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Review

Improving mechanical energy harvesters without complex fabrication using origami/kirigami

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THE BIGGER PICTURE Origami and kirigami structures can improve the performance and durability of devices, and even enable new functionalities without the introduction of new materials or components. Piezoelectric energy harvesters (PEHs) and triboelectric nanogenerators (TENGs) are devices that can convert mechanical energy to electricity, with PEHs relying on material deformation and TENGs on interlayer contact. Origami and kirigami techniques can help explore the geometrical possibilities of deformation and multilayer stacking to enhance the performance of PEHs and TENGs. This review highlights the use of these techniques in different kinds of PEHs and TENGs in situations ranging from wave energy-harvesters to self-powered implantable medical devices. The field-independent nature of origami/kirigami techniques means they can be applied across different scales and environments.

SUMMARY

Various strategies, spanning from material to structural perspectives, have been explored to enhance the mechanical and electrical attributes of energy harvesters. Compared to traditional strategies, origami/kirigami-based design strategies can enhance the mechanical integrity and device performance without the introduction of new components or materials. This review discusses origami/kirigami-based energy harvesters and their applications, emphasizing the contributions of these structures in enhancing energy output performance and showcasing their prospects spanning a wide scale and varied environments, from floating ocean energy harvesters to implantable medical devices.

INTRODUCTION

Piezoelectric energy harvesters (PEHs) and triboelectric nanogenerators (TENGs)[1–3] are representative technologies for harvesting and utilizing mechanical energy capable of converting random and irregular external mechanical energy into electrical energy. PEHs rely on piezoelectric transduction to harvest energy from mechanical vibrations or deformations, which generate electric charges in piezoelectric materials under compression or tension, converting mechanical energy into usable electric power. In comparison, TENGs use the triboelectric effect for power generation, which operates by utilizing the coupling of triboelectric charging and electrostatic induction in their layered structure to produce electric signals.

The operating mechanism of the PEHs is based on the positive piezoelectric effect of a piezoelectric material, which converts the energy of vibrations in a given environment into electrical energy. When vibrational waves or an external force in the environment is applied to a piezoelectric material, the material deforms and generates voltages on its surface. These voltages are converted and processed by energy-harvesting circuits into a stable direct current (DC), which ultimately powers low-power devices such as wireless sensor network nodes.[4–7] To expand the application scenarios of energy harvesters, researchers have devoted huge efforts to the innovation of nanoscale generators. In 2006, Wang et al. developed the first piezoelectric nanogenerator (PENG) using piezoelectric zinc oxide nanowire arrays to convert nanoscale mechanical energy into electrical energy.[8] A year later, they systematically proposed the original piezoelectric electronics concepts and fundamental theories.[9] Until 2012, Wang et al. creatively constructed the TENG prototype,[10] in which the operating principle is related to the contact electrification and electrostatic induction phenomena. When two materials rub against each other, electrons are transferred from one to the other, creating charge differentiation and an electrical potential difference between them. By connecting external circuits, the collection and application of electrical energy can be achieved.[11,12] To enhance the overall performance of the

TENGs, many optimization methods have been proposed and developed.[13–16]

There are several optimization strategies for energy harvesters regarding device design: (1) selecting and synthesizing functional materials, e.g., creating materials with better piezoelectric or triboelectric properties,[17,18] exploring synthetic composite materials,[19–21] and conducting interface modifications.[22–24] (2) Improving the structural characteristics of energy harvesters to increase the sensitivity and efficiency of the devices.[25–28] (3) Designing energy harvesters with multiple functions in a single device to enhance their modality.[29–31]

Advancements have been achieved through the optimization strategies mentioned above, leading to improved energy-harvesting performance. However, some challenges still need to be tackled to meet the evolving and diverse demands of various applications: (1) traditional energy harvesters have difficulty accommodating the excitations with irregular directions and varying frequencies. (2) The electrical properties of existing materials are not fully harnessed and exploited across diverse application scenarios. (3) The devices designed are generally bulky and require complex manufacturing processes, such as multi-step assembly procedures,[32] which can result in steep tradeoffs in cost and scalability.

To pursue practical applications, energy harvesters aim to make structural changes to accommodate a variety of work requirements. These include minimizing their sizes,[33,34] reducing manufacturing difficulties,[35,36] and transitioning from rigid to flexible structures.[37,38] A basic consensus is that the energy-harvesting field is still in its infancy and calls for further expansion.

Researchers have explored the potential of paper-based energy harvesters, with some instances of their application as sensors.[39–41] At the same time, paper is a flexible material that can be manipulated to form a three-dimensional (3D) structure through specific manipulations without leading to the destruction of the material. Origami/kirigami techniques are used to create complex 3D structures out of two-dimensional (2D) materials, endowing them with desired mechanical properties such as tunable stiffness,[42–44] negative Poisson's ratio,[45–47] and multiple stability.[48–50] While origami relies solely on folding, kirigami incorporates both cutting and folding, providing additional design flexibility. Both origami and kirigami use a blend of flexible and rigid structures, with the folds and cuts serving as the flexible elements while the panels remain rigid. The interplay between flexible and rigid components determines the various properties of the structure. With these beneficial attributes, origami and kirigami structures shine in a wide range of fields and are not limited by size.[51] The voltage output of a PEH is generally related to the mechanical deformation of the piezoelectric material, with greater mechanical stress resulting in a higher generated voltage output. The performance of a TENG primarily relies on the material's surface charge, meaning that a larger surface area enhances the energy output level. Through folding or stretching, origami/kirigami structures allow continuous and large deformations. Moreover, laminated structures with greatly expanded contact areas can be constructed using origami/kirigami, all within the same footprint. The above features of origami/kirigami structures can be potentially leveraged in developing energy harvesters, addressing the limitations mentioned above and improving performance. Hence, investigating origami/kirigami structures represents a promising avenue for advancing future energy-harvesting technologies.

There are currently numerous outstanding studies in the interdisciplinary field on the contribution of origami/kirigami structures to energy harvesters, and many breakthroughs have been made in enhancing output performance and application potential. This paper reviews origami/kirigami-based energy harvesters and their applications, summarizing recent results in this area and highlighting the suitability of origami/kirigami structures for energy harvesting. A collection of representative origami/kirigami-based energy harvesters are shown in Figure 1, and the rest of this paper is structured as follows. In the sections "origami-based energy harvesters" and "kirigami-based energy harvesters," origami/kirigami-based energy harvesters are reviewed and categorized into two camps, i.e., origami-based energy harvesters and kirigami-based energy harvesters. In the section "application of origami/kirigami-based energy harvesters," the applications of origami/kirigami-based energy harvesters are discussed and categorized into three main categories: self-powered sensors, ocean energy, and medical devices. Finally, this research field is summarized and potential future directions are discussed.

ORIGAMI-BASED ENERGY HARVESTERS

The main advantage of the origami structure lies in its ability to drive the system with minimal stimulus, as the energy stored in the folds of the mountains and valleys between the two faces provides the structural elasticity to restore the original configuration. The concept of combining a flexible stacking structure with TENG was initially proposed by Bai et al.[65] This stacking structure has demonstrated the potential to enhance the output energy,[66–68] making it a prominent area of research focus. This section briefly introduces the basic concepts of origami and then summarizes the categories based on the types of origami structures.

The theory of origami structure

An introduction to the basic terminology of origami structures is necessary for understanding, learning, and digging into the technique of origami. This paper introduces the basic concepts of origami using a simple crease diagram (Figure 2A). The crease diagram determines not only the aesthetics but also the movement pattern of the paper as it unfolds and compresses. Each crease diagram can be uniquely defined by the corresponding creases, vertices, and faces.[69] A crease is a line segment produced on a paper surface by the operation of folding. When the paper is fixed in a Cartesian coordinate system, if the sides of the paper are folded in a negative direction toward the z axis, the crease formed protrudes upwards; such a crease is known as a mountain crease, and conversely, it is known as a valley crease.[70] Mountain creases and valley creases are normally represented by different lines in a crease diagram. The intersection point where the different folds converge is known as the vertex.

The development of origami has two important historical moments[71]: the provision of a unified origami symbol and the

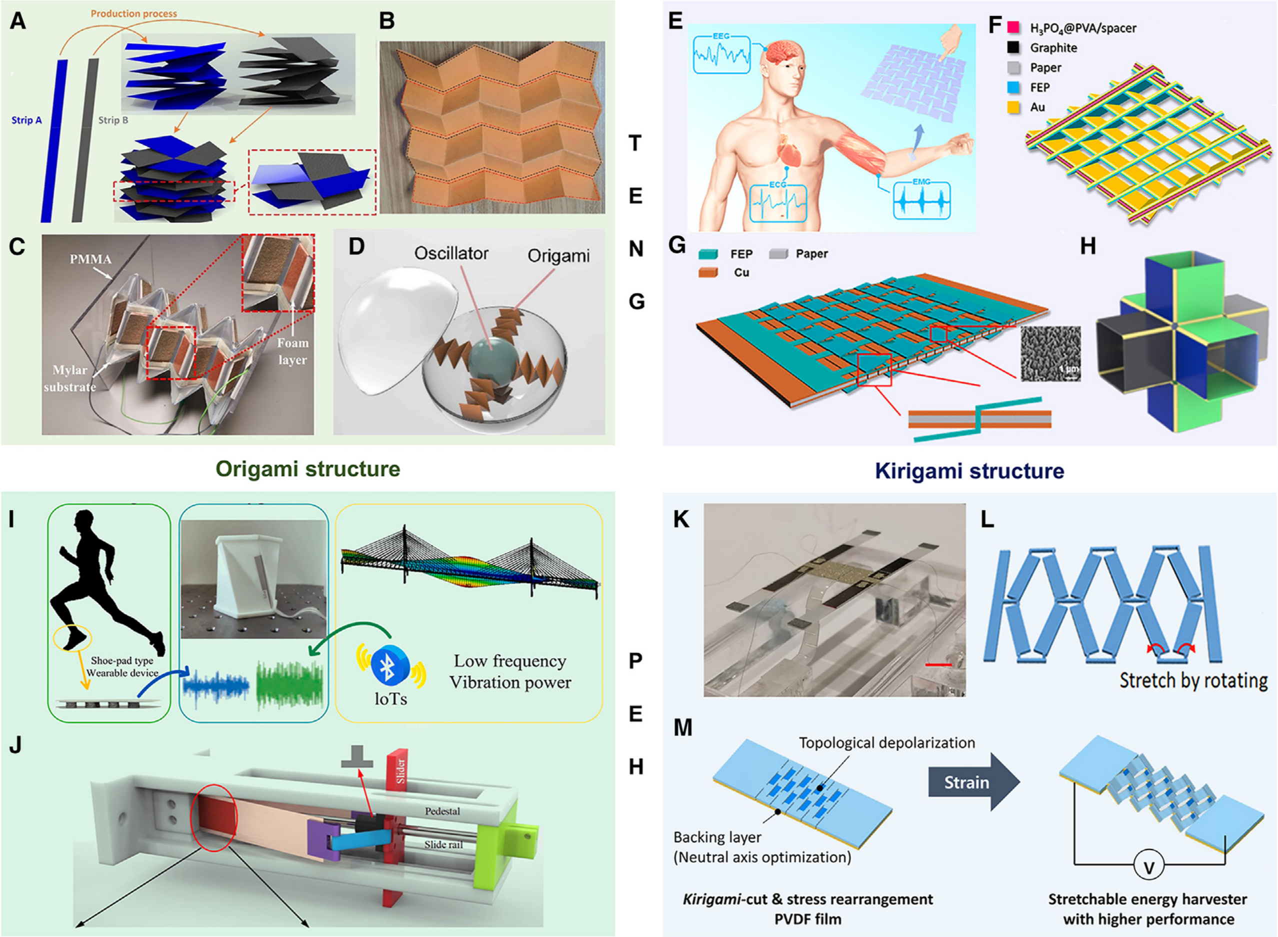

Figure 1. Instances of origami/kirigami-based energy harvesters, achieved through the utilization and integration of origami and kirigami techniques

(A) Schematic of a TENG with an origami-inspired structure.[52]
(B) Schematic of an instant-noodles-powder-based paper TENG with a Miura folding.[53]
(C) Schematic of a TENG based on a Miura-folded tubular structure.[54]
(D) Schematic illustration of spherical TENGs.[55]
(E) Diagram of e-skin combined with TENG.[56]
(F) Schematic of an ultralight paper-cut-based self-charging power unit.[57]
(G) Schematic of paper-based TENGs made of stretchable interlocking kirigami patterns.[58]
(H) Schematic of the rotation-folding kirigami TENG.[59]
(I) Schematic application of the bistable origami electricity generator.[60]
(J) Physical model diagram of the ori-inspired bistable PEH.[61]
(K) Schematic of an energy-harvesting system using a 3D, structurally tunable platform.[62]
(L) Schematic of a stretchable kirigami PENG using a 3D printing process.[63]
(M) Schematic of a portable stretchable PEH (SPEH) using a kirigami structure.[64]

introduction of mathematical theory into the art of origami. In the mid-20th century, mathematicians discovered that paper could be stacked multiple times, enabling it to transform into models of various shapes and structures. This discovery provides new methods for the manufacturing, assembly, and deformation of equipment and structures based on the origami principle. Hence, the mathematical theory is the foundation and the key to the research and development of origami structures.

