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Review

Soft Magnetoelastic Generators Advances in Energy Harvesting and Sensing

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Abstract: A new class of soft energy harvesters, known as magnetoelastic generators (MEGs), has been made possible by the giant magnetoelastic effect. These generators can efficiently convert low-frequency and irregular mechanical stimuli into electricity. This review summarises the mechanism of magnetoelastic coupling and recent progress in soft magnetic composites, flexible architectures, and bio-inspired designs. We focus on the application of MEGs in some specific fields, such as wearable electronics, self-powered sensing, acoustic energy harvesting, and blue energy systems, demonstrating their unique advantages over traditional harvesters. Despite the rapid advances, there are still some challenges remain in improving energy density, such as how to improve energy density, maintain long-term stability, realize large-scale manufacturing, and do a good job in system-level power management. Finally, we point out the important opportunities and future directions, hoping to help develop and integrate the next generation magnetoelastic energy system.

Keywords: Soft Magnetoelastic; Energy Harvesting; Sensing
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1 Introduction

With fossil-fuel depletion and environmental concerns intensifying, our demand for clean and decentralized power solutions has become greater, especially now the Internet of Things (IoT), wearable electronic devices and automatic sensing networks are developing rapidly [1–4]. These emerging systems need miniature, long-life and maintenance-free power supply—but traditional batteries and existing energy collection technologies can hardly meet these requirements [5–8]. Chemical batteries themselves have the problems of limited service life and being unfriendly to the environment, while Piezoelectric [9, 10], triboelectric [5, 11] , thermoelectric [12, 13], and traditional electromagnetic generators[14, 15] often have narrow working frequency band, low efficiency at low frequencies or structures [16].

A conceptual shift occurred in 2021, when Chen et al. reported the giant magnetoelastic effect found in soft magnetic composites [17]. It reveals a previously unrecognized coupling: the connection between mechanical deformation and magnetic flux modulation in elastomer. This discovery laid the foundation for the magnetoelastic generators (MEGs), a new class of soft energy harvesters. They convert mechanical energy into electricity through a combination of mechanically induced magnetic flux variation and electromagnetic induction [18]. Magnetoelastic generators are flexible, compact, and chemically inert platforms by nature. Built from compliant polymer matrices embedded with magnetic particles, they are capable of harvesting irregular, low-frequency mechanical energy, a regime in which conventional technologies consistently underperform [16, 19].

Over the past few years, this mechanism has driven rapid progress. This progress has been seen in the areas of materials engineering, structural design, and system-level integration. MEGs now demonstrate broad-band responsiveness, high mechanical compliance and exceptional operational durability. This is made possible by soft magnetic composites, multilayered architectures and bio-inspired structural motifs [20, 21]. These advances have transformed MEGs, turning them from a proof-of-concept phenomenon into a versatile technology. Its applicability is expanding. Recent demonstrations include

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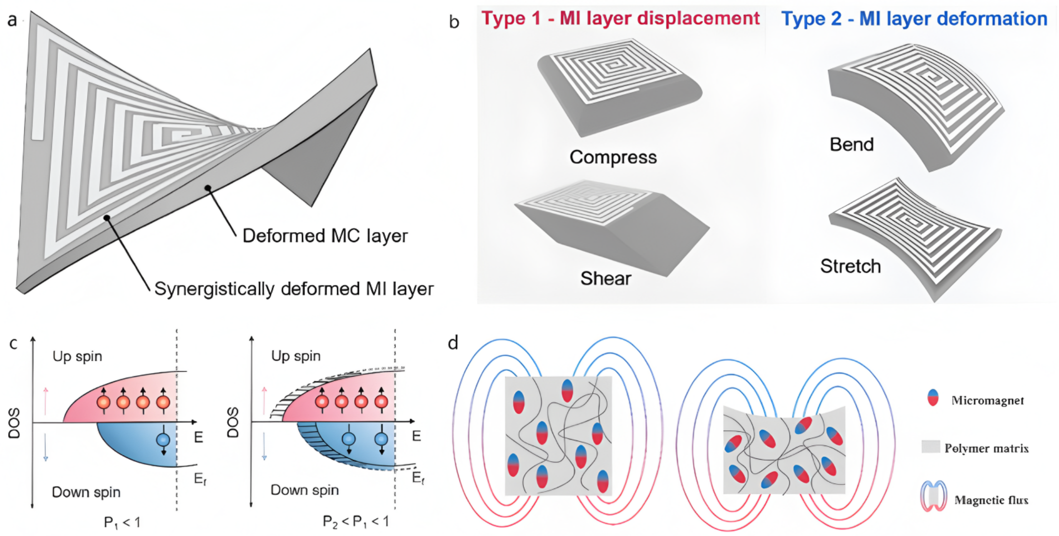

Figure 1: (a) Schematic illustration of the synergistically deformed magnetoelastic (MI) layer and deformed magnetic conductor (MC) layer in the magnetoelastic generator based on the giant magnetoelastic effect. [Adapted with permission from [25], copyright 2025 American Association for the Advancement of Science](b)Two deformation types of the MI layer. [Adapted with permission from [25], copyright 2025 American Association for the Advancement of Science] (c) Density of states (DOS) diagrams depicting spin polarization changes induced by deformations, reflecting modifications in the electronic structure. (d)Schematic showing micromagnets in a polymer matrix and their magnetic flux variation under pressure, demonstrating the magneto-mechanical response in the magnetoelastic generator.

highly efficient harvesting of low-level acoustic noise. Wave-driven power generation using floating starfish-inspired arrays is also included. These arrays are capable of sustained hydrogen production. Other demonstrations include skin-conformal devices. These convert human motion into continuous power for health-monitoring sensors [22–24]. Together, these studies highlight MEGs' unique potential to enable battery-free operation across wearable, environmental, and marine energy platforms. Several scientific and technological challenges remain before MEGs can be deployed on a large scale. Key issues include improving energy density and long-term stability of magnetoelastic composites. Another issue is designing structures that broaden frequency response. There is also the development of power-management circuits that efficiently handle low and fluctuating outputs [25, 26]. The development of strategies for scalable manufacturing, system-level integration and application-specific reliability standards is still in its early stages [27, 28].

In this review, we provide a comprehensive overview of recent progress in soft magnetoelastic materials and device architectures. We emphasise how the discovery of the giant magnetoelastic effect and advances in particle–polymer composites have reshaped the landscape of flexible energy and sensing technologies. We highlight key material innovations. These include permanent fluid magnets and low-field molecular ferroelectrics. We also examine how emerging structural designs enable efficient harvesting of mechanical, wind, wave, and acoustic energy. Examples of these designs include spherical, textile, fiber-based, and ultrathin membrane architectures. We also evaluate the performance of magnetoelastic generator (MEG) systems in wearable health monitoring, biomedical sensing, soft robotics and human–machine interaction. This highlights their unique ability to integrate energy harvesting and sensing within a single soft-matter platform. These demonstrations reveal the strong potential of MEGs to replace rigid, battery-dependent systems with flexible electronics in the future. Finally, we identify critical challenges, such as long-term stability, magnetic particle management, scalable manufacturing, and reliability under complex environments, and outline promising research directions. These include biodegradable magnetoelectric materials, implantable soft power systems, and AI-enabled adaptive sensing networks—advances that could accelerate the development of next-generation, self-powered and intelligent magnetoelastic systems.

