recognize gestures based on the voltage signal produced by changes in bending angles. And when placed at the bottom of shoes, it can monitor human motion according to the voltage signal generated by changes in pressure and frequency during walking or running.

Flexible supercapacitors (F-SCs) [187] are considered one of the most promising power supply devices for wearable applications. They offer advantages such as high energy and power density, fast charging and discharging rates, high cyclic life, and stability. More importantly, their flexible structural design allows them to function properly under bending and stretching conditions while maintaining wearer comfort. Currently, wearable devices are gradually developing towards integrated functionality and platformization, and the design of F-SCs facilitates their integration with other microelectronic wearable modules. Combining laser cutting technology, Wang et al. processed a kirigami island-bridge structure on a flexible rubber-reinforced substrate, and then coated it with an electrolyte PVA/KOH gel to form a supercapacitor [156]. This capacitor exhibits high areal capacitance and excellent energy density, and it can operate under stretched conditions. Furthermore, it maintains up to 90.85 % capacitance retention after 1000 bending cycles, demonstrating outstanding electromechanical stability (Fig. 8d). This enhanced stability can be attributed to the kirigami island bridge mode, which minimizes stress concentration at electrode connections, thereby reducing the occurrence of failure modes such as mechanical fracture or electrode delamination during long-term operation. Additionally, it retains recoverable elastic deformation at 60 % strain, meeting the requirements for wearability in daily life.

### 3.3. Wearable therapeutic devices

*In vitro* therapeutic devices play a crucial role in the treatment and rehabilitation of diseases. Therapeutic devices based on kirigami technology, with their unique structure, offer advantages in terms of compliance, adhesiveness, compatibility, and other performance aspects. These devices provide patients with a more comfortable and efficient treatment experience, offering innovative solutions for medical devices.

As shown in Fig. 9 for heaters and cold therapy devices, different types of temperature-controlled therapeutic devices [188] have varying treatment effects on diseases. Among these, wearable heaters [189–193] promote blood circulation and alleviate muscle pain through localized heating, enhancing wearer comfort and warmth [194]. They are used for treating joint injuries, sterilizing medical dressings, and promoting wound healing. Nanofiber composite materials, through simple kirigami parallel cutting, were fabricated into stretchable heaters that exhibit almost no change in resistance when stretched up to 250 %, with an electrothermal conversion efficiency of 90 % [195]. When a voltage of 1–4 V is applied, the temperature can rapidly increase, achieving a maximum heating rate of 87 °C/s. The entire heating area shows stable and uniform temperature distribution, maintaining performance stability even under bending and twisting conditions. This makes it suitable for temperature regulation applications involving heating and insulation on 2D curved surfaces such as wrists (Fig. 9a). In another study on temperature control devices, PI film substrates were subjected to laser scanning to generate LIG on their surface and were laser-cut into linear/Y-shaped kirigami patterns, designing both unidirectional and multidirectional heaters [196]. These heaters can maintain electrical conductivity within the range of skin deformation and are capable of rapid temperature increase along with uniform temperature distribution under large strains. When tested on various body parts, the heaters conform to the skin to deliver thermal therapy (Fig. 9b). Moreover, during 1000 stretch-unload cycles, these heaters demonstrated excellent durability.

Relative to heating devices, temperature-controlled cryotherapy devices are equipments that utilize low temperatures to treat medical conditions. By cooling, they can make blood vessels in body parts contract to relieve pain, reduce inflammation and promote tissue recovery. Generally, hydrogel blended with high thermal conductive fillers, such as aluminum nitride (AlN) and graphite, is chosen as the substrate for such flexible electronics. Chow et al. attached laser-cut serpentine kirigami-patterned PI/Cu circuits onto uncured AlN/silicone composite gel. After the AlN/silicone gel was fully cured, laser cutting was employed to create a kirigami orthogonal pattern, resulting in a kirigami-based wearable electrothermal device [197]. The openings created by this kirigami pattern endow the device with good water vapor permeability, which increases the comfort of the skin. Meanwhile, the flexibility and conformability are enhanced, enabling the device to

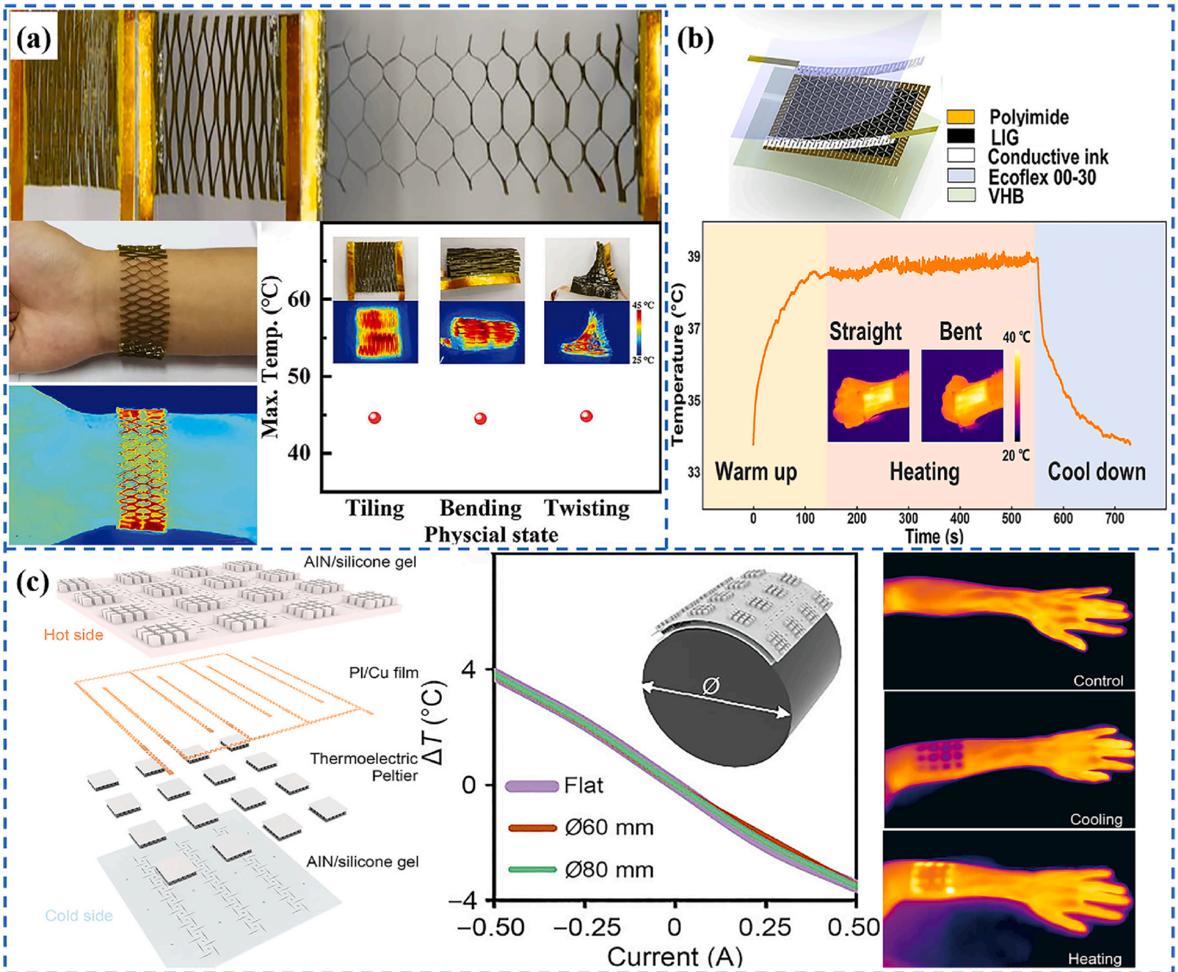


**Fig. 9. Kirigami-based temperature-controlled therapeutic devices.** (a) Infrared thermal images of a heater with parallel cutting patterns under various strains and worn on the wrist, along with the maximum temperatures achievable in different configurations. Reproduced with permission [195]. Copyright 2024, The Authors. (b) Design of a heater with Y-shaped cutting patterns and its conformal attachment to the wrist for temperature control adjustments. Reproduced with permission [196]. Copyright 2025, Royal Society of Chemistry. (c) Design of a multilayer kirigami material composite electrothermal device and its electrothermal effects at different bending degrees, along with infrared thermal images of it conformally attached to the arm. Reproduced with permission [197]. Copyright 2024, Zhejiang University Press.

withstand a 20 % tensile strain, a 60° torsion and a 30-mm bending. By applying a current of 0.5 A, a cooling effect of about 3.5 °C on human skin can be achieved (Fig. 9c). In the early stage of wound healing, this patch can reduce inflammation and pain by providing cryotherapy, while in the later stage or the case of chronic wounds, it can slightly increase the local temperature to accelerate the healing process.

In addition to temperature-controlled medical devices, devices with therapeutic functions such as rigid scaffolds and drug delivery patches in Fig. 10 can be prepared in combination with the kirigami technique. Lei et al. used carbon fiber-reinforced nylon materials to 3D print a spring structure with a kirigami parallel pattern [198], and connected it to the back of the hinge of the artificial vertebra for the treatment of adolescent idiopathic scoliosis braces (Fig. 10a).When the patient's spine bends, the kirigami spring transforms from 2D to 3D, providing supporting torque for the spine to reduce the stress concentration on the intervertebral discs, improving comfort, encouraging the patient to maintain a good upright posture, and improving the patient's spinal curvature to a certain extent. In the study, for spines with different cross-sections, the Cobb angle was improved by 4.6 %–50.5 %.