The construction of folding diagrams requires the observance of certain conditions, such as the Huzita-Hatori axiom, Maekawa theorem, and Kawasaki theorem. These basic principles define the necessary conditions for the collapsibility of partial planes in any given design. The Huzita-Hatori axiom is the most important and fundamental rule in origami, which describes all mathematical operations that can be achieved through origami using points and lines. The line is the crease or boundary of the paper, and the point is the intersection of two straight lines. The axioms are as follows[72]: (1) given two distinct points $p_1 = (x_1, y_1)$ and $p_2 = (x_2, y_2)$, there is a unique fold l that passes through both of them (Figure 2B). (2) Given two distinct points $p_1 = (x_1, y_1)$, $p_2 = (x_2, y_2)$,

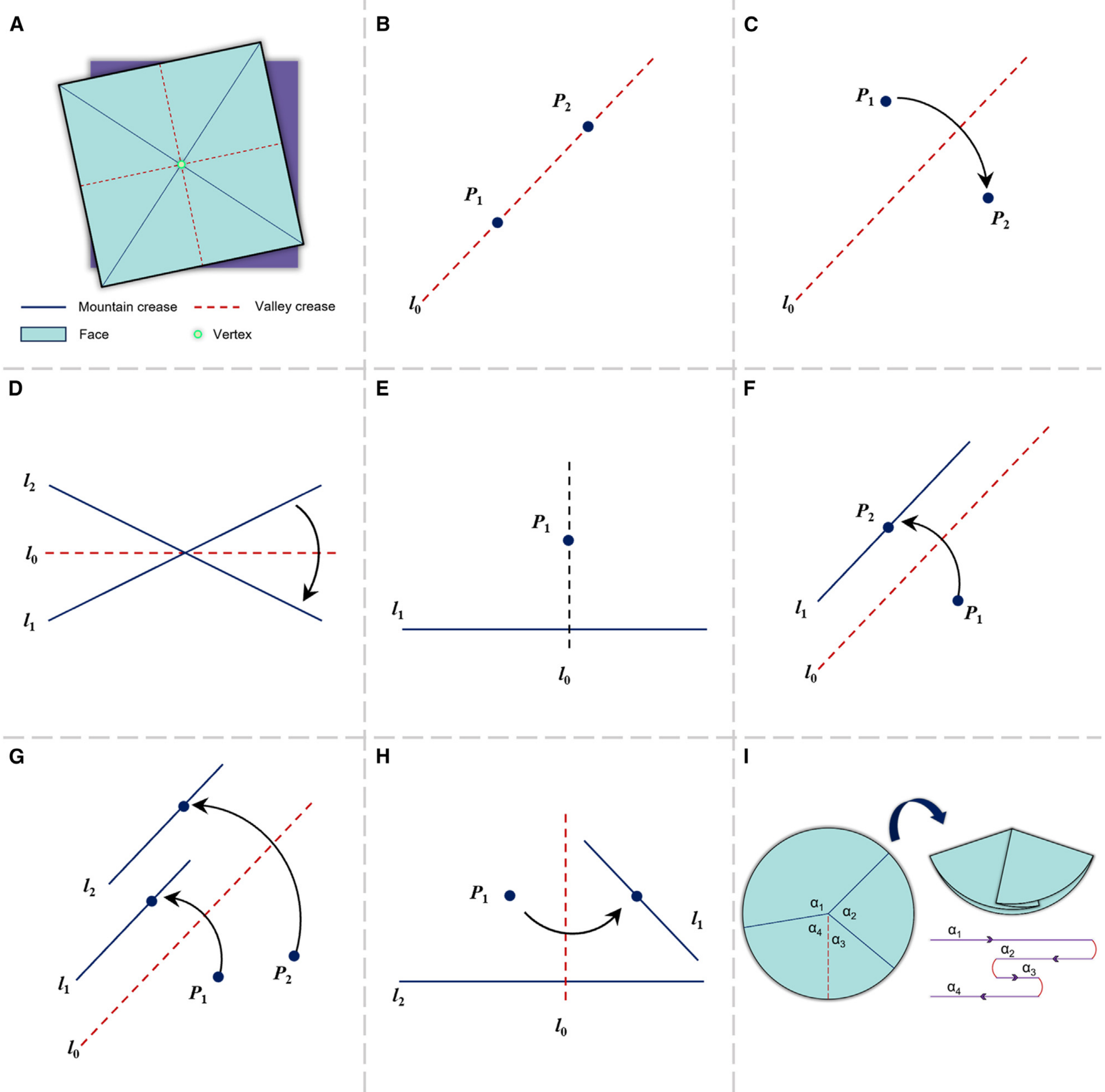

Figure 2. Schematic diagram of basic concepts of origami

(A) Schematic of a simple crease diagram illustrating various origami concepts.
(B) Image representation of Huzita-Hatori axiom 1.
(C) Image representation of Huzita-Hatori axiom 2.
(D) Image representation of Huzita-Hatori axiom 3.
(E) Image representation of Huzita-Hatori axiom 4.
(F) Image representation of Huzita-Hatori axiom 5.
(G) Image representation of Huzita-Hatori axiom 6.
(H) Image representation of Huzita-Hatori axiom 7.
(I) Image representation of the flat-foldability theory.

there is a unique fold l that places p_1 onto p_2 (Figure 2C). (3) Given two lines l_1 and l_2, there is a fold l that places l_1 onto l_2 (Figure 2D). (4) Given a point p_1 and a line l_1, there is a unique fold l perpendicular to l_1 that passes through point p_1 (Figure 2E). (5) Given two points p_1 and p_2, and a line l, there is a fold l that places p_1 onto l_1 and passes through p_2 (Figure 2F). (6) Given two points

p_1 and p_2 and two lines l_1 and l_2, there is a fold l that places p_1 onto l_1 and places p_2 onto l_2 (Figure 2G). (7) Given a point p_1 and two lines l_1 and l_2, there is a fold l that places p_1 onto l_1 and is perpendicular to l_2 (Figure 2H).

The ability of an origami structure to be completely flattened to a plane in the folded state, known as flat foldability, resulting in multiple overlapping panels involved in the structure,[73] is highly compatible with TENGs. The origami-multilayer design can help enhance the contact triboelectrification effect and the capacitance variation of electrostatic induction. When exploring the flat foldability of origami structures, it is important to consider the following two theorems[71]: (1) the Maekawa theorem states that, at every vertex, the number of mountain and valley folds always differs by two. (2) The Kawasaki theorem state that the sum of alternating angles around a vertex always equals 180°. Kawasaki's theorem is a necessary and sufficient condition for determining collapsibility, while Maekawa's theorem is only a necessary condition.[74] To be more specific, these theories are graphically illustrated in Figure 2I.

Miura-origami-based energy harvesters

Origami tessellation is an origami model with a periodic crease pattern that allows flat surfaces to be transformed into a variety of continuous 3D patterns by deformation operations such as bending and folding.[75] The most typical case of the origami tessellation model is the Miura origami. The Miura-ori pattern is composed of a series of grid-aligned parallelograms. These parallelograms are interconnected through alternating mountain and valley folds, resulting in a zigzag crease pattern. The folded parallelograms form a smooth and continuous tessellated surface, which ensures both the compactness of the structure and its ease of deployment. To facilitate the exploration of Miura origami structures by later researchers, this subsection first introduces the geometric parameters of the single-cell structure of Miura, as its geometric parameters determine the mechanical properties of the structure. The single-cell structure of a classical Miura is shown in Figure 3A. When the lengths a and b of the folds, the angle α between the folds, and the dihedral angle θ of the Miura origami unit are determined, its height h, dihedral angle γ, and the external dimensions u, l, and w of the unit in a partly folded state can be determined. The following equations describe these relationships between the above variables[76,77]:

$$\begin{cases} h = a \sin\alpha \sin\theta \\ \gamma = 2\arcsin\dfrac{\cos\theta}{\sqrt{1-\sin^2\theta\sin^2\alpha}} \\ w = 2b\sin\alpha\sin\left(\dfrac{\gamma}{2}\right) = \dfrac{2b\sin\alpha\cos\theta}{\sqrt{1-\sin^2\theta\sin^2\alpha}} \\ l = 2\sqrt{a^2-h^2} = 2a\sqrt{1-\sin^2\theta\sin^2\alpha} \\ u = b^2-\left(\dfrac{w}{2}\right)^2 = \dfrac{2ab\cos\alpha}{l} \end{cases} \tag{Equation 2.1}$$

The Miura origami is characterized by its ability to swiftly transform from a flat, unfolded state to a compact configuration and subsequently unfold back to its original flat shape. This distinctive property renders Miura origami highly versatile for designing spatially folded structures and expandable objects. The diverse applications of Miura origami have been used in folding solar panels,[80] energy absorption,[81] and robot devices.[82,83] Meanwhile, this structure with multiple creases and contact points provides suitable conditions for contact and operation of TENGs.

The lack of stiffness of the paper and the inability of some origami patterns to provide sufficient space for all the tribo-pairs to be located on the same layer prevented the pairs from making contact and separating at the same time, whereas the Miura pattern provided more space for the tribo-pairs to be on the same layer, improving the problem of unsynchronized movement. Zhang et al.[78] designed an origami tessellation-based TENG (OT-TENG) with an arc pattern and a Miura origami tessellation-based TENG, which were fixed between two acrylic plates, and tested the performance, as shown in Figure 3B. The experiments showed that the Miura OT-TENG has a better voltage output performance over the arc pattern OT-TENG when multiple tribo-pair subsets are connected in series or parallel to generate electricity.