2 Mechanism

In 2021, Chen et al. reported the discovery of giant magnetoelasticity in soft matter. Unlike conventional magnetoelastic rigid materials, this soft variant is characterized by its compatibility with the human body and low required actuation force. Moreover, it exhibits a magneto-mechanical coupling factor five times greater than that of rigid metal alloys (Figure 1(a)).

Traditional rigid materials require high uniaxial stress to alter electronic band structures and atomic-level spin-resolved density of states. In contrast, the soft magnetoelastic effect relies on the macroscopic reconfiguration of micro-magnets, thus exhibiting superior deformability. By applying forces in different directions, we can easily compress, shear, tension, and kink soft magnetoelastic bodies (Figure 1(b)). In contrast to the magnetic domain rearrangement mechanism in rigid materials, the rotation of macroscopic materials is emphasised by the soft magnetoelastic effect. From a microscopic perspective, this effect arises from the interaction between magnetic dipoles at the atomic level and magnetic particles at the microscopic level. Slight displacements and rotations occur

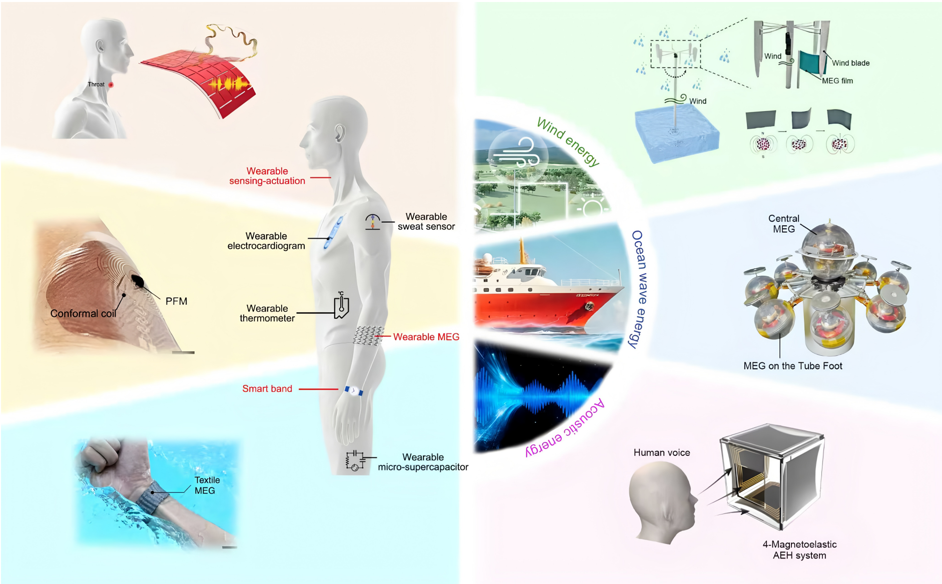

Figure 2: Classification of energy harvesting and sensing based on soft magnetoelastic Generators. [Adapted with permission from [29], copyright 2025 Wiley-VCH GmbH] [Adapted with permission from [30], copyright 2023 American Chemical Society] [Adapted with permission from [31], copyright 2022 Wiley-VCH GmbH] [Adapted with permission from [22], copyright 2025 Elsevier Inc.] [Adapted with permission from [32], copyright 2025 Elsevier Inc].

among the internal magnetic microparticles. This deformation increases the horizontal centre-to-centre spacing between particles while reducing the vertical spacing. This alters the interactions between magnetic dipoles, leading to significant changes in the overall magnetic flux density. When pressure is released, the micro-magnets within the elastic polymer revert to their original wavy chain structure. This restores the initial magnetic state, consequently changing the magnetic flux density (Figure 1(c) and (d)). Therefore, the variation in magnetic flux density during deformation in the elastomer system can be attributed to the deviation of the wavy chain structure, which caused by the motion and rotation of micro-magnets. From a technical perspective, soft magnetoelastic materials act as magnetic coupling layers that convert mechanical disturbances into changes in magnetic flux density. According to Faraday's law of electromagnetic induction, an alternating current proportional to the rate of change in magnetic flux is induced in the coil. This magnetic energy is then converted into usable electrical energy through magneto-mechanical coupling. Overall, deformation periodically alters particle spacing and orientation. This leads to fluctuations in magnetic flux density. It also induces alternating current in the coil. Coupling the giant magnetoelastic effect with Faraday's law has led to the development of magnetoelastic generators, which are a highly promising technology for biomechanical energy conversion.

3 Soft Magnetoelastic for Energy Harvesting and Sensing

Soft magnetoelastic systems exploit the inherent relationship between mechanical deformation and magnetic flux variation in particle-polymer composites, enabling efficient energy transduction and sensitive signal detection. As these materials have mechanical properties similar to those of soft biological tissues, they can undergo significant, reversible deformation while maintaining stable magnetoelastic responses. This makes them well-suited to applications requiring flexibility, conformability and real-time responsiveness. Recent advances in material formulations, structural designs and device engineering, magnetoelastic systems now have a wider range of capabilities. These include integrated energy harvesting and sensing across wearable electronics, biomedical monitoring and human–machine interfaces (Figure 2).

3.1 Magnetoelastic Energy Harvesting

The emergence of soft magnetoelastic composites has transformed the field of mechanical energy harvesting, as they allow magnetic flux to be modulated purely through material deformation. Unlike traditional piezoelectric, triboelectric or electromagnetic harvesters, MEGs do not require rigid components, external magnetic fields or chemical reactions. Their high magneto-mechanical coupling coefficient allows them to capture a broad spectrum of low-frequency mechanical energy sources. Their mechanical compliance and tolerance to irregular stimuli also help with this. This section evaluates recent progress in MEG-based harvesting from human motion, ambient vibrations, wind, ocean waves and acoustic fields. Particular emphasis is placed on the underlying mechanisms, device strategies and current application boundaries.