Unlike regular patches [201], kirigami-based drug-loaded patches enhance the compliance with the skin through their unique structural design. Even when dealing with joints that are bent in cases like arthritis, they can still maintain good adhesion, greatly improving the efficiency and accuracy of drug delivery, while reducing side effects and improving the treatment experience of patients. Li et al. investigated a flexible microneedle patch composed of spider silk protein/polyurethane composites [7]. This patch generates charges when it comes into frictional contact with negatively triboelectric materials, enabling drug release under electrostatic repulsion stimulation. However, although this drug-loaded microneedle patch has remarkable mechanical strength and shows puncture ability, its low flexibility makes it difficult to adapt to long-term dynamic movements. Therefore, a kirigami parallel pattern was cut on it by laser. The kirigami structure significantly enhances its strain-bearing capacity and also strengthens the mechanical behavior of friction, allowing it to adhere to different body positions for multi-functional applications. Not only can it monitor physiological signals through the electric energy generated by motion-induced friction, but the periodic electrical stimulation also accelerates drug release, which can be used for treating diseases in areas such as the knee and elbow joints (Fig. 10b). In another study, KPMDs (inspired by the field of Kirigami, smart patterned high-stretch microneedle dressings) was developed by integrating photonic crystal structures onto the film [199]. This patch improves the detection accuracy of biomarker concentrations, enabling it to measure the concentration of interleukins and reactive proteins in wound exudates. Additionally, epidermal growth factor can be encapsulated within the KPMDs film to promote the

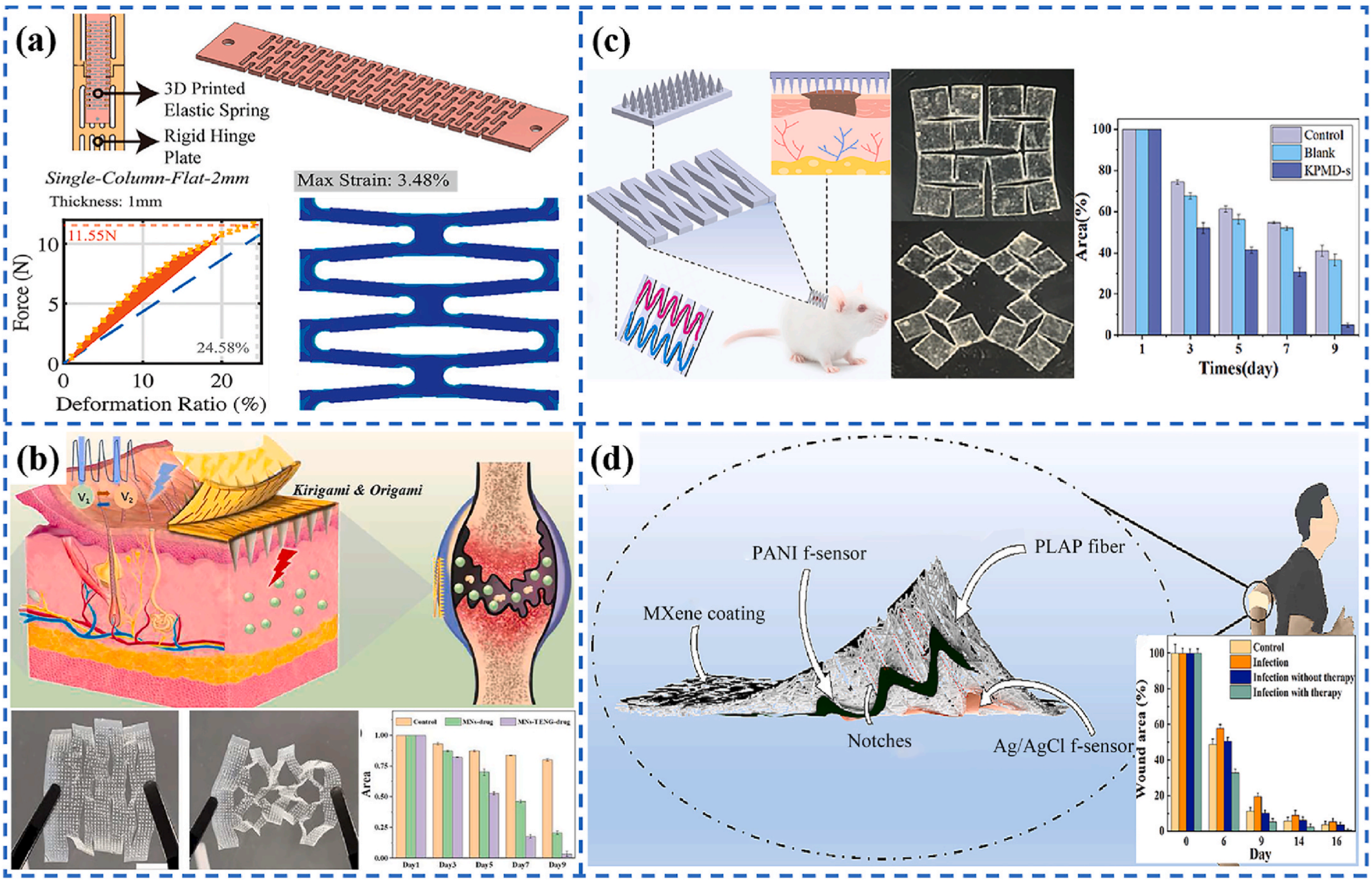


**Fig. 10. Other kirigami-based *in vitro* therapeutic devices.** (a) Design of a rigid brace with parallel patterns and the stretching experiment and FEA (Finite Element Analysis) diagram of kirigami spring components. Reproduced with permission [198]. Copyright 2023, The Authors. (b, c) Design of drug-loaded microneedle patches with parallel patterns and their therapeutic effects. Reproduced with permission [7]. Copyright 2024, The Authors. Reproduced with permission [199]. Copyright 2024, Elsevier. (d) Design of smart dressing with parallel patterns and its therapeutic effects. Reproduced with permission [200]. Copyright 2023, Elsevier.

healing of chronic wounds in diabetic mice. Observations of stained wound tissues revealed that the patch promotes granulation tissue growth and epithelial regeneration, increasing collagen fiber deposition (Fig. 10c). In addition, due to the excellent tensile strength, ductility, toughness and biocompatibility brought by the kirigami structure, the KPMDs patches can be attached to joint parts such as fingers, wrists and knees, and are endowed to obtain a highly sensitive motion sensing ability. They can monitor the resistance signals in real-time when the joints are in motion. Xu et al. studied a kirigami-based smart dressing that can achieve both monitoring and therapeutic functions [200]. Unlike dressing patches without kirigami structure that have only 13 % strain, the parallel linear kirigami structure increases the tensile properties of the PLAP fiber membrane to 831 %, which greatly improves the comfort of the dressing and gives it better permeability to ensure wound breathing. The integrated sensor can monitor wound conditions by responding to the pH levels of the wound environment. And the drug coating achieves a photothermal effect under near-infrared laser irradiation, effectively killing bacteria and inhibiting infection, thereby promoting faster wound healing (Fig. 10d). The closed-loop operation mode of monitoring and treatment effectively prevents dressing removal and tissue tearing, demonstrating superior performance in wound management.

## 4. *In vivo* medical device applications based on kirigami designs

Unique cut kirigami metamaterials have demonstrated significant potential for applications in the medical and healthcare fields. Following our overview of its wide range of applications in *in vitro* medical devices in Chapter 3, this chapter focuses on scenarios in *in vivo* environments where compatibility, safety, and stability are more demanding, and focuses on research advances on kirigami technology for implantable health monitoring, power supply, and therapeutics. Since implantable devices need to be in contact with human tissues for long periods of time, higher demands are placed on the biocompatibility of materials. The kirigami medical devices covered in this chapter are mostly made of flexible materials that have been widely used in biomedicine, such as Poly-p-xylene, PDMS, PVDF, etc., which have excellent biocompatibility and at the same time provide the mechanical basis for kirigami structures to realize deformation and response. And the introduction of the kirigami structure does not change the original biological properties of the material. Instead, it enhances the mechanical adaptability and functional controllability of the device in the complex *in vivo* environment through structural design.

### 4.1. *Implantable health monitoring devices*

Unlike the previously discussed *in vitro* wearable health monitoring devices, implantable devices directly contact the internal tissues of the human body and can obtain physiological signals more accurately and in real-time [202,203]. Moreover, the excellent reconfigurable characteristics of kirigami technology can better adapt to complex implant environments, Fig. 11 illustrates several *in vivo* health monitoring devices that have been applied. The earlier kirigami-based implantable monitoring device was studied by Morikawa et al., in 2018, a highly

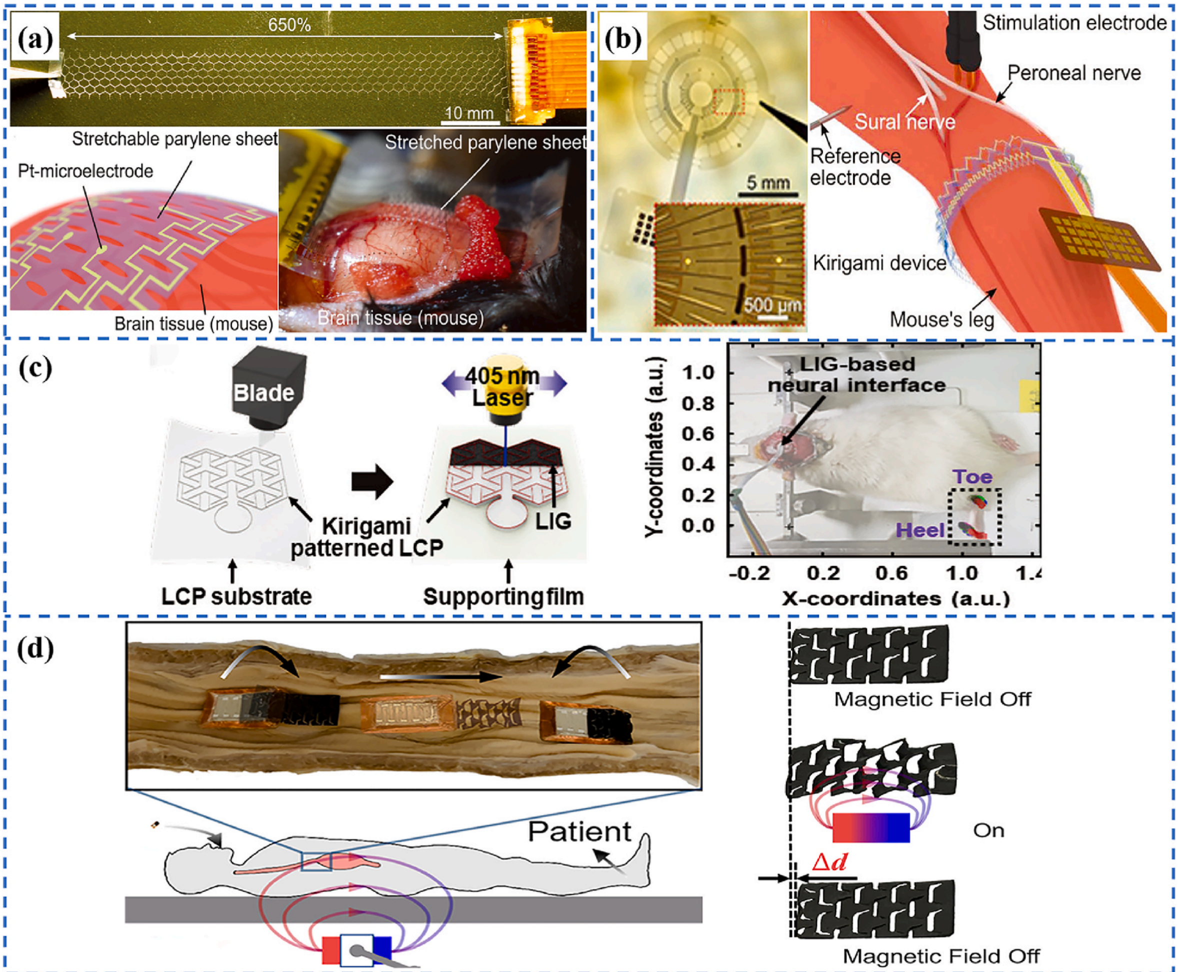


**Fig. 11. Kirigami-based implantable health monitoring devices.** (a) The design of the bio-probe with parallel linear cutting pattern and its monitoring ECoG signals from the mouse. Reproduced with permission [204]. Copyright 2017, Wiley. (b) The design of the doughnut-shaped kirigami probe and its monitoring of EMG signals from the mouse hindlimb. Reproduced with permission [205]. Copyright 2019, Wiley. (c) The design of the electrode patch with the Y-shaped cutting pattern and its monitoring of sensory signals from mouse tactile stimulation. Reproduced with permission [206]. Copyright 2023, The Authors. (d) The intervention device integrating a kirigami soft robot and sensor for wireless monitoring of GERD, and the movement form of the soft robot. Reproduced with permission [85]. Copyright 2023, American Chemical Society.

