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On-Body Piezoelectric Energy Harvesters through Innovative Designs and Conformable Structures

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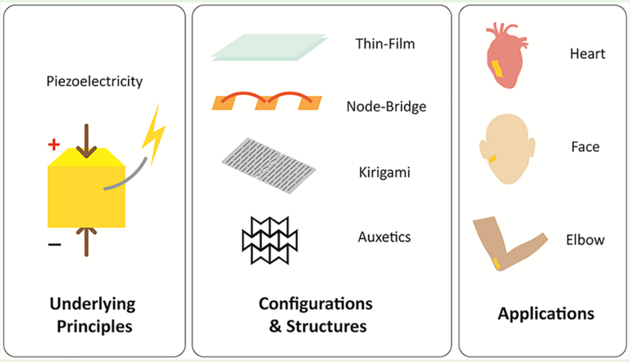

ABSTRACT: Recent advancements in wearable technology have improved lifestyle and medical practices, enabling personalized care ranging from fitness tracking, to real-time health monitoring, to predictive sensing. Wearable devices serve as an interface between humans and technology; however, this integration is far from seamless. These devices face various limitations such as size, biocompatibility, and battery constraints wherein batteries are bulky, are expensive, and require regular replacement. On-body energy harvesting presents a promising alternative to battery power by utilizing the human body's continuous generation of energy. This review paper begins with an investigation of contemporary energy harvesting methods, with a deep focus on piezoelectricity. We then highlight the materials, configurations, and structures of such methods for self-powered devices. Here, we propose a novel combination of thin-film composites, kirigami patterns, and auxetic structures to lay the groundwork for an integrated piezoelectric system to monitor and sense. This approach has the potential to maximize energy output by amplifying the piezoelectric effect and manipulating the strain distribution. As a departure from bulky, rigid device design, we explore compositions and microfabrication processes for conformable energy harvesters. We conclude by discussing the limitations of these harvesters and future directions that expand upon current applications for wearable technology. Further exploration of materials, configurations, and structures introduce interdisciplinary applications for such integrated systems. Considering these factors can revolutionize the production and consumption of energy as wearable technology becomes increasingly prevalent in everyday life.

KEYWORDS: *piezoelectricity, conformable devices, flexible electronics, wearable sensors, on-body energy harvesting, self-powered devices*

■ INTRODUCTION

Current State of Wearable Devices. The human body continuously generates valuable data—chief among these being vital biological signals—which can be transmitted to the user in real-time through wearable devices.[1,2] This enables various research applications, namely in sensing and monitoring.[3,4] These include heart rate monitors, fitness trackers, smartwatches, and pacemakers, all of which can provide insights for health monitoring, disease detection and intervention, sports training, and behavioral therapy.[5]

However, the portable nature of wearable devices necessitates battery power. Batteries impose physiological limitations to the seamless integration of such devices with the human body. As device fabrication must accommodate an internal battery unit, the bulkiness and rigidity of the battery set a restrictive precedent for the shape, size, and overall design of contemporary wearable devices.[6] Especially for users performing dynamic activity, bulky device design is indiscrete, inhospitable, and uncomfortable.[7]

Furthermore, batteries limit the longevity of the devices they power. This results in regular replacements or recharges, which can be incredibly costly, inconvenient, and environmentally unsustainable.[8,9] For instance, rechargeable wearable electronics such as the Apple Watch still require daily to weekly recharging, and battery life often falls short of consumer needs.[10] The need for more consistent and reliable power sources is especially critical for biomedical devices. The high turnover of such devices is particularly evident given that patients in the US consume over 150 thousand pacemakers annually.[11] Meanwhile, implanted defibrillators have a life span of approximately 10 years but need replacement every 4.7 years on average due to battery

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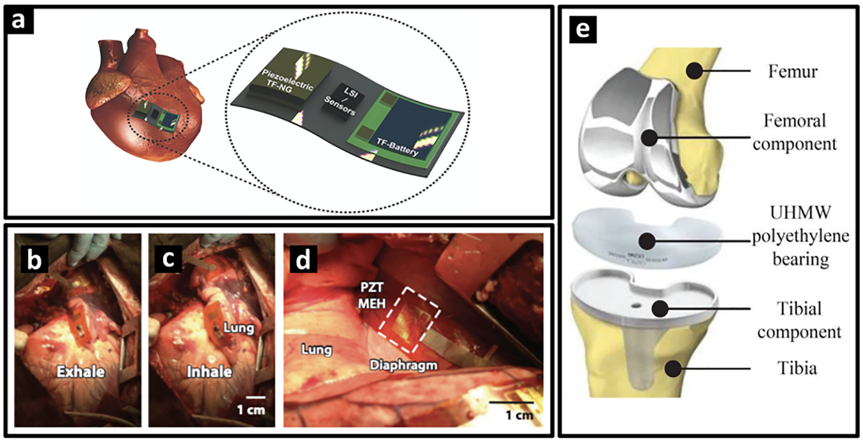

Figure 1. *In vivo* piezoelectric energy harvesters on various body parts: (a) the heart, (b, c) lungs, (d) diaphragm, and (e) limbs. (a) Schematic of a flexible thin-film self-powered piezoelectric system laminated on a heart. (b) PZT-based mechanical energy harvester (MEH) on a bovine lung during exhale and (c) inhale, with (d) a PZT MEH on the diaphragm. (e) Schematic of a total knee replacement with an ultrahigh molecular weight (UHMW) polyethylene bearing. Panel a is adapted with permission from ref 43. Copyright 2014 Wiley-VCH. Panels b, c, and d are adapted with permission from ref 38. Copyright 2017 Annual Reviews. Panel e is adapted with permission from ref 42. Copyright 2018 IEEE.

constraints.[11] This imposes significant financial, physical, and psychological burdens. Compounding costly doctor visits, invasive replacement surgeries, and fear of device failure thereby detriment the user's well-being. Moreover, with increasing multifunctionality, the power requirements of these devices are difficult to satiate.[12] Continuous data acquisition, especially when coupled with real-time analysis and relay, quickly drains battery life. This immediate transmission of information is essential for devices with applications intended for emergencies, i.e. the event of a fall or heart attack.[13] While advancements have been made toward improving battery efficiency and design,[14−16] these drawbacks demand further innovation. The growing industry of wearable devices requires a power source that can meet their energy needs, in both quantity and duration, while ensuring minimal size, weight, and obstruction to functionality.

Self-Powered Devices. Energy harvesting provides a promising alternative to fully battery-powered devices by converting otherwise wasted energy into storable electricity. Energies with piezoelectric,[17] flexoelectric,[18] dielectric,[19] and triboelectric[20] origins can be transformed electromechanically. Likewise, pyroelectric,[21] optoelectronic,[22] and electromagnetic[23] energies can be converted into electricity.

While energy harvesting alone is valuable for applications involving externally sourced energy, exploring ways to make technologies self-sufficient reinforces the utility of such methods. Researchers have already begun to modify energy harvesting techniques to develop self-powered devices.

One such method involves harnessing biomechanical energy from human motion. In 1995, Chen invented dynamoelectric shoes, a footwear energy harvester.[24] These shoes contain a pressure-operated electric generator unit within the heels that powers a rechargeable battery unit connected to an electric socket. Years later, the 2018 creation of boot harvesters by Qian et al. further exploited innately produced energy through the use of piezoelectric lead zirconate titanate (PZT) stacks incorporated into the design.[25]

Advances have also been made in implantable medical devices and biomedical sensors.[26] In 2005, Platt et al. developed piezoelectric ceramics for implantation in orthopedic prosthesis. The resulting self-powered total knee replacement (TKR) implant serves to operate low-power components vital to monitoring and diagnosis.[27] In a later study focusing on biomechanical energy harvesting, Riemer et al. emphasize that energy from the human body should not be wasted. Rather, capturing some of the 1.07×10^7 J the average person expends per day enables the advent of self-powered devices.[28]

Piezoelectrics for Self-Powered Devices. The aforementioned conversion of mechanical energy into electrical energy can be achieved through a variety of methods, including induction via electrostatic, electromagnetic, and piezoelectric effects.[29−31]

Among these relevant methods, the piezoelectric effect is the most studied.[32] With linguistic origins in the Greek words "piezein", meaning to squeeze or press, and "piezo", meaning push, piezoelectricity occurs when mechanical deformations of a dielectric material displace ions in a noncentrosymmetric crystal. This creates an electric dipole, and thus flow of electricity. Mirroring the direct piezoelectric effect, the converse piezoelectric effect occurs when an applied voltage generates stress within the material.

