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Review

Flourishing energy harvesters for future body sensor network: from single to multiple energy sources

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Summary

Body sensor network (bodyNET) offers possibilities for future disease diagnosis, preventive health care, rehabilitation, and treatment. However, the eventual realization demands reliable and sustainable power sources. The flourishing energy harvesters (EHs) have provided prominent techniques for practically addressing the concurrent energy issue. Targeting for a specific energy source, wearable EHs with a sole conversion mechanism are well investigated. Hybrid EHs integrating different effects for a single source or multi-sources are attaining growing attention, for they provide another degree of freedom concerning a higher-level energy utility. Merging EHs with other functional electronics, diversified functional self-sustainable systems are developed, paving the way for the accomplishment of bodyNET. This review introduces the evolution of wearable EHs from a single effect to hybridized mechanisms for multiple energy sources and wearable to implantable self-sustainable systems. Last, we provide our perspectives on the future development of hybrid EHs to be more competitive with conventional batteries.

Introduction

Wearable electronics that would well merge with our bodies are set to extend the way we perceive and interact with the world (Chu et al., 2017; Shi et al., 2020a, 2020b; Wen et al., 2020a). The rapid advancement in materials, sensors, circuits, and wireless transmission technologies will give way to the body sensor network (bodyNET) (Niu et al., 2019; Tian et al., 2019), which enables human physiological signal detection not only on the skin but also inside the body as shown in Figure 1A (Lee et al., 2019a; Zheng et al., 2020). Flexible electronic technologies allow the sensors to exist in various forms, including electronic skins that are directly attached to the skin (Chen et al., 2019a; Oh and Bao, 2019; Pu et al., 2017b), clothes that are worn on the human body (Chen et al., 2020b; Shi et al., 2020c), glasses (Vera Anaya et al., 2020), face masks (Zhang et al., 2020a), watches (Quan et al., 2015), gloves (Sundaram et al., 2019), insoles (Wu et al., 2020b), socks (Zhang et al., 2020c), shoes (Li et al., 2017), and implantable devices (Arab Hassani et al., 2020; Hinchet et al., 2019; Xiang et al., 2016), to provide comprehensive monitoring of the user's health status and motions. For instance, the sensors attached to the skin or worn on the body can record body temperature, pulse, respiration rate, blood pressure, etc. (Jayathilaka et al., 2019). Besides, the sensing masks would contribute an extended degree of freedom for health care assessment, by providing respiration diagnosis regarding the respiration rate and the exhaled gases (Su et al., 2020a; 2019; 2018; 2017; Wang et al., 2019e). Implanted bioelectronics, on the other hand, provides new feasibilities in detecting biological signals and stimulating nervous systems or organs (Lee and Lee, 2018). Besides, neural prostheses can assist patients by enhancing their sensory, cognitive, and motor modalities (Loeb, 2018; Wang et al., 2020a). The eventual realization of the exhaustive bodyNET will provide insightful information for disease diagnosis, preventive health care, rehabilitation, and even prompt treatment with the aid of surging drug delivery systems.

One of the key challenges of the bodyNET would be the reliable and sustainable power sources for the sparsely distributed sensor nodes around the body (Wang et al., 2020d; Wang, 2020). Batteries are still the widely adopted solutions for sensor networks but suffer from a limited lifespan, possible hazards to human health, long-term reliability, and periodic replacement (Hinchet and Kim, 2015; Zhu et al., 2020b). As the number of sensors dramatically increases, it has been much more challenging to replace, manage, and/or recycle the gigantic amount of batteries. Thus, energy harvesting technologies have been proposed as a cost-effective solution to future sustainable systems (Liu et al., 2018c; Liu et al.,

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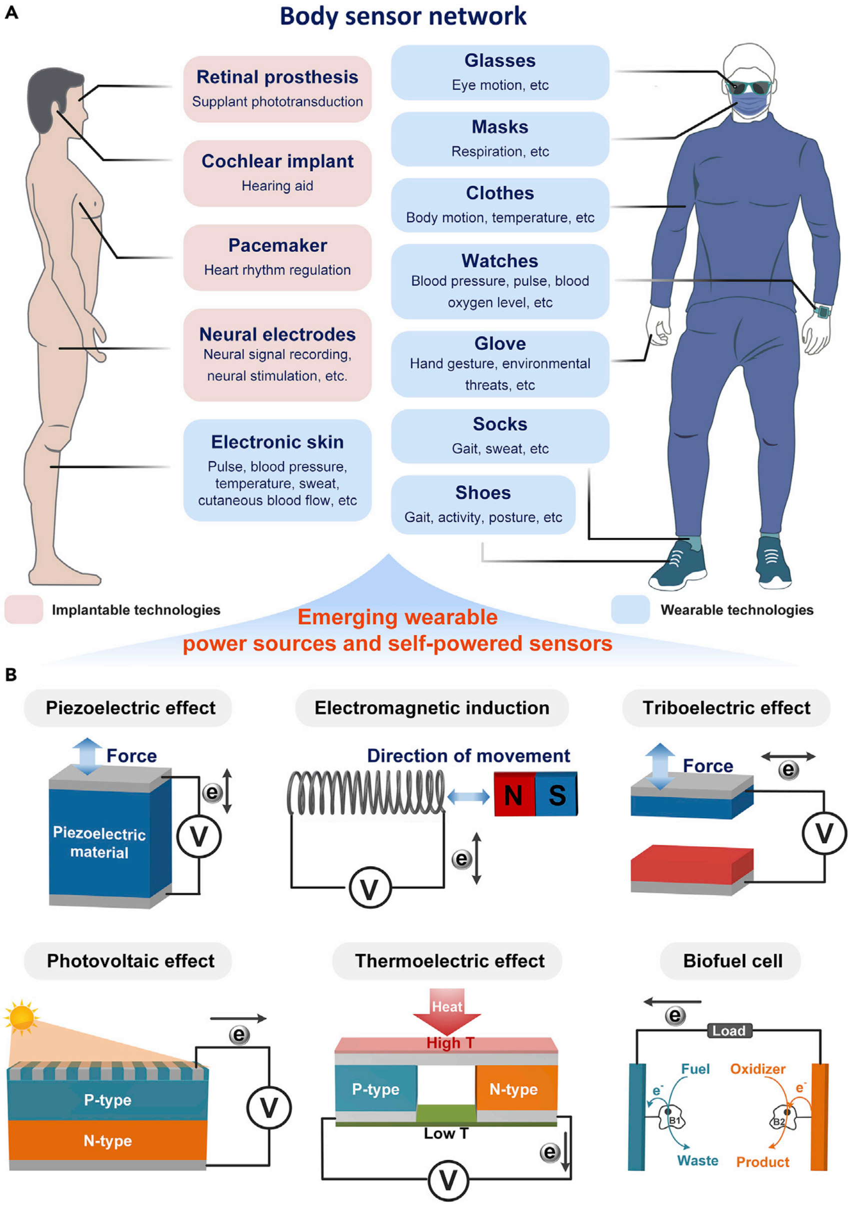

Figure 1. Overview of the emerging energy harvesters for future bodyNET

(A) Schematic showing the possible sites and functionalities of future body sensor network.

(B) Schematic illustration of various energy conversion mechanisms.

2015b; Liu et al., 2020b), which convert environmental energy that was dissipated and wasted into valuable electric energy in various ways (Kawa et al., 2020; Liu et al., 2015a, 2018a, 2018b). Generally, the available energy sources around us include mechanical energy (Liu et al, 2013, 2014), solar energy (Hashemi et al., 2020), thermal energy (Xie et al., 2011; Zhang et al., 2019a), and biochemical energy (Jeerapan et al., 2020). As illustrated in Figure 1B, there are various conversion mechanisms, including piezoelectric (Shi et al., 2016a; Sun et al., 2019a), triboelectric (Dong et al., 2021; Gunawardhana et al., 2020), and electromagnetic effects (Zhang et al., 2020b) for mechanical energy harvesting; the photovoltaic effect for solar energy harvesting (Park et al., 2018); the thermoelectric or pyroelectric effect for thermal energy harvesting (Sun et al., 2019c; Yang et al., 2012); and biofuel cell for biochemical energy harvesting in biofluids (Gong et al., 2020; Zhai et al., 2020). These renewable energy harvesters (EHs) have been attracting great attention and hold great promises to realize self-powered wireless sensor networks (WSN) for personal health care and smart home.

As kinetic energy is ubiquitously available in our surrounding environment in the forms of vibrations, body motions, deformations, respiration, etc., mechanical EHs have undergone tremendous development with a variety of structure designs and material choices. Among them, triboelectric nanogenerator (TENG) that uses the coupling effect of contact electrification and electrostatic induction stands out as a promising candidate for portable energy sources, due to its advantages of broad material availability, versatile working modes, low cost, easy fabrication, and large output at low-frequency range (Dong et al., 2020a; Qu et al., 2020; Shi et al., 2019a, 2019b; Wang et al., 2020b). Basically, any pair of materials with different electron affinities can be adopted to construct a TENG device (Wang and Wang, 2019). Ever since its invention in 2012 (Fan et al., 2012), TENG has been receiving intense efforts worldwide from a variety of aspects, including but not limited to materials, output performance, usage scenarios, stability, wearability, biocompatibility, systematic integration, and broad applications (Liu et al., 2019a; Zou et al, 2020b). Wearable TENGs can be directly worn on the body in the form of electronic skin (Chen et al., 2019a), embedded into clothing as fibers/textiles (He et al., 2019a; Kwak et al., 2019), integrated with face masks (Bai et al., 2018a), and integrated into accessories (Maharjan et al., 2018), allowing a variety of self-powered sensing functionalities such as body motion tracking (Liang et al., 2019), physiological signal recording (Liu et al., 2019c), chemical sensing (Wang et al., 2017), respiration monitoring (Su et al., 2016a, 2016b), and human-machine interfacing (Chen et al., 2018b, 2019b; Ding et al., 2019; Shi and Lee, 2019). On top of that, wearable TENGs can effectively scavenge biomechanical energy from diversified body movements to power other electronic devices for more applications (Chen et al., 2020a; He et al., 2019c; Lin et al., 2017).

Piezoelectric nanogenerator (PENG), which was first proposed in 2006 with zinc oxide (ZnO) nanowires (NWs) (Wang, 2006), is another major energy-scavenging technology aiming at on-body electricity generation as a sustainable power supply for portable and wearable electronic devices (Wang et al., 2020d; Zhang et al., 2018a). It is based on the principle named piezoelectric effect and was discovered by French physicists Jacques Curie and Pierre Curie in 1880 (Curie and Curie, 1880), describing a phenomenon that electric charges generated by polarized electric dipole moment will be induced if applying an external mechanical strain/stress to certain solid materials. PENGs have the advantage of high sensitivity (Guo et al., 2018a), high durability (Ghosh and Mandal, 2018), and large power density (Hu and Wang, 2014). A large number of researches have been performed toward novel wearable PENGs in the past decade bearing the propose of transferring human motions generally with a wide range and low frequency to electricity with a long lifetime and certain comfortability (Pu et al., 2018; Shi et al., 2020c; Wu et al., 2016). Typical improvement directions of PENGs include the capability to withstand large deformation and strain (Chou et al., 2018; Jeong et al., 2015), stability to endure a large number of operation cycles (Cheng et al., 2020; Lu et al., 2020), structure simplicity, lightweight to ensure portability and wearing comfortability (Kim et al., 2020; Wang et al., 2018c), sensitivity for minor motions like respiration (Jin et al., 2020a), and also high output performance (Jeong et al., 2018; Rovisco et al., 2020).