stretchable kirigami bio-probe device [204], which can be used for detecting and recording electroencephalography (ECoG) signals from the cortical surface and ECG signals from the heart surface. The device consists of upper and lower layers of Poly-p-xylene thin films and a middle layer of platinum-titanium electrodes, with parallel linear kirigami structures designed using techniques such as mask etching. To avoid stress concentration at the cut edges, circular edge designs were adopted, which reduces the stress by half compared to angular edges, making the film less prone to fracture when stretched. Compared to structureless, the kirigami thin-film probe exhibited ~250 % film strain at 0.08 MPa stress with a Young's modulus of 23 kPa, which is ~32 times lower even compared to conventional elastomeric PDMS, and by adjusting the electrode gap through film stretching, ECoG signals could be simultaneously recorded from the visual cortex (V1) and the somatosensory cortex (S1B) of the mouse brain (Fig. 11a). Under physical tactile and visual stimulation, neuronal activity signals from V1 and S1B were detected, with ECoG signals showing reasonable stimulus selectivity in each cortical region. When the kirigami membrane probe was wrapped around the beating mouse heart, ECG signals from the beating heart were accurately recorded. Comparison of the ventricular and atrial signals analysis confirmed the stability of the kirigami bio-probe device. Additionally, due to the biaxial deformation exhibited by many biological tissues and organs, a kirigami film with a bidirectional cutting pattern was also fabricated. This was demonstrated by placing it on a rubber balloon to show its "biaxial" stretchability.

Another type of kirigami probe instrument for monitoring EMG signals is also based on a three-layer composite structure of Poly-p-xylene thin films and platinum-titanium electrodes, with a kirigami pattern resembling a doughnut shape processed by mask etching technology [205]. Conventional EMG electrodes suffer from issues such as high Young's modulus and displacement on the tissue surface, which affect the accuracy and stability of signal recording. In contrast, the donut-shaped kirigami device has a lower effective modulus similar to that of resting muscle tissue, significantly reducing stress applied to the tissue. The kirigami probes are more flexible and stretchable than thin-film devices without kirigami patterning, and this device can conform around tissues and follow muscle deformations, minimizing displacement on the muscle surface. Furthermore, the kirigami probe device can be embedded within polyethylene glycol (PEG) scaffolds and released by melting the sacrificial PEG layer, simplifying the implantation process. *In vivo* experiments in the hind limbs of mice demonstrated that this device could not only stably record EMG signals but also distinguish responses caused by different neural stimulations (Fig. 11b). Moreover, the device does not interfere with muscle function or cause ischemia, even as muscles deform. Furthermore, Park et al. created LIG on a liquid crystal polymer film, which was then encapsulated with PET film and conductive hydrogel to form a hydrogel composite film, and finally used a cutting machine to prepare Y-shaped kirigami structures. Electrodes connected to ECG and EMG modules were respectively attached to the chest skin and calf muscles can be used to monitor real-time signals [206]. In *in vivo* experiments, the electrode patch was placed on the right primary motor cortex of rats. By applying current pulses to induce hindlimb movement, it was found that the stronger the stimulation, the larger the movement amplitude, demonstrating potential clinical applications for assisting patients with motor disorders. And when in contact with the somatosensory cortex, the device was able to monitor sensory information, including touch, pain, and proprioception (Fig. 11c).

In addition to monitoring these biological electrical signals *in vivo*, an interventional device integrating a kirigami soft robot and a passive impedance sensor has been applied in an effective wireless monitoring of gastroesophageal reflux disease (GERD) in a minimally invasive manner [85]. A soft robot is obtained by cutting the magnetized PDMS film into kirigami snake scale patterns by laser processing, and the multi-modal motion is achieved by using the out-of-plane 3D deformation of the kirigami structure induced by the magnetic field changes, which provides agile maneuverability, good loading capacity, and wide adaptability to various environments. The sensor consists of an internal sensor tag and an external reader. After being swallowed by the patient, the soft kirigami robot can be deployed and guided to the desired sensing location on the esophageal wall, where the sensor is fixed for wireless monitoring. When reflux occurs, the change in the medium around the sensor tag causes the resonant frequency to shift, which can be detected by the external reader, thus enabling effective monitoring and diagnosis of GERD. Animal experiments showed that the device reliably attached to the esophageal wall of pigs, with no signs of detachment, damage, or degradation during 24 h of GERD monitoring. When different types of liquids were used to simulate gastroesophageal reflux, the device could measure a shift in resonance frequency towards lower frequencies, detecting changes even with small amounts of liquid, demonstrating high precision (Fig. 11d).

### 4.2. Implantable power supply devices

Like most wearable electronic devices, many implantable devices also require a continuous power supply [207,208]. Most of them are powered by internal batteries, and their limited lifespan restricts long-term operation. Additionally, the need for battery replacement involves extra surgery, which increases patient discomfort and risks. Therefore, combining piezoelectric materials with the body's own sustainable power supply has become a potential solution, leading to the emergence of kirigami-based *in vivo* power supply devices as shown in Fig. 12.

Organic piezoelectric materials such as PVDF and its copolymer PVDF-TrFE have potential in biomedical applications due to their excellent piezoelectric properties, mechanical flexibility, and biocompatibility. However, the extremely low stretchability of traditional PVDF films limits their application in implantable devices. By introducing parallel linear cutting kirigami patterns and adopting a segmented electrode design, a stretchable PVDF piezoelectric device was obtained [210]. Experiments showed that under a frequency of 10 Hz and a stretching strain of 10 %, the segmented electrodes generated a voltage of 1.63 V, compared to only 0.63 V for continuous electrode mode. Furthermore, the performance of the kirigami-type piezoelectric device remained stable across different frequencies and strains, making it suitable for self-powered systems in implantable biomedical devices and sensors. Subsequently, Sun et al. proposed a novel stretchable piezoelectric device [209], which is not only used for wireless health monitoring but also capable of self-powering. Electrodes were deposited on both sides of a PVDF film, and a PI film was used as the substrate for a

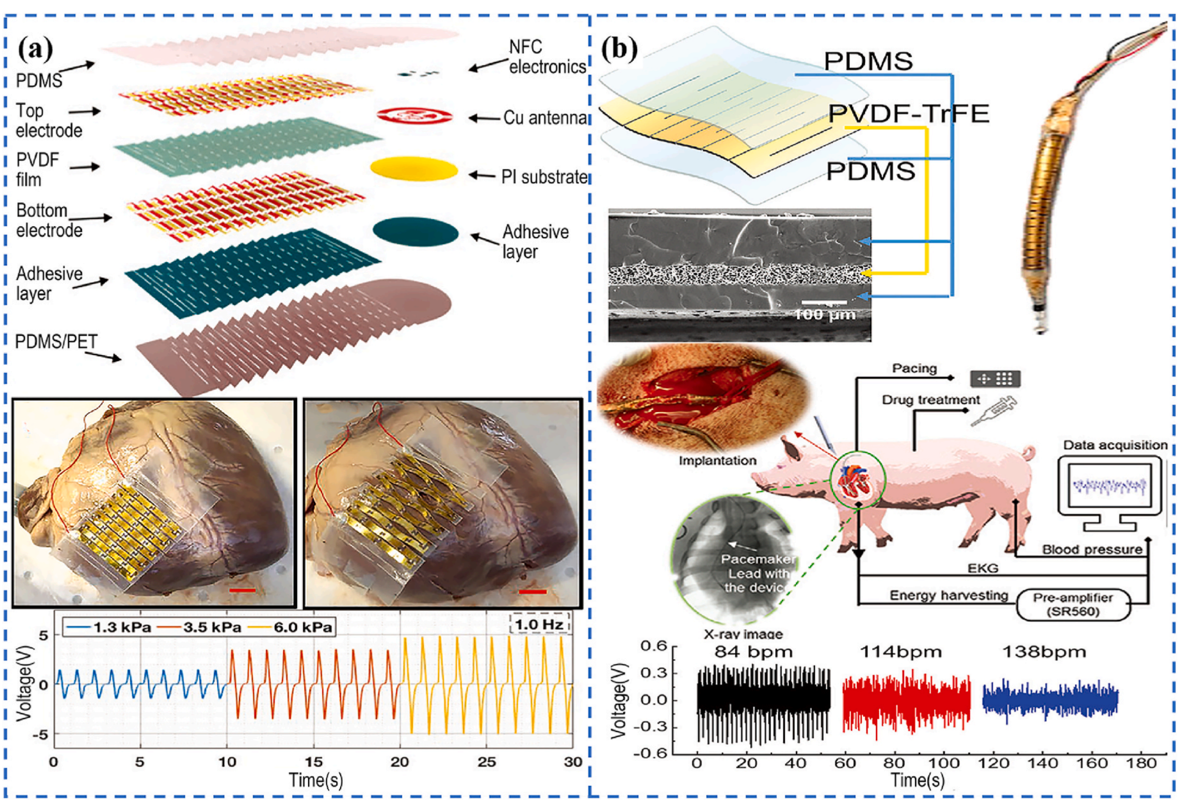


**Fig. 12. Kirigami-based implantable power supply devices.** (a) The design of the kirigami piezoelectric device with a parallel linear cutting pattern and its voltage output when applied to the surface of a pig heart. Reproduced with permission [209]. Copyright 2019, The Authors. (b) The design of the energy harvester for a pacemaker and its voltage output when implanted in a pig heart. Reproduced with permission [149]. Copyright 2020, Wiley.

flexible circuit board to create a wireless component. The two were then bonded side by side onto a PET film, and a stretchable piezoelectric sensor was obtained by laser engraving a parallel linear kirigami structure. In *ex vivo* tests, the sensor was applied to the surface of a fresh pig heart, where it was able to conform well to the heart surface and clearly capture the deformation characteristics of the heart during diastole and systole. The generated voltage had a linear relationship with pressure and frequency, and the device could store the collected energy in a capacitor, charging a 10 μF capacitor to 1 V within 200 s. This makes it suitable for powering systems in implantable electronic devices (Fig. 12a).