The intrinsic ability to convert mechanical strain energy into electrical energy makes piezoelectric materials suitable for applications in energy harvesting and sensing. Compared to typical energy storage units such as batteries, piezoelectric harvesters provide a stable, autonomous power source that does not require constant replacement or maintenance.

In the past decade, piezoelectric energy harvesting has been widely researched due to its high energy density, power density, sensitivity, and sustainability. Piezoelectric energy harvesting can be achieved without a separate voltage source or magnetic field, as is required by electrostatic and electromagnetic energy harvesting, respectively.[33] Harnessing the direct piezoelectric effect enables harvesting systems that typically operate on the order of microwatts to milliwatts.[34,35] As a result, common applications of piezoelectric energy harvesting provide power for portable electronics, implantable devices, and wireless sensors.[31,36,37]

Previous work has yielded piezoelectric generators that utilize the *in vivo* mechanical energy of the heart, lungs, diaphragm, and limbs, as shown in Figure 1.[27,38−43] Lu et al. proposed an ultraflexible piezoelectric energy harvester integrated with the heart to harvest the biomechanical energy of cardiac motions. When tested *in vivo*, the device achieved peak-to-peak voltage outputs of 3 V, demonstrating the feasibility of self-powered implantable devices.[40] In another study, Safaei et al. explored energy harvesting with embedded piezoelectric ceramic transducers in the knee, with simulations showing peak voltages of 2.3 V and an average power of 12 μW.[42]

Beyond energy harvesting, piezoelectric materials have also been used as both sensors and actuators due to their sensitive nature, high frequency response, and adaptable dimensions.[44] More specifically, piezoelectric materials have applications for sensing that are used in industry, household appliances, medicine, music, and everyday consumer electronics. For instance, wearable real-time monitoring devices provide a noninvasive alternative to current methods of long-term sensor systems. In 2020, the Conformable Decoders Group at the MIT Media Lab designed and manufactured the conformable Facial Code Extrapolation Sensor (cFaCES).[7] When laminated on the face, this thin-film device takes advantage of the direct piezoelectric effect to map facial strain distributions. Its ability to collect and analyze dynamic deformations aids nonverbal communication and at-home clinical monitoring of neuromuscular conditions.

Given their wide range of applications, it is important that piezoelectric energy harvesting sensors are tailored to their specific purpose. This includes deliberate selection and design of piezoelectric materials, fabrication processes, and the overall structure and configuration of the energy harvesting system.

Challenges. On-body energy harvesting is accompanied by a range of challenges. Especially for wearable biomedical devices, harvesters aim to provide intimate contact with the human body; however, curvilinear contours are difficult to match, often necessitating high degrees of flexibility and stretchability. Most notably, the shoulder, elbow, and knee joints make a proper fit elusive. Still, conformability is desirable as increased contact enhances the accuracy and precision of information extracted while ensuring the comfort of the user.[45] In order to accommodate for wearability, an attachment mechanism—such as van der Waals forces,[46] adhesives, or straps—must be implemented. Unfortunately, many reliable attachment mechanisms sacrifice flexibility for secure fastening. Conformability offers an opportunity for device functionality and attachment while also providing comfort.

With regard to health and wellness, the design of a user-friendly device must also account for biocompatibility, breathability, and durability. As with any medical device, compatibility with living systems is necessary to prevent physical irritation and a toxic response. Similar analysis should be conducted to evaluate the *in vivo* impacts on the mechanical and material properties of the device. Additionally, a device designed to operate under dynamic conditions should be flexible and permeable to accommodate movement and perspiration. Breathable materials as substrates prevent sweat accumulation, minimize user discomfort, and uphold the device conditions. Dynamic motion further necessitates device durability, especially for harvesters that rely on repeated deformation.

Current technology for on-body sensing is not only bulky and rigid but also expensive and inaccessible.[47] Mass-manufacturing and affordability are critical considerations when designing for the average user. This can be achieved by streamlining fabrication, selecting compatible materials, and utilizing modular parts. However, even if manufacturability is achieved, personalization is lost when looking to expand production. The challenge lies in designing a device that can be mass-manufactured and sufficiently well-tailored for a diverse range of consumers and body types. Self-powered conformable devices provide a potential solution for both personalization and increased longevity while reducing costs.

Despite their potential for interdisciplinary applications, self-powered devices face a variety of structural and material challenges. Especially for self-powered devices that incorporate piezoelectrics, integration with the human body proves difficult due to mechanical, biological, and fabricational limitations.

As for conformable materials used in self-powered devices, piezoelectric materials are characteristically brittle; for instance, aluminum nitride (AlN) and PZT—two commonly used inorganic piezoelectrics—have strain limits of ~0.1%.[48,49] The low strain limits of these materials pose design challenges for wearable piezoelectric devices that must endure the large mechanical deformations of the human body. For example, the strain on the knee can reach levels of over 30%.[50,51] Moreover, the coupling of a rigid mechanical system with the soft human body may constrain the same motion it is intended to harvest from.[31]

Another limitation to piezoelectrics' integration with on-body devices is that piezoelectric materials require a harvesting environment at their resonant frequencies in order to achieve maximal voltage output and performance.[52] A slight deviation from this ideal resonant frequency causes a significant reduction in voltage and power output.[53] With resonant frequencies on the order of kHz,[54] piezoelectrics are not well suited for harvesting from the human body, which has a resonant frequency of approximately 1 Hz.[55] To obtain the best results in energy harvesting under low-frequency conditions, a frequency up-conversion technique can be used.[69] In addition to the frequency up-conversion, resistive matching or using a nonlinear technique called synchronized harvesting on inductor (SHI) can be utilized, given that a piezoelectric transducer has a relatively large capacitive term with a low resonant frequency. As a result, an impractically large inductor (on the scale of tens of hundreds of Henry's) is required to extract the maximum power.[69] Nevertheless, the several challenges that piezoelectrics face—such as low strain limits and low levels of harvested power—can be tackled in various ways. Key approaches involve making thoughtful material selections, developing multifunctional materials, and modifying structures for enhanced power output, as described below.

Significance. Self-powered devices allow for continuous, real-time, and long-term data acquisition and transmission, enabling various sensing and monitoring applications. This makes them valuable in the commercial, fitness, and most notably, healthcare industries. These devices are at the forefront of user-centered innovation. The creation of self-powered wearables prioritizes the user's seamless interaction with technology and personalized experience. In particular, wearables can obtain information from a diverse range of people, from average users looking to track daily activity to patients requiring critical real-time health monitoring. The vast potential of self-powered on-body devices to revolutionize healthcare and daily life motivates exploration of how such technology can be optimally engineered.

The upcoming sections provide an overview of existing harvestable energies and explore these energies' advantages and limitations. Harnessing piezoelectricity is among the most effective methods for on-body energy harvesting. Expanding on this idea, the Findings section outlines various piezoelectric materials and their associated fabrication processes. This is followed by an exploration of how changing these parameters impacts the material properties, efficiency, power output, strain endurance, and mass-manufacturability of on-body devices. Further sections investigate how these parameters can be modified for desired applications and how device configurations and structures minimize and maximize experienced strain. Novel combinations of kirigami and auxetic structures lay the groundwork for future innovation, enabling the development of fully conformable devices.[56] With these advancements, applications such as strain sensing and gait monitoring can be realized in a more effective manner.