3.1.1 Biomechanical Energy Harvesting

A substantial portion of the mechanical energy produced by the human body during walking or other movements is often overlooked. Soft magnetoelastic generators provide an effective approach for harvesting this energy. In 2021, Chen and colleagues developed a laminated wearable magnetoelastic generator that, through simple actions such as finger tapping and without an external magnetic field, achieved a giant magneto-mechanical coupling of 4.7×10^{-8} T/Pa [17]. When subjected to finger tapping, the MEGs delivered a peak

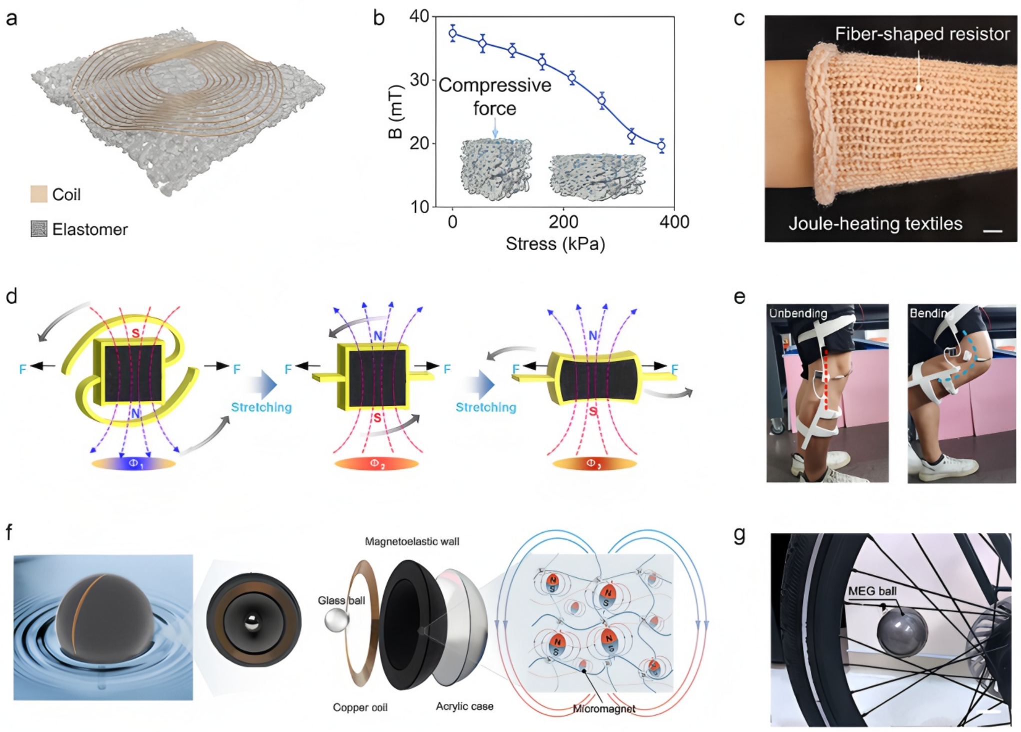

Figure 3: (a) Schematic of the wearable MEG, composed of a soft magnetoelastic film and a coil. [Adapted with permission from [17], copyright 2021 American Chemical Society] (b) Magneto-mechanical coupling factor. [Adapted with permission from [17], copyright 2021 American Chemical Society] (c) Joule-heating textile consisted of fiber-shaped resistors and a textile substrate. [Adapted with permission from [17], copyright 2021 American Chemical Society] (d) Structural evolution of the designed logarithmic helical structure from its unstretched state to deformation, showing a 180° rotation of the central magnetic block during stretching. [Adapted with permission from [33], copyright 2025 Wiley-VCH GmbH] (e) Schematic showing the stretching and recovery cycle of the self-powered system. [Adapted with permission from [33], copyright 2025 Wiley-VCH GmbH] (f) Schematic of the S-MEG assembly and its key components, including an exploded view and a sketch of the internal magnetoelastic wall structure, which generates magnetic flux via micromagnets (red and blue spheres), dispersed in a polymer silicone matrix (orange lines). [Adapted with permission from [34], copyright 2023 American Chemical Society] (g) Enlarged view of the S-MEG for vibration energy harvesting from a bicycle. [Adapted with permission from [34], copyright 2023 American Chemical Society].

short-circuit current of 97.17 mA (corresponding to a current density of 15.54 mA/cm^2) and an open-circuit voltage of 2.84 V. This output was sufficient to directly heat a 40 Ω fiber resistor by 0.2 °C, demonstrating self-powered Joule heating capability (Figure 3(a–c)).

Beyond intentional deformations, the natural deformations of the torso during motion can also be harvested. In 2025, Chen's team proposed a stretchable logarithmic spiral magnetoelastic generator, in which a three-dimensional printed flexible skeleton connects the logarithmic spiral arms to a central magnetoelastic membrane [33]. Upon stretching, the spiral arms rotate the central disc by 180°, reversing the magnetic field, while the microparticle chains inside the membrane are deformed. The magnetic flux completes a full reversal from positive to negative and back to positive within milliseconds, producing twice the initial flux variation. This device achieved 43 mA current, 8.6 mW power, and a current density of 7.17 mA/cm^2, and when integrated into 3D-printed TPU knee pads, it could continuously power small devices such as smartphones, LEDs, and headlamps within tens of seconds during walking (Figure 3(d) and (e)).

In addition to human-generated mechanical energy, ubiquitous environmental mechanical energy can also be harvested. In 2023, Chen's group developed a spherical magnetoelastic generator comprising an acrylic spherical shell with an inner magnetoelastic membrane and a 2 cm glass ball at the center [34]. When the device vibrates, the glass ball collides with the hemispherical wall in all directions, compressing the microparticle chains and causing an abrupt drop in magnetic flux density by 11 mT. The induced current in the coil reached 8 A/m^2 and 15 mW/m^2 at 24 Hz resonance. Owing to its omnidirectional energy-harvesting capability, this device is highly versatile and can be deployed on moving bicycle hubs or turbulent water surfaces (Figure 3(f) and (g)).

3.1.2 Environmental Energy Harvesting

Beyond mechanical energy, soft magnetoelastic generators can harvest renewable energies from the environment. These energies are otherwise elusive. Although wind energy is pervasive, it is frequently intermittent, and conventional technologies are encumbered by low conversion efficiency and intricate systems. In 2022, Chen's team came up with a basic structure fitted with spinning blades that can transform wind into mechanical vibrations [31]. The periodic deformation of