Following this, Xu et al. prepared the copolymer of PVDF into an energy harvester for use in pacemakers [149], thereby replacing traditional batteries and providing a sustainable energy solution. By spin-coating two layers of different PVDF-TrFE composite films, a free-standing porous film was constructed, where the first layer consisted of pure PVDF-TrFE, and the second layer contained ZnO nanoparticles and MWCNT. A custom-made dual-blade knife was then used to cut a parallel linear kirigami pattern on the composite film. Furthermore, the introduction of fillet geometries at notch edges effectively suppresses stress

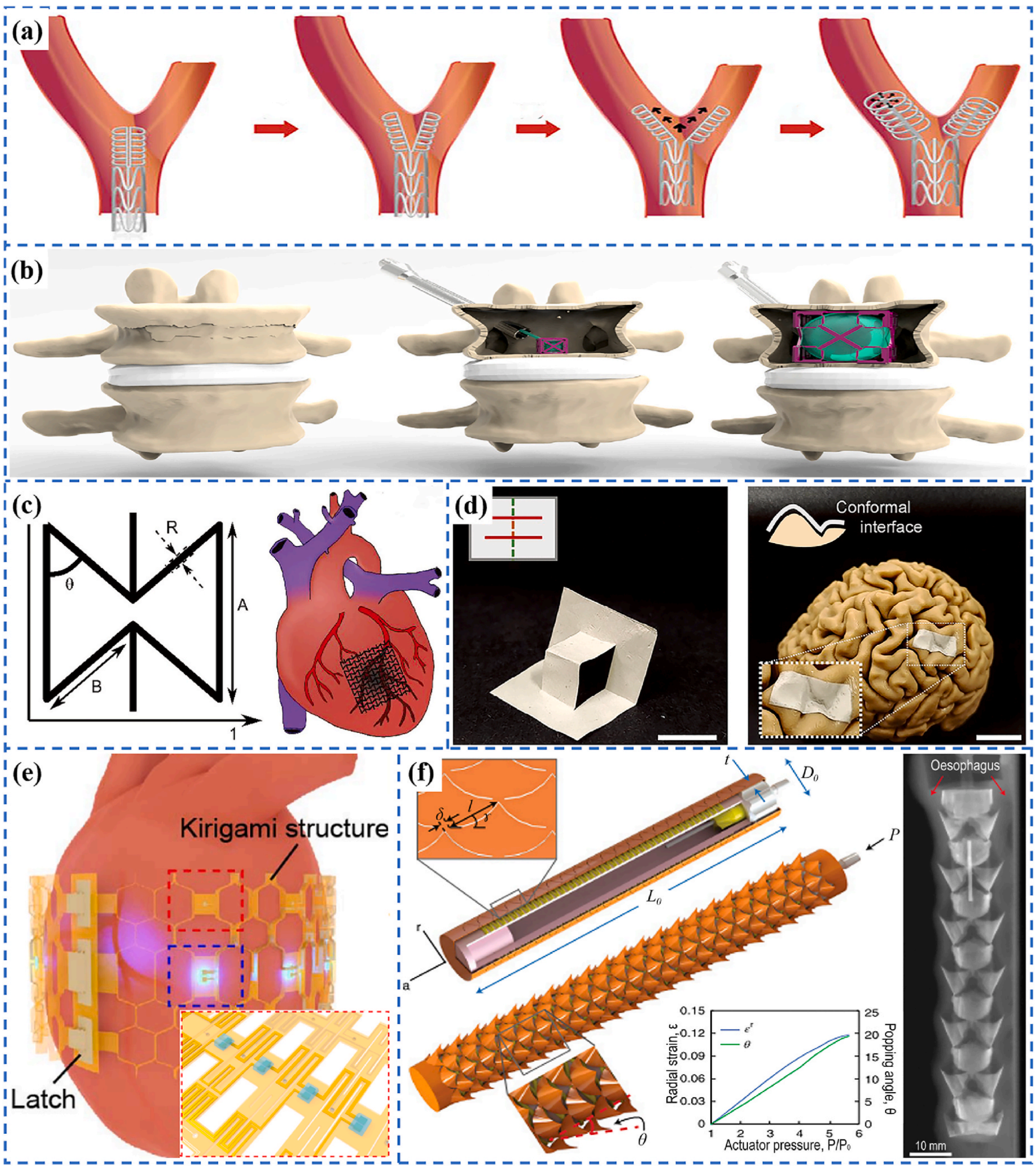


**Fig. 13. Kirigami-based Implantable Therapeutic Devices.** (a) The kirigami-based SMP is restructured from a cylindrical shape into a Y-shaped structure to expand narrowed bifurcated blood vessels. Reproduced with permission [219]. Copyright 2022, Wiley. (b) By combining cutting and folding, structural reconstruction can be achieved via balloon expansion for fracture treatment. Reproduced with permission [214]. Copyright 2020, The Authors. (c–e) Patches with different kirigami patterns can well adapt to the surface of the heart and brain, controlling cell movement through electrical and optical stimulation for disease treatment. Reproduced with permission [215]. Copyright 2018, The Authors. Reproduced with permission [217]. Copyright 2024, Wiley. Reproduced with permission [216]. Copyright 2019, IEEE.(f) Kirigami stent for drug delivery is restructured to form protruding angles, and CT scan images of the stent inside the esophagus. Reproduced with permission [86]. Copyright 2021, Springer Nature.

concentrations, extending fatigue life. Afterwards, gold electrodes were sputtered onto both sides of the film, and the device was encapsulated in a PDMS film and wrapped around pacemaker leads. Encapsulation in PDMS also buffers mechanical shock and protects internal circuits from delamination or wear under high-frequency heartbeats. When the heart expanded and contracted normally, the device harvested energy from the movement of the leads. In energy output tests, it was found that smaller cutting intervals resulted in higher voltage output. Additionally, increasing the film surface area and thickening the composite film further enhanced voltage output. *Ex vivo* tests simulating three possible anchor points on the heart showed that the device provided stable voltage output in different environments, with reliable operation. In a heart contraction level test, the introduction of dobutamine into a pig heart enhanced the heart's contraction, and as blood pressure increased, the voltage peak rose from 0.2 V to 0.7 V. In the test of the heart rate effect, it was observed that the voltage output of the kirigami device was highly negatively correlated with the heart rate. When the heart rate was 84 bpm, the voltage peak was 0.7 V, and even when the heart's contraction deformation was small at a high heart rate, there was still a voltage output of 0.2 V. The *in vivo* tests all demonstrated that this device can work effectively in the heart environment, generate voltage by efficiently collecting the movement of the heart, and has broad prospects in the application of self-powered implantable devices (Fig. 12b).

### 4.3. Implantable therapeutic devices

Kirigami technology endows materials with unique mechanical properties and morphological adaptability, making them better suited for the complex physiological environments within the human body in implantable therapeutic applications. This effectively overcomes the limitations of traditional implantable therapeutic devices in terms of treatment efficacy, adaptability, and invasiveness [211–213]. Through precise cutting of materials and ingenious structural design, a series of implantable therapeutic devices based on kirigami have emerged, including stent therapy, physical therapy, and drug delivery treatments in Fig. 13, offering new strategies for therapeutic approaches.

In the field of cardiovascular diseases, when atherosclerosis leads to significant narrowing of the blood vessels, it is generally necessary to implant a stent to restore smooth blood flow [218]. However, for cases that occur at vascular bifurcations, such as a major branch point of the coronary artery, traditional straight stents are inadequate because they cannot effectively cover and support the entire bifurcation area, resulting in suboptimal restoration of blood flow. Therefore, bifurcation stents are required. However, bifurcation stents protrude on both sides that make their delivery and deployment during implantation difficult. In a study, by combining kirigami and 3D printing technologies, polyurethane-based SMP was fabricated into compact foldable cylindrical structures [219,220]. Data from artificial blood vessel models showed that the folded kirigami bifurcation stent could navigate through vessels without interfering with the vessel walls. By applying external stimuli to the SMP (such as heating), the folded stent deformed into a bifurcated stent shape, capable of expanding obstructed or narrowed vessels and deploying well within branch vessels (Fig. 13a). Furthermore, for the repair of vertebral compression fractures, a deployable and foldable orthopedic implant has emerged as a potential alternative to vertebral stent implantation. A square flat plate was designed with a bistable kirigami cut pattern, and six such plates were arranged according to the unfolded shape of a cube. Aluminum sheets or titanium foils were then laser-cut into the aforementioned kirigami structure and folded into a cube to prepare the orthopedic implant [214]. This device can be deployed similarly to stents in vertebroplasty, achieved through an inflatable balloon. The high porosity imparted by the kirigami structure and the micro/nano surface structures facilitates bone ingrowth, eliminating the need for bone cement. The scalable kirigami structure ensures it can change under external stimuli, minimizing the invasiveness of orthopedic surgery. However, repeated load-bearing may cause microcracking near folding hinges. By configuring in a multi-layer Russian doll-style arrangement, it can withstand higher compressive forces, enhance structural robustness and delay mechanical fatigue (Fig. 13b). Moreover, the micro/nano-patterned patterns can stimulate stem cell osteogenic differentiation and kill bacteria, promoting bone regeneration and reducing infection risks. These studies all indicate that kirigami technology, which can be manufactured from 2D planar structures, allows for more precise control of complex micro/nano surface patterns and holds broad application prospects in the development of irregularly shaped implantable mechanics.

In addition to rigid stents, some physical therapies have also utilized kirigami technology. Kapnisi et al. used laser photochemical adhesion technology to attach a stretchable conductive cardiac patch (AuxCP) to the heart for the treatment of myocardial infarction [215]. The conductive patch is primarily composed of a network of interconnected polyaniline and phytic acid grown on the surface of chitosan. Subsequently, laser micro-ablation technology was used to fabricate a kirigami-based diffraction honeycomb cutting pattern. The kirigami structure endows the patch with a negative Poisson's ratio and anisotropy, while maintaining its conductivity. *In vitro* experiments showed no negative effects on cardiac electrophysiology and that the patch could conform well to the native heart's movement patterns. Studies in rat models demonstrated that, within two weeks of applying the AuxCP, there was no adverse impact on cardiac function, and it caused almost no fibrosis response (Fig. 13c). Furthermore, compared to the untreated myocardial infarction control group, the group of AuxPC showed less growth in left ventricular mass, which indicate that AuxPC reduced wall stress and inhibited hypertrophy. In the unique clinical and physical scenarios of electrotherapy, bioelectronic implants that provide electrical stimulation should ensure minimal invasiveness and safety, creating a demand for flexible and biodegradable bioelectronics. The copolymerization of magnetic-electric nanoparticles with PLGA was prepared into a high-fiber flexible bioelectronic membrane via electrospinning [217]. The high surface area-to-volume ratio and porous structure provide a biomimetic environment similar to the natural extracellular matrix. By adjusting the microstructure, it is possible to control cellular responses or diffusion permeability, achieving localized electrical stimulation of targets and high biocompatibility. Studies have shown that this bioelectronic membrane influences cell orientation and wirelessly modulates neuronal cell activity. Additionally, using kirigami techniques allows the flexible planar membrane to be transformed into specific 2D and 3D macrostructures to fit complex surfaces. Due to its biodegradable nature, the membrane can adjust its degradation rate according to the intended treatment period after implantation within the body, eliminating the need for secondary removal surgery and reducing long-term risks (Fig. 13d).

Compared with electrotherapy, Morikawa et al. proposed a highly stretchable optoelectronic device based on kirigami [216], which can conduct treatment through optogenetic stimulation and reduce the side effects brought by electrotherapy. The PI composite film was patterned with kirigami parallel patterns via reactive ion etching, and then bonded and encapsulated with LED lights to create the optoelectronic device. This device can be used in optophysiological experiments for perfused hearts, simultaneously achieving ECG measurements and optogenetic stimulation of cardiac tissue. The design of kirigami slits of varying lengths gives the device specific stretching properties to adapt to the shape of the heart, improving the fit of the device on the target tissue and reducing the distance between the electrode and the tissue surface. This significantly enhances the sensitivity of recording electrical signals from the tissue surface. Meanwhile, optogenetic stimulation allows the use of light to control the activity of cardiac cells expressing photosensitive proteins, providing a potential treatment for ventricular arrhythmias and other diseases (Fig. 13e).