FINDINGS: METHODS FOR HARVESTING

Overview of Energy Harvesting Methods. In the literature, there exists a wide range of energy harvesting methods, each with their corresponding applications, assets, and limitations.[12,57] Certain harvestable energies and their corresponding methods can be used to convert mechanical energy to electrical energy. These include piezoelectricity,[17] flexoelectricity,[18] dielectricity,[19] and triboelectricity.[20]

Piezoelectricity is the electric polarization produced when mechanical stress is applied to certain solid materials.[58] Thus, subjecting these materials to loading generates harvestable energy. Unlike piezoelectricity, flexoelectricity describes electric polarization due to a strain gradient as opposed to uniform strain.[59] The flexoelectric effect can exist in centrosymmetric materials and becomes more pronounced approaching the nanoscale. Even so, this phenomenon is difficult to interpret when seeking to identify distinguishable strain behaviors of target areas at the mesoscale and beyond and is not always reliable due to variations in material symmetry.[60] Piezoelectricity, by comparison, can be observed at all length scales and is directionally dependent. Dielectric elastomers are soft and stretchable lightweight materials that can withstand high strains, maintain high energy densities, and provide low costs. However, high performance can typically only be achieved with driving voltages above 2000 V, leading to a need for prestraining, significant physical bulk, reduced shelf life, relatively short lifespan, and increased risk to the user.[61] Triboelectric harvesters generate power when experiencing a compressive load. Although they are potentially promising for self-powered, implantable sensors, they are not as well suited as piezoelectric-based devices for on-body applications, because the body does not exert compressive, orthogonal loads of high magnitudes.[62]

Beyond mechanically converted energies, energies with thermal, optical, and magnetic origins can also be harvested. In pyroelectricity, materials with high internal electric fields can generate a surface charge when a temperature change over time induces a change in the internal structure.[63] Correspondingly, thermoelectric materials exploit the electric potential drops present in junctions between dissimilar materials to generate power from a thermal gradient across space. While thermal energy harvesting and thermal sensing applications have been explored, the fragility, water solubility, and humidity-invoked decomposition of pyroelectric materials are difficult to avoid in on-body contexts.[64] Likewise, although optoelectronic solar cells have begun to be employed, their need to be exposed to light renders them unsuitable for many wearable, on-body applications.[22] Unpredictable weather patterns, sun exposure, shadows, and clothing jeopardize functionality, all while acquiring very minimal information about the target area of the body. Beyond this, electromagnetic energy harvesters generate power from a changing magnetic field that manifests as vibrations while in the vicinity of an electric conductor through electromagnetic induction.[30] However, for on-body applications, vibrational sensing of a magnetic response does not provide holistic information and may even interfere with other coupled sensing components. More details on comparing other energy harvesting methods with piezoelectric-based methods can be found in a recent review article.[38] Of these energy harvesting methods, piezoelectricity shows the most promise for flexible, self-harvesting materials to be used on-body. Further evaluation of piezoelectricity follows in the section below.

Piezoelectricity. In the last few decades, there has been a surge in the use of piezoelectric materials as a mechanism of energy harvesting, especially for biomechanical technologies. Piezoelectricity has been observed in natural materials as well as in a myriad of synthetic materials with various electromechanical, mechanical, and thermal properties.[58] This section will describe and briefly compare the piezoelectric properties and performance of various traditional piezoelectric materials. Additionally, a basic mathematical formulation of the electromechanical properties of piezoelectric materials will be presented.

Defining Parameters. Piezoelectric materials can be classified through observing their dielectric constants and piezoelectric coefficients. The permittivity or dielectric constant, $\in$ for a piezoelectric material, is defined as the dielectric displacement per unit electric field. The dielectric constant represents a measure of a material's ability to store electrical energy. Materials with higher dielectric constants can store more energy compared to those with low dielectric constants, a property that is especially important in building self-powered energy harvesters leveraging piezoelectric materials. The piezoelectric coefficient d, or charge constant, represents the electric field produced by applied mechanical strain on a piezoelectric material.[65] The subscript of d_{ij} implies that the electric field is applied or charge is collected in the i direction for a displacement or force in the j direction. Namely, the piezoelectric coefficient, d_{ij} is the ratio of the strain in the j-axis to the electric field applied along the i-axis with all external stresses held constant. In piezoelectric energy harvesters, the linear piezoelectric effect can be defined through two behavioral laws which describe the combined effect of electrical and elastic mechanical behavior. The two constitutive equations of direct and converse piezoelectric effects represent the coupling of material stress and strain:

$$\begin{bmatrix} D \\ S \end{bmatrix} = \begin{bmatrix} s^E & d^t \\ d & \epsilon^T \end{bmatrix} \begin{bmatrix} T \\ E \end{bmatrix} \tag{1}$$

where S and T are strain and stress, respectively; E and D are the electric field strength and electric displacement, respectively; $[d]$ is the matrix for the direct piezoelectric effect; $[d^t]$ is the matrix for the converse piezoelectric effect; and ϵ and s are the permittivity (dielectric constant) and elastic compliance, respectively. The superscript E denotes a constant or zero electric field, the superscript T indicates a constant or zero stress field, and the superscript t stands for transposition of a matrix.[65] The first row of the matrix equation follows from Hooke's Law for linear elastic materials in which the strain of an elastic object or material is proportional to the stress applied to it. It should be noted that the piezoelectric effect is nonlinear in nature and the linear constitutive equations are applicable for low electric fields only. The second row is an equation that describes the process of a polar piezoelectric material undergoing mechanical deformation, resulting in it becoming electrically polarized and producing a fixed electric charge and displacement on the surface of the material.

Different Piezoelectric Materials. The choice of piezoelectric material for energy harvesters depends on the piezoelectric properties and suitability for a particular function. Broadly, piezoelectric materials[66] can be classified into the following:

(1) Ceramics: barium titanate (BaTiO3), lead zirconate titanate (PZT), potassium niobate (KNbO3)
(2) Single crystals: Rochelle salt, lithium niobate, quartz crystals
(3) Polymers: polyvinylidenefluoride (PVDF), polylactic acid (PLA)
(4) Composites: polyvinylidene fluoride-zinc oxide (PVDF-ZnO), cellulose BaTiO3, polyimides-PZT

Lead zirconate titanate (PZT) is the most frequently used piezoelectric ceramic due to its high electromechanical coupling ability. Polyvinylidenefluoride (PVDF) is another commonly used piezoelectric polymer due to its flexibility and biocompatibility and is often used in energy harvesting devices.[67,68] These materials have also previously been incorporated in the form of nanowires, thin films, and ribbons for use in piezoelectric energy harvesters.[31] Piezoelectric single crystals have also been integrated with energy harvesting systems to leverage their high electromechanical coupling. Araujo et al. address a renewable electric low-power piezoelectric energy harvesting generator based on a quartz single crystal. As a natural piezoelectric crystal, quartz is precise and has high acoustic quality.[69] However, quartz is often more costly[70] and has lower sensitivity[71] compared to piezoelectric ceramic materials.

The choice of piezoelectric materials for energy harvesting also depends on the material properties and suitability for desired applications. For a detailed analysis of organic, inorganic, and composite materials, please refer to the cited review paper.[44] Additionally, harvesting mechanical energy from the human body demands low harvesting efficiency; otherwise, with a higher efficiency, the device would absorb more mechanical energy, leaving the user with less recoverable energy, thereby causing them to expend more energy for the same amount of work.[31] The wearer may also experience physical discomfort.[72] Thus, the challenge remains to achieve a device efficiency that supports self-powered operation but does not impede the body's movements or adversely affect the wearer. However, while the ratio of energy stored to the total mechanical work out (a conversion efficiency of ~2%) is sufficient for a low-power device such as a heart pacemaker, this low efficiency may be insufficient for devices that require more energy to operate.[31]

Challenges with Piezoelectrics. The implementation of piezoelectric materials demands consideration of constraints, namely material, manufacturing, and integration challenges presented by device design and development. These challenges arise with the pursuit of higher voltage output, enhanced strain endurance, mass-manufacturability, and conformability.

Voltage output is largely influenced by the piezoelectric coefficient and material properties, as well as device fabrication processes. Most intuitively, a higher piezoelectric coefficient corresponds with greater voltage generation, making lead zirconate titanate (PZT) a popular material for energy harvesting purposes given its piezoelectric coefficient of up to 1000 pC/N depending on thickness and poling conditions.[73] Voltage output can be further enhanced with attention to the crystal structure of the piezoelectric and its substrate. The reduction of lattice mismatch is highly desirable, e.g., molybdenum (Mo) as an electrode substrate for PZT.[7,74] Similarly, the surface smoothness of the substrate, i.e. mitigation of surface defects, augments the quality of the piezoelectric response by allowing for higher *c*-axis alignment.[7] Beyond ensuring substrate mechanical compatibility, a common fabrication procedure is poling the piezoelectric material to guarantee alignment with the *c*-axis.[75] Increased radio frequency (RF) sputtering power has been shown to improve the *c*-axis orientation.[76] Higher *c*-axis alignment maximizes the voltage output by orienting dipoles in the direction of the electric fields. This is achieved by applying electricity to ceramics and mechanically deforming polymers.[77] Another procedure involves doping the piezoelectric material with other elements to improve both voltage output and mechanical properties, i.e. the d_{33} (effective piezoelectric constant) coefficient and toughness, respectively.[78−80] For instance, Guo et al. increased the d_{33} coefficient of a PZT-based ceramic from 252 pC/N to 292 pC/N through a doping of 0.2−0.4 wt % Dy_2O_3/Yb_2O_3.[81]