For TENGs, the broad choices for materials make them easy to be designed, mass fabricated, and integrated. PENGs typically have higher power density, sensitivity, and the ability to be fabricated in a very small dimension. However, the EHs with a sole mechanism like triboelectric and piezoelectric also show their imperfection at the same time, especially in the power output (Karan et al., 2020). Therefore, hybridized EHs with the combination of different energy conversion mechanisms to better leverage their distinctive advantages were designed and proposed (Bai et al., 2018b; Ryu et al., 2019). For scavenging biomechanical energy sources, non-flexible wearable devices generally integrate electromagnetic generator (EMG) with TENG or PENG for its outstanding output performance and large power density (Chen et al., 2020c). EMGs based on Faraday's law are able to induce large electric current with a varying magnetic field in a conductor coil due to the relative motion between the magnet and the coil. Such non-flexible hybridized designs include watches (Hou et al., 2019), bracelets (Maharjan et al., 2018), insoles (Jiang et al., 2020a), and accessories on other wearable devices like bags and clothes (Rahman et al., 2020). However, due to the existence of normally bulked and stiff magnets and non-durable and hardly deformable coils, EMGs are more difficult to be utilized in flexible devices compared with TENGs and PENGs (Wan et al., 2020). Therefore, for flexible wearable devices aiming at harvesting biomechanical energy, researchers are more focusing on the combination of TENG and PENG for their flexibility and stretchability (Dong et al., 2020d). As the human body motions can cause mechanical friction and deformation concurrently, wearable devices with a design of natural structure hybridization through the multi-layer structure to achieve energy scavenging via triboelectric and piezoelectric effects at the same time were designed, taking full advantage of the features of biomechanical motions (Song et al., 2018; Wu et al., 2019; Zhu et al., 2020d). To further optimize the energy conversion efficiency and improve the output, the enhancement of

TENG and PENG based on their coupling triboelectric-ferroelectric synergistic effect was also put forward (Yang et al., 2019; Yu et al., 2019).

Typically, an EH is designed for only one specific energy source. For instance, piezoelectric, electromagnetic, triboelectric generators, and their hybridized devices are only targeted at harvesting mechanical energy; solar cells can only harvest light, and thermoelectric generator (TEG) or pyroelectric generator are designed for thermal energy conversion. However, toward practical applications, the output power of a single-source EH is merely enough to fulfill the requirement of the sensor network, mainly because the energy source generally is neither persistently available nor stable on all occasions. For example, biomechanical energy only exists when we are moving (Donelan et al., 2008), e.g., walking, running, and exercising, and thermoelectric/pyroelectric EHs require a constant temperature gradient/fluctuation to produce a stable output voltage (Sebald et al., 2009). Solar cells are expected to generate power under good light illuminance, which will drop sharply in a dark environment such as night (Wang et al., 2019d). Meanwhile, the proper function of a wearable biofuel cell relies on the existence of biofluids (usually sweat) (Bandodkar and Wang, 2016), which would not remain on the skin continuously. In these conditions, the input energy from a single source provided to the EH may be insufficient to drive the sensors or other functional electronics. However, a variety of energy sources normally coexist in most situations, which are partially wasted with EHs solely designed for a single source. For instance, as a human performs outdoor activities, solar energy, kinetic energy, thermal energy, and biochemical energy sources coexist at the same time. A single-source EH, in this case, cannot maximize the energy harvesting capabilities from the ambient environment. Therefore, hybrid EHs have been reported to scavenge multiple types of energy sources simultaneously, with the most used methodology of structural integration (Brogan et al., 2014; Jella et al., 2018; Montgomery et al., 2016). The output power of the hybrid EH would be significantly improved when one or a few of the energy sources are unstable and dramatically declined, compared with previous EHs with a sole conversion mechanism.

Due to the instability of the available energy sources, power management circuits and storage units are introduced to be incorporated with the EHs for self-sustainable powering in a longer period (Chen et al., 2020c; Pu et al., 2016a). Meanwhile, a variety of sensors and other functional electronic devices can also be integrated to form a specific-function self-sustainable system. For example, Wang et al. proposed a self-powered wearable skin patch with a bendable microneedle array for transdermal drug delivery (TDD) by integrating a wearable TENG (Wang et al., 2016a). Over the past few years, we have witnessed the systematic integration of wearable EHs into self-sustainable systems for broad applications, such as temperature sensing (Parás-Hernández et al., 2020), gas sensing (Lin et al., 2019; Zheng et al., 2019), lighting light-emitting diode (LED) (Chen et al., 2018a), location sensing (Lim et al., 2019), human-machine interfacing (Qiu et al., 2020), electronic watch powering (Ho et al., 2020), electrocardiography (Kim et al., 2018), etc. Meanwhile, self-powered implanted systems for neural stimulation (Lee et al., 2017b; Wang et al., 2019a), sensing (Zhang et al., 2018b), wound healing (Jeong et al., 2020), and heart rhythm controlling (Li et al., 2019b) also emerge as another branch of the energy harvesting research. Although the EHs for lots of those implantable systems are still working outside the body, we believe the fully implanted self-sustainable systems will be vigorously developed with the ongoing advancement of flexible energy harvesting technologies.

This review focuses on the progress of wearable EHs toward hybridized methodologies, multiple energy sources, and eventually self-sustainable systems for future bodyNET applications. First, we provide a brief overview of the road map of representative wearable TENGs and their recent development, followed by the progress of wearable PENGs. Next, we introduce the hybrid EHs for scavenging a single energy source, i.e., mechanical energy, and the synergistic coupling effect between different mechanisms. Hybridized EHs designed for multiple sources are then introduced. In the next section, recent advances in self-sustainable wearable systems featuring the integration of EHs and other functional components are presented. Besides, we also briefly summarize some representative works of self-sustainable implantable systems. Finally, the conclusion and perspective are provided at the end of this review.

Wearable triboelectric nanogenerators

Since its first invention in 2012 by Prof. Z. L. Wang's group (Fan et al., 2012), TENG has been receiving immense attention from worldwide researchers and has become one of the most extensively investigated areas of EHs. With the substantial development of the materials, designs, and theories, we have witnessed pronounced progress of the wearable TENGs in terms of wear comfortability, durability, output performance, and other unique properties such as self-healing capabilities as shown in Figure 2A. In 2012, Wang's group developed the first TENG with polyethylene terephthalate (PET) and Kapton as triboelectrification materials and gold as the electrode, which is in a basic vertical contact-separation (CS) operation mode (Fan et al., 2012). Later in 2013 and 2014, TENGs with human skin as one of the electrification materials have been proposed for biomechanical energy harvesting and tactile sensing (Yang et al., 2013; Zhu et al., 2014). Besides common polymers, textiles have emerged as another platform for the wearable TENGs owing to their advantages of light weight, cost-effectiveness, breathability, stretchability, and softness. In 2015, Kim et al. developed a nanopatterned textile-based TENG with silver (Ag)-coated textile and polydimethylsiloxane (PDMS) nanopatterns on ZnO nanorods as the triboelectric active material (Seung et al., 2015). Moving forward, a stretchable and waterproof TENG based on silicone rubber and stretchable electrodes (compound of carbon black and silicone rubber) was reported for harvesting energy from diverse deformations (Yi et al., 2016). Besides being directly attached or worn on the body, TENGs embedded with accessories such as glasses or wrist bands have also been reported. In 2017, a TENG-based eye micromotion sensor embedded on a glass leg was proposed for a mechanosensation human-machine interface (HMI) system (Pu et al., 2017a). With an indium tin oxide (ITO) electrode and electrification materials (fluorinated ethylene propylene [FEP] and natural latex), the TENG can effectively capture eye blink motions with a high signal level. In 2018, to further improve the breathability and comfort of wearable TENG, a black phosphorus-based TENG textile with a waterproof layer was developed for durable biomechanical energy harvesting (Xiong et al., 2018). The black phosphorus is encapsulated with hydrophobic cellulose oleoyl ester nanoparticles, which gives rise to long-term reliability and high triboelectricity. Over the past few years, a lot of efforts have also been devoted to developing highly deformable and healable TENGs through various approaches. Recently, Parida et al. reported an extremely stretchable and self-healing conductor for all-three-dimensional printed TENGs, which is composed of thermoplastic elastomer with liquid metal and silver flakes as the stretchable conductor (Parida et al., 2019). The TENG showed an ultra-high stretchability of 2,500% and recovered its performance even after extreme mechanical damage owing to the supramolecular hydrogen bonding of the elastomer.

Over the years, wearable TENGs have undergone immense development in diversified applications, ranging from harvesting biomechanical energy, physiological signal sensing, activity monitoring, and human-machine interfacing (Dong et al., 2020b; Jin et al., 2020b; Zhu et al., 2020a). Figure 2B displays a thin TENG that can be conformally attached to the skin, with the aid of the polyvinyl alcohol (PVA) blend film (Wang et al., 2020c). The triboelectric sensor consisting of the optimized PVA-gelatin composite exhibits good and stable triboelectric outputs and is capable of detecting subtle skin deformations induced by the pule owing to its superior mechanical deformability. As a result, the sensor attached to the wrist with a copper embedded band-aid as the counter electrode can effectively capture the pulse signal detailing to the three distinctive characteristic peaks (P_1, P_2, P_3). These three peaks correspond to blood injection, blood reflection from the lower body, and blood reflection from the closed aortic valve. These peaks contain valuable cardiovascular information regarding the subject's health, which can be decoded from the sensory output of the proposed TENG device. Recently, Zhao et al. reported a self-powered and user-interactive electronic skin (SUE-skin) with a triboelectric-optical model, exhibiting a new application of the wearable TENGs for touch operation platform (Zhao et al., 2020). The SUE-skin that can generate electrical and optical signals simultaneously under touch stimuli is shown in Figure 2C. It is constructed with a multi-layer structure including a phosphor layer, an electrode, an insulating layer, a shield layer, and a substrate. As the finger leaves the surface of the SUE-skin, a varying electric field is induced to move the electrons toward the bottom of the phosphor particle within the lattice. During this process, some electrons would excite the luminescence centers, hence causing electroluminescence. Combining the SUE-skin with a microcontroller, a programmable touch operation platform is demonstrated for the easy control of an audio module with different touch tracks. In such a way, the SUS-skin has successfully achieved touch stimuli perception with the electrical output and the intuitive observation of human eyes. Besides various kinds of physical sensors, chemical sensors, especially gas sensors based on TENGs, have also been vastly investigated and developed. For gas sensing, the selective sensing materials are of vital importance to the triboelectric sensors' sensing performance. For instance, polyethylenimine (PEI) is a well-known CO_2-selective sensing material (Kim et al., 2019; Wang et al., 2017), and polyaniline (PANI) or PANI-based nanocomposites are commonly known materials sensitive to ammonia (Wang et al., 2018b, 2019f). Besides, metal oxide semiconductors have been widely utilized as sensitive materials for nitrogen dioxide (NO_2) detection, such as ZnO, In_2O_3, WO_3, etc. (Shen et al., 2018; Su et al., 2018). Breath is a vital and indispensable primary vital signal throughout our whole life, and respiration analysis has become an