Kirigami technology demonstrates unique advantages in stent and physical therapy applications, and it also has outstanding potential in drug delivery treatments. For tubular stenotic diseases *in vivo*, when a kirigami drug-eluting stent is implanted at the lesion site, the stent's flat expansion transforms into a three-dimensional, multi-point structure that embeds into the inner wall of the diseased blood vessel. This configuration allows for more efficient localized drug delivery treatment, improving the drug delivery efficacy. Babaee et al. studied the potential of kirigami-based drug-eluting stents for the treatment of esophageal stricture [86]. First, laser cutting was used to create snake-scale needle-like kirigami patterns on PI thin sheets, which were then rolled into tubular shapes. Silicone casting was subsequently employed to fabricate pneumatic actuators that control the popping out of the kirigami needle units. The deformation response control of the stent was achieved by changing the thickness of the sheet and the length of the kirigami needles. The research data showed that when the needle length was 10 mm and the shell thickness was 0.13 mm, the stent achieved the maximum radial expansion and relatively high out-of-plane stiffness of the needle surface. Moreover, by introducing an arc structure on both sides of the needles to control the penetration depth of the needles, perforation was effectively avoided. And while frequent deformations may lead to plastic deformation or material fatigue of the microneedle, optimizing the geometry of the kirigami microneedle also reduces peak stresses and ensures the reusability and functional life of the stent. After optimizing the structure, the surface of the outer shell was treated with plasma to improve the surface properties and adhesiveness, enabling the stent to carry drugs better. The animal experiment data showed that periodic high-fluorescence-concentration point arrays appeared at the penetration sites of the kirigami needles, and the drug particles could be well deposited in the submucosa and absorbed by the tissues. Meanwhile, drug release could still be detected 7 days after drug administration. It can be seen that the kirigami-embedded drug-loaded stent has effectively solved the limitations of traditional drug-loaded stents, such as uneven drug distribution and difficulty in accurately reaching the lesion site, and can continuously deliver drugs locally, providing a new approach for the treatment of various diseases (Fig. 13f).

## 5. Kirigami-based smart applications

Currently, with the rise of Artificial Intelligence and Megamodel, the era of intelligence has quietly arrived. In this chapter, we will discuss some intelligent applications inspired by the 2D and 3D reconfiguration and deformation capabilities of kirigami technology, and these applications' deformation actuation mechanisms. These applications primarily include human-machine interaction systems integrated with kirigami sensors [195,221], kirigami manipulators [222–225] capable of grasping and handling delicate objects, and various kirigami soft robots [226–230] that can move through narrow channels such as the gastrointestinal tract for internal inspections and drug delivery. The development of these intelligent applications holds significant importance for advancing research in smart healthcare.

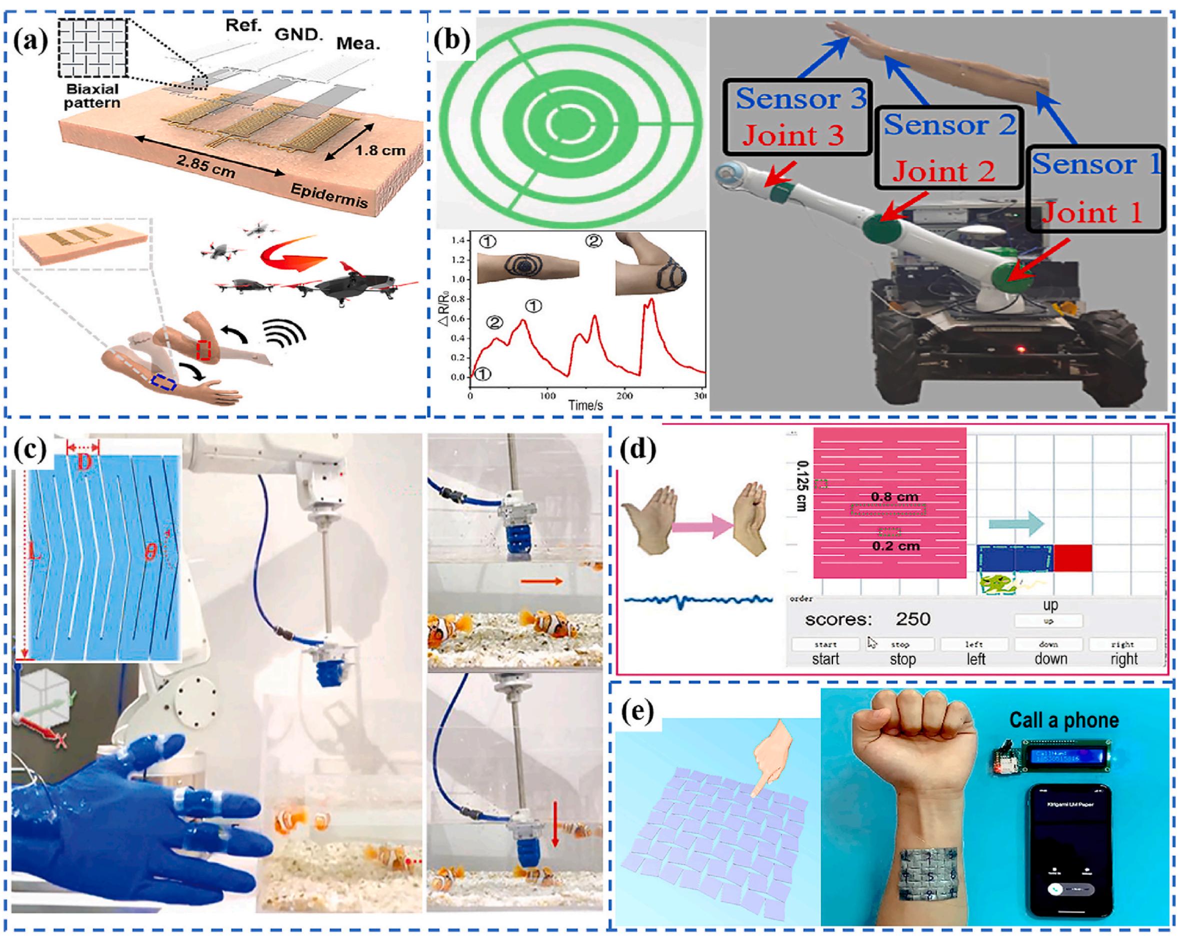


**Fig. 14. Kirigami sensors for human-machine interaction.** (a) AgNWs/PI composite film sensor with orthogonal cutting patterns used for controlling a quadrotor drone. Reproduced with permission [63]. Copyright 2019, American Chemical Society. (b) Flexible core-sheath fiber sensor with concentric arc patterns used for controlling a robotic arm. Reproduced with permission [232]. Copyright 2021, Elsevier. (c) Hydrogel sensor with V-shaped parallel cutting patterns used for underwater robotic arm operations. Reproduced with permission [61]. Copyright 2023, Wiley. (d) PEDOT:PSS electrode sensor with parallel cutting patterns enabling synchronized gameplay of the Snake game. Reproduced with permission [59]. Copyright 2023, The Authors. (e) Liquid-metal electrode sensor with orthogonal cutting patterns developed for an intelligent dialing communication system. Reproduced with permission [233]. Copyright 2022, American Chemical Society.

### 5.1. Kirigami sensors for human-machine interaction

In the process of continuous development of flexible sensor technology, many innovative achievements are gradually transforming the landscape of human-computer interaction and intelligent control [231], and some recently researched kirigami sensors for human-computer interaction are listed in Fig. 14. Won et al. designed a kirigami electrode sensor using AgNWs/PI composite films [63], which exhibits stable electromechanical properties under large tensile strains and is capable of detecting human EMG signals. By connecting to a computer or other devices, the sensor can recognize specific gestures, including making a fist, punching to the left, or punching to the right, thereby achieving control of a quadcopter drone (Fig. 14a). Similarly, Zhang et al. fabricated a flexible core-sheath fiber sensor by combining 3D printing and kirigami technology [232]. It can be installed on elbows, wrists and fingers to capture human gestures. It maintains high sensitivity under various stimuli, with an accuracy of approximately 3 mN and a rapid response to dynamic stimuli within 4 ms. Through the signal acquisition system, the signals are processed and analyzed to control the movement of the robotic arm (Fig. 14b). In addition, Zhu et al. used 3D printing technology to fabricate a hydrogel sensor device with parallel kirigami patterns and formed an underwater interactive human-machine interface system with an industrial robotic arm [61]. Through this system, users can wear integrated gloves to remotely control the movement of industrial robots in real-time, allowing precise and reliable manipulation of the robotic gripper to grasp underwater objects (Fig. 14c). When this sensor is attached to fingers, the resistance signals generated by finger movements can be classified using machine learning algorithms to achieve the recognition and translation of Morse code signals, thus enabling communication. These application studies offer vast potential for advancements in the fields of healthcare, intelligent control, and smart robotics.

The Y-shaped kirigami patterned PEDOT:PSS electrode sensor designed by Won et al., which was mentioned before, has been successfully applied in human-machine interaction. Besides stable electromechanical performance, it also boasts excellent biocompatibility, flexibility, breathability, and high coverage. However, different from the previous sEMG sensor, this one utilizes the electrooculogram (EOG) signals generated by eye movements. By detecting and recognizing EOG signals, it enables the control of household appliances, specifically for switching them on and off. Similarly, Xia et al. developed a skin-conformal electrode sensor using PEDOT:PSS composite material [59], which enables synchronized operations such as music playback or switching tracks by recognizing EOG signals, thereby assisting individuals with disabilities in performing basic daily tasks. The sensor exhibits excellent resistance to motion interference and can still acquire high-quality bioelectrical signals even after ultrasonic cleaning. In addition, it can also achieve the synchronous gaming process of the Snake game by recognizing EMG signals (Fig. 14d), providing application prospects for remote medical assistance. Similarly, a kirigami liquid metal electrode sensor studied by Li et al. is capable of acquiring high-quality physiological signals [233]. Based on this sensor, they developed an intelligent dialing communication system that enables making phone calls via self-powered electronic skin attached to human skin (Fig. 14e).