The energy harvesters inspired by Miura origami demonstrate remarkable adaptability, enabling the arrangement pattern of the support material or triboelectric material to be modified as needed. Xie et al.[53] proposed an instant-noodles-powder-based paper TENG with a Miura folding. Instant-noodle powder and polytetrafluoroethylene (PTFE) tape were employed as the triboelectric pairs, and paper was used as the supporting structural material. It was shown that the device can output different voltage signals depending on the received force and the operation time. The device was manufactured with green materials as the friction sub-material, which greatly reduced environmental pollution. Zargari et al.[54] proposed a TENG based on a Miura-folded tubular structure (Miura-Ori-TENG), as shown in Figure 3C. They used a Mylar film instead of paper as a flexible support structure for the TENG, providing it with high flexibility and durability. Li et al.[84] proposed a Miura-folding-based TENG with charge excitation (MF-CE-TENG). It has two working sides: one side of the device acted as the main TENG, and the other acted as the excitation TENG, which was used to replenish the charge in the main TENG. The optimum output charge and maximum peak power of the MF-CE-TENG were 4.61 and 10.55 times higher than those of the Miura-folding TENG without charge excitation. Pongampai et al.[85] presented a Miura-origami-inspired composite TENG simultaneously combined with an electromagnetic nanogenerator (MO-CTENG-EMG). A composite material based on bacterial cellulose (BC) and $BaTiO_3$ nanoparticles (BT-NPs) was used in this research. The electromagnetic part was realized by designing a lightweight cylindrical tube and a magnetically levitated structure. The hybrid system was experimentally demonstrated to be capable of charging a wireless GPS device by human shaking.

TENGs are usually affected by environmental variables, especially in humid environments where liquids can dissipate the charges generated by the friction of electrical materials, thereby limiting the performance of the TENG.[86] In severe cases, they can even lead to corrosion of the frictional electrical materials. Ocean energy has become a hot topic in current scientific research, and ensuring the performance of TENG and improving its watertightness is at the heart of this hot topic. In the past, many scientists

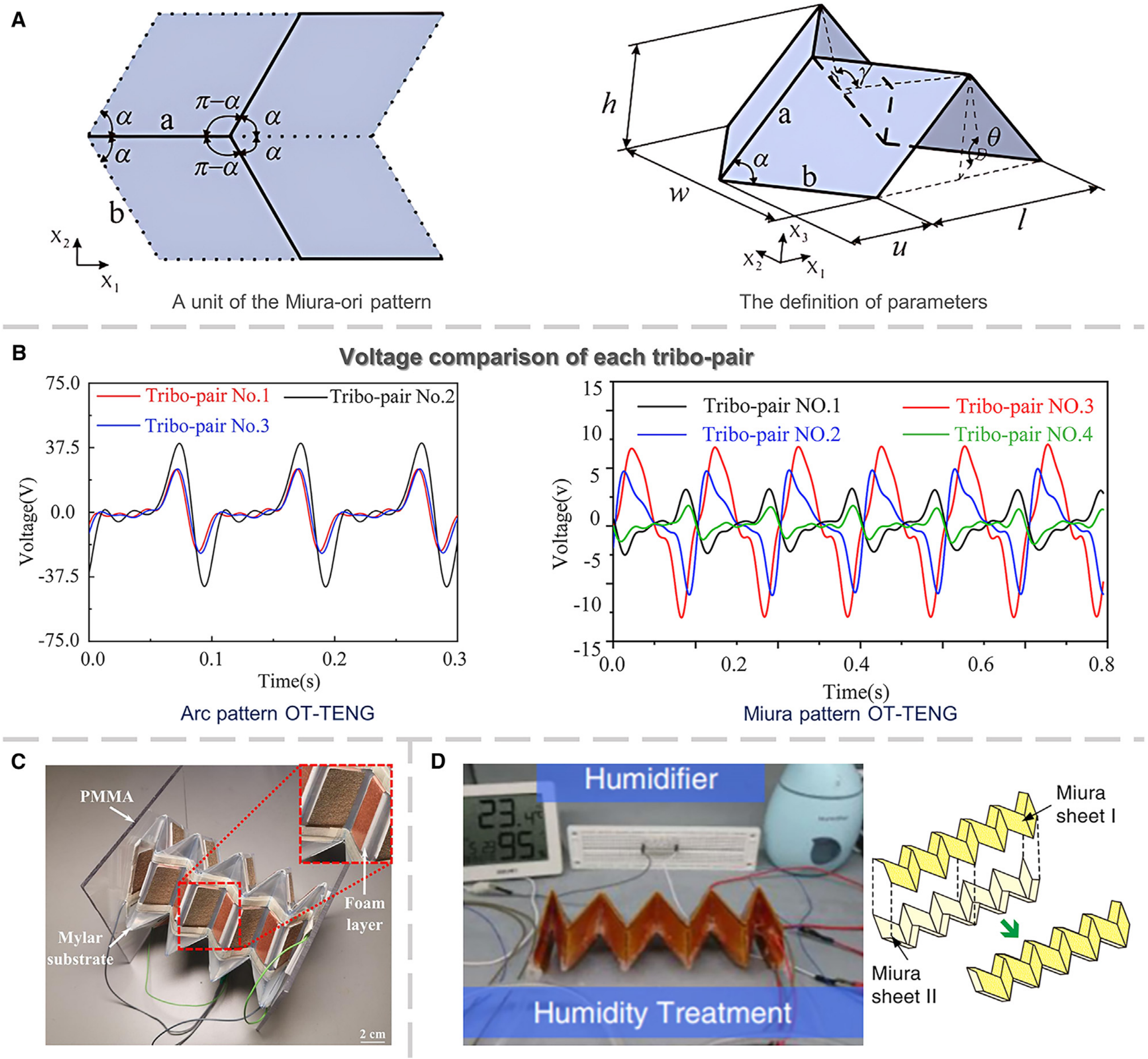

Figure 3. Schematic diagram of Miura origami and its mechanism

(A) Schematic of a single Miura origami unit and its corresponding geometric representation of the crease pattern.[77]

(B) Schematic of an origami tessellation-based TENG.[78]

(C) Schematic of a TENG based on a Miura-folded tubular structure.[54]

(D) Schematic of an origami-inspired W-tube-shaped TENG.[79]

have tried to make breakthroughs in materials, but it is difficult to produce frictional electrical materials that are completely waterproof and have excellent properties. The advent of encapsulation technology has provided new inspiration.[87,88] The origami structure can encapsulate the power-generation structure for protection without requiring complex procedures. Tao et al.[79] designed a fresh origami-inspired W-tube-shaped TENG (W-TENG) consisting of two thin-film electrets folded based on Miura origami, and its structure is shown in Figure 3D. The device overcomes the problem of poor charge survival and stability of triboelectric devices in humid environments by sealing the power-generating components inside the tube. In a controlled environment with 95% humidity, the W-TENG exhibited superior performance compared to an unprotected TENG, highlighting its effectiveness in mitigating environmental challenges.

Waterbomb-origami-based energy harvesters

The waterbomb-origami structure is a single vertex-driven bistable model.[89] The traditional waterbomb base is created from a square sheet of paper with eight folds: four mountain

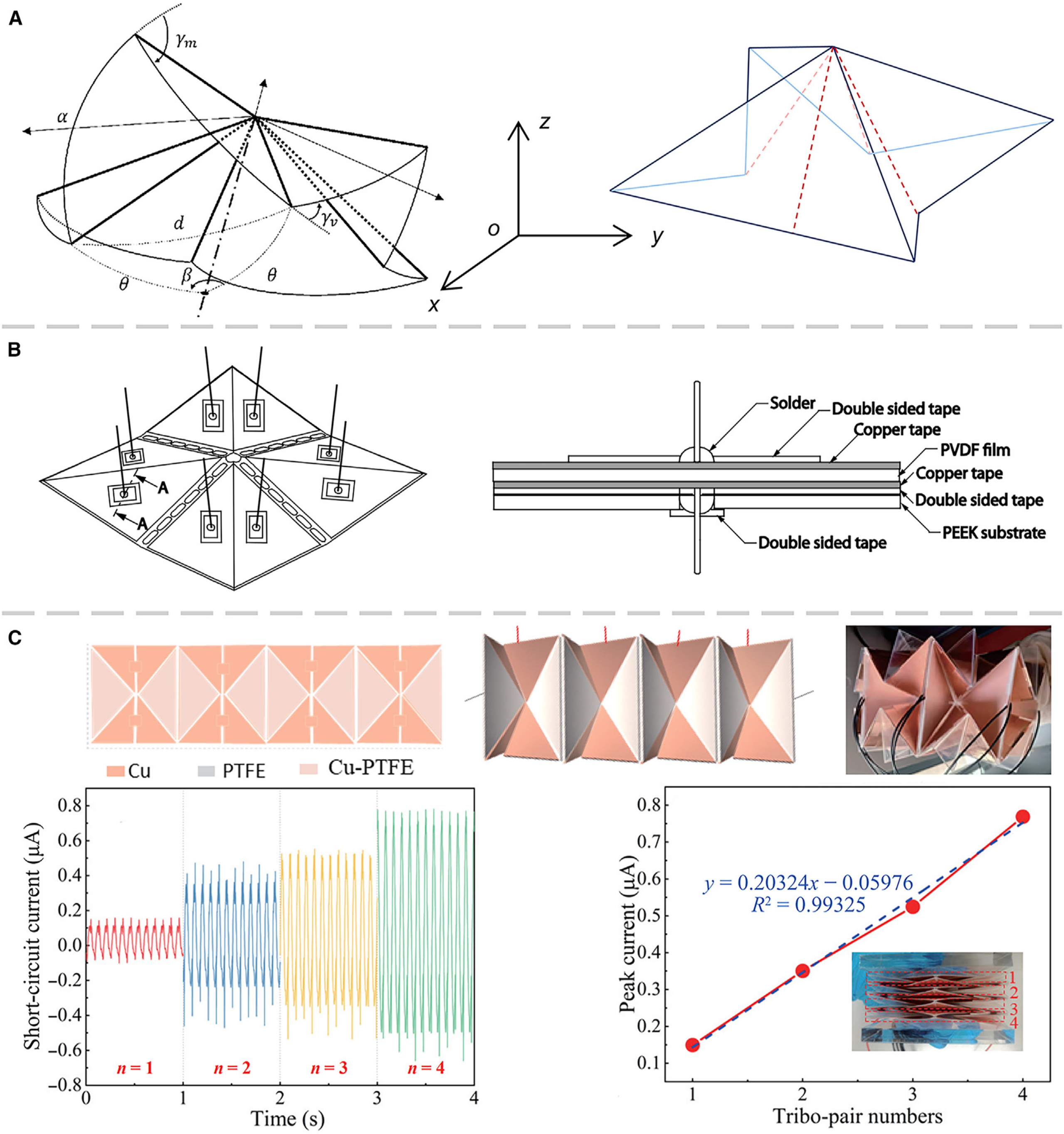

Figure 4. Schematic diagram of waterbomb origami and its mechanism

(A) Parametric diagram of the waterbomb unit[92] and 3D model of the waterbomb unit.

(B) Schematic of energy harvester based on a waterbomb-origami mechanism.[93]

(C) Schematic of a waterbomb-origami-inspired TENG and the influence of tribo-pair number on current.[94]

folds and four valley folds, alternating around the central vertex. In contrast, the generalized waterbomb base maintains the alternating pattern of mountain and valley folds around the central vertex but is not restricted to only eight folds. Due to its simple geometric features and multiple modes of motion ranging from simple to more complex, the waterbomb-origami structure shows potential to acquire new properties through geometric design alone, without altering the materials,[90] and may facilitate the development of self-regulating systems. The geometric model of the waterbomb is shown in Figure 4A, and its geometric parameters can be expressed by the following equation[91,92]:

$$\begin{cases} \alpha = 180^\circ/n \\ \beta = 360^\circ/n \\ 0 \le \theta \le 180^\circ - \alpha \end{cases} \qquad \text{(Equation 2.2)}$$

The parameter n is used to indicate the number of mountain folds (or valley folds) present in the folded state; e.g., a waterbomb of n degrees means a waterbomb with n mountain folds or valley folds. α is the facet sector angle, β represents the angle between two adjacent folds of the same type, and θ is the angle between the fold and the central axis.