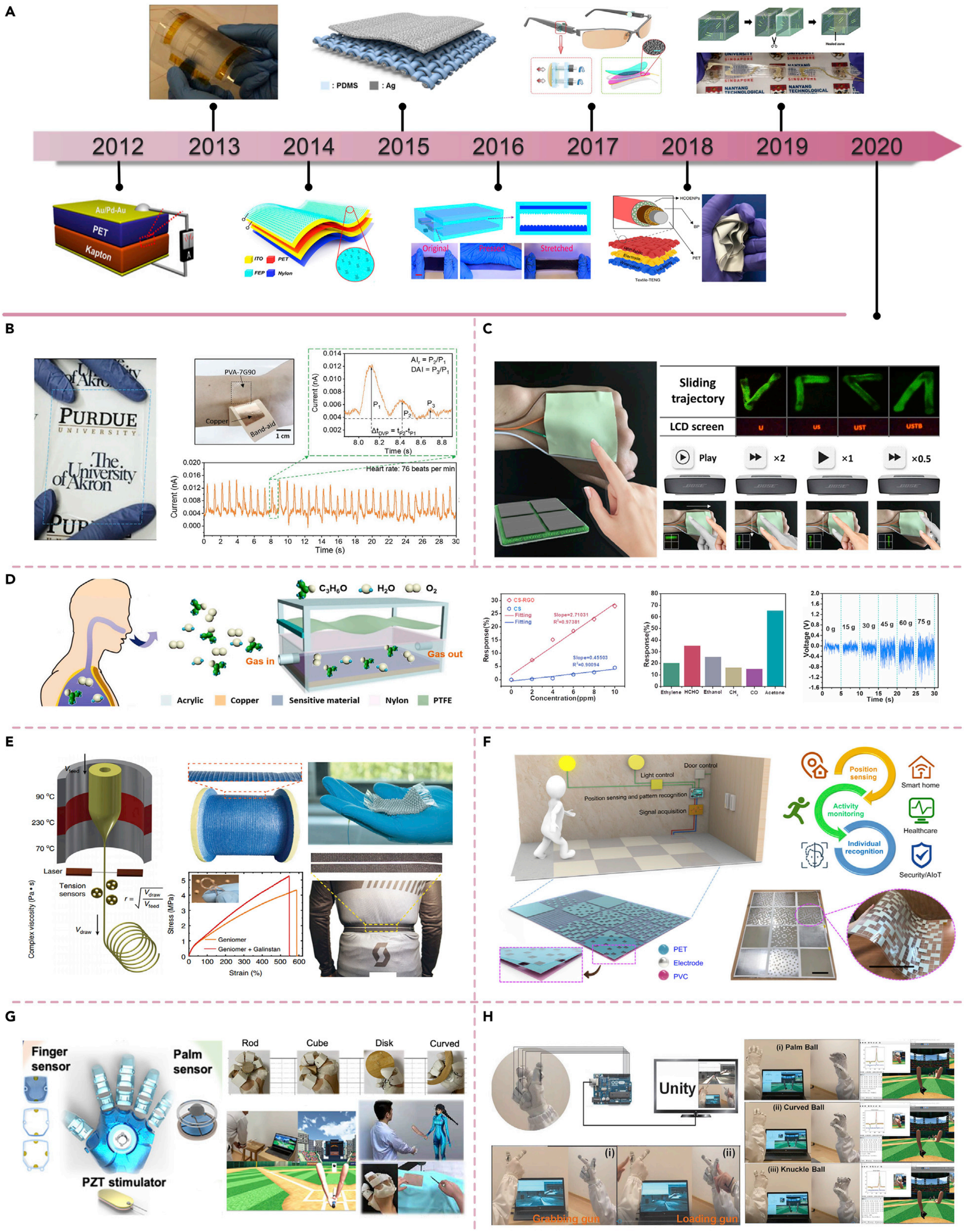
A
2012
2013
2014
2015
2016
2017
2018
2019
2020
: PDMS
: Ag
Au/Pd-Au
PET
Kapton
ITO
PET
FEP
Nylon
Original
Pressed
Stretched
HCOENPs
BP
PET
Textile-TENG
Healed zone
B
PURDUE UNIVERSITY
The University of Akron
PVA-7G90
Copper
Band-aid
1 cm
AI$_r$ = P$_2$/P$_1$
DAI = P$_3$/P$_1$
P$_1$
P$_2$
P$_3$
Δt$_{DVP}$ = t$_{P2}$-t$_{P1}$
Current (nA)
Time (s)
Heart rate: 76 beats per min
C
Sliding trajectory
LCD screen
U
US
UST
USTB
Play
×2
×1
×0.5
D
C$_3$H$_6$O
H$_2$O
O$_2$
Gas in
Gas out
Acrylic
Copper
Sensitive material
Nylon
PTFE
CS-RGO
CS
Fitting
Fitting
Slope=2.71031
R^2=0.97381
Slope=0.45503
R^2=0.90094
Response(%)
Concentration(ppm)
Ethylene
HCHO
Ethanol
CH$_4$
CO
Acetone
0 g
15 g
30 g
45 g
60 g
75 g
Voltage (V)
Time (s)
E
V$_{feed}$
90 °C
230 °C
70 °C
Laser
Tension sensors
r = $\sqrt{V_{draw}/V_{feed}}$
V$_{draw}$
Complex viscosity (Pa • s)
Stress (MPa)
Strain (%)
Geniomer
Geniomer + Galinstan
F
Door control
Light control
Position sensing and pattern recognition
Signal acquisition
PET
Electrode
PVC
Position sensing
Activity monitoring
Individual recognition
Smart home
Healthcare
Security/AIoT
G
Finger sensor
Palm sensor
PZT stimulator
Rod
Cube
Disk
Curved
H
Unity
(i)
(ii)
Grabbing gun
Loading gun
(i) Palm Ball
(ii) Curved Ball
(iii) Knuckle Ball

Figure 2. Recent progress of wearable TENGs

(A) A road map of representative wearable TENGs in the past decade. Reprinted from ref (Fan et al., 2012; Parida et al., 2019; Pu et al., 2017a; Seung et al., 2015; Xiong et al., 2018; Yang et al., 2013; Yi et al., 2016; Zhu et al., 2014) with permission, Copyright©2012 Elsevier Ltd, Copyright©2013 American Chemical Society, Copyright©2014 American Chemical Society, Copyright©2015 American Chemical Society, Copyright©2016 American Chemical Society, Copyright©2017 American Association for the Advancement of Science, Copyright©2018 Springer Nature, Copyright©2019 Springer Nature.

(B) An optimized PVA-gelatin composite film for high-performance TENG, capable of detecting subtle skin deformation induced by human pulse. Reprinted from ref (Wang et al., 2020c) with permission, Copyright©2020 WILEY-VCH Verlag GmbH & Co.

(C) A user-interactive electronic skin to map touch via electrical readout and visual output concurrently. Reprinted from ref (Zhao et al., 2020) with permission, Copyright©2020 American Association for the Advancement of Science.

(D) A wireless energy transmission-enabled wearable acetone biosensor for non-invasive prediabetes diagnosis. Reprinted from ref (Su et al., 2020b) with permission, Copyright©2020 Elsevier Ltd.

(E) A super-elastic and liquid metal-based triboelectric fiber fabricated with a controlled thermal drawing process. Reprinted from ref (Dong et al., 2020c) with permission, Copyright©2019 Springer Nature.

(F) A triboelectric-based smart mat with unique electrode patterns as a scalable floor monitoring system enabled by advanced deep learning analytics. Reprinted from ref (Shi et al., 2020b) with permission, Copyright©2019 Springer Nature.

(G) A 3D-printed haptic-feedback smart glove as a creative HMI for diversified VR/AR applications. Reprinted from ref (Zhu et al., 2020e) with permission, Copyright©2020 American Association for the Advancement of Science.

(H) A machine-learning glove consisting of superhydrophobic textile-based TENG sensors for hand gesture recognition in various VR/AR applications. Reprinted from ref (Wen et al., 2020b) with permission, Copyright©2020 WILEY-VCH Verlag GmbH & Co.

alternative to endoscopy and blood analysis by enabling physiological monitoring. The exhaled gases during respiration generally contain hundreds of volatile organic compounds, carrying enormous pathological information. Figure 2D presents a self-powered wearable acetone biosensor for breath monitoring and prediabetes diagnosis (Su et al., 2020b). This wireless power transmission-enabled self-powered acetone sensor (WSAS) contains two components: an energy harvesting component on top and a gas-sensing component on the bottom. As illustrated in Figure 2D, the airflow from breathing induces vibration to the PTFE film, generating a time-varying displacement that can be coupled to the bottom metal electrode. A chitosan-reduced graphene oxide (CS-RGO) film was coated on the bottom electrode, and its permittivity will change with the chemisorption of the acetone molecules, which varies the screening effect and thus the output signals. It is interesting to note that there is no wire connection between the top energy harvesting component and the bottom test chamber due to this unique sensing mechanism. Compared with the pure chitosan (CS), CS-RGO shows a pronounced monotonic increase of output voltage at increasing acetone gas concentrations with much higher sensitivity. The selectivity of CS-RGO over a few other common gases was also tested, showing a 2-fold response over other interfacing gases. To demonstrate the practical application of the sensing system, the WSAS was implemented to analyze the exhaled gases after 1 h of anhydrous glucose intake. The testing result shows an increasing output voltage with the escalated glucose ingestion, implying its capability to diagnose prediabetes. Besides polymer-based thin film structures, functional textiles and soft fibers are becoming another promising platform for wearable TENGs. Figure 2E shows a super-elastic liquid metal-based triboelectric fiber fabricated with a thermal drawing process, which exhibits high electrical outputs and superior stretchability up to 560% (Dong et al., 2020c). Such fibers can also be woven into machine-washable textiles with an output voltage of 490 V. Fixing the fiber on a stretchable belt that is worn around the torso, highly sensitive, and self-powered breathing monitoring is demonstrated with the aid of the surface texture and six liquid metal electrodes inside a single fiber. On top of that, the sensing fiber is also attached to a glove to detect finger bending motions, demonstrating its multifunctional properties in terms of wearable applications. Owing to the versatile choices of materials, diversified working modes, and cost-effective fabrication process, a growing number of large-area TENGs for wider application scenarios such as smart home or athletic big data analysis have been reported. For instance, Shi et al. recently developed a smart floor monitoring system by integrating triboelectric floor mats with deep learning data analytics (Shi et al., 2020b). As shown in Figure 2F, the floor mats are characterized with unique "identity" electrode patterns fabricated with the highly scalable and low-cost screen printing technique, which enable the parallel connections between each mat to reduce the systematic complexity. Each triboelectric mat contains three stacking layers, i.e., a PET friction film, silver electrode, and a polyvinyl chloride substrate. Generally, the "identity" electrode patterns are differentiated by the overall areas that determine the triboelectric outputs proportional to the effectively induced charges on the electrode patterns. The assembled floor mat array with 12 pixels is illustrated in Figure 2F, where six electrode coverage rates from 0 to 100% are designed for a good balance between the clear differentiation and number of floor mats. With the aid of a CNN model for advanced data analysis, the smart floor mat is capable of real-time position sensing and identity recognition. The floor mat is then placed in a corridor for demonstration, where the position of each step is adopted for lights control at the corresponding sites, and the full walking signal is sent to the convolutional neural network (CNN) model to identify the registered users for door access auto-control. The smart floor monitoring system produces a high prediction accuracy of 96% of a 10-person model, offering a highly secure, convenient, and accurate approach for individual recognition bypassing the image privacy issues.

HMIs, especially wearable HMIs functioning as the communication channel between the user and equipment, robot, or digital world, are experiencing rapid development toward intuitive and effective manipulation approaches (Zhu et al., 2020c). As our hand is one of the most dexterous part of our body, glove-based HMIs have emerged as a newly emerging platform for diversified control applications (He et al., 2019b). Figure 2G depicts a glove-based HMI consisting of a 3D-printed glove case, which is embedded with doom-shaped triboelectric sensors distributed on different locations of the inner side and in direct contact with the fingers (Zhu et al., 2020e). Generally, four dome sensors are located at each segment of the fingers to detect the up/down bending and right/left bending regarding the output signals from the four of them. A palm sliding sensor is also introduced with the same structure but with four electrodes for normal and shear force detection (in eight directions). To perform haptic feedback for an augmented HMI, the authors place lead zirconate titanate (PZT) chips at the root of each finger, which function as mechanical stimulator. This smart glove can recognize gasping objects with machine learning techniques and achieve multidimensional manipulation with different hand gestures. Moreover, it is used for versatile application scenarios allowing the user interface with the objects in the virtual world, e.g., playing baseball game, social activities with a virtual figure, and surgical training program. The PZT chips will be activated by pulse width modulation signal when the interaction event is detected by the triboelectric sensors, thus creating an immersive experience for the users. Although this glove is powerful in terms of sensitive and haptic feedback capability, the 3D printed glove case is still rigid and not deformable to provide a satisfactory wear comfortability especially considering long-term wearing. Wen et al. recently reported a machine learning glove that is made of soft and stretchable textile, which allows complex hand gesture recognition with a minimalist design as shown in Figure 2H (Wen et al., 2020b). The glove contains five arch-shaped sensors, and each of them consists of a silicone rubber layer as the negative friction material and a superhydrophobic textile as both the charge collection electrode and the positive friction layer. The superhydrophobic functional textile is fabricated with a carbon nanotubes (CNTs)/thermoplastic elastomer coating process, which can help suppress the effect of sweat while wearing the glove. The glove has been readily used for hand gesture recognition in a virtual shooting game, where grabbing, loading, and shooting gun has been demonstrated. With the aid of machine learning analytics, more complex gestures can be recognized with a high accuracy, which is applied in a baseball game for demonstration. Moreover, the authors have demonstrated flower arrangement with both hands wearing the gloves in the augmented reality space, which involves movements of all the 10 fingers in different postures. With the compelling features of cost-effective, self-powered, multifunctional, and versatile applications, wearable TENGs would cater to the development of bodyNET as possible power sources and functional sensors.