Regardless of voltage output, the efficacies of piezoelectric materials can be compromised by geometrical fracture. While organic piezoelectrics, such as PVDF, boast higher strain tolerances than inorganic piezoelectrics,[82,83] the latter have much greater voltage and current outputs under the same force conditions. This renders the implementation of inorganic piezoelectrics more desirable for energy harvesting purposes—albeit more challenging due to brittleness. The strain tolerances for AlN and PZT, for instance, are less than 0.1%: a difficult limit to satisfy for on-body energy harvesting applications, given that the human skin may stretch over 30% (e.g., at joints such as the knee and elbow).[48−51]

The most promising of current approaches for circumventing the strain limit of inorganic piezoelectrics are material and mechanical alterations to device design. These can be described in two categories: (1) enhancement of strain endurance and (2) the mitigation of strain that the piezoelectric element experiences. For the former, the use of organic piezoelectric materials (i.e., PVDF) and doping have allowed for higher strain tolerance.[44,81]

For the latter, device configurations and structures take precedence. Explored in depth in the section Configurations and Structures, various arrangements including node-bridge structures, thin films, elastomeric substrates, serpentine structures, hydrogels, kirigami, and auxetics accommodate large deformations as to minimize deformation where the piezoelectric element is located. A vital design parameter to consider is the neutral mechanical plane (NMP) which effectively undergoes 0% strain between the compressive and tensile regions of the device.[84,85]

The NMP of the device should be used as a reference point such that brittle piezoelectric components are placed far enough away from it to experience sufficient strain to be self-powered, without exceeding the strain fracture limit.[31] Aligning the piezoelectric component with reference to the device's neutral mechanical plane (NMP) further ensures minimal experienced strain, as this plane effectively undergoes 0% strain between the compressive and tensile regions of the device.[84,85]

The miniaturization of systems becomes more necessary as modern technology converges toward developing smaller and faster portable devices. Such devices require different strategies of fabrication since material properties at the microscale differ from those at the macroscale. Microfabrication allows for the fast, high-precision, and low-cost mass production of complex

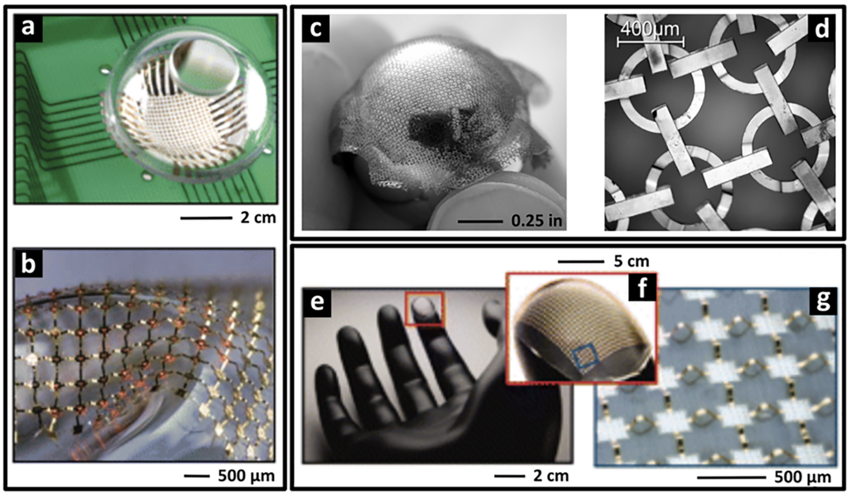

Figure 2. Examples of stretchable configurations and conformable structures: (a, b, e, f, g) thin-film, (a, b, e, f, g) node-bridge, and (c, d) chain mail. (a) Electronic eyeball camera using a conformable array of silicon photodetectors. (b) Microscale LED display device with stretchable interconnects between organic and inorganic LEDs. (c) Released metallic fabric draped over a 1′′ diameter metal ball and (d) a magnified chain mail structure. (e) Stretchable mesh design of a silicon circuit conforming to a fingertip model with (f) greater magnification of the fingertip and (g) greater magnification of the intricate connections of the circuit. Panels a, b, e, f, and g are adapted with permission from ref 85. Copyright 2010 American Association for the Advancement of Science. Panels c and d are adapted with permission from ref 102. Copyright 2007 IOP Publishing.

structures at these small scales.[86−89] It has numerous applications and has already revolutionized a multitude of scientific fields by offering alternative solutions to development in therapeutics, biology, circuit engineering, energy harvesting, materials science, and wearable technology.[90−93]

There are many techniques used to create devices in the micrometer range. Some are unique to microfabrication while others are traditional approaches that have been scaled down and applied in the micro regime. Typically, the process of microfabrication includes iterations of film depositions, micropatterning features, and etching to create the desired layers of a device. One method of fabrication, transfer printing, exemplifies a traditional practice that has been scaled down to be compatible with microscale designs. This assembly technique involves transferring objects from a donor to a receiver substrate, avoiding the issues that some polymers have with conventional fabrication techniques.[94] Transfer printing enables the organized combination of materials with different properties onto flexible substrates.[95] Microscale 3D printing is another process that seems to be emerging as a popular technique. This technological approach is achieved through various additive manufacturing processes such as microstereolithography, multiphoton lithography, laser chemical vapor deposition (LCVD), laser-induced forward transfer (LIFT), and UV lithography. It is especially being utilized in the electronics field to make miniature devices more flexible, customizable, and easier to produce.[96]

Unfortunately, this technology is not without material and structural limitations. Many microfabrication techniques are not compatible with biological systems, and certain materials are not suited for cleanroom environments due to their particular thermal, mechanical, or chemical properties.[94,97,98] The fabrication process often needs to be significantly modified to be compliant with an otherwise unsuited material. There also seems to be an unavoidable trade-off between the rate and accuracy with which 3D devices can be microfabricated. It is very difficult to generate high-resolution features on complex geometries unless time is sacrificed. For example, recent experiments attempting organ printing using photolithography require time- and energy-consuming techniques to achieve intricate shapes that realistically model organ tissues, rendering the process slow and inefficient.[99] Additionally, the more complex the microfabrication process, the more expensive it becomes.[86]

Despite limitations, microfabrication enhances device properties in various ways. By reducing the size and surface area-to-volume ratio of devices, devices' driving voltages decrease while increasing portability, heat dissipation, speed of analysis, and ability for electronic integration.[92] Decreasing the volume of a device also means reducing cost and waste while increasing the ease of detection. Further, microfabrication allows for batch processing, making the device mass-manufacturable and thus less expensive.[92] This paper will focus specifically on how microfabricated devices are manufactured for conformability, which is the capacity of a material or structure to interface closely and comfortably to the contour of a surface. It is an important aspect to consider for wearable technology because it increases the mobility of the wearer, improves spatial efficiency, and maximizes interaction between the user and the device. Certain materials possess intrinsic properties, such as a low Young's modulus and mechanical flexibility, that make them conformable. Most silicon-based organic polymers have these characteristics, and the most widely used silicone is polydimethylsiloxane (PDMS). Its applications are present in medicine, cosmetics, and electronics alike. Although flexible materials help achieve conformability, structures and configurations that enhance pliability are essential for integrating more rigid parts into conformable devices.

FINDINGS: CONFIGURATIONS AND STRUCTURES

Conformable devices enable continuous, long-term data collection by matching the curvilinear forms of the human body. Implementing conformable configurations and structures can reduce rigidity and bulk, resulting in more comfortable form-fitting devices. Chain mail, node-bridge, and thin layer structures have been explored, as shown in Figure 2. Chain mail structures consist of interlinked closed loops that can slide past and rotate against each other, allowing flexible structures to be

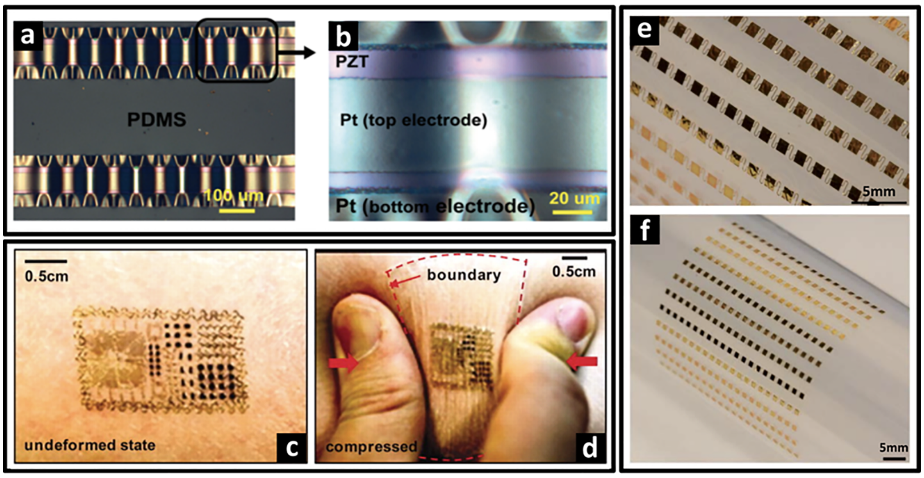

Figure 3. Examples of configurations and structures that minimize strain: (a, b) prestrained and (c, d, e, f) serpentine. (a) Prestrained PZT nanoribbon device on PDMS in a wavy, relaxed state and (b) corresponding magnification of the black boxed region in part a. (c) Epidermal electronic system (EES) on skin in the undeformed state and (d) compressed state. (e) Magnification of node-bridge structures with serpentine interconnects of (f) an ultrastretchable metal electrode conforming to a curved surface. Panels a and b are adapted with permission from ref 104. Copyright 2011 ACS Publications. Panels c and d are adapted with permission from ref 103. Copyright 2011 American Association for the Advancement of Science. Panels e and f are adapted with permission from ref 106. Copyright 2013 Royal Society of Chemistry (United Kingdom).