The type of fold in the mountain range or valley depends on the slope angle at the fold, which can be defined by the following equation:

$$\begin{cases} \gamma_{\mathrm{m}} = -180^\circ + \cos^{-1}\left(1 + \dfrac{\cos d - 1}{\sin^2 \alpha}\right) \\ \gamma_{\mathrm{v}} = \begin{cases} -180^\circ + 2\cos^{-1}\left(\cot \alpha \tan \dfrac{d}{2}\right) + 2\cos^{-1}\left(\cot \theta \tan \dfrac{d}{2}\right), \text{if } \theta \le 90^\circ \\ 180^\circ - 2\cos^{-1}\left[(\cos d - 1)\dfrac{\cot \theta}{\sin d}\right] + 2\cos^{-1}\left(\cot \alpha \tan \dfrac{d}{2}\right), \text{if } \theta > 90^\circ \end{cases} \end{cases} \qquad \text{(Equation 2.3)}$$

where γ_m and γ_v represent the dihedral angle at the mountain crease and the dihedral angle at the valley crease, respectively, and d, θ, and α are the sector angles. The parameter d can be further expressed as:

$$d = \cos^{-1}\left[\cos^2 \theta + \sin^2 \theta \cos \beta\right] \qquad \text{(Equation 2.4)}$$

When the system receives vibrational excitation, the same origami mechanism can adapt to different energy harvesters depending on the direction in which it is compressed and stretched. When the waterbomb-origami structure moves along the z axis in Figure 4A, i.e., folds in the direction of the crease, the device is more suitable for PEHs because it undergoes strong bending deformation. Ngo et al.[93] presented a vibrating energy harvester based on a waterbomb-origami mechanism through piezoelectric energy conversion, as shown in Figure 4B. This design exploits the bistability of the origami structure to broaden the bandwidth of the frequency response and enable the piezoelectric film to generate high electrical power at large bending deformations. The device's compactness and light weight facilitate easy integration into equipment and stable operation even in low-frequency vibration environments. If the waterbomb-origami structure in Figure 4 is shifted along the x or y axis, the panels between the different folds come into contact, and this will be more suitable for a TENG. Pang et al.[94] designed a novel waterbomb-origami-inspired TENG (WO-TENG), as shown in Figure 4C. The 3D structure of the TENG comprises two sets of 2D origami panels, each featuring four mountain folds and two valley folds, assembled facing each other. When four friction pair units are connected in parallel, the current increases with the tribo-pair number, which means that the WO-TENG has a strong synchronization when subjected to vibration excitation.

Kresling-origami-based energy harvesters

Kresling origami structures use special folds to create curved and undulated shapes, as opposed to the straight lines and angles of traditional origami. Kresling-patterned origami offers the remarkable advantage of scalability and rotational coupling under axial and torsional loads. This means that only moderate plate deformation can compress to a compact state during the folding process. The movement mode allows many devices to exhibit better mechanical performance when combined with this structure.[95,96] Typically, Kresling-patterned origami structures are categorized into two types: triangular cylindrical and conical structures.[97] Most existing studies focused on the cylindrical structure, exploring their benefits to energy harvesters.[98,99]

Kresling origami structure is constructed by dividing a thin, flat, foldable material into n parallelograms, each of which is bisected into two similar triangles,[100] as shown in Figure 5A. This structure can be represented by the following parameters[97]:

$$\begin{cases} L_{\mathrm{AB}} = a \\ L_{\mathrm{AD}} = L_{\mathrm{BC}} = a \sin \alpha / \sin \beta \\ L_{\mathrm{BD}} = a \sin(\alpha + \beta)/\sin \beta \end{cases} \qquad \text{(Equation 2.5)}$$

where a represents the length of the bottom edge of the small triangle, and α and β represent two angles.

After folding, the four-point coordinates of a unit can be represented as

$$\mathrm{A}\left(R \cos\left(\frac{2\pi}{n}\right), -R \sin\left(\frac{2\pi}{n}\right), 0\right)$$

$$\mathrm{B}(R, 0, 0)$$

$$\mathrm{C}(R \cos \varphi, -R \sin \varphi, h)$$

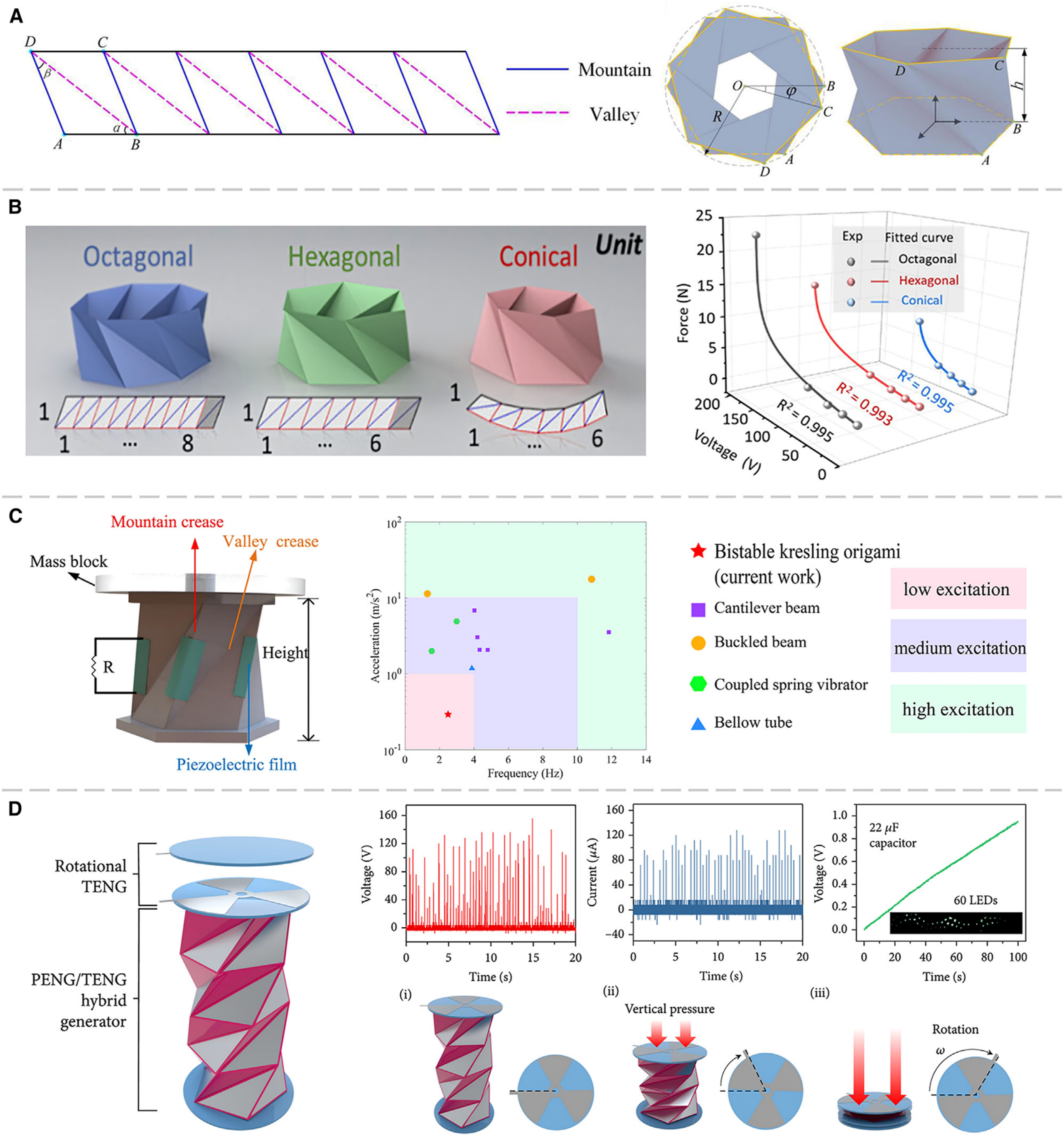

Figure 5. Schematic diagram of Kresling origami and its mechanism

(A) The flat sheet with crease patterns of Kresling origami and its corresponding geometric representation during the folding process.[97]

(B) Schematic of the octagonal, hexagonal, and conical origami units and their peak voltages.[101]

(C) Schematic of a soft bistable electricity generator based on Kresling origami and excitation threshold of inter-well motion for bistable Kresling origami.[60]

(D) Schematic of the model, operating mechanism, and electrical performance of a triangulated cylinder origami-based piezoelectric/triboelectric hybrid generator.[99]

$$\mathrm{D}\left(R\cos\left(\frac{2\pi}{n}+\varphi\right),-R\sin\left(\frac{2\pi}{n}+\varphi\right),h\right)$$

where R, h, and φ represent the radius, height, and twist angle of the folded cylinder, respectively, and n represents the number of edges at the bottom. The lengths of the crease lines are determined by measuring the distance between the coordinate points:

$$\begin{cases} l_{AB} = 2R\sin(\pi/n) \\ l_{AD} = \sqrt{h^2 - 2R^2\cos\varphi + 2R^2} \\ l_{BD} = \sqrt{h^2 - 2R^2\cos(2\pi/n + \varphi) + 2R^2} \end{cases} \quad \text{(Equation 2.6)}$$

According to the above formula, Kresling origami models with different bottoms can be constructed. Jiao et al.[101] introduced origami tribo-metamaterials (OTMs), as shown in Figure 5B. OTMs are designed by integrating triboelectric materials into origami-enabled tubular metamaterials with octagonal, hexagonal, and conical origami units. In particular, the octagonal OTM exhibits a high correlation in force-voltage, force-current, and force-charge relations, achieving a peak open-circuit voltage (V_{OC}) of 206.4 V and a short-circuit current (I_{SC}) of 4.66 μA. The Kresling structure undergoes deformation when driven, which is also applicable to PEHs. Huang et al.[60] presented a flexible bistable energy harvester utilizing Kresling origami, as depicted in Figure 5C. This design combines the elastic potential energy of the origami structure with the gravitational potential energy of a top mass, resulting in the formation of two asymmetric potential energy wells. The unique bistable Kresling origami structure enables the device to engage in inter-well motion at low frequencies and accelerations, distinguishing it from other components. Furthermore, the study demonstrates the harvester's capability to effectively power LCD electronic clocks and UV sensors.

This multi-degree-of-freedom origami model allows different types of nanogenerators to be integrated into a single device. Hybrid nanogenerators, which harvest mechanical energy from the environment through multiple energy-conversion mechanisms, represent a novel approach to address energy scarcity and improve energy efficiency by utilizing multiple energy sources concurrently or individually through diverse mechanisms.[102] Chung et al.[99] designed a triangulated cylinder origami-based piezoelectric/triboelectric hybrid generator (TCO-HG) using a Kresling structure, as shown in Figure 5D. The device integrates a vertical TENG, a rotating TENG, and a PENG. When the TCO-HG is compressed, it collapses in the vertical direction while rotating around the vertical axis, at which point the hybrid nanogenerator is activated and outputs a voltage. By combining the generator with a rectifier circuit, the TCO-HG assembly has a peak V_{OC} of 120 V and a peak closed-circuit current of 90 μA. The TCO-HG has excellent structure stability and can charge a commercial 22-μF capacitor and power 60 light-emitting diodes (LEDs). The design is inspired by Kresling origami techniques possesses the potential to effectively address and mitigate the following limitations commonly associated with conventional hybrid nanogenerators: (1) the performance of TENGs may be reduced by the addition of piezoelectric materials. (2) The design of conventional hybrid nanogenerators requires consideration of many factors, such as material selection and structural optimization, which increases the complexity of development and manufacturing. (3) Conventional hybrid nanogenerators result in large devices due to the combination of multiple energy-harvesting mechanisms, limiting the ability of hybrid nanogenerators to operate at miniature scales.

Double-helix origami-based energy harvesters

An origami double-helix structure is a shape constructed using origami techniques that mimic the structure of a double helix commonly found in the biological world, such as the structure of a DNA molecule. The structure typically consists of several interlaced and folded origami sections, creating an elegant and complex design. The origami double-helix structure is formed by folding one or more strips of paper (usually rectangular), as shown in Figure 6A. By folding and rotating the paper strips in a particular way, two or more intertwined spirals can be formed.