Wearable piezoelectric nanogenerators

Apart from the triboelectric effect, the piezoelectric effect is another promising and feasible working mechanism for harvesting biomechanical energy aiming at on-body electricity generation (Dagdeviren et al., 2016; Kim et al., 2011; Liu et al., 2018c). Since the direct piezoelectric effect was reported by French physicists Jacques Curie and Pierre Curie in 1880 (Curie and Curie, 1880), many piezoelectric materials have been discovered and studied. In the 1960s, the ferroelectric lead zirconate titanate [$Pb(Zr_{1-x}Ti_x)O_3$ or PZT] was the most widely utilized material for its high piezoelectric coefficient in the d_{31} and d_{33} modes (Damjanovic and Rossetti, 2018). After that, zinc oxide (ZnO) has been deeply investigated in the 1990s (Choi and Polla, 1993), and other new materials like barium titanate ($BaTiO_3$) (Park et al., 2010) and single-crystal piezoelectric ceramic lead magnesium niobate-lead zirconate titanate (PMN-PZT) (Erturk et al., 2008) were also utilized for piezoelectric EHs. Bearing the purpose of energy scavenging from minor mechanical motions, the first PENG was proposed by Prof. Z. L. Wang in 2006 through ZnO NWs (Wang, 2006). Since then, PENGs have received flourishing development and shown remarkable performance for biomechanical energy harvesting (Qin et al., 2008). A road map for representative wearable PENGs is shown in Figure 3A (Huang et al., 2017; Hwang et al., 2014; Jeong et al., 2018; Kim et al., 2012; Mokhtari et al., 2019; Shin et al., 2016; Sim et al., 2015; Zeng et al., 2013; Zhu et al., 2012). In 2010, Prof. Z. L. Wang's group further proposed the vertically and laterally aligned ZnO NWs with a synchronized charging and discharging process to enhance the output performance of PENGs for powering real devices with the help of

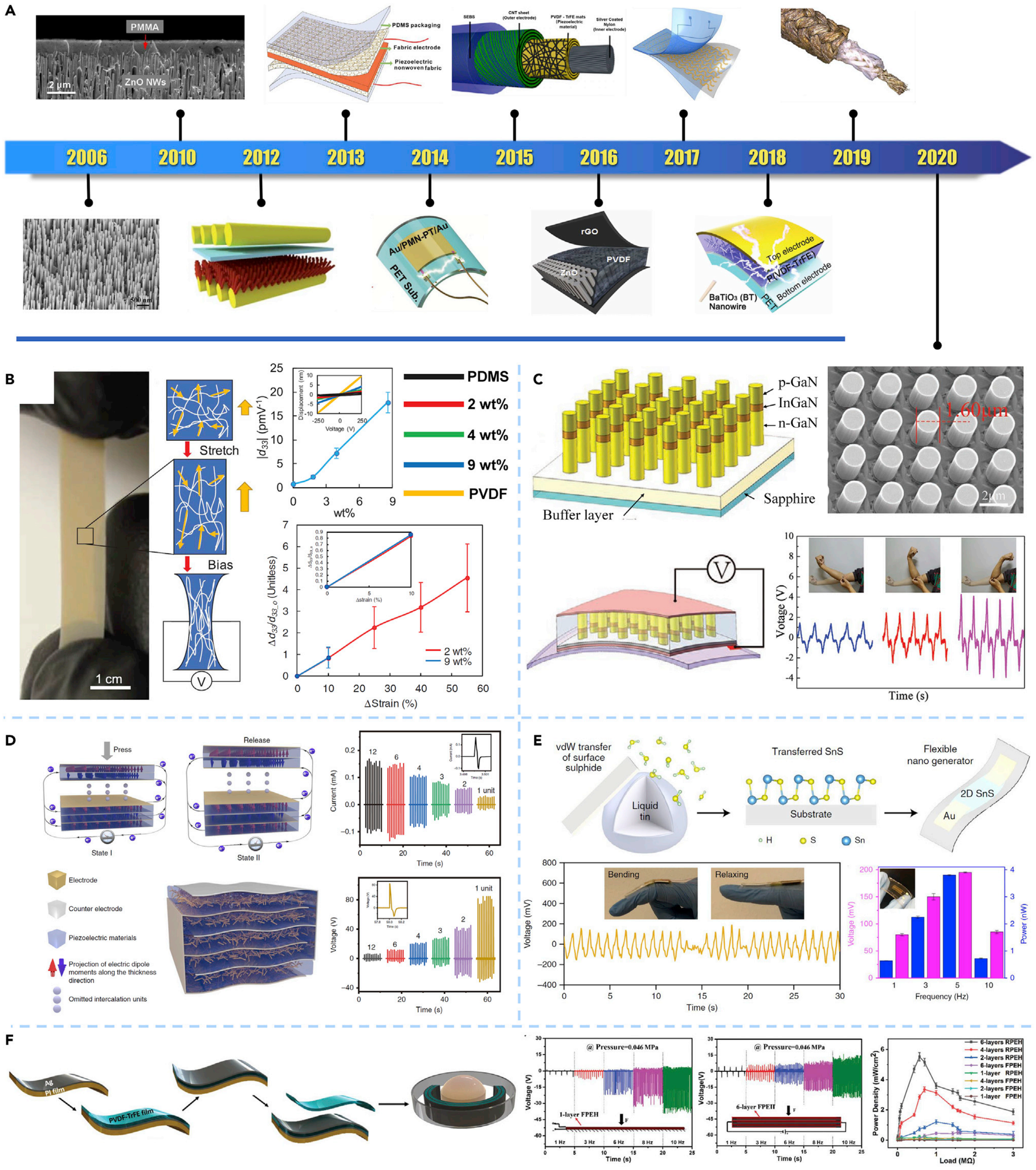

Figure 3. Recent progress of wearable PENGs

(A) A road map of representative wearable PENGs in the past decade. Reprinted from ref (Huang et al., 2017; Hwang et al., 2014; Jeong et al., 2018; Kim et al., 2012; Mokhtari et al., 2019; Shin et al., 2016; Sim et al., 2015; Zeng et al., 2013; Zhu et al., 2012) with permission, Copyright©2009 Elsevier Ltd, Copyright©2012 American Chemical Society, Copyright©2012 The Royal Society of Chemistry, Copyright©2013 The Royal Society of Chemistry, Copyright©2014 WILEY-VCH Verlag GmbH & Co, Copyright©2015 WILEY-VCH Verlag GmbH & Co, Copyright©2016 Elsevier Ltd, Copyright©2017 Elsevier Ltd, Copyright©2018 WILEY-VCH Verlag GmbH & Co, Copyright©2019 The Royal Society of Chemistry.

Figure 3. *Continued*

(B) A stretchable PENG based on BNNT/PDMS with tunable piezoelectricity and enhanced mechanical strength and thermal conductivity. Reprinted from ref (Snapp et al., 2020) with permission, Copyright©2020 WILEY-VCH Verlag GmbH & Co.

(C) A wearable strain sensor based on GaN pn junction microwire arrays with high sensitivity and robustness. Reprinted from ref (Cheng et al., 2020) with permission, Copyright©2020 WILEY-VCH Verlag GmbH & Co.

(D) A PENG with novel three-dimensional intercalation electrode with improved current density. Reprinted from ref (Gu et al., 2020) with permission, Copyright©2020 The Authors.

(E) A flexible PENG based on monolayer 2D material SnS. Reprinted from ref (Khan et al., 2020) with permission, Copyright©2020 The Authors.

(F) A bull-structured PENG with multilayer P(VDF-TrFE). Reprinted from ref (Yuan et al., 2020) Copyright©2020 The Royal Society of Chemistry.

polymethyl methacrylate (PMMA) (Xu et al., 2010; Zhu et al., 2012). For further applications in wearable devices, a substrate with the characteristics of deformability, flexibility, and stretchability is generally required. The integration of ZnO NWs with a charged dielectric film on a textile substrate was successfully achieved by Prof. Y. J. Park's group in 2012 (Kim et al., 2012). Except for the inorganic nanomaterials, poly(vinylidene difluoride) (PVDF) as an organic material also shows excellent advantages in stretchability and flexibility with good durability and power density (Cha et al., 2011; Lee et al., 2012). In 2013, an all-fiber PENG with a sandwich structure consisting of two conducting fabric electrode layers and one PVDF-$NaNbO_3$ nanofiber nonwoven fabric layer was reported by Prof. X. M. Tao's group, which can maintain its output performance after 1,000,000 cycles with frequency and pressure comparable to human walking motion (1 Hz and 0.2 MPa) (Zeng et al., 2013). Another single-crystal piezoelectric material $(1-x)Pb(Mg_{1/3}Nb_{2/3})O_3$-$xPbTiO_3$ (PMN-PT) also shows exceptional piezoelectric coupling coefficient up to 2,500 pC/N (Park and Shrout, 1997; Xu et al, 2012, 2013). And this material has demonstrated the potential for wearable and implantable applications as a thin film on a flexible substrate by Prof. K. J. Lee's group in 2014 (Hwang et al., 2014). Although the utilization of piezoelectric materials in flexible PENGs and self-powered sensors had been explored, robust piezoelectric fibers still highly demand the enhancement in flexibility and stretchability for wearer comfort and excellent conformability to scavenge energy from a wide range of body movements (Kechiche et al., 2013). A stable PENG fiber with a maximum tensile strain of 5% and output over 50 $\mu W/cm^3$ was constructed by Prof. S. J. Kim's group in 2015, with electrospun polyvinylidene difluoride-co-trifluoroethylene (PVDF–TrFE) fibers mats as the piezoelectric material and CNT sheets as the outer electrode (Sim et al., 2015). In the following years and till now, further improvement in output power as EH, in sensitivity as a self-powered sensor, and in stretchability, flexibility, and robustness for practical applications of wearable PENGs are constantly being explored and studied (Huang et al., 2020a). In 2016, with the hybrid ZnO/PVDF films, a minimum detective pressure of 4 Pa was achieved by Prof. J. Jang's group, and the sensing of small pulses like heart rate monitoring was successfully demonstrated (Shin et al., 2016). In 2017, a hyper-stretchable self-powered sensor with maximum mechanical stretchability up to 300% and durability after 1,400 cycles with 150% strain was proposed by Prof. Z. Yin's group (Huang et al., 2017), based on hydrodynamic printing PVDF nano/microfibers, liquid metal, and Ecoflex. Another flexible hybridized PENG with $BaTiO_3$ NW and PVDF-TrFE was reported by Prof. S. H. Kim's group in 2018, which exhibits great output performance with voltage and current signals up to 14 V and 4 μA and high durability for 10,000 cycles operations (Jeong et al., 2018). In 2019, with braiding melt-spun PVDF powder and conductive silver-coated nylon yarns, a high-performance piezoelectric fiber with exceptional improvement in power density reaching 29.62 $\mu W/cm^3$ was fabricated by Prof. G. M. Spinks' group (Mokhtari et al., 2019).