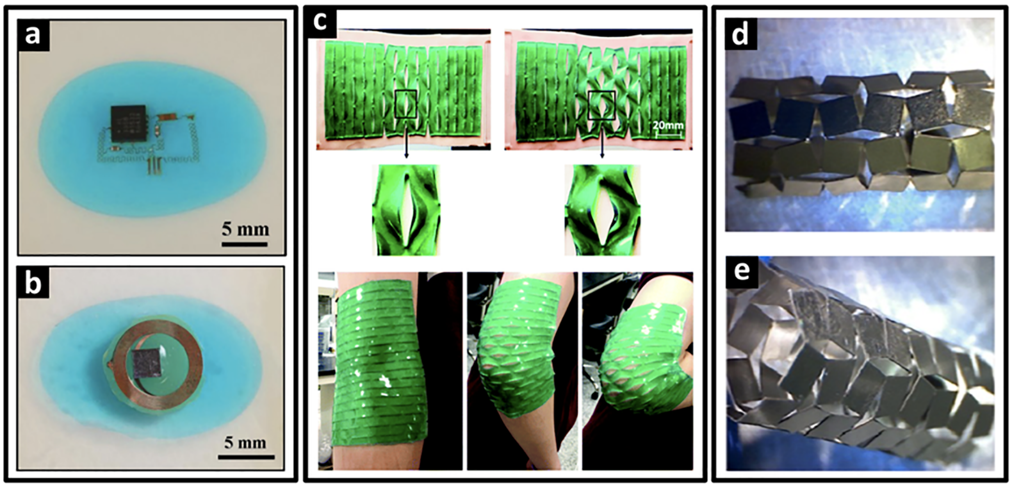

Figure 4. Examples of configurations and structures that minimize (a, b, c) and maximize (d, e) strain: (a, b) hydrogels, (c) kirigami, and (d, e) auxetics. (a) Mechanoacoustic hydrogel sensor with a stretch of 30% and (b) wireless hydrogel temperature sensor with a stretch of 40%. (c) Inhomogeneous deformation of laminated kirigami cuts on a substrate under maximum uniaxial stretching $\lambda = 1.25$ (above), and inhomogeneous deformation of a laminated kirigami film on the elbow during cyclic bending (below). (d, e) Hollow, stent-like cylinder of rotated auxetic structures with a rigid, tubular design. Panels a and b are adapted with permission from ref 110. Copyright 2016 John Wiley & Sons - Books. Panel c is adapted with permission from ref 115. Copyright 2018 Royal Society of Chemistry. Panels d and e are adapted with permission from ref 118. Copyright 2016 John Wiley & Sons - Books.

constructed from rigid materials. In Ploszajski et al., ferromagnetic composites enabled an actuatable chain-mail-like splint.[100] Fabrication processes such as photolithography and electrodeposition have been used to create chain-mail-like structures on a micro scale.[101] Due to the structure's reversible deformability and its mechanically responsive electrical properties, promising applications for chain mail in smart wearable technology and embedded electronic systems have begun to be explored.[102] In Rogers et al., a node-bridge structure involving arc-shaped interconnecting bridges that were bonded at nodes to a sheet of PDMS could endure strains of over 100%.[85] Given that the bridges accommodate the deformation by moving out of the plane, rigid or brittle components can be located at the nodes without experiencing significant strain. On the other hand, a simple but effective technique to accomplish conformability is to reduce device film thickness so that adhesion to the skin relies on van der Waals forces while remaining unobtrusive.[103]

Structures That Minimize Strain. *Prestrained and Serpentine Structures.* Instead of manipulating the properties of piezoelectric materials to ensure conformability, prestrained methods modify the geometric structure of rigid materials to minimize the overall strain experienced by the piezoelectric, shown in Figure 3. This is similar to the way that a metal spring allows for high flexibility despite its materials' high elastic moduli. Releasing a patterned elastomeric substrate while stretched results in structures that are capable of enduring these same strain levels once integrated with a device. Feng et al. implemented a prestrain procedure to increase stretchability and minimize strain experienced by the piezoelectric elements.[104] This was performed by heating the PDMS substrate to induce

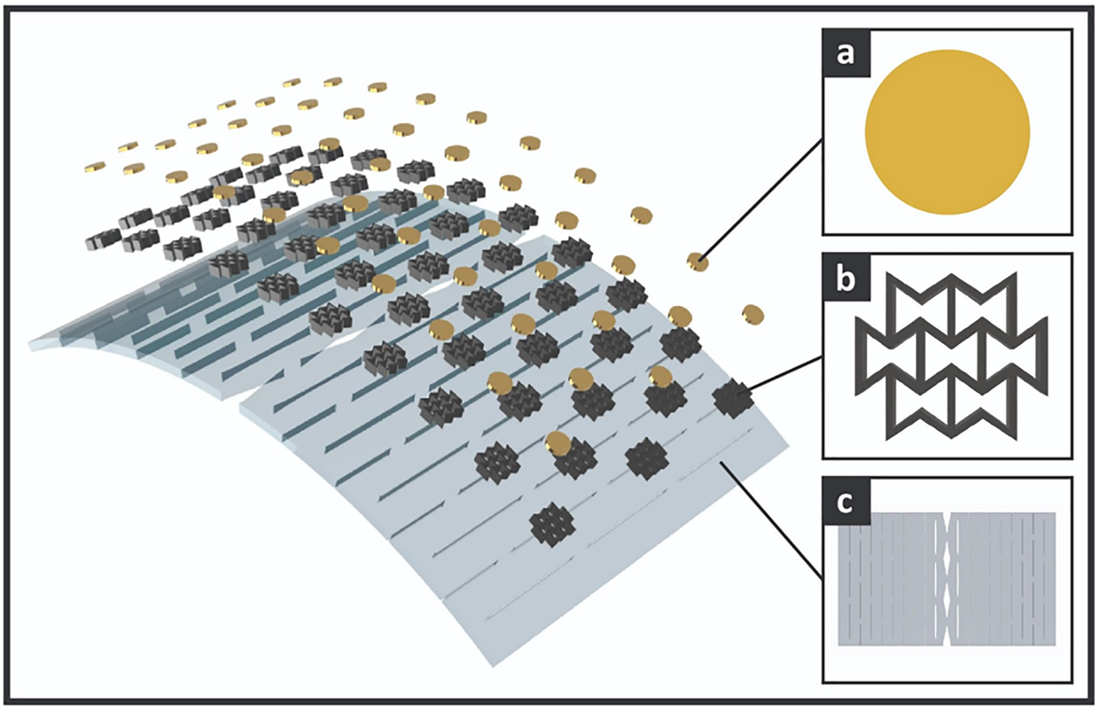

Figure 5. Proposed composite kirigami and auxetic structure for piezoelectric energy harvesting: a patterned kirigami substrate with a layer of auxetic and piezoelectric elements in a grid configuration. Schematics of individual components are shown on the right-hand side: (a) piezoelectric, (b) auxetic, and (c) kirigami.

thermal expansion. In this case, the polymer chains expanded to approximately 5% prestrain, well below the 8% limit. After transfer printing, slow cooling was followed with a subsequent shrinking of the PZT nanoribbons, leading to an accordion-shaped structure geometry. This allowed the experienced strain to decrease, thereby increasing the strain the device could withstand from 0.1% when on a hard silicon substrate to 0.3% in the prestrained PDMS case. Similar prestrain techniques were implemented by other researchers with comparably favorable results.[44,105,106]