With such an ingenious design combined with different materials, numerous energy harvesters inspired by the double-helix origami structure have been created.[105,106] Thakur et al.[107] designed a compact, flexible, and durable 3D TENG fabricated from carboxymethylated cellulose nanofiber (CM-CNF) and perfluoroalkoxy (PFA) films. The CM-CNF/PFA TENG exhibits enhanced output performance through carboxymethylation of the cellulose nanofiber, generating up to 2,000 μW of power. The TENG is capable of driving LEDs. Tao et al.[55] proposed an origami-inspired TENG integrated with a folded thin-film electret. A double-sided corona discharge process was used to maximize the charge density generated by the electret film. The device showed remarkable performance through optimization, achieving an instantaneous V_{OC} of up to 1,000 V only by fingertip excitation. Gao et al.[108] designed a complex double-helix-structured TENG (DHS-TENG). Polyvinylidene fluoride (PVDF) piezoelectric material was fused into the TENG, leading to a notable enhancement in charge density by utilizing a positive charge trap. The tests demonstrated that the TENG output performance increases gradually with the increase in PVDF film thickness. The device also provides sufficient energy for the remote data transmission to a smart home control system within a range of 10 m. Apart from the different materials, Xia et al.[104] proposed an elastic origami structure TENG (EO-TENG) by introducing three components, i.e., a cylindrical shell, an elastic origami frictional electrical element, and an elastic sphere, as shown in Figure 6B. The EO-TENG arrays integrate with a power-management circuit to produce stable DC voltage to an external load and consistent power supply. Pongampai et al.[109] proposed a 3D multilayer origami TENG (O-TENG). The O-TENG integrated three optimization schemes: a multilayer origami-optimized design, physical surface roughness modification, and the attachment of a self-charged pumping module. By combining these three strategies, O-TENG had 18 times higher V_{OC} and 52 times higher I_{SC} than unoptimized polyimide TENG. Liu et al.[103] designed a swinging origami-structured TENG (SO-TENG), as shown in Figure 6C. This novel configuration integrates an oscillating structure with weighted elements at the base, which responds to passing water waves by generating reciprocating motion driven by inertia. This setup not only demonstrates robust power generation in low-frequency water wave environments for electronic devices but also reduces metal corrosion.

As the field of research continues to evolve, scientists have sought to modify the folding techniques for a pair of elongated strips, aiming to increase the efficiency of TENGs by implementing folding methods. Hu et al.[52] designed a novel TENG with an

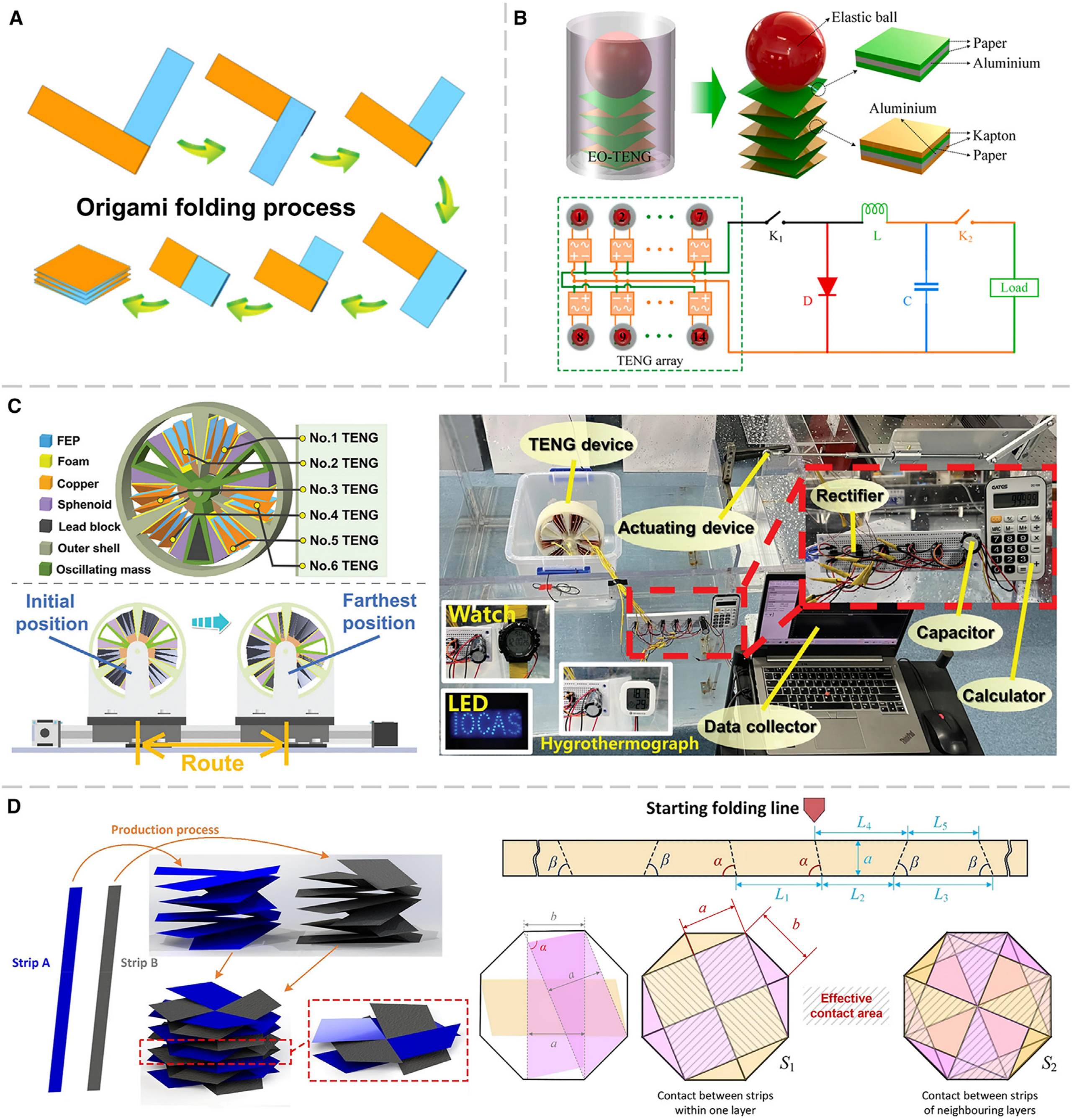

Figure 6. Schematic diagram of double-helix origami and its mechanism

(A) Folding schematic of a double-helix origami structure.[103]

(B) Schematic of an elastic origami structure TENG (EO-TENG) and the power-management circuit for the EO-TENG array.[104]

(C) Schematic of a swinging origami-structured TENG and real testing environment for wave-energy harvesting.[103]

(D) Schematic of a TENG with an origami-inspired structure and representative folding lines of a single strip.[52]

origami-inspired structure, as shown in Figure 6D. Unlike the conventional double-helix structure described above, where the two materials are folded repeatedly, the team first determined the fold line of the slender strip as follows:

$$\begin{cases} L_1 = \left(1+\sqrt{2} - \cot\alpha\right)b \\ L_2 = L_5 = 2a \end{cases} \quad \begin{aligned} L_3 &= 2(1+\cot\beta)a \\ L_4 &= (2+\cot\alpha+\cot\beta)a \end{aligned} \quad \begin{aligned} \alpha &= 78.75^\circ \\ \beta &= 67.5^\circ \end{aligned} \tag{Equation 2.7}$$

where $b = a/\sin\beta$. This design further enhances the effective contact area of the friction pair. The device has been evaluated to have a power output level of 200 μW.

Other origami-based energy harvesters

Origami is a highly creative design, offering a wide array of designs that can be conceived and integrated with energy-harvesting devices. Yang et al.[110] designed a paper-based TENG with a slink origami structure. The structure consists of seven parallel units, each of which consists of paper, PTFE, and aluminum foil. The experiments of the TENG output I_{SC} and V_{OC} were measured up to 2 μA and 20 V, respectively. The power density of 0.14 W m^{-2} was obtained under a load resistance of 400 MΩ. Kim et al.[111] presented a foldable paper-based TENG (FP-TENG) with a sandwich structure and demonstrated its versatility by powering a wristwatch and LEDs. It can act as a wristband, generating power by tapping with the hand and delivering it to the watch face. With origami flexibility, it can also be formed into different shapes and drive multiple LEDs. In addition to increasing the effective contact areas of TENGs, the origami structure also adds nonlinearity to PEHs, thereby extending their frequency response ranges. The piezoelectric vibrating cantilever beam is a common method in the energy-harvesting device.[112–114] This energy-harvesting method relies primarily on the dynamic bending of the beam during its resonant state. Performance degradation in harvesters due to the mismatch between their frequency response ranges and vibration excitations is one of the pain points of current research. Qin et al.[115] proposed a broadband nonlinear dual piezoelectric cantilever energy harvester coupled with an origami component to overcome the limitations of conventional linear piezoelectric harvesters, such as narrow frequency range and suboptimal energy-conversion efficiency. The origami structure is introduced to achieve dynamic coupling of two beams and increase nonlinearity, thereby broadening the frequency bandwidth and increasing the output power. The optimal position of the origami structure was investigated, and the origami structure exhibits superior performance when positioned near the free end of the cantilever beam. Table 1 compares the output performance of the featured origami-based energy harvesters.

KIRIGAMI-BASED ENERGY HARVESTERS

Kirigami essentially releases constraints by deliberately breaking the C^0 continuity. C^0 continuity, which dictates that any curve on a deformed sheet must be continuous, imposes strict limitations on potential shapes.[118] Introducing kirigami patterns in functional nanocomposites can enhance material flexibility and stretchability, maintaining resilience against mechanical fractures and electrical malfunction even under high stretching conditions.[119] Engineers can freely explore different cutting and folding techniques tailored to specific needs, allowing for the development of distinctive shapes and structures. This flexibility offers solutions to complex engineering problems in real-world applications.[120,121] The fundamental elements of kirigami typically include cutting patterns, nodes, units, and geometric designs. These elements play a crucial role in shaping the structure, operational characteristics, and functionality of the kirigami after the cutting process. Subsequently, this paper explores and discusses the performance of kirigami-based energy harvesters in two different configurations based on the approach used to convert mechanical energy into electricity.

Kirigami-based PEHs

Kim et al.[122] developed a stretchable energy harvester through the integration of piezoelectric composites and kirigami structures. They demonstrated that the S-PEH can stabilize the output voltage at 150% of the repetitive tensile strain. These findings highlight the potential of utilizing kirigami structures to fabricate cost-effective and efficient stretchable piezoelectric devices. Kirigami structures rely on incisions for their mechanical performance.[123] Fang et al.[124] investigated the effects of introducing architected cuts on the mechanical and piezoelectric properties of piezoelectric polymer thin films. The piezoelectric conversion efficiency can be improved by up to 30% under dynamic loading, enabling energy harvesting from low-frequency mechanical signals or low-velocity winds commonly found in the environment. Increasing the cutting ratio to 0.75 results in a sample that is 15 times more flexible and stretchable while retaining the piezoelectric properties of the uncut material, facilitating the development of wearable and self-powered devices. Cantilever beam-energy harvesters can only harvest energy in a single direction, but PEHs that can harvest energy in multiple directions and under broadband conditions are desired. Sun et al.[62] proposed a new energy-harvesting system using a 3D, structurally tunable platform that incorporates piezoelectric materials into multi-directional structures, as shown in Figure 7A. This system aims to boost energy-harvesting efficiency by enhancing vibration scavenging across a broader frequency spectrum and in multiple directions, with its efficacy verified under specific wind conditions. Han et al.[125] introduced a controlled process to transform lithographically defined planar piezoelectric microsystems into complex 3D frameworks. The authors have created over 20 different 3D geometries to showcase their engineering versatility. They enable multi-directional, broadband, and low-frequency energy harvesting, mechanical-to-electrical energy conversion, intensity sensing, and biomechanical energy harvesting and sensing.