Piezoelectric-based nanogenerators and self-powered sensors also have shown significant development in 2020. A stretchable multifunctional piezoelectric device with uniformly dispersed boron nitride nanotubes (BNNT) on a stretchable substrate (PDMS) is demonstrated in Figure 3B (Snapp et al., 2020). With a tetrahydrofuran (THF) co-solvent, BNNTs were dispersed in PDMS in a simultaneously slow stirring and drying procedure. This facile fabrication process makes the mass production possible, and this dispersion also advantages in the availability to be cast into PDMS without influencing its stretchability. Compared with previously reported nanotube composites (Cho et al., 2016; Hong et al., 2010), this BNNT/PDMS composite with evenly distributed long BNNTs through this method shows a significant improvement in Young's modulus (200% at 9 wt% BNNT) and thermal conductivity (120% at 9 wt% BNNT). These improvements may ensure a stretchable piezoelectric device with good robustness and thermal dissipation for heat generated during operation. Besides, this composite also shows comparable piezoelectric response (18 pm/V at 9 wt % BNNT) compared with widely utilized piezoelectric polymers like PVDF (33 pm/V). Self-powered vibration sensing with it was successfully demonstrated as well. On top of that, the mechanical strength, thermal conductivity, and piezoelectric response can all be tuned with the varying of BNNT contents and applied strain. Figure 3C shows a wearable strain sensor based on GaN pn junction microwire arrays (Cheng et al., 2020). Compared with ZnO, GaN exhibits advantages in higher stability and more accessible control in doping concentration, whereas its piezoelectric performance is not satisfied due to free carriers screening. One solution for this drawback is applying high-aspect-ratio NWs instead of bulk or film materials (Hu et al., 2018; Zhu et al., 2012). Herein, to leverage GaN's merits and compensate for this drawback, a novel fabrication process for high-quality GaN pn junction microwire arrays was put forward, with controllable aspect ratios and outstanding uniformity. Through a top-down technique with lithography, dry etching, and wet etching, uniform GaN microwire arrays can be fabricated on a buffer layer and a sapphire layer. A much higher piezoelectric coefficient (d_{33}) was measured, varying from 7.23 to 14.46 pm/V with different aspect ratios. This device is further packaged with two metal electrode layers to form a flexible self-powered strain sensor, and the GaN microwires with the aspect ratio achieving the highest d_{33} value were selected. This wearable strain sensor can detect minor human motions like a heartbeat with an output voltage of 2 mV or an arm bending with an output voltage of 4.25 V. A good mechanical robustness was also achieved with the testing of 10,000 cycles of operations. Figure 3D shows a novel method to increase the current density of PENG by applying a three-dimensional intercalation electrode based on a newly reported piezoelectric material Sm-PMN-PT with an outstanding piezoelectric coefficient (Gu et al., 2020). Although the two-dimensional interdigital electrode design has been widely utilized to improve the current density, it still has the limitation of either low output current density with wide strips or poor strain uniformity with narrow strips (Bowen et al., 2006). Therefore, the three-dimensional interdigital electrode structure was designed to overcome this constraint. Compared with traditional interdigital structures, the well-sandwiched design has an evenly distributed electric field and, at the same time, can be fully polarized even with very thin thickness. This structure was fabricated by dividing a whole piezoelectric layer into many units with the same thickness. An increased output current with a maximum value reaching 329 μA is achieved. Except for conventional piezoelectric ceramic thin films, two-dimensional (2D) materials also provide viable avenues in this field for their ability to withstand large strains and potential of large piezoelectricity. And one of the group IV mono-chalcogenides, tin monosulfide (SnS), has been predicted theoretically to have excellent piezoelectricity. However, its synthesis in large-scale surface coverage is still challenging and highly hinders its applications. Through a novel synthesis process via the van der Waals exfoliation technique as shown in Figure 3E, a large-scale and highly crystalline semiconducting monolayer SnS was successfully completed (Khan et al., 2020). This monolayer showed a very large piezoelectric coefficient of about 26.1 pm/V and was further applied to a PENG. Attributing to the large d_{11} value, a high energy conversion efficiency is realized, with a large average peak voltage output around 150 mV at only 0.7% strain. And its suitability for low-frequency motion energy harvesting and wearable applications was also demonstrated. A PENG based on flexible P(VDF-TrFE) copolymer with multiple thin layers is shown in Figure 3F (Yuan et al., 2020). The flexible multilayer design is able to increase the energy scavenging efficiency, and a rugby ball-structured PDMS layer was designed to further augment the output performance compared with a simple flat structure. For the PENG with six layers, the maximum output power density of 16.41 mW/cm^2 is achieved, which is nearly 22 times higher than the flat PENG.

Hybridized EHs for a single energy source

Although TENG and PENG have their distinctive advancement and have shown significant development since their inventions, in some cases, the output power of a sole TENG/PENG generally cannot completely fulfill the power requirements of the widely used wearable electronic devices with limited energy conversion efficiencies (Khan et al., 2019; Zi et al., 2015). At the same time, biomechanical energy sources usually include various types of human motions, and an EH with a single mechanism may not be able to fully utilize all of the mechanical energy generated by such movements (Liu et al., 2020a; Zhang et al., 2019b). Therefore, hybridized wearable EHs with the combination of multiple energy conversion mechanisms, including TENG, PENG, and EMG, have been put forward for harvesting mechanical energy, which can leverage the advantages of each mechanism's characteristics and as a complementary part for each other (Tang et al., 2021; Wang et al., 2021; Zhu et al., 2021). For non-flexible wearable EHs, EMG is generally integrated for its high output current compared with PENG and TENG (Toyabur Rahman et al., 2020; Zhang et al., 2019c). Figure 4A shows a rotational pendulum-based hybrid energy generator with a combination of electromagnetic and triboelectric effects (Hou et al., 2019). This device's electromagnetic component comprises a magnet made of neodymium iron boron (NdFeB) with a copper ring around, alloy support made of aluminum, and four disk-like coils connected in series. The triboelectric component contains two blades with one side fixed on the acrylic frame and the other side freestanding, both of which are made of three layers (FEP-Cu-FEP). When external acceleration is applied, the pendulum-based structure will start to

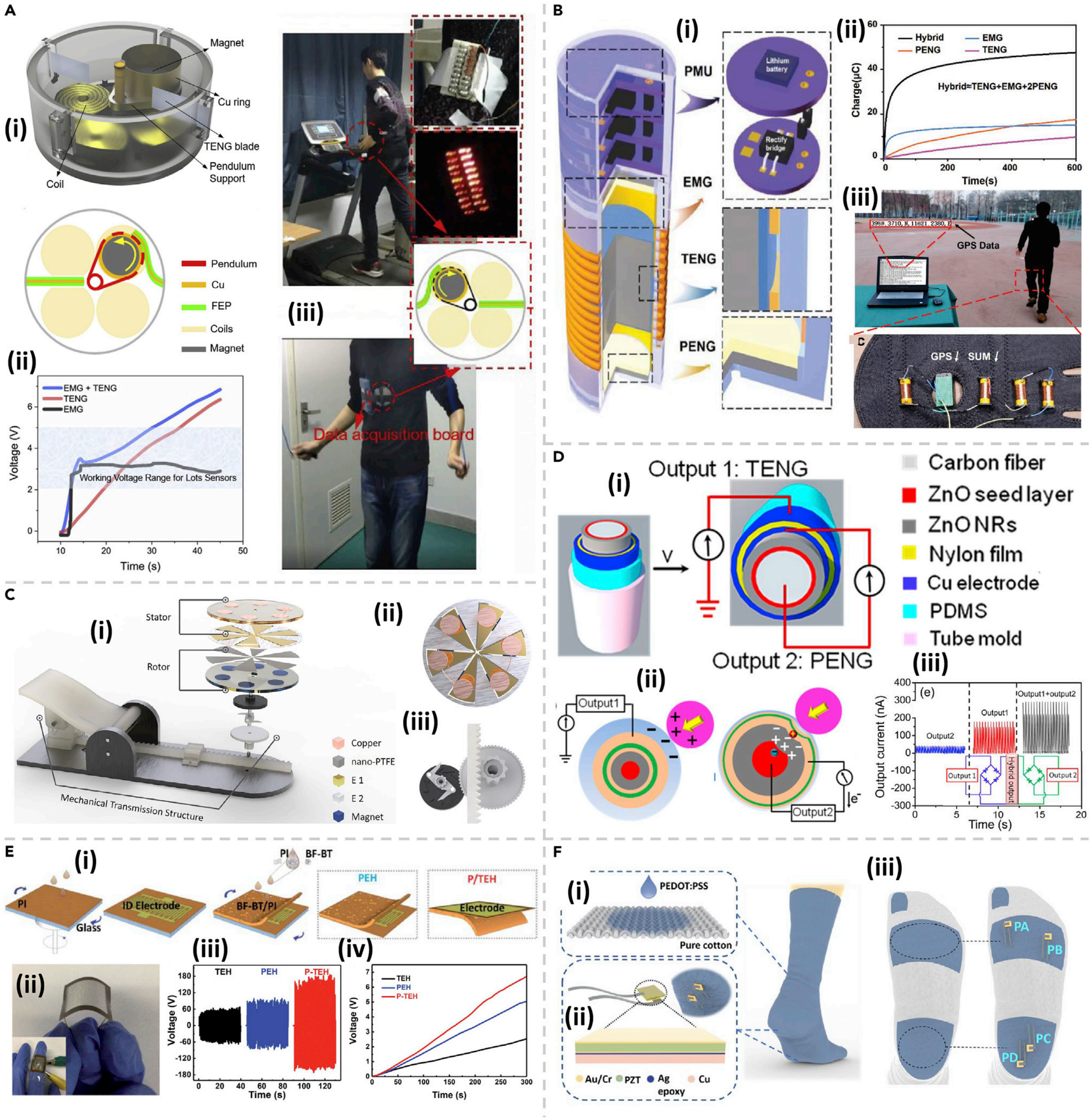

Figure 4. Hybrid EHs for single source (mechanical energy)

(A) A rotational pendulum-based hybrid EH with EMG and TENG as a wearable watch. Reprinted from ref (Hou et al., 2019) with permission, Copyright©2019 Elsevier Ltd.

(B) A battery-like hybrid EH with EMG, PENG, and TENG as the accessory on cloth. Reprinted from ref (Tan et al., 2019) with permission, Copyright©2015 WILEY-VCH Verlag GmbH & Co.

(C) A free-rotating hybrid EH with EMG and TENG applied in shoes. Reprinted from ref (Jiang et al., 2020a) with permission, Copyright©2020 The Authors.

(D) A flexible fiber-based hybrid EH with TENG and PENG. Reprinted from ref (Li et al., 2014) with permission, Copyright©2014 American Chemical Society.

(E) A flexible hybrid EH with TENG and PENG able to working in high-temperature environment. Reprinted from ref (Sun et al., 2020b) with permission, Copyright©2020 The Royal Society of Chemistry.

(F) A cotton sock with hybrid TENG and PENG. Reprinted from ref (Zhu et al., 2019a) with permission, Copyright©2020 American Chemical Society.

rotate around the shaft. The contact and separation process between the magnet's outer copper layer and the FEP layers of two blades can generate triboelectric charges. Simultaneously, the pendulum rotor magnet's motion also causes the varying magnetic field distribution for the four coils and induces the electromagnetic current. Figure 4A(ii) shows an optimized charging curve with the combination of EMG and TENG for charging a capacitor with 22 μF. Moreover, Figure 4A(iii) shows the practical demonstrations for this hybridized wearable EH with human motions like running and rope skipping. Thanks to the pendulum structure, motions with small amplitude or low frequency can also drive the magnet to rotate clockwise or counterclockwise and generate considerable electric output. Maximum power densities of 3.25 and 79.9 W/m^2 are successfully achieved by TENG and EMG, respectively, under a driving frequency of 2 Hz and amplitude of 14 cm. Figure 4B shows a battery-like EH with the combination of EMG, TENG, and PENG (Tan et al., 2019). On top of the device is a power management unit that is utilized to convert and store the electricity generated from three generators and improve efficiency. The EMG part is composed of $\sim$2,000-turn copper coils around the surface of the polylactic acid tube, and a NdFeB magnet is placed in the tube, which can move up and down. There are also two small magnets placed at the inner top and inner bottom of the tube to achieve magnet levitation. The PENG part is placed at the end of the tube beyond end magnets consisting of two PZT ceramic sheets. The TENG part is achieved by a PTFE film with nanostructure surface by treating with inductively coupled plasma in a freestanding mode. The main magnets will move up and down to generate electromagnetic current and triboelectric current under applied vibration, through the varying magnet field passing through coils and friction between the magnet surface and Au electrode, respectively. When the external acceleration is large enough to make the magnet collide with PZT sheets, the piezoelectric current will also be generated through their deformation. Figure 4B(ii) shows the improved charging curve with the combination of three generators, and Figure 4B(iii) shows the practical demonstration for applying several hybridized generators as pendants on the cloth. The maximum normalized output power of 2 mW/g is achieved under low-frequency motions (5 Hz). Figure 4C shows another case for a non-flexible wearable EH placed in shoes with the combination of TENG and EMG (Jiang et al., 2020a). A PTFE film tailored into a fan-shaped structure with six segments and an acrylic disk holding six magnets form the rotor part. And two separated aluminum sheets and another acrylic disk holding six coils form the stator part. When vertical force on the pedal is applied, the gear transmission structure shown in Figure 4C(iii) is able to transfer it to a rotating movement with a considerable rotation speed of the rotor. While rotating, triboelectric and electromagnetic current can be generated through the electrification process between the PTFE layer and the metal electrode layer and the relative movement between the magnets and coils, respectively. The maximum output energy of 14.68 mJ can be generated through each stepping process.