### 5.2. Kirigami-based soft manipulators

As a commonly used actuator in intelligent applications, the development and performance improvement of manipulators have promoted

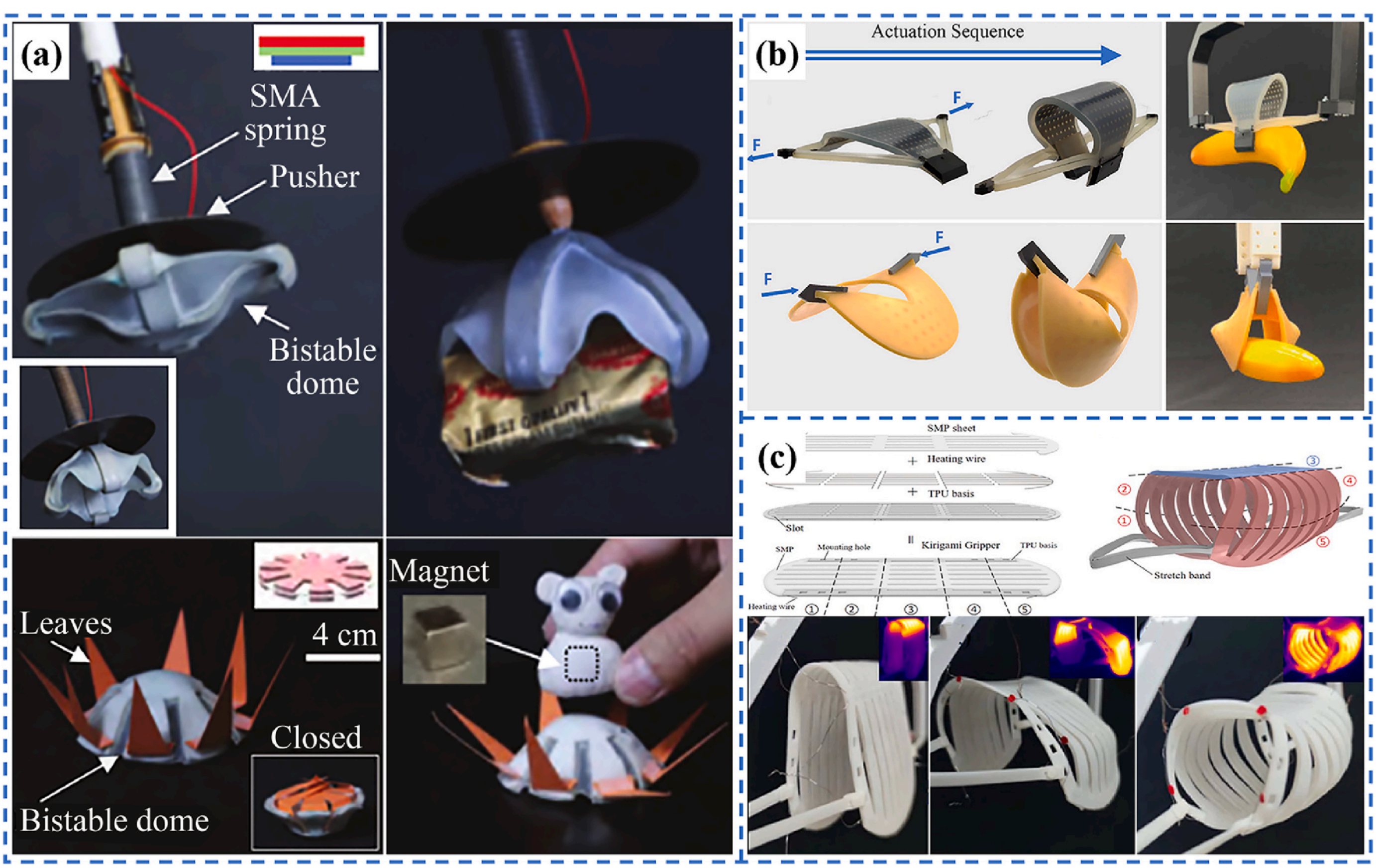


**Fig. 15. Kirigami-based grippers.** (a) Cross-shaped and chrysanthemum-shaped bistable grippers. Reproduced with permission [22]. Copyright 2023, Wiley. (b) Soft grippers based on stretching and compressive buckling. Reproduced with permission [234]. Copyright 2024, The Authors. (c) Thermally actuated grippers based on stretching buckling. Reproduced with permission [235]. Copyright 2024, IOP.

the expansion of intelligent applications (Fig. 15). In the medical field, such as in surgeries requiring extremely high precision, manipulators can accurately manipulate surgical instruments to reduce surgical errors. Kirigami technology can bring multi-stable characteristics to substrates, and Mungekar et al. utilized this feature to design a gripper with a bistable structure, consisting of a three-layer composite material where two pre-stretched substrate layers are bonded to the two sides of a kirigami structural layer with a cross-shaped pattern, then, a shape memory alloy (SMA) spring and a mechanical push rod are assembled to form the kirigami manipulator [22]. When not driven, the gripper is in an upward stable equilibrium state; when the SMA spring is activated by being electrified, it pushes the push rod, causing the gripper to change to a downward stable state and form a hook-shaped structure. The 2D and 3D reconstruction and deformation capabilities brought by the kirigami technology can achieve the grasping function under moderate interference. In addition, inspired by the flytrap, the kirigami pattern was designed into a chrysanthemum shape, and obtaining a bionic robot. It can rapidly capture objects using magnetically induced deformation of the kirigami structure (Fig. 15a).

Compared to the multi-stable performance brought about by the complex multilayer structures of the former, Buzzetto et al. obtained two actuation methods for a soft robotic hand by designing some relatively simple kirigami patterns on thin sheets of materials such as PET [234]. One is driven by stretching that the users need to pull both ends to induce out-of-plane motion of the gripper, thereby closing it. It is suitable for handling objects with uncertain positioning or for one-time grasping of contaminated and hazardous materials. The other is driven by compressing that the users need to push the two ends of the gripper together to form a more compact grasping system. The compliance of the materials and the design features enable it to form a sealed cavity during the grasping process, and the control method is simple. It is used for handling food, liquids, fragile items or ultra-fine objects (Fig. 15b). Among them, the kirigami soft gripper driven by stretching can be actuated by thermal modes [235]. It is assembled from TPU materials with kirigami patterns, SMP sheets and heating wires, and uses spiral polymer artificial muscles (SCPAMs) as actuators. When the SMP sheet is softened by heating, the SCPAMs contract to generate a tensile force that gradually closes the gripper to wrap or pinch the object. When the heating wire is turned off, the SMP sheet returns to its high stiffness state, maintaining the gripping posture, and reheating to release the tensile force, the gripper releases the object and returns to its initial state. Different heating modes are applicable for grasping objects of varying sizes, shapes, hardness, and weights (Fig. 15c).

### 5.3. Kirigami-Based Flexible soft robots

As an intelligent application carrier, intelligent robots can assist healthcare professionals in transporting equipment, and even some miniature robots can be used for drug delivery to aid in internal treatment [236–238]. Compared to traditional rigid robots, soft robots [239–245] have attracted significant attention due to their high flexibility and safety, and their key components, soft actuators, have also

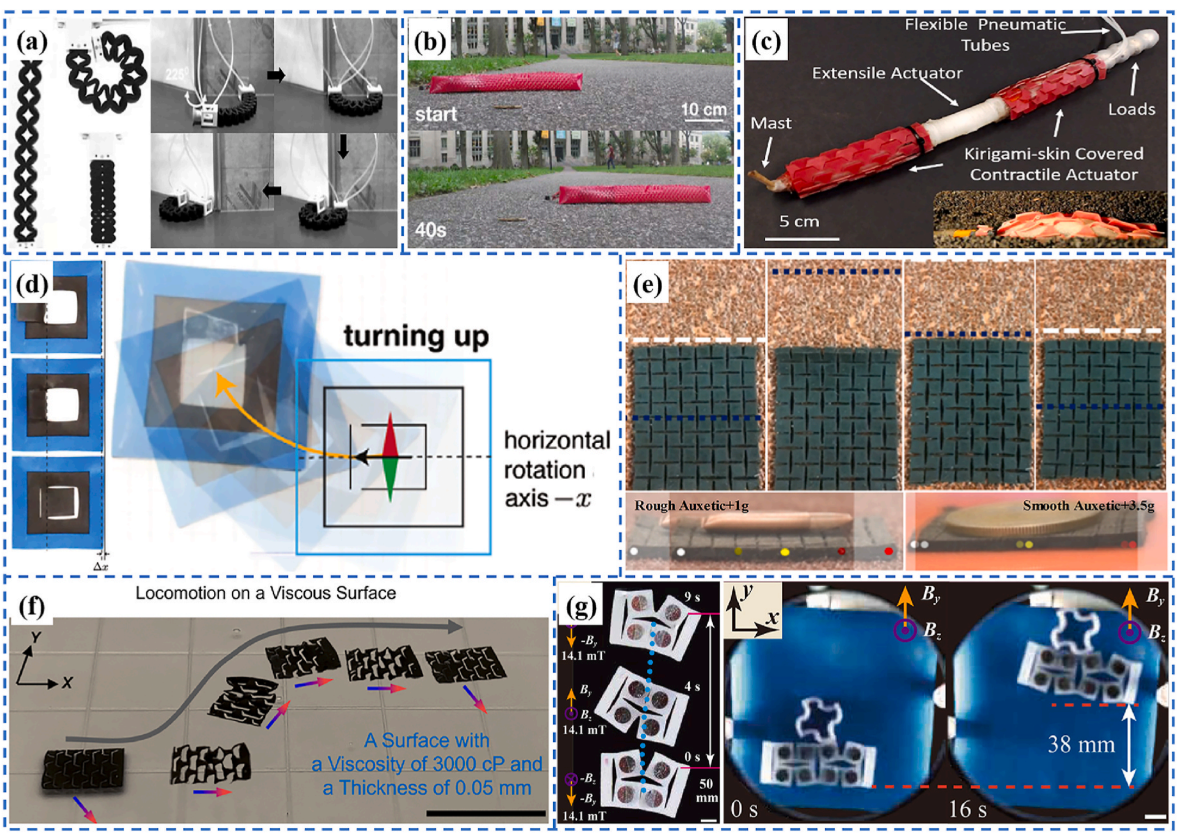


**Fig. 16. Kirigami-based flexible locomotion robots.** (a) Design of flexible actuators with snake-like patterns and assembly of multiple actuators to form a crawling robot. Reproduced with permission [246]. Copyright 2021, Mary Ann Liebert, Inc. (b) Snake-inspired soft robot driven by a single pneumatic actuator and using V-shaped cutting pattern skin. Reproduced with permission [79]. Copyright 2018, The Authors. (c) Earthworm-inspired soft robot driven by three pneumatic actuators and using trapezoidal cutting pattern skin. Reproduced with permission [83]. Copyright 2019, IEEE. (d) Soft robot with a U-shaped cutting pattern, capable of setting crawling paths by altering the magnetic field. Reproduced with permission [247]. Copyright 2023, The Authors. (e) Magnetic thin plate robot with orthogonal cutting patterns, capable of carrying a load twice its own weight. Reproduced with permission [140]. Copyright 2023, The Authors. (f) Magnetic-tile robot with trapezoidal cutting patterns, capable of towing a load 90 times its own weight. Reproduced with permission [85]. Copyright 2023, American Chemical Society. (g) Soft robot assembled with magnetic discs and orthogonal cut rubber, enabling multi-directional movement. Reproduced with permission [60]. Copyright 2023, AIP Publishing.

been extensively studied. Currently kirigami-based soft robots can be mainly categorized into pneumatic and magnetic types according to the drive method in Fig. 16.