Another common pattern used in conformable devices is the serpentine structure, shown in Figure 3. By fabricating materials into an s-shaped, precompressed state, the piezoelectric can experience high levels of tension without damage. In 2019, Yan et al. developed a multidirectional mesh of serpentine structures with a variety of arc angles, radii, and widths to achieve stretching up to 27.5%, similar to that of human skin.[107] To maximize stretchability while effectively utilizing available space, serpentine layouts may be combined with other complex geometric layouts, such as fractal-inspired designs. Fractal designs generate multiorder structures with a single base configuration.[108] By using the serpentine layout in a fractal design—i.e., creating a serpentine shape composed of even more serpentines—researchers have achieved even higher levels of strain due to the consecutive stretching nature of the geometry. In other words, as a serpentine-based fractal design experiences strain, the largest serpentine structure present in the design is the first to straighten while the subserpentines remain largely undeformed, followed by the second largest serpentine structure, and so on.[109]

Hydrogels. Researchers have also explored hydrogel substrates in order to absorb strain, thereby serving as a buffer between surface deformation and the brittle device component, i.e. the piezoelectric element. Ma et al. evaluated the strain-isolation effects of a fluid-filled cavity encapsulated by a low modulus elastomeric substrate. The design effectively eliminated any experienced strain for the device under 30% stretching.[110] Moreover, the device, a mechano-acoustic sensor, maintained full functionality throughout stretching—further indicating minimal disturbance merited by the strain-isolating effect. Coupling hydrogels, such as those depicted in Figure 4a and b, with piezoelectric elements, would allow for devices with structurally enabled high strain tolerances.

Kirigami. In order to increase the conformability of 2D sheets on the human body, researchers have started turning to unconventional artistic methods such as kirigami, shown in Figure 4c. Kirigami is similar to the Japanese art style of origami but employs paper cutting rather than paper folding. This method is used to simply and elegantly transform two-dimensional surfaces into three-dimensional structures. It has been utilized in the scientific community in applications such as reconfiguration robotics, architecture, and smart materials.[111−113] Researchers have been exploring new methods of fabricating these complex patterns. In 2017, Oyefusi and Chen developed a chemical 3D shaping mold technique that involves reverse patterning and heating of Nafion films.[114] After molds were created, a spray coating technique was utilized to make polymer copies of the structure. This strategy decreases production cost and time and enables a versatile and low-cost process for creating 3D kirigami structures. Kirigami structures have also been successfully fabricated via additive manufacturing techniques such as 3D printing.[115] Zhao et al. 3D printed molds to produce an elastomer knee bandage with complex cutting patterns. They found that kirigami enhanced three properties in particular: (1) the shear-lag effect (i.e., diminution of stress in wide beam flanges as distance increases from web(s) due to shear stress), (2) partial bonding, and (3) inhomogeneous deformation. These allow the films to adhere by controlling the distribution of stress in certain parts of the knee, bonding the film more closely in certain places, and increasing overall adhesion despite uneven stretching. Kirigami structures can also be directly 3D printed. In order to increase the stretchability and conformability of kirigami designs, in 2020, Zhou et al. realized a T-joint-cut kirigami piezoelectric nanogenerator that could undergo 300% strain without degradation of output voltage or detrimental out-of-plane deformation.[116] This exemplifies how strategic cut placement in tandem with consideration of the material's directional properties can significantly enhance the conformability of kirigami structures.

Structures That Maximize Strain. *Auxetics.* Auxetics are materials and structures that possess a negative Poisson's ratio, such as those in Figure 4d and e. When subjected to stretching in the longitudinal direction, they exhibit a marginal expansion in the direction perpendicular to the applied strain.[117] They expand laterally under tension and/or contract laterally under compression, contrary to conventional materials. Various material structures exhibit auxetic behavior that can be coupled with energy harvesters. For instance, Gibson et al.'s re-entrant honeycomb configuration demonstrates the unconventional mechanical behavior of auxetics.[118] The honeycomb's cell-like structures have recently been incorporated in energy harvesting systems in order to increase stretchability, conformability, and power output. Similarly, Li et al. recently presented a piezoelectric bimorph energy harvester with an auxetic substrate that was able to increase the power output of the system by up to 2.76 times.[119] Similarly, using a layer of auxetic substrate, Ferguson et al. concentrated stress in the piezoelectric element of a strain energy harvester that ultimately increased the electrical power output.[120]

Piezoelectric ceramics coupled with auxetic structures signify a novel composite material group that leverages the high strength and strain response of each individual component. Various applicable auxetic structures have been proposed. For instance, Fey et al. implemented a two-dimensional auxetic lattice structure fabricated from PZT. A mechanical and piezoelectric strain response of the lattice structure was examined and demonstrated strain amplification by a factor of 30−70 compared to PZT bulk material.[121] Various geometric layouts of auxetic structures have also been proposed. For instance, Eghbali et al. proposed the use of two novel circular auxetic substrates for circular piezoelectric elements, resulting in enhanced power output as the piezoelectric elements were stretched in two perpendicular directions simultaneously.[122] Further integrating auxetic designs into energy harvesters is still being explored, enabling more efficient wearable self-powered devices.

Perspective: Combining Kirigami and Auxetics. Given the conformability and stretchability of kirigami and the enhanced efficiency merited by auxetics, these structures can be integrated with piezoelectric energy harvesters to circumvent strain limits while ensuring high power output. We propose the coupling of a kirigami elastomeric substrate with a layer of auxetics, as shown in Figure 5. This can be configured such that the piezoelectric elements are (1) directly in contact with the auxetic structure and (2) located at low-strain regions of the kirigami substrate. The kirigami layer would be laminated onto the curvilinear surface to provide conformability. By utilizing the auxetic layer in this way, the piezoelectric components can experience sufficient strain to make the constituent device fully self-powered. Furthermore, due to auxetics' negative Poisson's ratio, the piezoelectric elements will undergo stretching in two directions at once, increasing the total power output.

Depending on the device requirements and materials, piezoelectric harvesters need a minimum strain amplitude to be self-powered. Piezoelectric materials also have specific yield points that limit the deformation the device can withstand. Thus, a combination of structures such as kirigami and auxetics, that respectively minimize and maximize strain, can be balanced to optimize the device's experienced strain for sensing applications and beyond.

Researchers are already exploring how to create new structures that combine the properties and geometries of both kirigami and auxetics in a single layer. For example, Farhangdoust et al. applied kirigami cuts to an auxetic framework to introduce a blended layer design for use in piezoelectric energy harvesters.[123] Their metamaterial-based substrate (MetaSub) was shown to generate significant power when compared to conventional piezoelectric energy harvesters, boasting a 75.5% higher efficiency of PZT capacity while maintaining conformability.

However, other methods of combining kirigami and auxetic structures into patterns, such as layers or arrays, are less explored but show theoretical promise. In order to harness the elevated power capabilities provided by auxetics and the enhanced conformability of kirigami, we must take a combinatorial approach to fully realize the potential of self-powered piezoelectric sensors. Such an approach has the potential to impact a variety of disciplines given current applications of self-powered piezoelectric devices.

FINDINGS: APPLICATIONS FOR SELF-POWERED PIEZOELECTRIC DEVICES

For the application of self-powered piezoelectric devices, the conversion of mechanical energy into electricity merited by the direct piezoelectric effect is well suited for strain sensing purposes, as voltage output correlates with strain magnitude while conveniently powering the device. Intuitively, larger mechanical deformation results in a higher voltage output. Recording and interpreting voltage sequences allows for the acquisition of time-scaled strain patterns along the surface the device is laminated upon. These patterns can be used to analyze any phenomenon of interest that results in mechanical deformation by employing piezoelectric sensors. Therefore, piezoelectric devices can replace inertial measurement units (IMUs), electromyography (EMG), and electrocardiography (ECG) to measure heart rate, respiration, and physical activity.[124−127] As the popularity of wearable devices grows, so does the need for flexible, comfortable, and reliable power sources. For this reason, the application of piezoelectric materials for on-body and in-body self-powered sensing has also been widely explored.[37,125,128]

Wearable Devices *In Vivo*. As a clinical tool for health-related applications, on-body, self-powered piezoelectric strain sensing technologies have great prospects for use in physical therapy, sports medicine, and the rehabilitation and diagnosis of medical conditions.