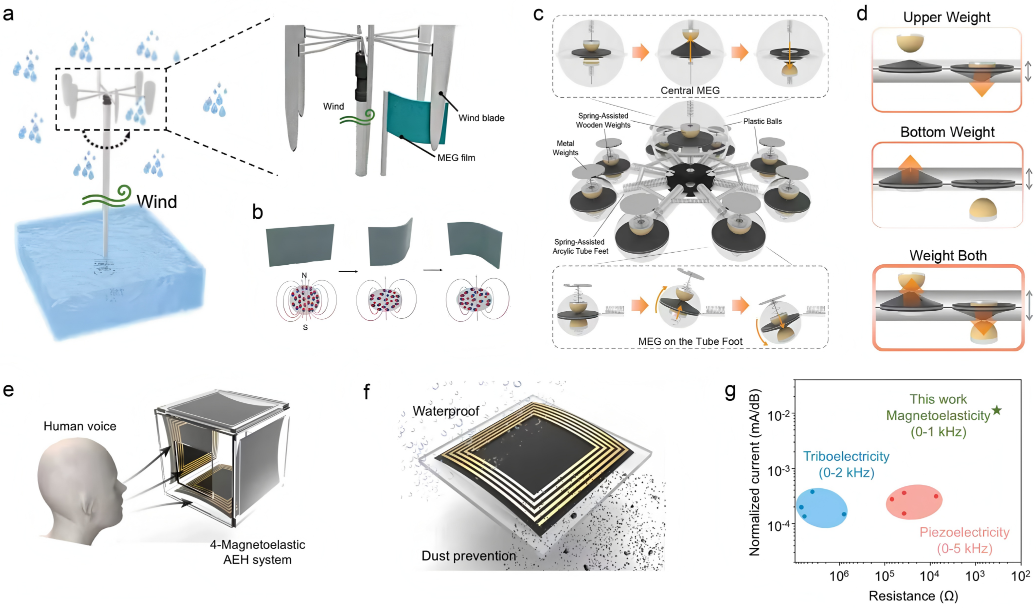

Figure 4: (a) Schematic demonstration of the wind initiating the rotation of the generator. High-magnification view of the area revealed a further detailed schematic of the zoomed-in wind blade and the corresponding rotation that it undergoes due to the wind. The MEG can be seen on the right, in its compressed state. [Adapted with permission from [31], copyright 2022 Wiley] (b) A schematic showing the relaxed and compressed states of the MEG film. The corresponding magnetic dipole order can be seen in the images on the bottom. [Adapted with permission from [31], copyright 2022 Wiley] (c) Illustration of starfish-inspired MEG array with schematic diagram describing the distinguished working mechanism of central MEG and MEGs on the tube feet. [Adapted with permission from [22], copyright 2025 Elsevier Inc.] (d) The difference in the position and number of weights. [Adapted with permission from [22], copyright 2025 Elsevier Inc.] (e) Schematic diagram of integrated magnetoelastic AEH system for human voice energy harvesting. [Adapted with permission from [32], copyright 2025 Elsevier Inc.] (f) Schematic of integrated magnetoelastic AEH system working with waterproofness and dust prevention functionalities. [Adapted with permission from [32], copyright 2025 Elsevier Inc.] (g)Comparison of the current output and internal resistance of this work and other reported energy-harvesting mechanisms. [Adapted with permission from [32], copyright 2025 Elsevier Inc.]

thin films affects the distances and orientations of particles, leading to variations in magnetic flux density and the generation of alternating current in the coils. This method produced an output of 1.17 mA/cm^2 with a 68 Ω low internal resistance and 0.82 mW/cm^2 power, which is three times that of current nanogenerators. The devices are inherently waterproof due to the penetrability of the magnetic field (Figure 4(a) and (b)).

Similarly, wave energy, which is also intermittent and unstable, can be harvested effectively using analogous principles. Chen's team developed a starfish-inspired flexible magnetoelastic generator array, consisting of a central sphere and eight "arms," all made of soft magnetoelastic membranes [22]. The devices are self-floating and efficiently respond to low-frequency ocean waves. Wave-induced vibration of the spring–mass system causes periodic bending and compression of the composite membranes, altering inter-particle spacing, generating magnetic flux fluctuations, and inducing alternating current in the coils. When rectified and connected in series, the device achieved a peak voltage of 4.33 V, 39.88 mA current, a maximum power of 60 mW, and could directly drive seawater electrolysis for hydrogen production (Figure 4(c) and (d)).

In addition to large-scale renewable energy, MEGs can harvest lower-density, more difficult-to-collect energy, such as acoustic energy. In 2025, Chen's team proposed a 400 μm-thick membrane-type magnetoelastic generator [23]. Owing to the ultra-thin film's high sensitivity to minute sound waves, microvibrations are amplified through a Helmholtz resonator, modulating particle spacing and inducing magnetic flux changes in the coil. With a membrane Young's modulus of 2.59×10^7 Pa, the device generated 107 mA/m^2 under 95 dB sound. Recently, further improvements yielded an ultra-thin, rollable magnetoelastic acoustic energy harvester [32]. Using a spray-coating and orientation process, the team produced a magneto-mechanical coupling film just tens of micrometers thick, stretchable up to 142%. Introducing 2.6 kPa pre-stress and a resonant cavity, the device reached a peak power of 0.11 mW. MEGs operate stably in humid and dusty environments without encapsulation and can directly harvest acoustic energy from voices or car audio systems to power capacitors and small electronics (Figure 4(e–g)).

3.2 Magnetoelastic Sensing and Human-Machine Interaction

Leveraging the Young's modulus compatibility of soft magnetoelastic materials with human tissues and their high sensitivity to magnetic flux changes under minute external forces and physiological signals, MEGs based on the giant magnetoelastic effect exhibit remarkable advantages in the sensing domain. These devices not only enable precise conversion