Several researchers have undertaken optimizations and modifications to tailor the kirigami structure for energy-harvesting applications. Zhou et al.[63] presented a novel approach to fabricate a stretchable kirigami PENG using a 3D printing process, as shown in Figure 7B. The key innovation is the implementation of a modified T-joint-cut kirigami structure, which overcomes the limitations of traditional kirigami structures by minimizing protrusions during stretching. The device is designed to be integrated into wearable textiles, such as socks, thereby constituting an energy-harvesting mechanism that harnesses energy from pedestrian locomotion. Kim et al.[64] presented the development of a portable stretchable PEH (SPEH) using a kirigami structure on a PVDF film, and its structure is shown in Figure 7C. The performance of the SPEH is enhanced by stress redistribution within the film using two approaches: topological depolarization and neutral axis optimization. Experimental results show a 21.57% increase in output voltage compared to the original film. The

Table 1. Comparison of energy harvesters based on different origami structures

		Performance			
Mechanism	Materials	Voltage output	Power output	Tested durability	Reference
Miura					
TENG	aluminum and piezoelectric and flexible thin film (PFF)	131.3 V and 1.10 μA at 4 Hz and 25 N	77 nW/cm^2 at 100 MΩ.	over 10,000 cycles	Zhao et al.[116]
TENG	Ni/Cu polyester and PTFE	308.6 V, and 55.5 μA at 4 Hz.	5.1 mW at 16 MΩ.	N/A	Zargari et al.[54]
TENG	copper and fluorinated ethylene propylene (FEP)	328 V at 5.0 g and 15 Hz	2152 μW at 50 MΩ	N/A	Lyu et al.[117]
Waterbomb					
TENG	copper and PTFE	250 V and 3 μA at 200 N	165 μW at 100 MΩ	over 57,600 cycles	Pang et al.[94]
Kresling					
TENG	FEP and paper	206.4 V and 4.66 μA at 1.78 Hz and 5 cm	0.96 μW/cm^2 at 20 MΩ.	over 10,000 cycles	Jiao et al.[101]
Hybrid generator	TENG part: polyimide and aluminum PEH part: PVDF	120 V and 90 μA.	none	over 48 h.	Chung et al.[99]
Double helix					
TENG	copper and PTFE (PVDF: increasing the charge density)	420 V and 140 μA at 40 N	9.08 mW at 4 MΩ	N/A	Gao et al.[108]
TENG	copper and FEP	1000 V and 110 μA	0.67 mW/cm^3 at 6.28 MΩ.	over 144,000 cycles	Tao et al.[55]
TENG	polyimide and aluminum	110 V and 26 μA.	697 μW at 10 MΩ.	did not change	Pongampai et al.[109]
TENG	Kapton and paper	105 V and 58 μA at 2.4 cm and 1 Hz	162 μW at 2 MΩ	Over 18,000 cycles	Xia et al.[104]
TENG	CM-CNF and PFA	185 V and 20 μA at 10 N and 2 Hz	2076W at 10 MΩ	Over 10,000 cycles	Thakur et al.[107]

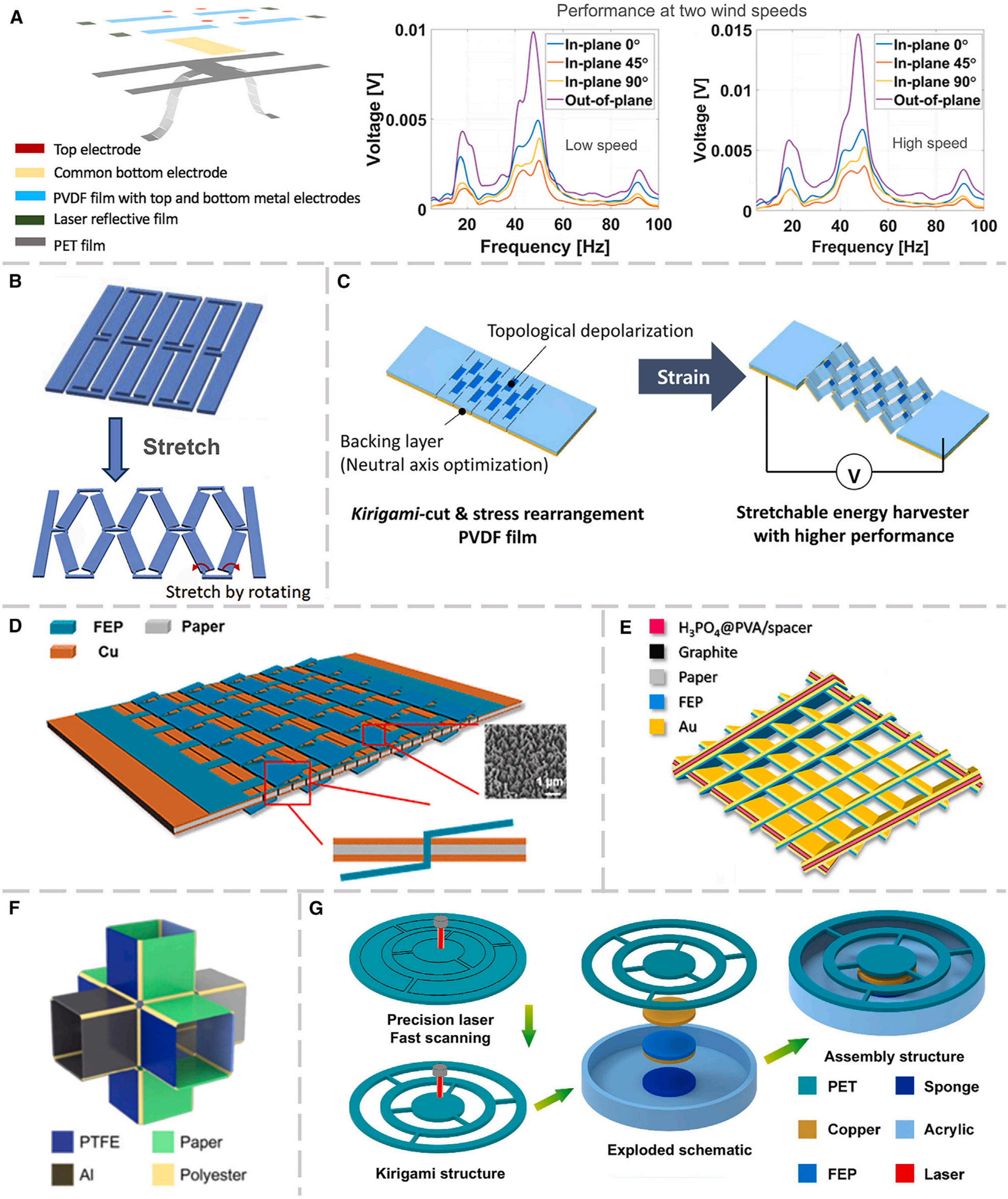

Figure 7. Schematic diagram of kirigami-based energy harvesters

(A) Schematic of the integrated energy-harvesting system and the voltage output for multi-directional wind with different levels of speed.[62]

(B) Schematic of a stretchable kirigami PENG using a 3D printing process.[63]

(C) Schematic of a portable SPEH using a kirigami structure.[64]

(legend continued on next page)

developed SPEH is applied to intelligent transmittance-changing contact lenses. After 100 cycles of stretch and release, the lens showed a change in transmittance from 15.17% to 22.28%. Farhangdoust et al.[127] introduced a PEH with a metamaterial-based substrate (MPEH) combining auxetic and kirigami topologies. The MPEH generates 19.2 times more power than a conventional PEH at low frequencies and 18.1 times more power than a conventional PEH at high frequencies. Simulations have demonstrated that the improved performance of the MPEH is due to the excellent geometry design and is not dependent on the excitation conditions.

Kirigami-based triboelectric energy harvesters

In 2015, an ultrathin, rollable, paper-based TENG modified with an array of microholes was proposed, a structure similar to the kirigami structure, and the microholes were shown to broaden the frequency response.[128] Wu et al.[58] presented a highly stretchable type of TENG by using a kirigami structure made from conventional, inelastic materials such as paper, as illustrated in Figure 7D. The kirigami design enables the TENGs to withstand high tensile strain and harvest energy from stretching, squeezing, and twisting motions. The maximum power values for the stretch and twist modes are similar, with the press mode being an order of magnitude more powerful than the other two modes. It is worth noting that the kirigami-based TENG has strong recovery energy when subjected to stretching, but this recovery is comparatively weak when the device undergoes twisting. Guo et al.[57] presented an ultralight paper-cut-based self-charging power unit (PC-SCPU) that combines a paper-based TENG and a supercapacitor (SC) for energy harvesting and storage, and its structure is shown in Figure 7E. Owing to the assembled kirigami design, the device integrates a large number of rhombic-shaped TENG units in a given volume to increase the output charge. The PC-SCPU can effectively charge the SC to 1 V. The wallet-contained PC-SCPU is showcased as an eco-friendly power supply for operating wearable and portable electronic devices, including wireless remote controls, electric watches, and temperature sensors.

The exceptional tensile deformation ability of kirigami enables the kirigami-based TENG to modify the device's original motion state. Kong et al.[59] introduced the rotation-folding (R-F) kirigami TENG, which is a highly efficient and durable rotational energy-harvesting device, as shown in Figure 7F. The R-F kirigami TENG efficiently converts rotational motion into multiple folding-unfolding vibrations. The unit is remarkably durable, retaining 86% of its initial power even after 288,000 continuous revolutions. Qi et al.[126] developed a kirigami-inspired TENG (KI-TENG), as depicted in Figure 7G. The KI-TENG, with its unique kirigami architecture, served as an ultra-broadband vibration energy harvester. The KI-TENG's friction layer can be effortlessly converted into a kirigami structure with one or two degrees of freedom on a PET sheet. The test found that, by increasing the acceleration, decreasing the gap distance, and increasing the mass, the operating range of the KI-TENG can be increased. With meticulously optimized structural parameters, the KI-TENG can harvest vibration energy from 2 to 49 Hz in its vertically vibrating state. In addition, it also provides exceptional output performance over a wide frequency range in the horizontal mode.

APPLICATION OF ORIGAMI/KIRIGAMI-BASED ENERGY HARVESTERS

The origami/kirigami structures offer the possibility of simplifying the design and manufacture of high-power energy harvesters. Meanwhile, researchers from various fields have begun to explore the possibility of using energy harvesters inspired by different types of origami/kirigami to harvest vibrational energy from the environment for real-world applications. In this section, research on applications of origami/kirigami-based energy harvesters in the fields of transportation, marine, wearable devices, and medicine are reviewed to demonstrate the potential of these energy harvesters in commercial applications.

Applications in self-powered sensors

The introduction of nanogenerators has spurred advancements in self-powered sensor technology. These nanogenerators have the capability to sustainably power sensors by harnessing ambient energy, eliminating the need for an external power source and enabling real-time monitoring of environmental variables.[129–131] Qi et al.[126] developed a kirigami-inspired TENG (KI-TENG) tailored for use as an acceleration sensor. The KI-TENG is designed to operate as an acceleration sensor capable of detecting variations from 1 m s^{-2} to 9 m s^{-2}. In addition, a supervisory circuit based on the KI-TENG is designed to efficiently track the operating status of the machine.