However, all of these applications demand a seamless interface with the human body. A conformable, stretchable substrate enables both lamination to a curvilinear surface and endurance during dynamic movement. In 2019, Ryu et al. demonstrated a stretchable fiber with energy-harvesting and strain-sensing capabilities.[45] They proposed a composite structure of PVDF-TrFE nanoparticles and PDMS for the active

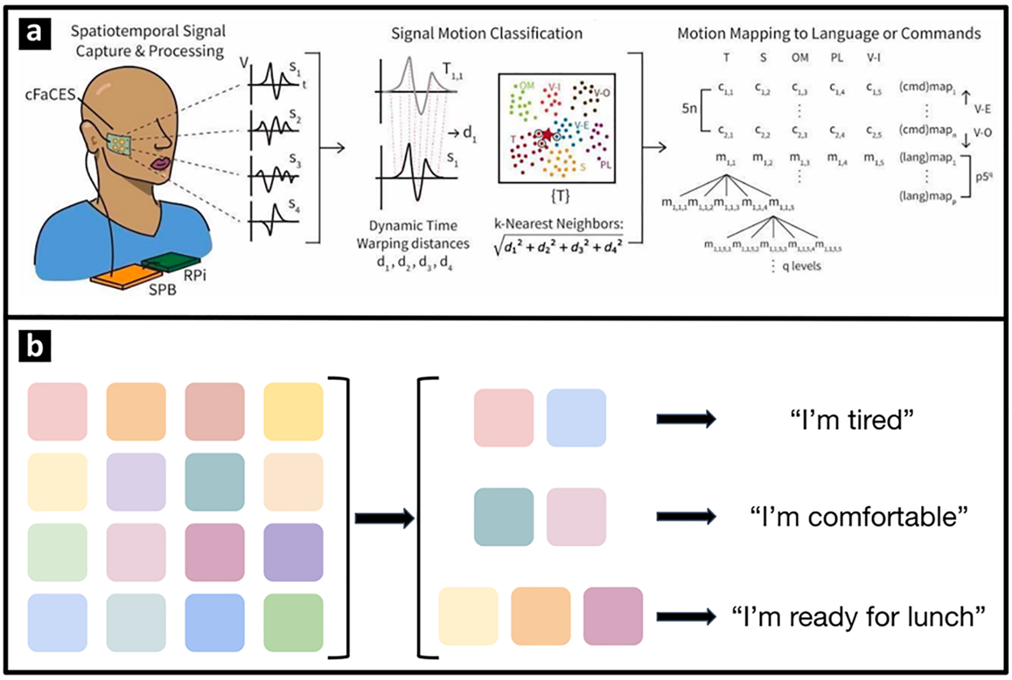

Figure 6. Real-time decoding (RTD) of facial motions using the conformable Facial Code Extrapolation Sensor (cFaCES). (a) Motion library construction. Voltage waveforms are indicated by S_i where $i = \{1, 2, 3, 4\}$ for each of the four sensing elements. The signal processing board (SPB) digital signal is sent to the Raspberry Pi, which automatically detects and classifies facial motions as those in the individual's motion library. These facial motions map to language. (b) Visual representation of how sequential combinations of encoded motions are decoded into language. Panel a is adapted with permission from ref 7. Copyright 2020 Springer Nature.

sensing layer sandwiched between composite MWCNT (multi-walled carbon nanotubes)/PEDOT:PSS electrodes. While their work contributes to the further development of self-powered sensors directly integrated into clothing, thereby maximizing seamless incorporation of sensing capabilities, these fiber-based sensors do not allow for conformable on-skin applications and thereby limit direct on-body sensing capabilities. Chen et al., on the other hand, proposed a highly conformable piezo- and triboelectric nanogenerator suitable for on-skin applications for physiological monitoring.[129] Employing a BaTiO3/PDMS composite sensing layer between spray-coated Ag-nanowire electrodes, they demonstrated a self-powered stretchable, foldable, and twistable, highly transparent sensor patch that may be attached directly on human skin. The authors showed successful detection of eye-blinking, pronunciation, arm movement, and heartbeat using their conformable sensors. Such device−user interfaces allow for more precise monitoring of motion and detection of tactile input, making wearable sensing applications possible.

Nonverbal Communication. Wearable real-time monitoring devices provide a noninvasive alternative to current methods of long-term sensor systems. One recent realm of interest has been the use of conformable sensors to aid in communication, particularly as a human−machine interface and for patients with medical disorders that lead to aphasia.[130] In 2011, Kim et al. introduced their epidermal electronic system (EES), a thin-film device with customizable sensor options that can be applied to the skin like a temporary tattoo. When configured for EMG and laminated onto the throat, the device could successfully be used to control a simple video game by distinguishing between vocalizations of "up", "down", "left", and "right".[103] Similarly, Yan et al. later developed a stretchable, piezoelectric film with an optimized serpentine layout to detect micromotions at the throat due to speech vocalizations.[107]

More recent efforts have realized truly nonverbal communication via self-powered piezoelectrics. In 2020, the Conformable Decoders Group at the MIT Media Lab designed and manufactured cFaCES, a thin-film device that can be laminated onto the face and takes advantage of the piezoelectric effect to map facial strain.[7] The device successfully distinguishes between different facial micromotions such as smiling, opening the mouth, and pursing the lips for healthy individuals and amyotrophic lateral sclerosis (ALS) patients in real time, as shown in Figure 6. This system of collecting and analyzing dynamic deformations could aid in nonverbal communication and at-home clinical monitoring of neuromuscular conditions.

Gait Monitoring. A further application in gait monitoring has become a prevailing point of research, especially in conjunction with emerging sensing and self-powered technologies. Gait monitoring and analysis involve systematic measurement and assessment of quantities that characterize human locomotion. In practice, researchers have captured gait signals from various joints as well as pressure distributions from the foot.[131,132] With the advent of self-powered piezoelectric devices, harvesting energy from human motions while implementing sensors for gait monitoring becomes possible.

Previously, Fuh et al. explored three-dimensional PVDF structures for increased output voltage with the potential to advance biomedical and wearable electronics.[133] Zhao et al. proposed a piezoelectric energy harvester that leveraged mechanical energy in shoes, demonstrating the possibility of applying such devices to power on-body sensors.[134] More recent efforts have begun to investigate the energy harvesting performance of self-powered piezoelectric devices and their potential to monitor human gait signals. For example, Wang et

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al. presented self-powered smart insoles integrated with piezoelectric PVDF nanogenerators for monitoring human gait signals and illustrated clear gait identification through biosignal analysis of subject stride intervals.[135]

Furthermore, machine learning and artificial intelligence enable rapid and effective signal interpretation from wearable sensors. For gait monitoring applications, machine learning models have the potential to leverage data output to perform real-time tracking of human motion. Recently, Shah et al. implemented deep learning algorithms on gait signals collected from a piezoelectric-based smart shoe and achieved up to 96.2% accuracy in differentiating gait patterns.[136] Further research efforts have explored the application of convolutional neural network (CNN) and artificial neural network (ANN) architectures for achieving deep learning from sensor gait data. These demonstrate a promising step toward more robust and automated personalized healthcare.[137,138]

■ CONCLUSIONS

Diverse Applications and Future Directions. In the realm of personal health monitoring, self-powered devices have a strictly constrained power budget. As a result, self-powered medical sensors that rely on the emission of energy such as pulse oximetry, imaging technologies such as ultrasound imaging, and sensing modalities requiring high bandwidth are likely to remain out of reach in the near future. However, numerous sensing modalities exist that could soon be operated on the microwatt or even nanowatt power scale. For example, low-bandwidth signals such as ECG, skin impedance, and accelerations from heart rate and breathing as well as modalities such as humidity and pressure could all be sensed using methods that largely decouple performance and power metrics with self-powered devices. Sensing these signals over extended periods of time would offer insight into patient behavior and, by extension, the diagnosis and progression of disease.

In the clinical health setting, two of the most common patient complaints focus on cumbersome wired health monitoring systems and the periodic check-ins by nurses, which can continue through the night and interrupt sleep. Self-powered, continuous health monitoring devices have the potential to alleviate both of these issues, improving the quality of care while simultaneously reducing the workload on clinicians and physicians in nursing homes and hospitals alike.

With limited battery requirements and the capability for compact, conformable design, piezoelectric energy harvesters show great promise in revolutionizing the healthcare and wearable industries with real-time health monitoring in nonclinical settings as well. Piezoelectric energy harvesters with the ability to measure vital signs such as heart rate, respiration, and body temperature have been successfully realized. Current research efforts have also begun to explore the use of piezoelectrics for monitoring physical activity and performance through strain sensing, presenting value for high-performance athletes, average users, and patients with muscular degenerative disorders alike. Such devices could enable a multitude of possibilities for bettering patient lives, from monitoring and predicting anomalies in human locomotion to realizing nonverbal communication. The application of new machine learning techniques could further amplify the capabilities of piezoelectric sensors, allowing for more robust and personalized automated wearable devices.