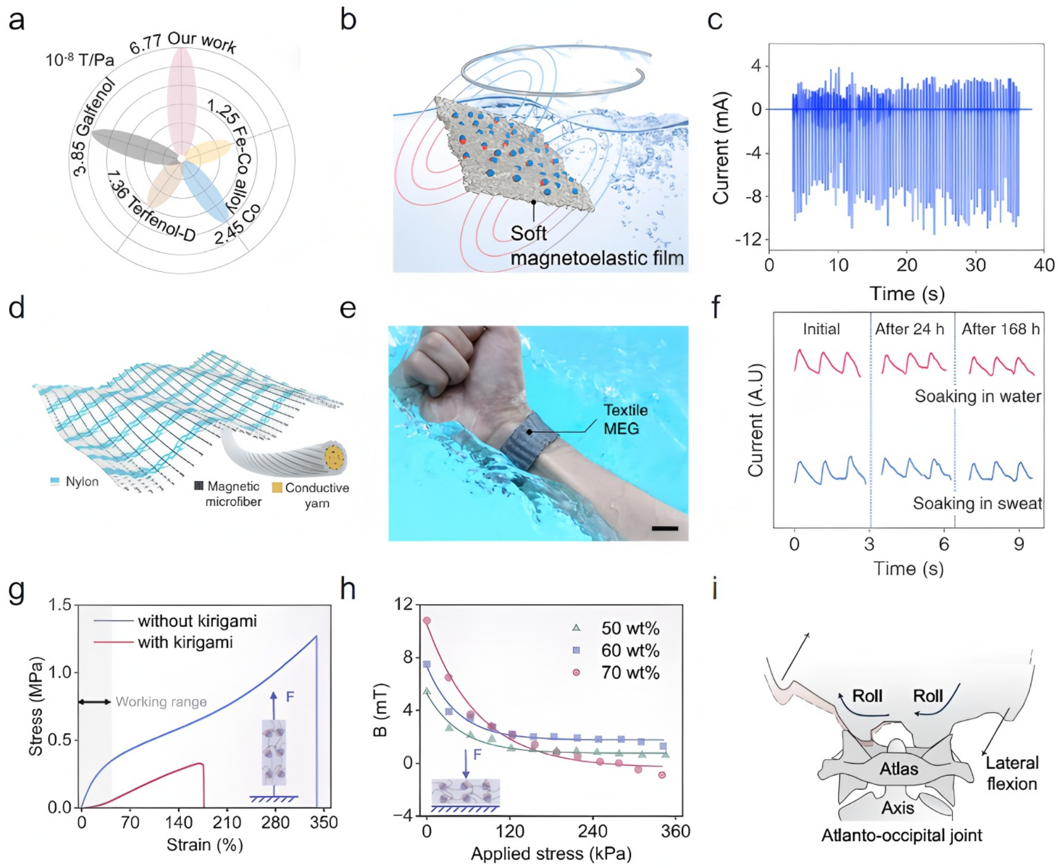

Figure 5: Wearable and Flexible Magnetoelastic Sensing Performance and Applications. (a) Comparison of Magneto-mechanical Coupling Factor (d_{33}) Performance Across Different Magnetoelastic Systems. (b) Illustration of the waterproof ability of textile MEGs. (c) Short-circuit current (I_{sc}) output of the textile MEG under continuous hand tapping. (d) Schematic illustration of the textile MEG architecture: soft magnetic fibers interlaced with conductive yarns to form a wearable fabric. (e) Photograph of the textile wristband employed as a wearable pulse sensor during underwater, encapsulation-free operation. (f) Pulse-wave profiles accurately recorded by the textile wristband after immersion in sweat and water for 24 h and 168 h, demonstrating long-term chemical stability. (g) Comparative strain–stress response of the kirigami-enhanced structure, highlighting the stretchability of the MC layer. (h) Variation in surface magnetic flux density of magnetoelastic sensors with different micromagnet mass fractions (50 wt%, 60 wt%, 70 wt%) under applied compressive stress. (i) Finite-element analysis of the strain distribution across the MC layer during yaw motion, validating the multichannel sensor's ability to detect infant cervical rotation. [(a-c) Adapted with permission from [26], copyright 2021 Elsevier Inc. (d-f) Adapted with permission from [30], copyright 2026 Elsevier Inc. (g-i) Adapted with permission from [36], copyright 2021 Nature Portfolio.]

of subtle mechanical signals into electrical outputs, fulfilling the dual demands of flexible substrates and high-precision detection, but also overcome the limitations of traditional magnetoelastic generators. Unlike conventional devices that rely on relative motion between magnets and coils to induce flux changes, MEG-based sensors exploit intrinsic variations in magnetic flux density within the material, integrating energy harvesting and sensing functionalities into the material itself. This intrinsic property allows for scenario-specific breakthroughs in three core application areas: wearable sensing, medical monitoring, and human–machine interaction, thereby expanding a wide range of innovative use cases.

3.2.1 Wearable and Flexible Magnetoelastic Sensing

Extensive research has explored the application of MEGs in wearable devices. Compared with traditional generators that rely on mechanical motions, such as rotation or translation, to induce relative displacement between magnets and coil windings and thereby cut magnetic field lines, the intrinsic nature of giant magnetoelastic materials simplifies device structures, facilitating seamless coverage in wearable scenarios.

In 2021, the Chen team first discovered the giant magnetoelastic effect in soft matter. Its magneto-mechanical coupling coefficient is five times greater than that of traditional rigid metal alloys and its mechanical properties match those of human tissues. This overcomes the limitations of traditional rigid materials [26]. The textile-based MEG developed based on this effect has high short-circuit current density and low internal resistance. It is also inherently waterproof, enabling stable operation in sweating scenarios without encapsulation. In combination with algorithms, it can also monitor respiration and identify abnormalities such as coughing, thereby circumventing the issue that conventional sensors are readily influenced by humidity (Figure 5(a–c)).

In the same year, the Zhao team extended this effect to one-dimensional soft fibers. The magneto-mechanical coupling coefficient of the developed magnetic fibers is 8.4 times that of traditional rigid alloys, allowing large-scale production [30]. The textile MEG based on these fibers can monitor arterial pulses underwater (detection limit as low as 0.05 kPa) and can also build a wireless cardiovascular monitoring system, breaking the application limitations of two-dimensional thin-film MEGs (Figure 5(d–f)).

In 2024, significant progress was made in the large-scale application of MEGs. The research team optimised the magnetic particle ratio of textile MEG patches, determining that a concentration of 70 wt% was optimal. This ensures both signal output and flexibility [35]. At the same time, they solved practical problems in production such as uneven distribution of magnetic particles and interference in sewing operations. The final device can monitor biological signals in multiple parts such as the throat and wrist, and can also adapt to personalized muscle physical therapy, filling the gap between MEG's laboratory research and large-scale application.

Recently, the Liu team launched a soft magnetoelastic patch with an origami structure, applying this technology to infant cervical spine care for the first time [36]. Its Young's modulus is as low as 108.2 kPa (matching infant skin), with high signal-to-noise ratio, and the origami structure improves conformability, enabling accurate capture of multi-directional dynamic pressure of the cervical spine. Compared with traditional detection methods such as MRI and CT, it requires no external power supply, has no radiation, and supports long-term non-invasive wear, completely solving the pain points of traditional methods and promoting wearable magnetoelastic sensing to extend to segmented scenarios for vulnerable groups such as infants (Figure 5(g–i)).

3.2.2 Clinical and Physiological Monitoring

Magnetoelastic sensors have distinct advantages in terms of high sensitivity, low invasiveness and biocompatibility, and can be used for everything from routine health monitoring to precision medicine. They have enabled multiple breakthroughs in clinical diagnostics, rehabilitation monitoring and intraoperative assistance.

Physiological Parameter Monitoring: Traditional respiratory sensors often suffer from poor wearability. They also have a limited signal-to-noise ratio. This is due to airflow constraints. In 2021, Wang et al. developed a wearable respiratory monitoring device that adhered closely to the skin on the chest. It converted respiratory motion directly into quantifiable magnetic signals [37]. The device provided a home-based monitoring tool. This was for patients with respiratory diseases. Examples of these diseases are asthma and chronic obstructive pulmonary disease. It also supported remote diagnosis. It even provided early warning of disease progression. Meanwhile, the non-invasive nature and excellent biocompatibility of magnetoelastic effects have facilitated significant advances. These have been in the area of in vivo monitoring. Zhao and colleagues have demonstrated that sensors based on permanent fluidic magnets could be used to conform to heart models of various sizes, thereby addressing the mismatch between rigid bioelectronics and dynamic biological tissues [29, 38]. Dynamic monitoring achieves signal stability of over 90%, providing flexible, high-precision solutions for intraoperative cardiac monitoring and bedside ICU observation. This avoids the discomfort and signal interference caused by conventional rigid sensors. When integrated into microfluidic chips, these magnet-based fluidic sensors enable highly accurate, self-powered monitoring of liquid flow rates and glucose concentrations. Crucially, the results of the toxicity tests showed that more than 97% of the mouse fibroblasts survived, which confirms the excellent biocompatibility of the substance, which makes it suitable for in vivo tissue fluid analysis, injectable sensors and flexible microfluidic electronic applications. These advances successfully overcome the inherent limitations of rigid magnetic materials in liquid electronics, paving the way for new possibilities in this field. (Figure 6(a–c))

With excellent magneto-mechanical coupled effect and ultra-soft adaptation characteristics, the soft magnetoelastic sensor can accurately convert subtle eyelid movements into high-fidelity electrical signals. This capability has been leveraged. Soft magnetoelastic eyelid sensors with skin conformity, waterproofing and lightweight design have been developed. These sensors are for real-time fatigue monitoring. They offer early warning systems for high-intensity occupations. These occupations are in manufacturing and transportation [19].