As the EMG typically consists of a solid and bulk magnet and the metal coils are usually difficult to be stretched or bent, it is much more challenging to integrate EMG into flexible wearable EHs. Therefore, the integration of TENG and PENG attracts more attention for such designs, and this combination at the same time can leverage the characteristic of human motions, in which the mechanical friction and deformation usually happen concurrently (Tan et al., 2020; Zheng et al., 2017; Zou et al., 2020a). Figures 4D and 4F show some examples for hybridized TENG and PENG wearable devices through simple structural combination with a multi-layer design. Figure 4D shows a fiber-based hybridized generator with a core-shell structure by covering the TENG on the surface of an inner fiber-shaped PENG (Li et al., 2014). The PENG was fabricated by growing ZnO nanorods on a carbon fiber with the physical evaporation deposition and hydrothermal growth approach. Two Ti/Cu thin films were sputtered on a nylon film as electrode layers. The inner electrode layer acts as the top electrode of PENG, and the outer electrode layer acts as the electrode for TENG. And the whole fiber was further packaged by a PDMS tube. The working principles of TENG and PENG are shown in Figure 4D(ii). When a nylon fiber contacts with the PDMS layer and separates, triboelectric charges are generated due to coupling effect of contact electrification and electrostatic induction as output 1. And the deformation of inner ZnO nanorods caused by this process can generate piezoelectric current as output 2. The improved output performance is presented in Figure 4D(iii), in which a significant enhancement can be noticed through this hybridization structure compared with a single mechanism. Figure 4E shows another flexible hybrid EH with PENG and TENG (Sun et al., 2020b). A polyimide (PI) layer was first spin-cast onto a glass substrate and then coated with interdigital (ID) electrodes. After that, $BiFeO_3$-$BaTiO_3$ (BF-BT) nano/micro-particles were uniformly dispersed in a printer ink (PI) solution then spin-coated on the electrode. Thereafter, the fabricated device was peeled off the glass substrate after solidification and then poled under an electric field as a PENG. And a TENG was also integrated through a Pt electrode layer sputtered on the bottom surface of the BF-BT/PI film. This hybridized EH shows a maximum power density of 4.1 mW/cm^3 with high-temperature stability up to 200°C. Recently, a smart cotton sock with a combination of triboelectric and piezoelectric effect was demonstrated as shown in Figure 4F (Zhu et al., 2019a). Four PZT chips were inserted into a triboelectric sock coated by poly(3,4-ethylene dioxythiophene) polystyrene sulfonate as shown in Figure 4F(iii). And a PTFE film with an aluminum electrode layer was attached on the surface of the shoes for a TENG with contact-separation mode. The power density of 11 μW/cm^2 and 128 μW/cm^2 was achieved for TENG and PENG, respectively. Apart from simultaneous energy conversion, this hybrid EH sock can also function as a sensing sock for gait analysis, and the integration of PENG is advantageous in calibrating the triboelectric sensing output that is susceptible to humidity and sweat.

Except for directly integrating TENG with PENG through straightforward structure hybridization, a more effective combination between TENG and PENG was explored to further enhance their electric behavior, and the piezoelectric-enhanced triboelectric nanogenerators (PETNGs) were proposed (Guo et al., 2018b; Shi et al., 2019d; Yu et al., 2019). A textile-based and sandwiched TENG and PENG multi-layer structure is proposed as illustrated in Figure 5A (Guo et al., 2018b). Silk and PVDF nanofibers were electrospun, respectively, on the two conductive fabrics as the top TENG and bottom PENG parts. And the PVDF fabric layer can also act as the piezoelectric-enhanced layer for augmented electric output through the interaction principles shown in Figure 5A(ii and iii). If the PVDF layer is negatively polarized, negative piezoelectric charges will be induced on the upper surface of PVDF fibers when compressed, and positive triboelectric charges will be induced in the upper electrode fabric. This process leads to the accordant working state of TENG and PENG, which means they have the same potential direction, and higher electric output can be achieved. The PETNG achieved an outstanding maximum output performance with 500 V output voltage, 12 μA current, and 0.31 mW/cm^2 power density through the well-collaborative work between TENG and PENG. Another flexible PETNG is shown in Figure 5B with the tribo-ferroelectric synergistic effect (Yang et al., 2019). This device contains seven functional layers, including the two outer moisture-wicking fabric layers, two nickel-copper (Ni-Cu) conductive fabric layers as electrodes, two nanofiber nonwovens P(VDF-TrFE) layers, and one central polyamide 6 (PA6) layer with opposite tribo-polarity. The detailed working mechanism of this tribo-ferroelectric synergistic effect is shown in Figure 5B(ii). With two polarized ferroelectric P(VDF-TrFE) layers, the Fermi level of PA6 increases, thus further leading to the increase of the surface potential difference between two dielectric materials. Starting from the original state, when the P(VDF-TrFE) layer first contacts with the PA6 layer, a large number of electrons are transferred, and their Fermi levels become equal. When separated, an internal electric field is built between the dielectric layer and the conductive layer and promotes further polarization of the ferroelectricity of P(VDF-TrFE). Furthermore, the enhanced ferroelectricity leads to the augmented capability of capturing charges in the next contact and results in a further increased electric performance. Except for the enhanced output, this device also shows good thermal-moisture comfortability by utilizing two moisture-wicking fabric layers. This work reaches a power density of 5.2 W/m^2 with low frequency (2.5 Hz), which is seven times higher than previous nanogenerators with breathable textiles. Figure 5C also shows a PETNG with enhanced output based on the augmented triboelectric output through the surface charge generated by piezoelectric materials (Huang et al., 2020b). In this study, to further improve the output performance, spider silk protein was utilized to increase the surface potential difference of PET, and graphene was also introduced to enhance the PVDF performance. An outstanding improvement of this PETNG can be noticed when the TENG and PENG are in the accordant state, and a maximum instantaneous power density of 4,016 mW/m^2 is achieved. Besides, a large-scale and continuous roll-to-roll fabrication process is also available for the PETNG device, showing its great potential for large-area applications. Apart from graphene, Figure 5D shows the application of an alternative nano-filler material, the commercially available PI, to improve the PENG performance (Tayyab et al., 2020). For the TENG enhanced by 5 h-grown PVDF-PI nanofibers, an outstanding maximum power output of 22 W/m^2 was achieved. The enhancement in the electric output of the nano-filler material, PI, is shown in Figure 5D(ii). Furthermore, Figure 5D(iii) demonstrates practical applications for this flexible device in a wearable environment like wrist, elbow, and knee. Except for impressive output enhancement, flexible and wearable PETNGs mentioned above also show broad application scenarios, including strain sensor, force sensor, and humidity sensor, and are easy to be integrated into a completely flexible system, which makes them play competitive roles in the future bodyNET.

Hybridized EHs for multi-sources

Single-source EHs are promising technologies to provide considerable electricity to the sensor network with ideal input energy that mostly only exists in laboratory conditions. However, the output power of a single-source EH may suffer a sharp decrease with more practical input sources, e.g., indoor light, random

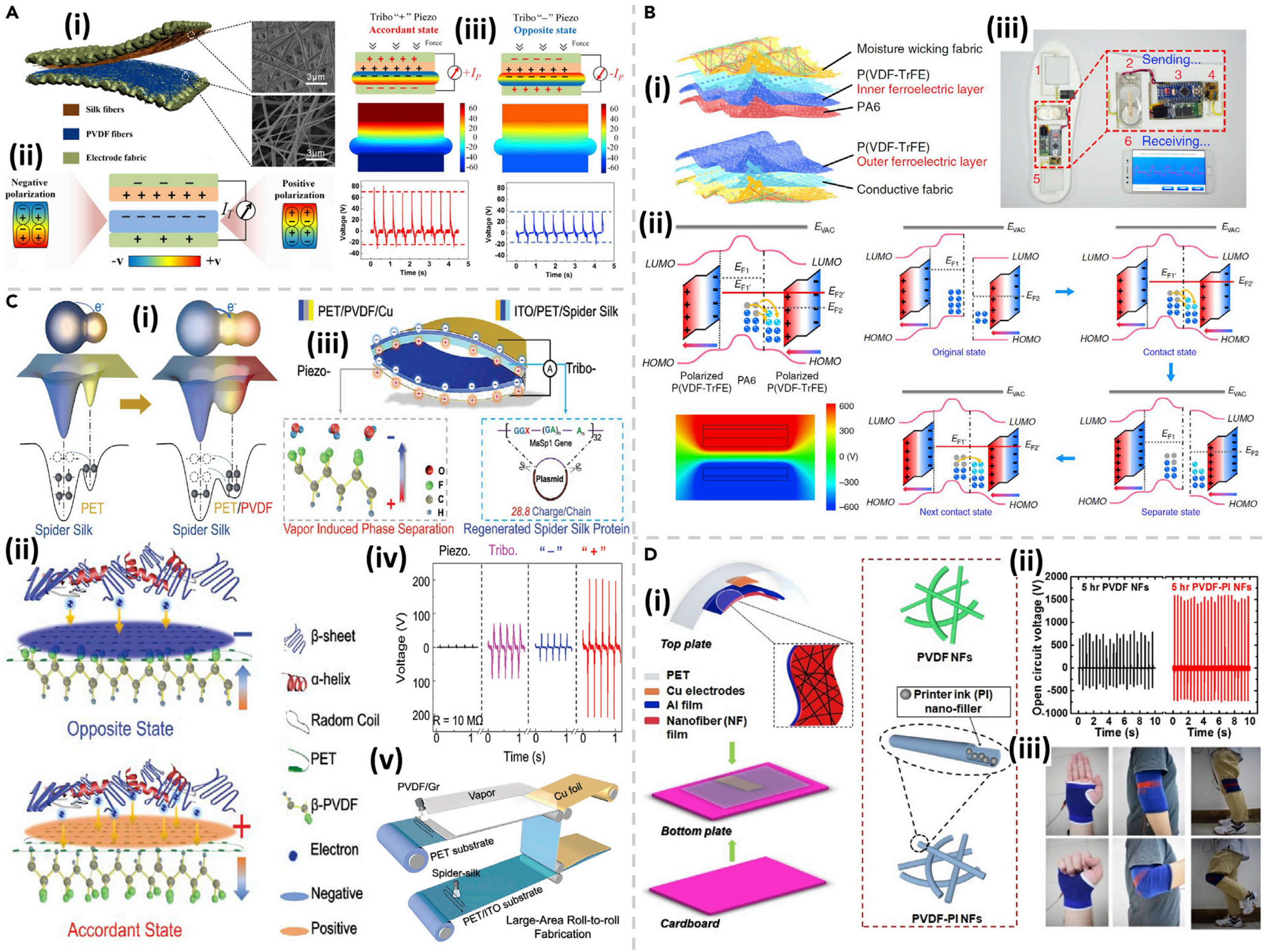

Figure 5. Hybrid PETNGs

(A) An all-fiber PETNG with PVDF and silk. Reprinted from ref (Guo et al., 2018b) with permission, Copyright©2019 Elsevier Ltd.