The kirigami-inspired flexible pneumatic actuator induces bending, stretching, contraction, and composite motions by varying the input air pressure, which causes the expansion and contraction of two air channels [246]. Moreover, by combining multiple actuators, it can be extended to various robotic applications, such as the soft manipulators mentioned earlier for grasping delicate objects or objects in complex environments, as well as crawling robots capable of flipping and climbing over obstacles, etc. (Fig. 16a). Currently, bionic science has been receiving increasing attention, and inspired by snakes and earthworms in nature [248], a series of worm-like soft robots [249] that combine kirigami skin with pneumatic actuators have been widely studied. Among them, Ze et al. designed a small earthworm-inspired soft crawling robot based on origami technology with magnetic actuation [250]. This robot can overcome significant resistance in confined spaces while demonstrating anisotropic and magnetically tunable structural stiffness. Moreover, the internal cavity of the robot is utilized for drug storage and release, showcasing its multifunctional potential for biomedical applications. Additionally, He et al. proposed a magnetically responsive soft actuator based on origami and modular strategies [251], achieving complex 3D deformation and multifunctional integration. Through modular design, they developed a multifunctional quadrupedal soft actuator capable of sensing environmental signals such as ultraviolet light, temperature, and pH. They also created a magnetically responsive microneedle module actuator for oral drug delivery, which can precisely locate and release drugs in the intestines. Notably, Rafsanjani et al. used fiber threads to constrain the radial expansion of the actuator, allowing the kirigami skin to deform only axially. And the kirigami skin designed with a V-shaped parallel pattern could be reconstructed to form snake-scale-like spikes to generate anisotropic friction, imitating the crawling mechanism of snakes. When the actuator was inflated, the spikes popped out, causing the tail to be anchored and the head to move forward. When deflated, the spikes gradually retracted, causing the head to be anchored and the tail to move forward. This inflation-deflation cycle enables the robot's crawling motion. In addition, by integrating some control components, a tetherless kirigami skin soft crawler was fabricated to realize crawling movements in various complex environments (Fig. 16b). While Liu et al. imitated the crawling mechanism of earthworms. They connected three actuators, and used fiber threads to constrain the middle part making it only capable of axial telescopic movement, then the two ends were covered with the kirigami skin that was designed with a trapezoidal parallel pattern. When driven by radial expansion, the kirigami skin can form bristle-like spikes as anchor points to meet the anchoring requirements, enabling the robot to have a larger forward displacement and higher traction, thus realizing the crawling movement (Fig. 16c).

In addition to pneumatic stimulus-responsive driving, in many studies, factors such as light [66,252,253] and magnetic fields are utilized to induce the kirigami structures to generate 3D deformations, to fabricate a series of tetherless soft robots. For example, a $CO_2$ laser cutting is used to create a U-shaped kirigami pattern with linear cuts in magnetized soft silicone rubber, and then attaching it to a harder silicone rubber rectangular frame to obtain a magnetic sheet robot [247]. Under a rotating magnetic field, the leaf-like structures formed by the U-shaped cuts and the foot-like structures formed by the linear cuts work together. When the leaves open, the feet bend to establish anchor points; and when the leaves close, the feet return to their original shape and push against the anchoring points to generate propulsion, moving the robot forward. Its movement is affected by the geometry of the cuts and the rotation direction of the magnetic field. The movement mechanisms are different under different actuation methods, and the crawling path can also be programmed by changing the factors related to the magnetic field (Fig. 16d). In contrast, Silva et al. designed magnetized soft silicone rubber into an orthogonal kirigami pattern without using a flexible frame for constraint [140]. The combination of static friction and oscillating magnetic forces lifts the robot's head and triggers the stretching strain induced by the rotational cutting structure, simulating the limbless crawling motion of animals. This magnetic sheet kirigami robot also possesses transportation capabilities. It can transport a payload equal to its own weight on a rough surface and a payload twice its own weight on a smooth surface. Additionally, under a rotating magnetic field, the robot can roll into a cylindrical shape and achieve rolling movement (Fig. 16e). As discussed in Chapter 2 on deformation mechanisms, different kirigami patterns yield distinct performance characteristics. The previously mentioned kirigami robot [85] for *in vivo* drug delivery, also a magnetic sheet-based soft robot, employs a V-shaped kirigami pattern that endows it with greater motion deformation and static friction compared to orthogonal kirigami patterns. This robot can bear up to 150 times its own weight and drag up to 90 times its own weight. It is capable of traversing gaps as wide as 2 mm and can move on vertical walls, in water, and on surfaces with a certain degree of viscosity (Fig. 16f), meeting the operational demands within the body.

Different from the previous two methods of magnetizing rubber by blending magnetic particles within it, Wang et al. placed magnetic discs on kirigami silicone rubber modules with orthogonally cutting patterns to form a magnetic-sheet robot [60]. Under specific magnetic field conditions, its hinges will change their states according to the changes in the magnetic field, thus enabling the robot to move forward or backward. Robots with asymmetric structures can generate local forward and lateral driving forces to achieve circular motion. Furthermore, these kirigami robots can use specific shapes, such as V-shaped patterns, to carry payloads and use their own output force to clear obstacles (Fig. 16g). Additionally, by leveraging their significant bending deformation capabilities, they can connect or disconnect circuits via attached wires, functioning as remote circuit switches.

## 6. Kirigami-based simulation performance study

With the advancement of computer hardware and computational power, simulation studies have become increasingly essential in various fields. For devices based on kirigami [254–258], simulation studies can help researchers better understand the performance and behavior of the devices, predict their performance under different conditions, and thus optimize the design of the kirigami structures, so as to reduce experimental costs and improve research efficiency. This section focuses on reviewing typical simulation model construction and analysis in different kirigami applications over the past three years, the output of the simulation analysis is shown in Fig. 17.

Midas NFX software, with its user-friendly interface, has emerged as a commendable option for investigating structural deformation properties. In the optimization design of kirigami patterns, Kang et al. utilized Midas NFX software to iteratively adjust the pattern designs and analyze the stress generated within each pattern under t identical strain conditions [157]. They ultimately determined that patterns with narrower widths, longer V-shaped diagonal lengths, and larger fillet radii exhibited superior performance, leading to the development of an optimal snake-skin pattern (Fig. 17a). Subsequent simulations under the optimal pattern analyzed changes in resistance and conductivity under various mechanical stresses, demonstrating excellent stretchability, flexibility, and stability of the kirigami snake-skin pattern electrodes. However, Midas NFX's capabilities in handling complex nonlinear problems are limited, a challenge that ANSYS, a comprehensive simulation software, is well-equipped to address. In the study of stretch/compression-based kirigami grippers, Buzzatto et al. provided a more detailed simulation methodology using ANSYS software [234]. They simplified the gripper model using shell elements, modeled the PET sheet with linear elastic material properties, and applied frictionless contact between the gripper and the support plate. The simulation revealed that the stability of the gripper's effects under two different

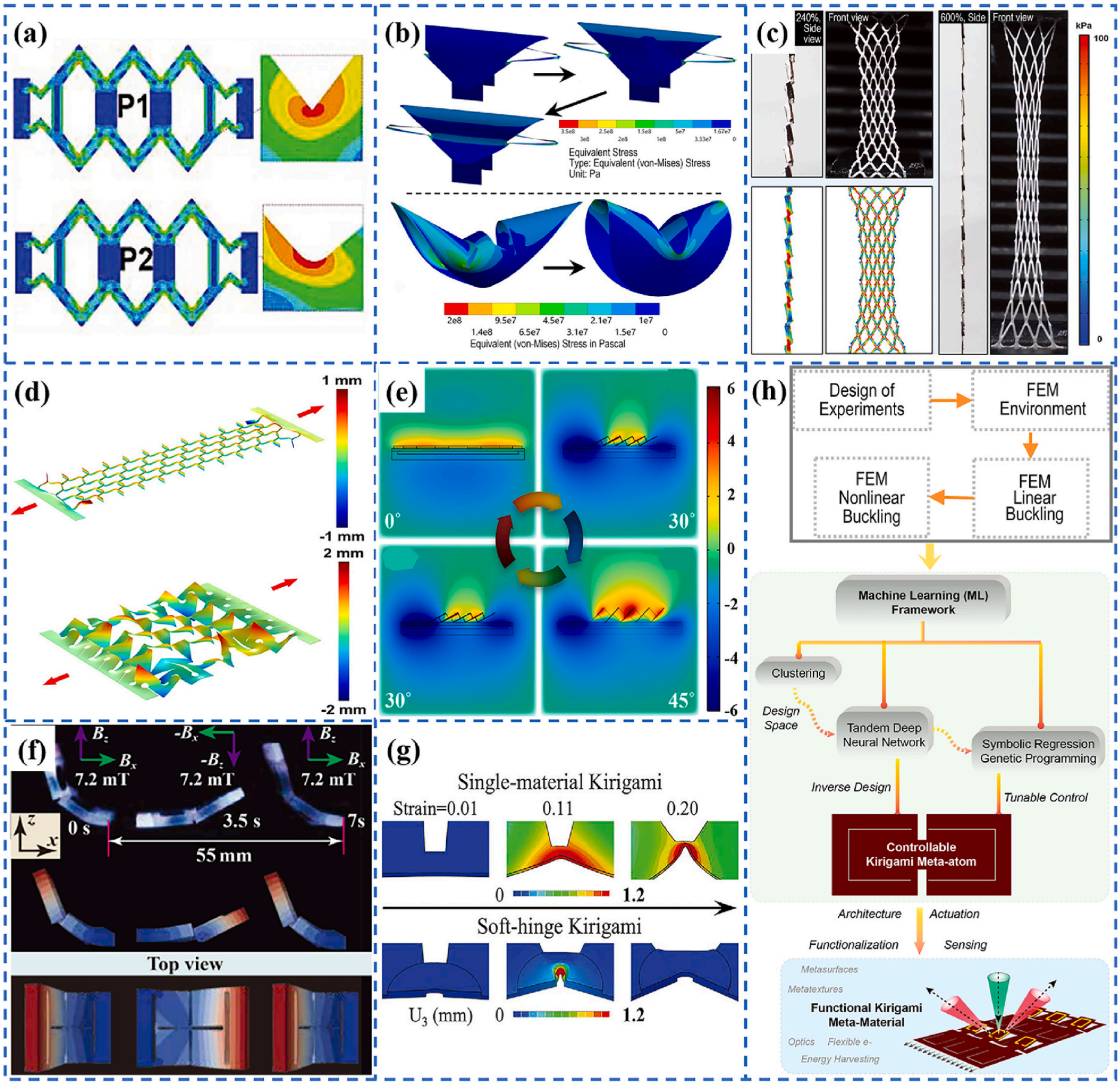


**Fig. 17. Simulation performance studies based on Kirigami technology.** (a) Optimization design of the notch tip structure using Midas NFX. Reproduced with permission [157]. Copyright 2023, The Authors. (b) Research on the deformation effects of different grippers using ANSYS. Reproduced with permission [234]. Copyright 2024, IEEE. (c, d) Investigation of the deformation effects of kirigami metamaterials using COMSOL. Reproduced with permission [146]. Copyright 2023, The Authors. Reproduced with permission [196]. Copyright 2024, Royal Society of Chemistry. (e) Study of the potential distribution in kirigami metamaterials using COMSOL. Reproduced with permission [169]. Copyright 2024, Elsevier. (f) Analysis of the deformation effects of soft robots using ABAQUS. Reproduced with permission [60]. Copyright 2023, AIP Publishing. (g) Optimization design of the notch hinge structure using ABAQUS. Reproduced with permission [139]. Copyright 2022, Wiley. (h) Machine learning assisted design of 3D kirigami metamaterials. Reproduced with permission [259]. Copyright 2022, The Authors.

modes necessitated varying mesh sizes and induced out-of-plane deformation curvatures. Nonetheless, the simulations achieved results closely aligned with experimental findings, reducing experimental costs while enhancing the understanding of the mechanical characteristics of kirigami grippers. Furthermore, by continuously adjusting model parameters, they analyzed the stress and deformation of each gripper under different working conditions (Fig. 17b), thereby providing the grippers with superior grasping capabilities and adaptability.