Rehabilitation Applications: The same high-precision, user-friendly sensing technology can be used in rehabilitation scenarios to address the limitations of conventional wearable devices, such as poor adaptability and delayed feedback. In 2024, a magnetoelastic pressure sensor was designed by Zhu et al., in which the giant magnetoelastic effect significantly enhanced sensitivity compared to traditional inductive sensors [39]. Integrated into rehabilitation gloves, joint motion was continuously tracked by this system, with real-time, precise data being provided to guide postoperative rehabilitation plans. Similarly, the Che research group developed a non-invasive auxiliary voice system for patients with vocal cord disorders, thereby overcoming the inconvenience and invasiveness of electronic larynxes or tracheoesophageal punctures [40]. This system accurately captured subtle laryngeal muscle motions. It converted them into electrical signals. These signals drove a voice output device. With a response time of 40 ms and a signal-to-noise ratio of approximately 17.5, it operated continuously for 40 minutes without any increase in temperature or degradation in performance, effectively improving the patient experience compared to conventional assistive devices (Figure 6(d–f)).

Disease Diagnosis: Magnetoelastic sensing also shows great potential for disease diagnosis. Traditional methods for the early detection of neurological disorders such as Parkinson's disease are often costly and limited in accessibility. In 2025, Tat et al. were the first to use soft magnetoelastic materials to non-invasively and continuously monitor Parkinson's patients at home [41]. The sensors accurately captured minute human movements, effectively identifying subtle tremors and bradykinesia cycles with substantially less interference than conventional accelerometers. This achieved a diagnostic accuracy of 96%, overcoming the subjectivity and intermittent nature of traditional diagnostic methods. Moreover, Chen and colleagues developed a Parkinson's handwriting analysis method, which combined a magnetoelastic diagnostic pen with neural network analysis [42]. Leveraging the deformation of the magnetoelastic pen tip and the motion of

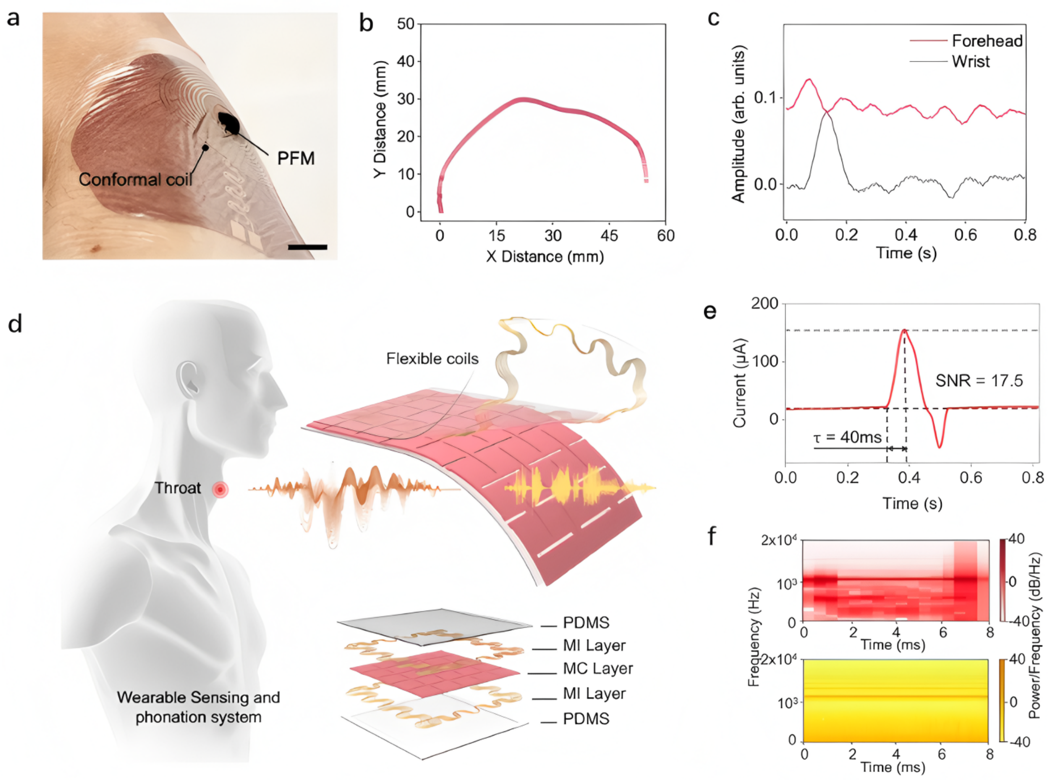

Figure 6: (a) Image of the liquid cardiac sensor on the wrist. Scale bar, 8 mm. (Adapted with permission from [29], copyright 2024 Nature Portfolio) (b) Plots of the outline of the skin surface. (Adapted with permission from [29], copyright 2024 Nature Portfolio) (c) Liquid sensors measured simultaneously at two sites: one on the forehead and one on the wrist. (Adapted with permission from [29], copyright 2024 Nature Portfolio) (d) Illustration of the wearable sensing-actuation system attached to the throat, demonstrating its application for vocal fold–independent speech. [Adapted with permission from [40], copyright 2024 Nature Portfolio] (e) Characterization of the device's response time and signal-to-noise ratio (SNR), demonstrating its high sensitivity and rapid response performance. [Adapted with permission from [40], copyright 2024 Nature Portfolio] (f) Spectral comparison between the commercial loudspeaker (red) and the proposed device (yellow) at 900 Hz under maximum strain (164%), demonstrating high-quality sound reproduction. [Adapted with permission from [40], copyright 2024 Nature Portfolio].

the ferrofluid ink to enhance magnetic flux fluctuations enabled the system to capture writing pressure, acceleration and high-frequency signals (10–12 Hz) without lag. Classification accuracy between patients with Parkinson's disease and healthy individuals reached 96.22%, clearly identifying subtle peak variations caused by tremor and prolongation of the writing cycle by 44% due to bradykinesia. This provides practical and reliable technical support for the early diagnosis of neurological conditions.