The origami/kirigami-based energy harvesters have favorable flexible structures and hold considerable potential for use as wearable devices. Li et al.[56] presented a novel LM electrode called kirigami-structured LM paper (KLP), which, when integrated with a TENG, demonstrated the ability to function as a self-powered electronic skin, as shown in Figure 8A. Building on this self-powered e-skin concept, The KLP extended to an intelligent dialing communication system. By placing a prepared KLP on the arm and sequentially touching the keys with a polydimethylsiloxane (PDMS)-coated finger, each digit press generates a voltage signal. Lu et al.[132] introduced a self-powered wearable visual tactile sensor that combines a high-output TENG and a visual light source, as shown in Figure 8B. The TENG's structural design enhances the transferred charge and drives the light source to generate a bright light signal easily. This sensor provides visual feedback on palm-grasp state and strength without requiring an external power supply, showing promise for human-computer interaction interfaces.

(D) Schematic of paper-based TENGs made of stretchable interlocking kirigami patterns.[58]
(E) Schematic of an ultralight paper-cut-based self-charging power unit.[57]
(F) Schematic of the rotation-folding kirigami TENG.[59]
(G) Schematic of a kirigami-inspired TENG.[126]

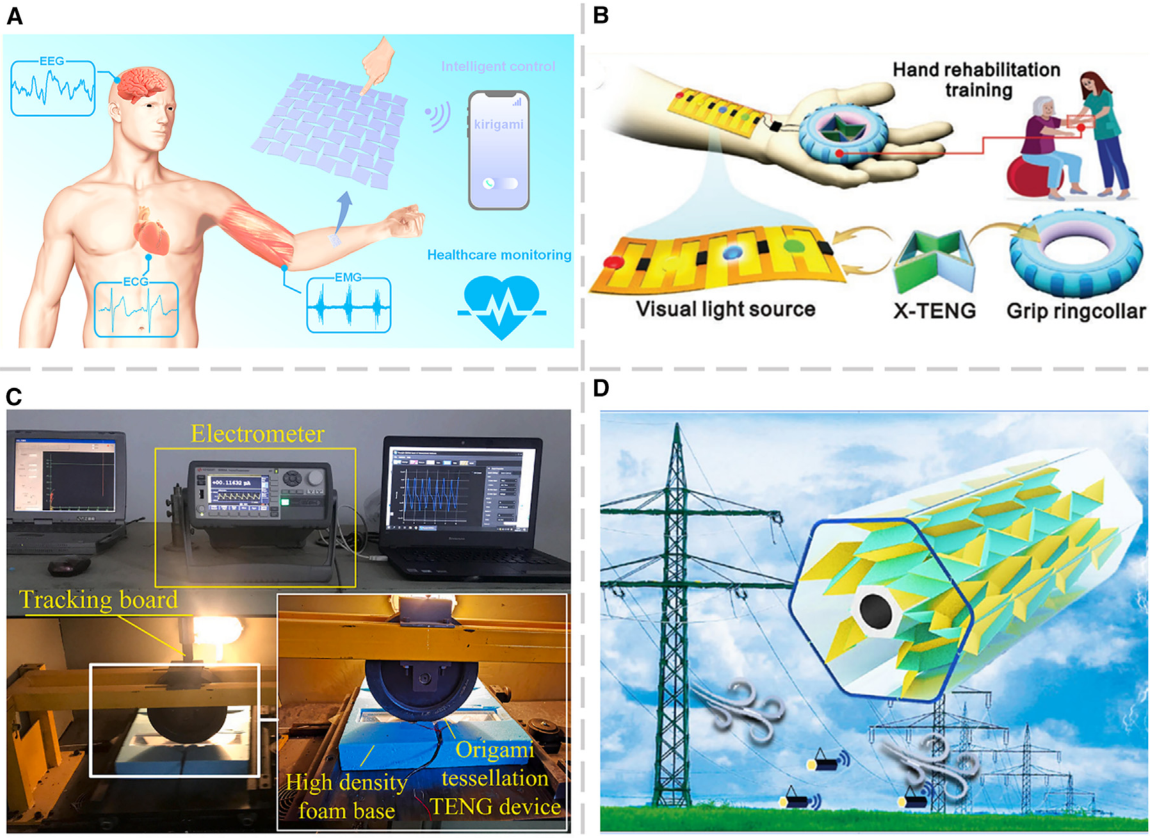

Figure 8. Schematic representation of origami/kirigami-based energy harvesters in the direction of self-powered sensors
(A) Schematic illustration of the KLP based e-skin for applications in healthcare monitoring and intelligent control.[56]
(B) Diagram of the self-powered wearable visual tactile sensor combines a high-output TENG and a visual light source.[132]
(C) Diagram of the tracking board test of the OT-TENGs.[78]
(D) Diagram of vibration recognition enabled by self-powered sensing and machine learning.[117]

Energy harvesting and sensors have been applied in environmental monitoring. The self-powered sensors improve efficiency by monitoring the state of the road surface and improving road safety. Zhang et al.[78] conducted tracking plate experiments on the Miura OT-TENG, as shown in Figure 8C. A single wheel was used to simulate a car wheel, and tracking plate samples with embedded devices were used to simulate the road surface through which the wheel passed. The Miura pattern OT-TENG can output a current of 0.05 μA when the wheel passes through the tracking plate periodically at a frequency of 0.36 Hz. The technology has the potential to harvest mechanical energy from the vibration of the road surface. Pang et al.[94] explored the promising application of WO-TENG for traffic monitoring sensors. They performed real vehicle tests on an asphalt road embedded with WO-TENG modules, showing that the voltage output increased with vehicle load. This finding suggests potential applications for WO-TENG as a sensor to measure vehicle weight. Xia et al.[104] presented a self-powered bridge health monitoring system utilizing an EO-TENG array. A simulation scenario was established using a remotely operated vehicle and a bridge model to evaluate the system's performance. The system can detect vehicle information and monitor bridge health by analyzing sensor signals from piezoelectric patches mounted on the bridge deck. In power grids, overhead transmission lines are susceptible to strong vibrations, posing a serious threat to the safety and stability of the grid system. The integration of self-powered sensors for monitoring these lines is crucial for grid operation and safety. Lyu et al.[117] developed a hexagonal electret generator with integrated six-phase OPGs as an "airborne buoy," illustrated in Figure 8D. The signals were measured under different vibration conditions, and a neural network algorithm that recognizes the vibration of the transmission line was used to identify the signal waveforms generated by the internal generator with 92% accuracy.

Application of ocean-energy harvesting

Ocean-energy resources represent a valuable but underutilized source of energy. Despite their theoretical potential to generate approximately 151,300 TWh per year, the technology for harvesting ocean energy still encounters numerous challenges. These challenges include efficiently harnessing wave energy with irregular direction and frequency and developing effective methods to prevent or delay seawater-related issues. Wave

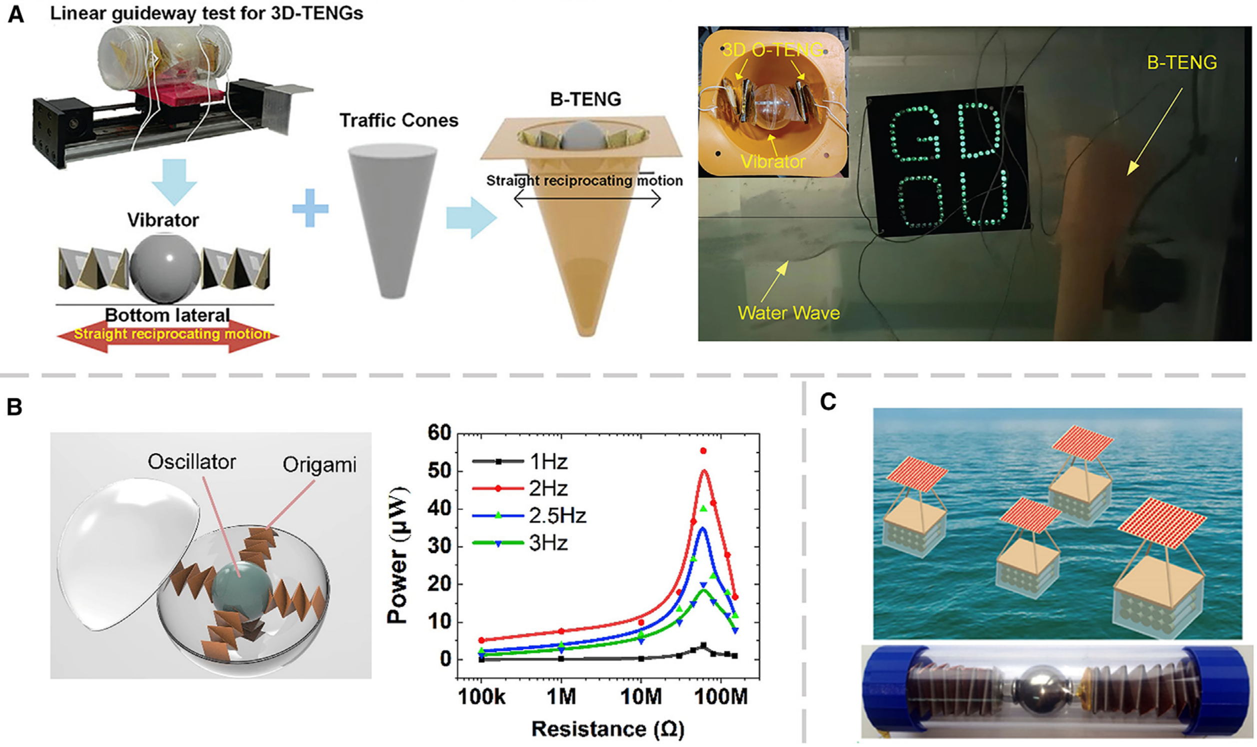

Figure 9. Schematic representation of origami-based energy harvesters for marine energy applications

(A) Diagram of the internal structure of a self-powered buoy TENG and the device driving LEDs through water waves.[134]

(B) Schematic illustration of spherical TENGs and power optimizations versus different load resistances and wave frequencies.[55]

(C) Image of the integrated dh-TENGs as a power source for navigation lights and a polymethyl methacrylate tube sealed with two dh-TENGs.[105]

energy from the ocean has the largest share. It has a potential resource of almost 18,500 TWh.[133]

Gao et al.[134] proposed a nanofiber-enhanced buoy-triggered TENG (B-TENG) with a double-helical origami structure, as shown in Figure 9A. The B-TENG can easily light up to 100 blue LEDs under slow-water wave motions, demonstrating the potential for harvesting blue energy in real-world water environments. Tao et al.[55] proposed an origami-inspired TENG integrated with a folded thin-film electret. A spherical floating buoy device can be integrated with six such TENGs, as shown in Figure 9B. This device can be used to capture wave energy with irregular and random mixed amplitude and frequency oscillations. Hong et al.[135] presented a seesaw-structured spherical triboelectric-electromagnetic hybrid nanogenerator (SSTE-HNG). This device is designed to efficiently harvest wave energy over a wide frequency range and enable wireless positioning on the sea surface. The device maintains a stable output voltage in the range of 2.7–3.3 V, effectively powering a global positioning system (GPS) module. Wang et al.[105] integrated and arranged multiple double helix structure TENGs (dh-TENGs) in a single navigation-light base, as shown in Figure 9C. This can be used as a power source for navigation-light arrays that float in the ocean all year round. This unique spherical design not only allows origami-based energy harvesters to capture multi-directional wave energy but also protects TENGs from seawater corrosion. This provides a superior solution for capturing irregularly oriented wave energy.