(B) An all-fiber PETNG with P(VDF-TrFE) and PA6. Reprinted from ref (Yang et al., 2019) with permission, Copyright©2020 The Authors.

(C) A self-matched PETNG with PET, PVDF, and spider silk. Reprinted from ref (Huang et al., 2020b) with permission, Copyright©2020 WILEY-VCH Verlag GmbH & Co.

(D) A PETNG with PI as the nanofiller material in PVDF. Reprinted from ref (Tayyab et al., 2020) with permission, Copyright©2020 Elsevier Ltd.

vibration, fluctuating thermal source, etc. Take a solar cell as an example; the output power of solar panels can drop to 0.04%–1% of their original values under bright sunlight (Roundy et al., 2003). To boost up the output power of the EHs such that they become more competitive with batteries in practical scenarios, hybrid EHs should be developed to enable increased energy by employing different mechanisms to harvest diverse energy sources that coexist in the surroundings (Khan et al., 2019).

Over the past decade, we have witnessed the development of hybrid energy cells for multimode energy harvesting including but not limited to piezoelectric and photovoltaic (Xu and Wang, 2011), piezoelectric and thermoelectric/pyroelectric (Oh et al., 2019; Song et al., 2019a; You et al., 2018; Zhu et al., 2019b, 2020f), piezoelectric and biochemical (Hansen et al., 2010; Pan et al., 2011), triboelectric and photovoltaic (Guo et al., 2019; Jung et al., 2020; Liu et al., 2018d; Song et al., 2019b), triboelectric and thermoelectric/pyroelectric (Seo et al., 2019; Shin et al., 2020; Wang et al., 2020e; Wu et al., 2018), triboelectric and biochemical (Li et al., 2020), and three mechanisms among them (Jella et al., 2018; Ji et al., 2019; Wang et al., 2016b; 2016c). Targeting for wearable applications, the material choices and structure designs of the hybrid EH would be more challenging considering the high performance and good flexibility. Fiber-based dye-sensitized solar cells (FDSSCs) have attracted wide attention in recent years owing to their light-weight, flexibility, high output, and cost-effective fabrication process. Meanwhile, fiber/textile-based

TENGs also experienced rapid development oriented toward better performance and wear comfortability. Figure 6A depicts a hybrid energy cell consisting of a grating TENG and FDSSCs integrated onto a cloth for harvesting energy from both sunlight and human motions (Pu et al., 2016b). The TENG fabrics consist of a slider fabric and stator fabric, which is separately located on the sleeve and underneath the arm, and seven FDSSCs are embedded into the cloth on the shoulder with good exposure to sunlight. The rectified TENG output is connected to the FDSSCs in parallel to charge a lithium-ion battery (LIB) with an additive current of both of them, forming a self-charging system with two input energy sources. Compared with the sole energy source, the hybrid cell allows the LIB discharging at 1 μA for a longer period (i.e., 98 min), indicating higher energy harvested from the ambient environment. Similarly, Wen et al. reported a self-powered textile by hybridizing fiber-shaped TENG, solar cell, and supercapacitor for higher systematic integrity and flexibility, as shown in Figure 6B (Wen et al., 2016). The TENG fibers are woven into a fabric and placed under the arm to harvest biomechanical energy from arm swing motions, and meanwhile the fiber-shaped solar cells (FDSSCs) scavenge solar energy from the surrounding light illumination. When charging the supercapacitor with the FDSSCs, the maximum charging voltage is capped at 1.8 V due to the low output voltage of the FDSSCs. Therefore, the high-output TENG can not only harvest kinetic energy from the environment but also improve the charging capability of the self-charging textile. Besides the ubiquitous solar energy, thermal energy source is also widely available in our surrounding environment, and body heat is a typical one that can be used. A hybrid thermo-triboelectric generator (HThTG) targeting human motions is presented in Figure 6C (Seo et al., 2019). As one touches the HThTG surface, body heat creates a temperature difference across the n-type and p-type bismuth telluride (Bi_2Te_3), which will produce a thermoelectric voltage between the upper and bottom electrodes. In the meantime, the triboelectric output can be collected from the bottom electrode when the skin touches the PDMS layers. As the touching frequency increases, the thermoelectric output would decrease due to the shorter contact time, but the triboelectric output is observed to increase gradually. Considering the distinct behavior of the two outputs, an optimized output power is achieved at 2.5 Hz, resulting in a power density of 3.27 $\mu W/cm^3$. Besides energy harvesting for subsequent use, the hybrid nanogenerator with multiple energy source conversion capabilities can also function as self-powered multimode sensors. A multifunctional tactile sensor has been developed recently with a hierarchical structure as shown in Figure 6D (Wang et al., 2020e), which incorporates a TEG and a TENG. The sponge-like graphene/PDMS composites allow for both pressure sensing via piezoresistive effect and temperature sensing with thermoelectric effect. The PTFE on top of the device enables triboelectric effect for material-type sensing with the aid of the electrification between the PTFE and the touching objects. The multifunctional sensor is featured with a high temperature detection resolution of 1 K and a pressure detection sensitivity of 15.22 kPa^{-1}. Moreover, the material properties can be inferred by the electric output of the single-electrode TENG, and it has been demonstrated to successfully distinguish 10 common flat materials.

Biomechanical, solar, and thermal EHs and their hybrid devices have demonstrated their great potential for powering wearable electronics or serving as self-powered sensors to complement wearable supercapacitors or batteries for continuous system functioning. Apart from them, flexible biofuel cells that rely on diverse biofluids to generate electricity also offer an attractive methodology for addressing the omnipresent challenges of wearable power sources (Bandodkar, 2017; Sharifi et al., 2020). BFCs can be generally categorized into microbial and enzymatic types, where anode and cathode of the system are built out of biological entities to consume chemicals through natural processes. The surging of wearable BFCs in recent years has shown the wealth of biochemical energy (e.g., glucose) in body fluid, which could further boost up the usable energy from the wearable EHs. Figure 6E presents a typical work of a hybridized nanogenerator consisting of a fiber-based PENG and a fiber biofuel cell (FBFC), which can be put into bio-liquid for energy harvesting (Pan et al., 2011). For the first time, the PENG and FBFC are fully integrated on single carbon fiber to scavenge mechanical and biochemical energy simultaneously. The PENG is designed based on the ZnO NWs grown on the carbon fiber that serves as the core electrode, and the FBFC uses the CNTs/gold as electrodes followed by immobilization of glucose oxidase and laccase to fabricate the anode and cathode. Immersing the hybrid nanogenerator into a bio-liquid, the FBFC produces a DC output voltage of 100 mV and a current of 100 nA. When a cyclic pressure is applied to the bio-liquid, the compressive strain results in an AC output with a peak voltage of 3 V and current of 200 nA. Moreover, the hybrid nanogenerator is demonstrated as a self-powered pressure sensor in bio-liquid, where the FBFC serves as the power source and PENG functions as the pressure sensor. Similarly, Li et al. reported a hybrid biofuel and TENG on a larger scale as shown in Figure 6F (Li et al., 2020). The hybrid energy harvesting system (HEHS) incorporates a TENG and glucose fuel cell (GFC) on a flexible PET substrate for simultaneously

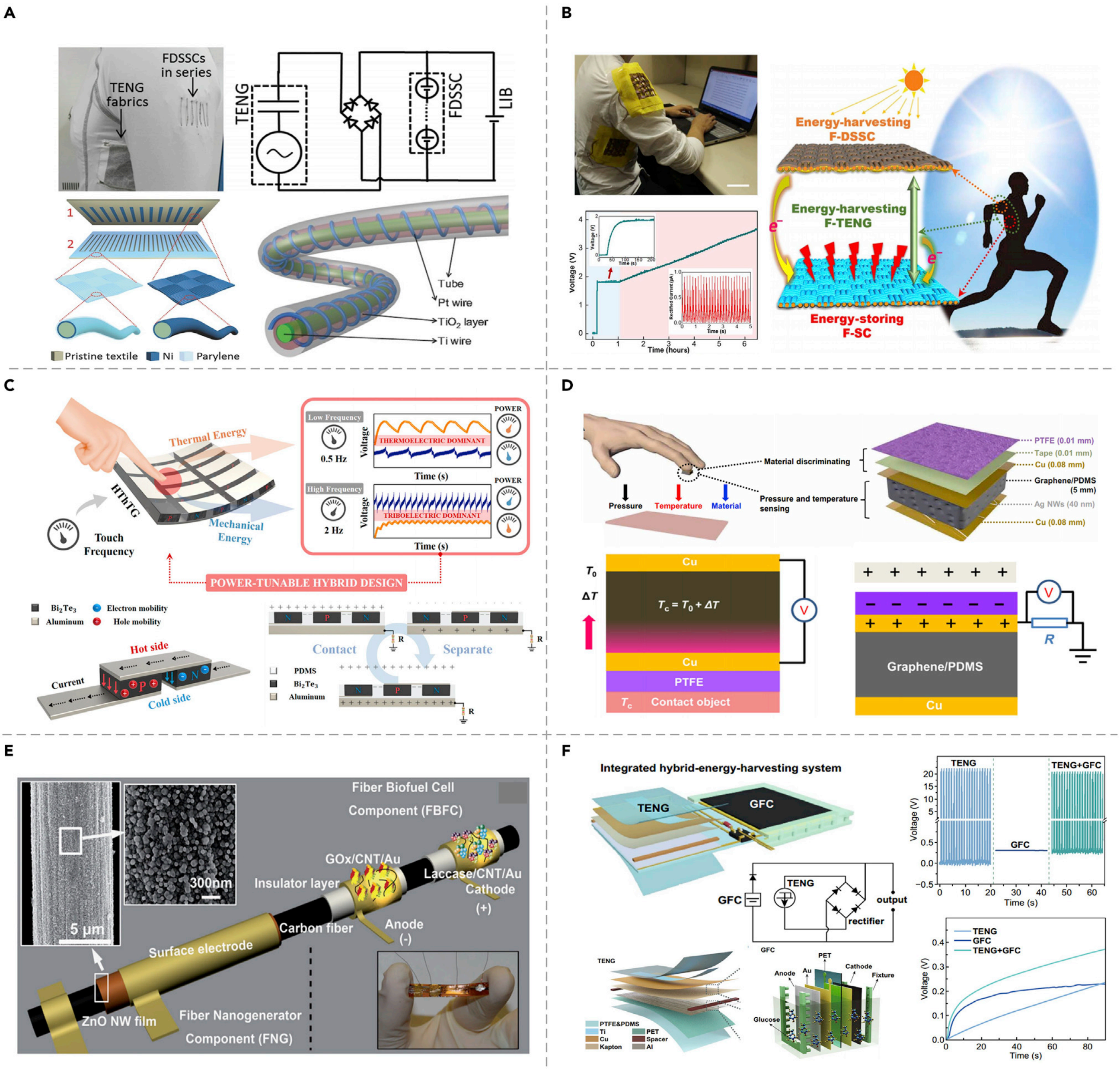

Figure 6. Hybrid EHs for multi-source

(A) A hybrid energy cell integrating a gating structure TENG fabric and FDSSCs for simultaneous solar energy and kinetic energy conversion. Reprinted from ref (Pu et al., 2016b) with permission, Copyright©2016 WILEY-VCH Verlag GmbH & Co.

(B) A self-powered textile hybridizing fiber-shaped TENG and solar cell. Reprinted from ref (Wen et al., 2016) with permission, Copyright©2016 American Association for the Advancement of Science.

(C) A hybrid thermo-triboelectric generator targeting human motions. Reprinted from ref (Seo et al., 2019) with permission, Copyright©2019 American Chemical Society.