In contrast to the steep learning curve and higher costs associated with ANSYS, COMSOL stands out with its user-friendly interface and robust multi-physics coupling capabilities, making it well-suited for investigating the mechanical, electrical, and thermal properties of kirigami devices [7,17,134]. Choi et al. employed COMSOL software to analyze the mechanical and electrical performance of liquid metal-based elastic kirigami electrodes under various deformation states [146]. Their simulation results validated theoretical models, providing a foundation for optimizing kirigami designs and ensuring electrode stability and high performance under high-strain conditions (Fig. 17c). Similarly, Chen et al. leveraged COMSOL software in their research on kirigami-based laser-induced graphene (LIG) heaters [196], conducting simulations to study the effects of different deformation modes on performance. By adjusting the cutting spacing ratio, they compared uniaxial and biaxial stretching deformation data, analyzed changes in heater resistance, and evaluated the stability and uniformity of heating performance. Their findings indicated that a larger cutting spacing ratio enhanced the mechanical, electrical, and thermal performance of the heaters (Fig. 17d). Furthermore, they provided detailed simulation recommendations, such as using the Yeoh hyperplastic model for materials like Ecoflex and treating LIG as a homogeneous material to simplify the model. For boundary conditions, they applied a sufficiently small displacement perpendicular to the heater to induce out-of-plane buckling deformation while minimizing disturbances to the heater. Xu et al., in their study of kirigami-based stretchable/compressible buckling sensors (BS) [169], utilized COMSOL software to simulate the potential distribution on the surface of the contact layer of the stretching buckling sensor (Fig. 17e). They intuitively observed that the potential difference changes with the electrode angle during operation, further validating the theoretical analysis. Simultaneously, the buckling deformation of different electrode structures under various pre-strains was simulated to investigate the effects of electrode shape and pre-strain on voltage output performance, providing a basis for determining suitable structures and materials.

When addressing the highly complex nonlinear behaviors of kirigami metamaterials, ABAQUS stands out as the most suitable software. It excels in simulations involving large deformations, material nonlinearity, and contact problems [23,75,80,153,166,188,235,260], making it a preferred choice for an increasing number of researchers. In the study of a previously mentioned bistable kirigami gripper [22], the pre-stretched substrate and multi-layered composite structure introduce significant complexity to the deformation process. Mungekar et al. combined experimental characterization with simulation analysis of the overall structure of the kirigami gripper. By iteratively adjusting structural dimensions and pre-stretching values, they analyzed deformation and stress distribution under various conditions, identifying multiple stable modes of the structure. In the motion simulation study of kirigami magnetic sheet robots [60], Wang et al. considered factors such as structural symmetry and interlayer nodal connections, systematically investigating the influence of kirigami structure and magnetic field variations on the deformation and motion patterns of the robot (Fig. 17f). Through combined experimental analysis and iterative adjustment of structural parameters, they studied the static deformation behavior and characteristics of the kirigami soft robot under different static magnetic field configurations. They also utilized various static deformation shapes to control oscillating magnetic fields, generating multimodal dynamic motions, providing a theoretical foundation for the programmable motion and multifunctionality of kirigami soft robots. Additionally, Jiang et al. discovered through simulations that the design of soft hinges effectively suppresses local buckling in traditional kirigami structures (Fig. 17g), significantly enhancing the conformability and tensile performance of soft-hinged kirigami metamaterials [139]. This finding offers theoretical support for their application in flexible electronic armor. Meanwhile, Zhuo et al. investigated the strain sensitivity and deformation behavior of kirigami structures under different stretching conditions through simulations [61], validating the enhancement of strain sensitivity in hydrogels by kirigami structures and the improvement in conductivity due to the incorporation of nanosheets. In the study of programmable hierarchical kirigami structures, Pan et al. systematically examined the effects of different cutting angles and methods on the deformation behavior of kirigami structures through simulations [126]. They demonstrated that controlling local cutting patterns enables programmable deformation of kirigami structures. Furthermore, they designed kirigami structures with encryption capabilities, showcasing the emergence of embedded information during stretching.

Moreover, with the increasing application of machine learning techniques in materials science and engineering simulations in recent years, researchers have begun leveraging machine learning to address challenges in the automated design of kirigami, particularly demonstrating significant advantages in modeling and optimizing complex nonlinear systems [261–265]. For kirigami structures, traditional simulation methods often require substantial computational resources and time due to their intricate geometric deformations and multi-physics coupling characteristics. Machine learning, through a data-driven approach, can accelerate the simulation process and enhance prediction accuracy. For instance, Alderete et al. proposed a machine learning-based framework for designing and controlling shape-programmable 3D kirigami metamaterials [259]. By integrating cluster analysis, Tandem Neural Networks, and symbolic regression analysis, they successfully achieved inverse design of kirigami structures (Fig. 17h). This approach not only reduces the number of iterations required in traditional simulations but also enables the rapid generation of kirigami structures that meet specific design requirements. Additionally, they designed various kirigami structures, including linearly deformable structures for light modulation and nonlinearly deformable structures for mechanical gripping, and experimentally validated that the deformation behaviors of these structures align closely with simulation predictions. These advancements underscore the immense potential of machine learning in kirigami design, particularly in addressing complex nonlinear deformations and multi-objective optimization problems.

Simulation calculations provide a visual reference for experimental research. However, in order to improve the accuracy of simulation results, model establishment must align with actual experimental setups. This requires not only reasonable analysis steps, such as boundary condition settings that introduce small perturbations to induce out-of-plane deformations, but also appropriate mesh partitioning, which demands researchers to be experienced and thoroughly understand various experimental factors. Additionally, selecting the right simulation software is crucial to meet diverse research needs. Midas NFX, with its user-friendly interface, is ideal for beginners and excels in linear static and dynamic structural analyses but struggles with highly nonlinear or complex multi-physics problems. ANSYS, known for robust multi-physics capabilities, is suited for complex systems but requires significant learning and computational resources. COMSOL offers exceptional multi-physics coupling, flexible modeling processes and an intuitive interface but may lack the solver stability and efficiency of Abaqus for highly nonlinear or large deformation problems. Abaqus, despite its steep learning curve and significant computational resource demands, excels in nonlinear mechanics and large deformation analyses, making it the preferred choice for simulating kirigami structures' nonlinear behaviors. Researchers should choose software based on specific needs, leveraging each tool's strengths to ensure accurate and practical results. At the same time, the integration of machine learning techniques into kirigami simulations offers a promising avenue for addressing the challenges posed by complex nonlinear systems. This synergy between traditional simulation methods and machine learning not only accelerates the design process but also opens up new possibilities for the automated and intelligent design of kirigami-based devices, paving the way for more innovative and efficient solutions in the field.

In summary, simulation is not only a helpful tool but an essential component in the early-stage design and evaluation of kirigami-based medical devices. Accurate modeling enables researchers to predict structural responses under physiological loading conditions, explore parameter variations efficiently, and optimize designs before physical prototyping. Without simulation, the development process risks being prolonged and less efficient, as design iterations would rely heavily on trial-and-error experimentation. Therefore, incorporating computational simulation into kirigami device development is very necessary for achieving both performance reliability and research efficiency.

## 7. Summary and outlook

This paper reviews the various applications of kirigami technology in the medical field, demonstrating its extensive use in both *in vitro* and *in vivo* medical devices through unique geometric cutting techniques combined with advanced materials and manufacturing technologies. Whether in health monitoring devices, power supply systems, or therapeutic equipment, kirigami technology endows the core components with exceptional stretchability, enabling them to easily deform into 2D curved surfaces or complex 3D structures. Moreover, simulation approaches and intelligent system about kirigami technology were also discussed, showcasing the breadth and depth of this rapidly developing area. Although studies have already demonstrated that different kirigami patterns will result in corresponding 2D/3D reconstruction effects, there is still a lot of research to be carried out in the future, to further advance this promising field.

Despite the promising adaptability of kirigami structures, challenges related to stability, material compatibility, and functional integration remain. Identical cutting patterns may lead to uncontrolled structural deformation due to variations in size, arrangement, and material properties, complicating design optimization. Kirigami structures also show insufficient dynamic adaptability in complex physiological environments, where delayed material responses or mechanical failure may compromise functional stability. Moreover, the field lacks systematic research on multiscale coordination between macroscopic deformation and microscopic functions such as drug release, which limits therapeutic precision. As kirigami research expands, a broader range of materials, including biodegradable, conductive, and responsive substrates, has been introduced, but these materials often face compatibility issues with manufacturing processes. For instance, UV laser cutting may damage soft substrates or degrade bioactive components. In such cases, CO2 lasers might be a better choice. These issues highlight the need for more complete and tunable fabrication strategies. Building on this foundation, further development of reconfigurable 3D kirigami structures such as programmable stents, microneedles or drug carriers offers valuable potential, though such efforts are still at an early stage and require deeper investigation.

While structural simulation has played a key role in guiding kirigami device design, most existing studies remain focused on mechanical deformation parameters such as stress and strain. However, functional simulations involving conductivity, thermal transport, or controlled drug release remain relatively underdeveloped. This gap between mechanical modeling and functional outcomes limits the predictive power of current design approaches. To solve this problem, future research should give more consideration to multi-physics field simulation that combines biological, electrical and chemical parameters under real physiological conditions. Such efforts could bridge the gap between theoretical assumptions and clinical performance, ultimately enhancing the development and translation of functional kirigami-based medical systems.

Finally, the integration of intelligent technologies with kirigami structures presents enormous opportunities for medical and healthcare applications. Human-machine interaction systems based on kirigami sensors can provide greater convenience in daily life. Kirigami soft gripper can precisely grasp tiny items or hazardous materials, offering more precise and safer guarantees for medical applications. However, their applications in the healthcare field remain underdeveloped. Moreover, kirigami soft robots are evolving towards miniaturization and wireless actuation, and have achieved remote control from outside the body through integrated control devices. However, there is currently limited research on their application *in vivo* devices. And many untethered robots driven by stimuli such as light, magnetism, or electricity often require strong magnetic fields or high voltages, which can cause certain adverse effects on the human body. At the same time, how to realize the two-way information interaction between the device and the human body is still a key bottleneck in the development of intelligence. The future development trend of medical devices based on kirigami technology will be interdisciplinary, integrated, intelligent, and digital. Addressing numerous challenges will require the collaborative efforts of scientists and engineers from various disciplines to provide new breakthroughs for the advancement of kirigami smart technologies, thereby enabling their broader application in the healthcare field.

## CRediT authorship contribution statement

**Fengqin Li:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization. **Yang Zhou:** Writing – original draft, Data curation. **Yuxue Hu:** Writing – review & editing. **Xiaoming Feng:** Supervision, Resources, Project administration. **Guizhong Tian:** Supervision, Resources.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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