Applications in the medical field

The application of energy harvesters has expanded into the medical field, driven by design and advancements in medical technology. Nowadays, the use of portable implantable devices and medical equipment for humans is becoming increasingly important, and energy harvesters can provide a stable and long-lasting power supply for these devices, effectively avoiding the inconvenience caused by battery depletion or battery replacement.[136–138] This advancement proves particularly advantageous for patients requiring long-term usage, especially in the context of health services monitoring and preventive alert systems. In addition, energy harvesters can be used as sensors to monitor the conditions of patients.[139–141] The deformation capabilities of origami/kirigami-based energy harvesters enable a more comprehensive human-computer interface, enhancing their relevance in the field of medicine even further. Bhatia et al.[142] proposed a gravity-assisted device with integrated TENGs for shoulder rehabilitation, as shown in Figure 10A. The gravity-assist part of the device is based on a waterbomb-origami design, and the TENG is designed as a zigzag structure. The origami structure integrated with TENG not only provides gravity support for injured patients but also serves as a signal sensor to detect damage and recovery of the upper limb. Through patient feedback, O-TENG is accepted for use in rehabilitation exercises. Hong et al.[143] introduced a kirigami-structured highly anisotropic piezoelectric network composite

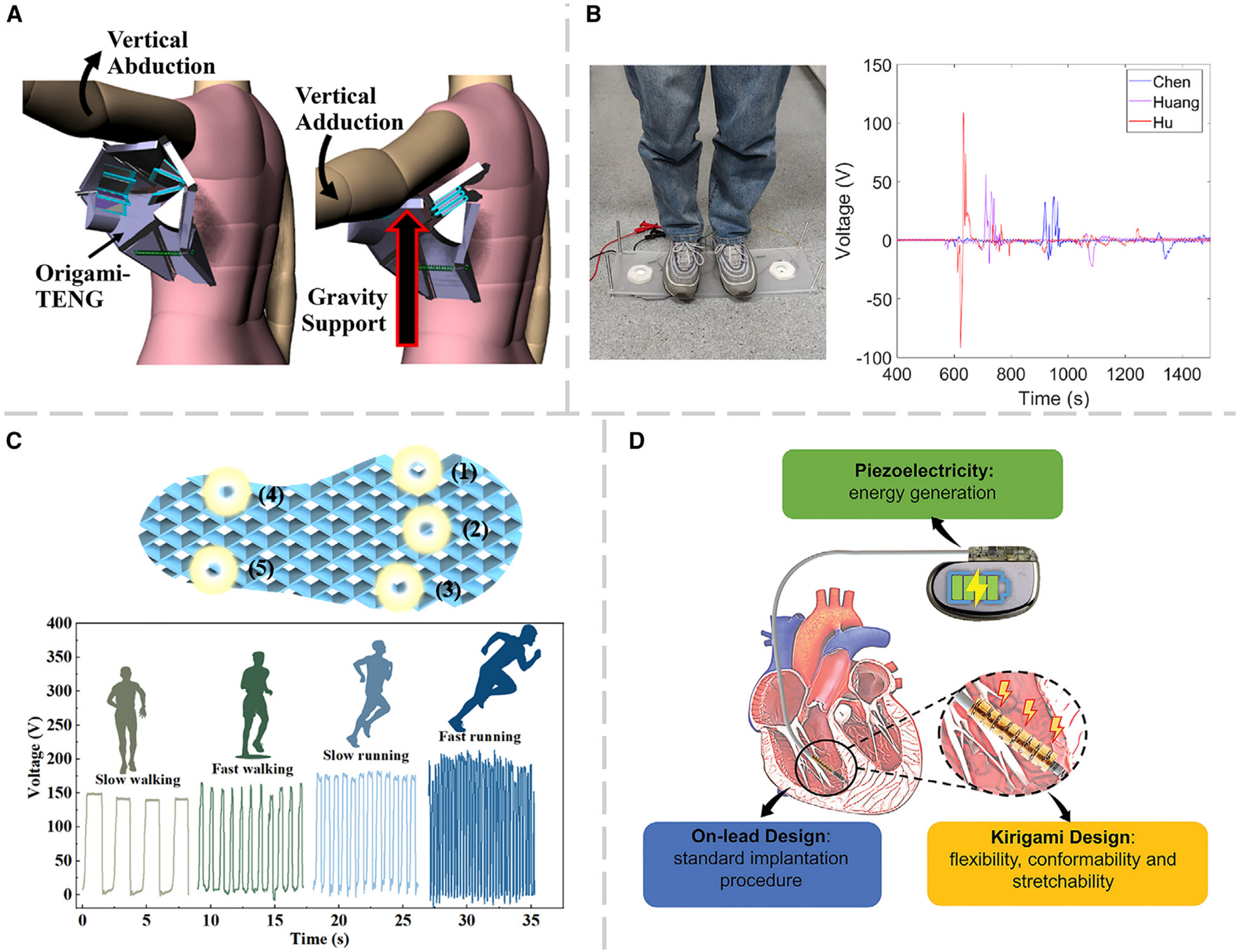

Figure 10. Schematic representation of origami/kirigami-based energy harvesters for medical applications

(A) Diagram of the vertical shoulder adduction-abduction motion utilizing a gravity-assisted device with integrated TENG for shoulder rehabilitation.[142]

(B) Diagram of a pedal-type self-powered biosensor that combines Kresling origami structure and PEH.[144]

(C) Diagram of 4D printed shape memory metamaterials with sensing capabilities derived from origami concepts applied to the design of integrated TENG soles.[116]

(D) Diagram of a kirigami-inspired energy harvester for powering implantable electronics.[145]

(HAPNC) sensor. The sensor is fabricated using a modified template-assisted sol-gel method and exhibits stretchability, high sensitivity, and remarkable anisotropic piezoelectric response. Using the kirigami design enhances the connectivity of the piezoceramic phase, improving the sensor's overall performance. When attached to the human neck and shoulder, the HAPNC sensor can identify four different joint movement patterns with 95% accuracy. A monitoring alert system has been designed to monitor neck and shoulder joint movements over time and to improve long-term sedentary habits. In the realm of life medicine, step-frequency signals can be utilized to monitor a patient's movement patterns. The electrical signals generated by the piezoelectric or the friction electric can respond to the patient's movement status. As an effective early warning system, it can be used to detect pathological features associated with non-strenuous exercise. Huang et al.[144] presented a conceptual design based on a pedal-type self-powered biosensor that is combined with a Kresling origami structure and a PEH, as shown in Figure 10B. The device is designed to capture the unique biological information based on individual footsteps. This is achieved through a generator that converts mechanical energy into electrical energy, generating unique voltage signals. Each individual exhibits distinct characteristics in their voltage signals, offering potential for biometric identification. Zhao et al.[116] proposed a 4D printer to print the shape-memory metamaterial with sensing capability, which is derived from the origami concept. Figure 10C shows that this material is used to design a shoe sole with an integrated TENG and realize gait detection. The device can recognize four modes of movement: slow walking, fast walking, jogging, and fast running.

Nanogenerators with different configurations hold potential for applications in the biomedical field. Nevertheless, the diverse nature of biological tissues and organs and the intricate operational environments of medical devices pose a challenge in finding a universal generator or sensor structure adaptable to different medical contexts. Due to the nature of the kirigami structure and the special design, the biological surfaces, including skin and organ surfaces, can be implemented for human monitoring purposes. Peng et al.[146] presented a kirigami-based piezoelectric/triboelectric hybrid nanogenerator (K-HENG) that could produce a stable power output. K-HENG has been proved to have the capability to harvest energy from diverse body movements, notably showcasing its potential for attachment to the larynx for audio-recognition purposes. This application offers possibilities for rehabilitating and strengthening the throat muscles in patients with injured vocal cords. Xu et al.[145] present a practical application of a kirigami-inspired energy harvester for powering implantable electronics, specifically pacemakers, as shown in Figure 10D. The device is integrated into the pacemaker lead and converts the biomechanical energy of cardiac motion into electrical energy using a piezoelectric composite film and a flexible kirigami pattern. The optimization of the kirigami structure aimed to attain greater flexibility and voltage output based on various factors such as the width of the cuts, the density of the cuts, the thickness of the film, and the surface area. The kirigami design offers advantages that enhance the flexibility, compliance, and shape adaptation for the device to adapt to complex deformations and adhere to various surfaces. *In vivo* experiments using a porcine model have shown that the mechanism can be implanted into the heart and generate voltages of up to 0.7 V. Sun et al.[147] presented a kirigami-based stretchable strain sensor that features an intersegmental electrode design to enhance its electrical and mechanical performance. The sensor can be attached to various surfaces and serve as a wearable or implantable system without causing mechanical stimulation. Through experimentation using balloons and porcine hearts, the sensor acquires signals in various conditions and enables wireless data transmission to external devices for real-time monitoring.

Conclusions and perspectives

The combination of origami/kirigami and energy-harvesting technology has the potential to overcome the inherent limitations of conventional energy-harvesting systems and to facilitate the incorporation of a range of optimization approaches. Origami/kirigami-based energy harvesters are expected to possess the following advantages.

Increasing effective area

Origami structures are characterized by the formation of 3D multilayered structures through folding operations, while kirigami structures are rich in cuts and gaps, and all of these structures have excellent deformation capabilities. These structures have been shown to enhance the functionality of energy harvesters. For TENGs, origami and kirigami structures enable the harvesters to have wider specific surface areas (i.e., the surface area per unit mass or volume of material). For PEHs, the origami and kirigami structures allow for larger effective deformation areas under the same external force.

Multi-directional excitation response

Origami/kirigami-based energy harvesters can respond to multi-directional excitations, such as vertical or horizontal tensile, compressive, and even torsional excitations. Such capability greatly enhances the application scenarios of energy harvesters, thus increasing their adaptability and practicality.

Flexibility and light weight

The flexibility and deformation of materials can be improved by folding or shearing them. The origami/kirigami structures benefit from their own lightness and compactness, allowing energy harvesters to fit different parts of the body and maintain excellent contact even when in motion. Due to their respective structural advantages, origami-based energy harvesters are more suitable for motion-detection wearables, while kirigami-based energy harvesters are more suitable for physiological sensing wearables. Meanwhile, origami/kirigami-based energy harvesters maintain satisfactory performance after a high number of operations, making them a vibrant potential option in the field of wearable devices.

Future directions

With the surge of enthusiasm in areas such as energy-harvesting technology and origami/kirigami metamaterials, the following fields should be explored in future research to further refine origami/kirigami-based energy harvesters.

Structures and geometrical designs

Origami and kirigami offer diverse artistic expressions, but their application in energy harvesting has been limited to simple graphical representations. Integrating more complex origami/kirigami structures with energy-harvesting technology is an underexplored research area. Future studies should explore the performance enhancements of energy harvesters inspired by intricate designs. Additionally, most origami and kirigami structures can be described using mathematical and geometric relationships, particularly origami, so there is significant potential for parametric studies. Researchers should focus on parameterizing and optimizing these structures to improve the efficiency and precision of energy-harvesting technologies.

Materials

The combination of origami/kirigami and energy harvesters is a structural innovation on which future breakthroughs in materials can be attempted. Energy harvesters are essential to the functionality of wireless sensor networks, wearable electronics, and many other applications. However, the longevity and endurance of these devices are paramount and affect their practical utility and reliability. The development and refinement of energy harvesters can be greatly promoted by exploiting the inherent advantages of origami/kirigami structures in combination with better support materials.

Functionalities

Energy harvesters, drawing inspiration from origami/kirigami, present many advantages. Future research should focus on the unique properties of these structures rather than simply using them as models. This idea can be referred to a bistable energy harvester inspired by origami structure[61] and is worth pondering. In addition, most extant research remains largely in the performance-testing phase, with limited promotion in practical applications. Bridging this gap is crucial for advancing the field, shifting the focus from performance optimization to widespread, practical deployment. It is essential to develop and adopt flexible energy-storage solutions, such as flexible batteries and supercapacitors, which can improve the performance and applicability of origami/kirigami-based energy harvesters in various practical applications.

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AUTHOR CONTRIBUTIONS

J.W., writing – original draft, methodology, conceptualization, and formal analysis; Z.S., writing – original draft, conceptualization, and methodology. G.H., formal analysis and writing – review & editing; H.D. and X.L., writing – review & editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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