Along the same vein of real-time monitoring for diagnostic and prognostic purposes, piezoelectric energy harvesting devices have extensive applications in rehabilitation. Users can receive real-time feedback for physical therapy exercises and can track their overall progress without requiring the presence of a trained medical professional. Self-powered ECG and EMG capabilities can further enhance the rehabilitation process by reducing the need for device replacement.[139]

Although this paper has thus far discussed applications primarily focused on wearable technologies, some piezoelectric materials are sufficiently biocompatible to render themselves useful for implantable devices. These devices may be laminated within the human body onto organs, muscles, and bones in order to enhance, modify, heal, or gather data more efficiently than nonembedded devices.[140−143] These devices could convert otherwise wasted mechanical energy in the human body into usable energy to help users track injuries, illnesses, daily activity, or other health related concerns.[144]

Self-powered piezoelectric energy harvesters will additionally enable a variety of applications beyond the biomedical setting. Piezoelectric devices have great potential to revolutionize the practice of structural analysis and fatigue detection by nature of the piezoelectric stress response. This could be used to improve mechanical and civil engineering practices by providing a more hands-off method for ensuring high-quality construction with reduced energy costs. Using these devices to monitor architectural structures can likewise reduce maintenance costs and increase a structure's longevity.[145] On a smaller scale, these devices could be used to structurally analyze electronics given the increase in the density of integrated circuits, power levels, and operating temperatures.[146]

As discussed more in-depth in a previous paper, opportunities for off-body implementations are even more wide-reaching.[147] Improved interactive teaching, surgical modeling, assistive technology, entertainment, and cultural expression can be achieved through the implementation of conformable piezoelectric devices. Human interaction and experience can grow even further if these technologies can be adapted for self-powered implementations. Likewise, self-powered capabilities can be introduced for robotics, prosthetics, and brain−computer interfaces. Using piezoelectric harvesters can also lead to more advantageous urban planning and facilitate sustainable buildings and infrastructure. Beyond the urban, environmental issues can also be tackled. Agriculture, climate, ocean, and space each provide their own sets of challenges that can be addressed using this technology.

More specifically, self-powered conformable devices have significant applications in both aquatic and arid settings. Piezoelectrics have already been used as generators of electric power in oceanographic buoys. Since recurring battery replacement is inefficient and expensive, buoys would benefit from self-powered devices capable of providing electrical energy to measurement and information systems.[148] The buoy is subject to the movement of ocean waves in three planes with three different accelerations, so piezoelectric devices could be used to obtain the electrical energy corresponding to these movements in a more economically feasible manner.

Self-powered piezoelectric devices are additionally useful in cases of emergency survival and rescue efforts. In urgent and challenging environments, the standard battery-powered electronics are usually not reliable and stable when the climate or conditions are harsh and unpredictable. In certain settings, access to a power supply or network connectivity may also be lost, indicating the need for alternate sources of power for devices. Thus, employing self-powered piezoelectric technologies that actively transform environmental energy into sustainable energy for use in driving emergency electronics is vital.

In combating global challenges such as the COVID-19 pandemic, the use of flexible and wearable piezoelectric sensors for healthcare monitoring and potential early intervention is promising. The development of smart personal protective equipment (PPE) integrated with piezoelectric sensors has great potential in carrying out multisensing tasks for diligent and enhanced patient monitoring. Similarly, the incorporation of self-powered piezoelectric technologies in face masks could ensure proper face mask usage and effective filtration efficiency and combat virus transmission.

Challenges and Perspectives. Although considerable achievements have been made in wearable self-powered devices, certain challenges still remain for implementing such devices for new and emerging applications. Energy harvesting technology has seen great progress in the past few decades, especially in application-oriented devices tested *in situ*. However, reliability, conformability, and long-term endurance have yet to be well-examined. This examination is crucial to facilitating the use of such devices in day-to-day life.

Regarding the advantages of conformable devices related directly to the user, conformable devices are well suited for the dynamic and curvilinear surface of the skin. With a bulky and rigid form factor, the device would be uncomfortable and obtrusive. Not only would this hinder the user's movement, but this would also undermine the device's ability to measure the phenomenon of interest. For instance, a device that measures strain across a region of the skin cannot relay meaningful data if the user cannot execute a full range of motion. In addition, the need for battery power also increases the frequency of replacement, which is costly and inefficient, as compared to if these devices were self-powered. Material and structural approaches have aided in both increasing conformability, such as elastomeric substrates and node-bridge structures, and increasing the longevity of biomedical devices.

As with any device that interfaces closely with humans, biocompatibility is also required. Each specific application defines its own standard of biocompatibility, and two broad categories stand out. The system must not be harmful in any way, nor should it be intrusive. Harm could potentially be caused by toxic responses to materials in the device with intrusiveness inhibiting motion, causing sweat accumulation, or yielding further discomfort.

With regard to the market of conformable devices, as wearable sensing in healthcare progresses, an inherent trade-off between mass-manufacturability, cost, and personalization prevails. Development of sophisticated micro- and nanofabrication techniques, formation of multifunctional composite materials, and greater inclusion of novel 0D, 1D, and 2D components (e.g., nanoparticles,[45,129] nanowires,[129,149] CNTs,[45] and graphene[149,150]) are needed to tackle traditional material limitations. However, these advancements will inflate initial costs. Considering this balance throughout device design and creation will yield tailored results for each respective purpose.

Unfortunately, energy-harvesting technology is not without its limitations in materials and structures. Many microfabrication techniques are not compatible with biological systems, and certain materials are not suited for cleanroom environments due to their particular thermal, mechanical, or chemical properties.[94,97,98] The fabrication process often needs to be significantly modified to be compliant with an otherwise unsuited material. There also seems to be an unavoidable trade-off between the rate and accuracy with which 3D devices can be microfabricated. It remains difficult to generate high-resolution features on complex geometries without sacrificing time. For example, recent experiments attempting organ printing through photolithography require time- and energy-consuming techniques to achieve intricate shapes that realistically model organ tissues, rendering the process slow and inefficient.[99] Additionally, the more complex the microfabrication process, the more expensive it becomes.[86] However, microfabricated devices have increased portability, time-efficiency of analysis, electronic integrability, and heat dissipation because of their reduced volumes and surface area-to-volume ratios and can be manufactured quickly in batches due to their small size.[92]

Despite their suitability for a variety of consumers and body types, particularly conformable microfabricated devices maintain several mechanical, biological, and fabricational limitations. These include low strain limits and resonant frequencies far higher than those of the human body. However, these can be overcome by prudent material choice and continual improvement to their energy harvesting capabilities through implementing prestrained serpentine structures, hydrogels, kirigami cuts, auxetics, or a hybrid. A combination of these can serve to both minimize and maximize strain to optimize the voltage of self-powering devices.

Another consideration of piezoelectric energy harvesters and sensors is the trade-off between power output and strain endurance. While inorganic piezoelectrics typically exhibit much larger power output than polymeric material solutions, their strain limits are significantly lower. To combat this, structural enhancement alongside the creation of novel composite materials can allow for an increasingly seamless integration of piezoelectric devices with the human body while maintaining a large power output.

In addition to functional constraints, many of these emerging technologies must be reusable in order for them to be practical. However, parameter constraints in designing conformable devices increase the difficulty of making reusability feasible. For example, thin devices that rely on van der Waals forces alone can result in high susceptibility to tears during lamination and delamination. For devices targeted toward everyday people, a simple and reliable method for detaching, reattaching, and storing must be designed. Other challenges include protecting potentially exposed regions of the complex kirigami and auxetic structures from damage during wear. Considering these factors in tandem will best serve future applications of conformable, self-powered piezoelectric technologies.

A comprehensive review on various piezoelectric materials, energy harvesting mechanisms, configurations, structures, and associated applications of on-body energy harvesters has been presented. This paper proposes existing and novel structures and configurations for enhancing the conformability of self-powered piezoelectrics. In addition, we observe the potential for new structural designs of wearable, conformable self-powered devices coupled with specific material selection for use in real-time monitoring systems. Current progress in the field of piezoelectric energy harvesting has demonstrated great advancement in the creation of on-body medical devices and lays the groundwork for more specific applications in sensing and monitoring.

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Notes

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