3.2.3 Human-Machine Interfaces Based on Magnetoelastic Sensors

MEG technology's unique advantages extend naturally into human–machine interaction, as well as having physiological and medical applications. Its combination of mechanical compliance, fine-scale sensing and self-powered operation effectively overcomes the limitations of conventional interaction devices, which are often rigid, slow to respond and reliant on external power sources. When coupled with machine learning algorithms and modular design, MEG sensors enable the evolution of human–machine interfaces. These can be made from command-driven to natural, precise, and adaptive operation. This achieves deep integration across diverse interactive scenarios. For instance, in 2022, Xu and colleagues developed a MEG sensor array. This meets the low-cost and low-power requirements of skin-integrated electronic interfaces [43]. The array is combined with programmable coils. This allows the activation regions and sensitivity to be dynamically customized. It also enables support for single-point touch and multi-point gesture recognition. This is across fifteen interaction modes. With a response time of 20 ms, the system achieved 95% accuracy in gesture recognition. It could also generate power independently through touch-induced pressure, thus eliminating the need for external power. These devices were successfully integrated into smartwatch displays. They were also integrated into industrial control panels. And they were integrated into VR/AR controllers. In 2024, an adaptive haptic glove was designed by Luo and his colleagues [44]. This glove was based on MEG sensing coupled with linear-resonant actuators. The glove incorporated tactile sensing and vibratory feedback, enabling haptic information to be captured, transmitted and shared across space and time. This represents a fully interactive human–machine interface (Figure 7(a) and (b)). Meanwhile, Zhou et al. developed a multimodal magnetoelastic artificial skin that could be used underwater. This material not only allowed autonomous robots to sense and identify marine debris. It also offered a

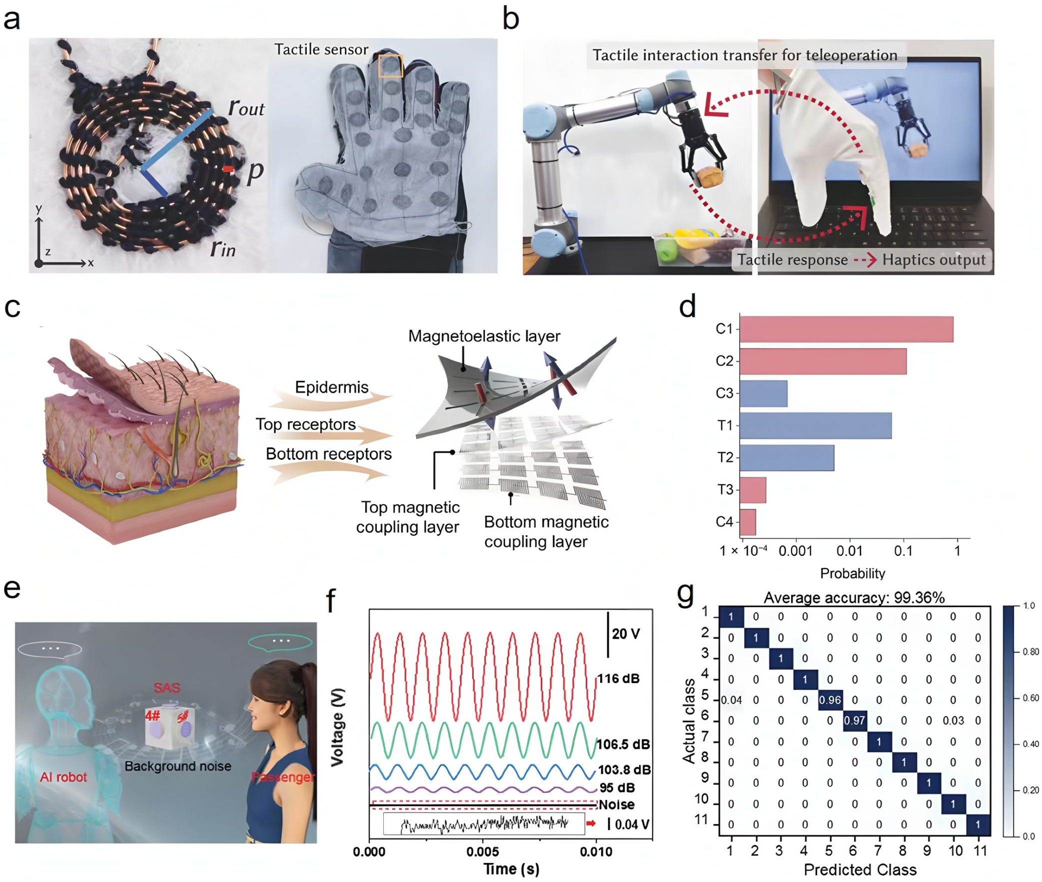

Figure 7: (a) Micrograph of the embroidered magnetic coil (inner/outer radii and pitch) and photo of the outer sensing glove for tactile capture. [Adapted with permission from [44], copyright 2024 Nature Portfolio] (b) Smart glove for skill teaching, teleoperation and tactile compensation. [Adapted with permission from [44], copyright 2024 Nature Portfolio] (c) Schematic illustration of the three-layer architecture of the bioinspired magnetoelastic artificial skin (BMAS), consisting of an untethered magneto-mechanical coupling (MC) layer and dual magnetic induction (MI) sensing layers, emulating the hierarchical structure of human skin. [Adapted with permission from [27], copyright 2024 American Association for the Advancement of Science] (d) Softmax probability distribution of the green sea mollusk shell classification result by the 1D convolutional neural network (1D-CNN), demonstrating the model's high confidence (probability $\approx$ 1) in its prediction. [Adapted with permission from [27], copyright 2024 American Association for the Advancement of Science] (e) Enlarged view of the voice-interaction scene between the passenger and the intelligent driving system via the SAS under background music noise interference. [Adapted with permission from [27], copyright 2024 Wiley-VCH GmbH] (f) Output voltage waveforms of a single TAS under different sound pressure levels, used for calculating the signal-to-noise ratio (SNR). [Adapted with permission from [20], copyright 2024 Wiley-VCH GmbH] (g) Confusion matrix of 11 voice commands after deep learning with a convolutional neural network (CNN), achieving an average recognition accuracy of 99.36%. [Adapted with permission from [20], copyright 2024 Wiley-VCH GmbH].

cost-effective solution for multi-channel and multi-mode haptic interaction. This demonstrates broad application potential (Figure 7(c) and (d)) [27].

In more specialised tactile applications requiring greater precision, Hu and colleagues proposed super-resolution magnetoelastic tactile skins [28]. These devices achieved unprecedented sensing precision. This was through structural innovation and algorithmic optimization. The devices were successfully applied to robotic dexterous hands for grasp force feedback. They were also applied to rehabilitation devices for monitoring hand motion pressures. This brought tactile interactions between humans and machines closer to natural sensory experience.

Voice-controlled interfaces, which are often hindered by environmental noise, motion artefacts and low skin compliance, have also benefited from MEG technology. Zhao et al. designed a wearable MEG-based voice recognition system [21]. It weighs less than 5 g. It can be attached behind the ear or on the neck. The device captured speech signals across 20 Hz–20 kHz. It had a signal-to-noise ratio of 69.1 dB. It incorporated self-filtering. This was to eliminate low-frequency biomechanical artifacts. Even in noisy environments where the noise level was 50 dB, more than 85% of the time, it was possible to recognise voices. This means that voice control for wheelchairs and other assistive devices can be relied on. Furthermore, Qiao et al. developed a self-powered triboelectric stereo acoustic sensor (SAS), which achieves a wide frequency response range of 100–20,000 Hz, an ultra-high sensitivity of 3172.9 mV_{pp}/Pa, and a signal-to-noise ratio (SNR) of 56.37 dB [20]. This sensor effectively eliminates environmental noise interference and accurately extracts target audio signals. Even in noisy environments, the average deep learning accuracy for sound recognition reaches 98%. This breakthrough has facilitated reliable voice-based interactions in scenarios such as auxiliary conference systems (Figure 7(e–g)).

Beyond providing tactile feedback and enabling remote control, MEG technology has had a significant impact on compact, integrated interactive devices. For instance, Lin et al. developed a soft magnetoelastic multi-sensor system based on a Fourier series design. This system employed a three-layer structure consisting of a top porous PDMS energy absorption layer, a middle magnetoelastic sensing layer and a bottom coil array [45] .This architecture enabled programmable mechanical responses and sensing performance and could be produced at a low cost using 3D printing. It is therefore suitable for use in touch panels and interactive systems in industrial robots and VR/AR platforms [43].

With the rapid development of artificial intelligence and the increasing demand for secure information exchange, MEG technology has also been applied to identity verification. In 2025, Zhang and colleagues designed an intelligent keyboard. It used a dual-mode authentication system. This combined fixed and dynamic typing patterns. This enabled highly interactive user verification [46]. This approach showcases MEG's ability to improve security, enable natural interaction and ensure adaptability in human–machine interfaces.

Together, these innovations demonstrate the flexibility, environmental adaptability and multifunctional integration of MEG sensing technology. MEG devices can harvest diverse energies, including human motion, wind, waves, and sound, without external power thanks to their self-powered operation, mechanical compliance, high sensitivity, and biocompatibility. This addresses the limitations of traditional technologies, such as low conversion efficiency and poor adaptability. Furthermore, MEG sensors are environmentally resilient and resistant to water, humidity, and dust. They can power small electronic devices directly or enable innovative applications such as seawater electrolysis for hydrogen production.

In wearable applications, MEG technology addresses both the power supply requirements of the device and the need for physiological monitoring. In medical diagnostics, it enables continuous monitoring of everything from body surfaces to internal organs, spanning health management and disease diagnosis. In human–machine interfaces, MEG technology facilitates a transition towards more natural and precise interaction methods, surpassing the limitations of conventional rigid and power-dependent systems. Continued optimisation of core materials (e.g. NdFeB magnetic particles embedded in PDMS or Ecoflex elastic matrices) and structural designs (e.g. arrayed, fibre-based and fluidic) combined with machine learning and modular fabrication techniques breaks traditional barriers in terms of rigidity, power dependence and sensitivity while broadening the potential applications across health, rehabilitation and intelligent interaction.

4 Summary and Outlook

Despite notable progress, there are still several challenges to overcome before MEGs can be deployed more widely:

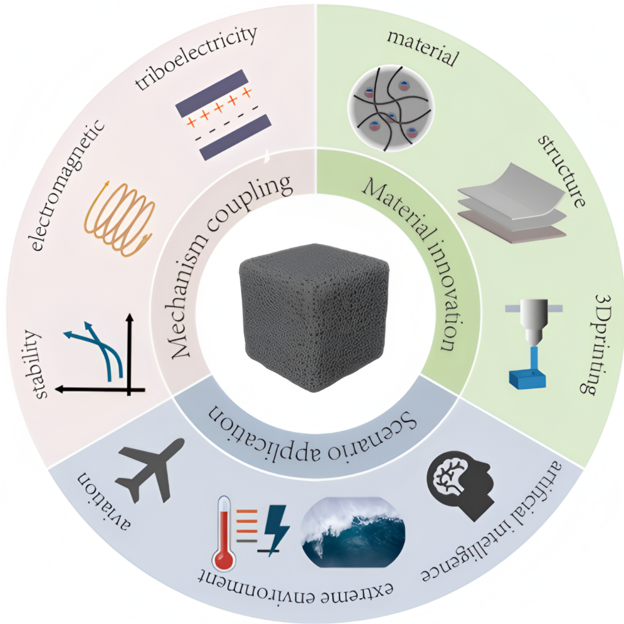

Figure 8: Schematic Diagram of Key Directions for MEG Technology Development.

(1) Stability and Reliability: Existing MEGs technology relies on magnetoelastic coupling for energy conversion and sensing. Future development via multi-physical mechanism synergy and material innovation will extend functional boundaries, elevate performance limits, and enhance energy density and long-term stability.

(2) Miniaturization & Cost Reduction: Current MEGs face issues of large size, heavy weight and high manufacturing costs, restricting their application in microelectronic devices and large-scale deployment. Future efforts will focus on miniaturized structural design, integrated manufacturing and material optimization to address these constraints for flexible integration.

(3) Special Environmental Adaptability: MEGs currently lack scenario-specific optimization for extreme conditions (extreme temperature, high pressure, corrosion) and show insufficient environmental robustness. Future development will rely on tailored material modification and structural reinforcement to enhance adaptability, enabling reliable operation in special application scenarios (Figure 8). MEGs have emerged as a promising type of soft energy system. They leverage the giant magnetoelastic effect in elastomeric matrices that are embedded with micromagnetic particles. Unlike traditional rigid magnetoelastic systems, soft MEGs offer high magneto-mechanical coupling and large deformability, as well as mechanical compliance that is compatible with human tissues. These features allow them to efficiently convert subtle mechanical inputs, ranging from human motion and ambient vibrations to wind, waves and acoustic energy, into electrical energy without the need for external power sources. Recent advances encompass both materials and structural innovations. In terms of materials, developments include permanent fluid magnets, low-field molecular ferroelectrics, and high-performance NdFeB-based elastomers. Structural design strategies, such as fibre-based textiles, spherical geometries and origami-inspired architectures, can further enhance

the efficiency of energy conversion, the mechanical adaptability and the long-term operational stability of devices. Meanwhile, MEG devices have demonstrated exceptional performance in wearable sensing, physiological and medical monitoring, rehabilitation assistance, and human–machine interfaces. Their self-powered operation, resilience to the environment, high sensitivity and biocompatibility enable applications ranging from daily health management to precision diagnostics and interactive robotics. Overall, MEGs integrate energy harvesting and sensing functionalities within a single soft material system, representing a significant advancement over traditional rigid, power-dependent technologies. Their modularity, flexibility and scalability highlight their potential as components of the next generation of flexible electronics, self-powered sensors and adaptive human–machine systems.

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Author Contributions

Conceptualization, methodology, investigation, formal analysis, data curation, writing—original draft preparation, writing—review: Q.L.; software, validation, visualization, writing—editing: Y.Z.; validation, visualization, writing—editing: X.W.; resources: W.Z.; Writing – review, editing, Supervision: J.L.; Writing – review & editing, Supervision, project administration, funding acquisition: X.X.; All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

All the authors declare that they have no conflict of interest.

Data Available

Data will be made available on request.

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