(D) A multifunctional sensor with a hierarchical structure combining thermoelectric and triboelectric effects for self-powered temperature sensing and material property detection. Reprinted from ref (Wang et al., 2020e) with permission, Copyright©2020 American Association for the Advancement of Science.

(E) A fiber-based piezoelectric-biochemical hybrid nanogenerator for self-powered systems in biological liquid. Reprinted from ref (Pan et al., 2011) with permission, Copyright©2011 WILEY-VCH Verlag GmbH & Co.

(F) A biofuel and triboelectric hybridized generator for bioenergy harvesting. Reprinted from ref (Li et al., 2020) with permission, Copyright©2020 Springer Nature.

mechanical and biochemical energy harvesting. It can be observed that TENG produces an AC output with a large amplitude and GFC is featured with a small DC voltage from their characterization. By connecting them in parallel, the two distinct electric outputs are superimposed successfully, which contributes to a faster-charging speed to a regular capacitor in comparison with the single units. A green LED and a portable calculator were powered by the HEHS in simulated body fluid, showing its potential for driving low-power electronics for other applications.

Emerging self-sustainable systems

With the persistent efforts devoted to the advancement of the energy harvesting technologies, we have seen their evolution trend toward more capable and advanced systems. Single-source wearable EHs have experienced unprecedented development in the past decades, including but not limited to triboelectric (Jiang et al., 2020c), piezoelectric (Kim et al., 2020), electromagnetic (Maharjan et al., 2019), photovoltaic (Hu et al., 2019), thermoelectric (Sun et al., 2020a), and biofuel cells (Chen et al., 2019c) as listed in Figure 7A. Their mechanical property and output performance have been largely improved targeting for various wearable applications, and the hybridized EHs to further improve the energy conversion efficiency of a single source or to collect more energy from the surroundings have also been attaining growing attention. Moving toward a practical system, the EHs are generally required to be integrated with other functional electronics such as sensing units, power management circuits, energy storage units, wireless transmission modules, etc. For instance, Figure 7B shows a self-powered wearable pressure sensing system for continuous health care monitoring, which consists of a wearable TEG as the power source and a micro-patterned pressure sensor (Wang et al., 2020f). The self-powered pressure sensing system has achieved high sensitivity (17.1% kPa^{-1}), a fast response time (24.9 ms), and good durability (over 3,000 cycles under 1.3 kPa). To demonstrate the practical functionalities of the self-powered system, the pressure sensor is attached to various body parts for motion detection and physiological signal monitoring with the flexible TEG attached to the skin to provide power. Besides directly integrating the EHs and sensors, energy storage units can also be introduced to the system with a simple or sophisticatedly designed power management circuit. In Figure 7C, a flexible perovskite solar cell (PSC) is integrated with a lithium-ion capacitor and a strain sensor to enable solar energy-powered wearable sensing system (Li et al., 2019a). The integrated PSC-LIC system shows good flexibility that can be directly attached to the clothing for smart garment. To demonstrate the synchronous energy harvesting-storing-utilizing functionality of the system, it is used for self-powered on-skin physiological signal monitoring, namely, pulse detection. Besides, finger motion recording for more than 40 min is also achieved with the self-powered sensing system. As wireless signal readout and communication is a key property that is highly desired for the construction of the body sensor network, self-powered wireless transmission systems have also been developed with various integration schemes. Generally, commercial wireless modules are directly incorporated with the energy harvesting-storing-sensing units to endow the wireless transmission capability. Figure 7D introduces a unique methodology for direct transmission of the triboelectric sensory output, in which a textile-based TENG is connected to a coil in series through a controllable switch (Wen et al., 2020c). The switch assists control the charge flow in the closed loop, and a resonant signal can only be generated when the switch is closed to release all the accumulated charges due to the press or release of the TENG textile. The TENG here is equivalent to a capacitor with a varying capacitance, hence the resonant frequency of the RLC circuit is controlled by the force applied to the TENG. Compared with the wireless sensing according to the signal amplitude that is highly susceptible to environmental interferences, this simple configuration creates frequency shift with different applied pressures, which is stable and robust against environmental noises such as humidity. Meanwhile, the capacitance of the TENG can be easily tuned by stacking multiple layers in parallel or in series, which can broaden the frequency range for diversified applications. The self-powered wireless sensing system is successfully demonstrated for 2D car control and 3D virtual reality (VR) drone control with a single coil.

As the diversity of the functional electronics increases, the applications of the self-powered wearable systems are extended from common physical sensing such as body motion sensing or physiological signal monitoring to chemical sensing and other intriguing implementations. Wu et al. developed a self-powered iontophoretic TDD system, where the wearable TENG converts body motions into electricity for iontophoresis with a hydrogel-based patch enabling noninvasive TDD (Figure 7E) (Wu et al., 2020a). Practically, the TENG is connected to the soft patch (namely, drug carrier) electrically through a rectifier, generating alternating outputs from body motions to accelerate the TDD rate without other power sources. The feasibility test was performed on pig skin using dyes as simulated drugs, with fluorescence and bright-field images

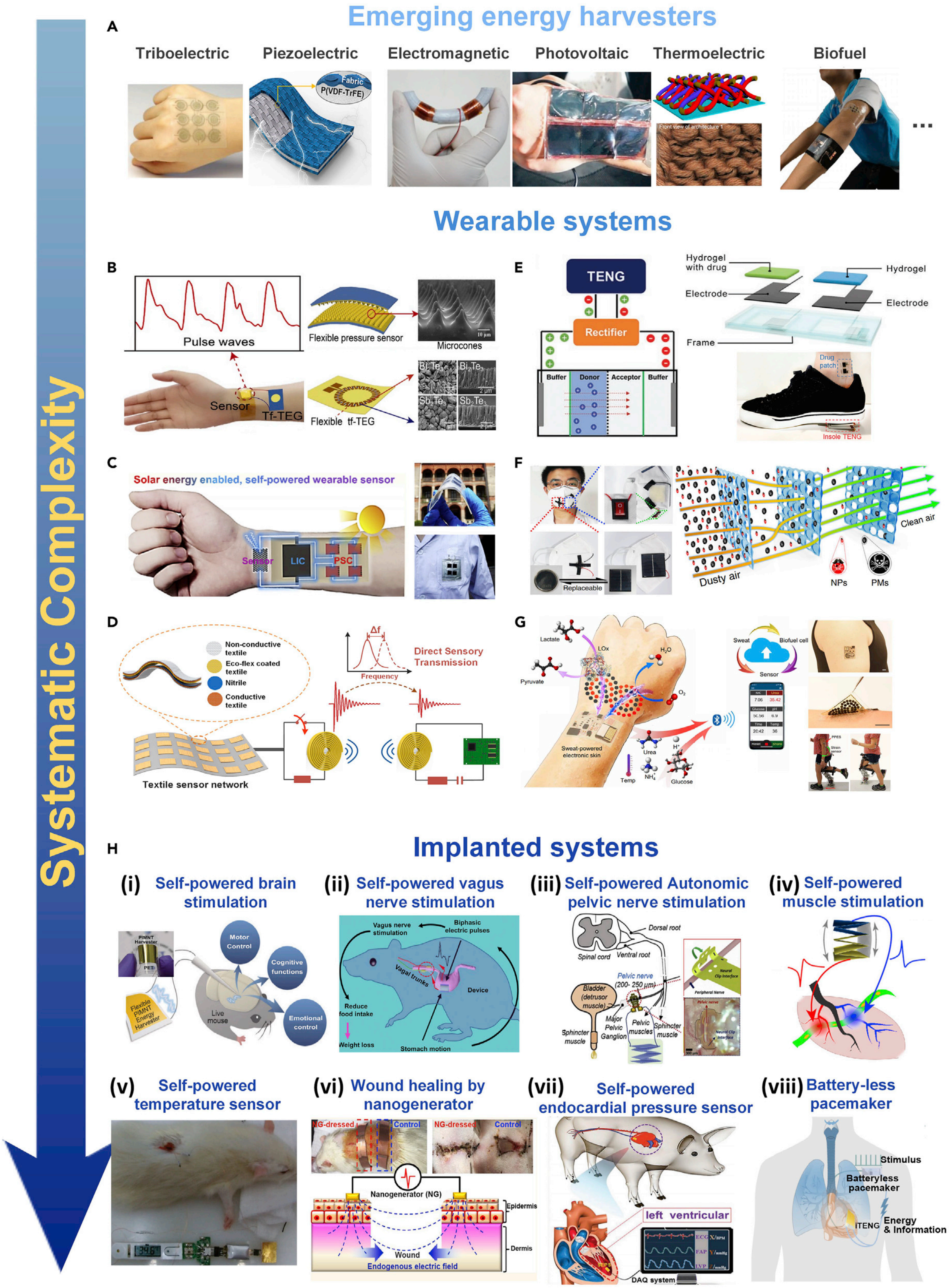
Systematic Complexity
A
Emerging energy harvesters
Triboelectric
Piezoelectric
Electromagnetic
Photovoltaic
Thermoelectric
Biofuel
Fabric
P(VDF-TrFE)
...
Wearable systems
B
Pulse waves
Flexible pressure sensor
Microcones
Sensor
Tf-TEG
Flexible tf-TEG
E
TENG
Rectifier
Buffer
Donor
Acceptor
Buffer
Hydrogel with drug
Electrode
Frame
Hydrogel
Electrode
Drug patch
Insole TENG
C
Solar energy enabled, self-powered wearable sensor
Sensor
LIC
PSC
F
Replaceable
Dusty air
Clean air
NPs
PMs
D
Non-conductive textile
Eco-flex coated textile
Nitrile
Conductive textile
Δf
Frequency
Direct Sensory Transmission
Textile sensor network
G
Lactate
Pyruvate
LOx
H₂O
O₂
Sweat-powered electronic skin
Urea
NH₄
Temp
Glucose
Sweat
Biofuel cell
Sensor
H
Implanted systems
(i) Self-powered brain stimulation
PIMNT Harvester
PET
Flexible PIMNT Energy Harvester
Motor Control
Cognitive functions
Emotional control
Live mouse
(ii) Self-powered vagus nerve stimulation
Vagus nerve stimulation
Biphasic electric pulses
Vagal trunks
Device
Reduce food intake
Weight loss
Stomach motion
(iii) Self-powered Autonomic pelvic nerve stimulation
Dorsal root
Spinal cord
Ventral root
Pelvic nerve (200- 250 μm)
Bladder (detrusor muscle)
Major Pelvic Ganglion
Pelvic muscles
Sphincter muscle
Sphincter muscle
Neural Clip Interface
Peripheral Nerve
Pelvic nerve
(iv) Self-powered muscle stimulation
(v) Self-powered temperature sensor
(vi) Wound healing by nanogenerator
NG-dressed
Control
NG-dressed
Control
Nanogenerator (NG)
Epidermis
Dermis
Wound
Endogenous electric field
(vii) Self-powered endocardial pressure sensor
left ventricular
ECG
FAP
LVP
DAQ system
(viii) Battery-less pacemaker
Stimulus
Batteryless pacemaker
iTENG
Energy & Information

Figure 7. The evolution trend of the EHs in terms of growing systematic complexity

(A) Emerging energy harvesters with versatile effects targeting different energy sources. Reprinted from ref (Chen et al., 2019c; Hu et al., 2019; Jiang et al., 2020c; Kim et al., 2020; Maharjan et al., 2019; Sun et al., 2020a) with permission, Copyright©2020 WILEY-VCH Verlag GmbH & Co, Copyright©2020 2020 Elsevier Ltd, Copyright©2019 Elsevier Ltd, Copyright©2019 The Royal Society of Chemistry, Copyright©2020 Springer Nature, Copyright©2019 WILEY-VCH Verlag GmbH & Co.

(B) A self-powered wearable pressure monitoring system powered by a flexible thin-film thermoelectric generator. Reprinted from ref (Wang et al., 2020f) with permission, Copyright©2020 Elsevier Ltd.

(C) Self-powered strain sensing enabled by a flexible perovskite solar cell (PSC) and lithium-ion capacitor (LIC). Reprinted from ref (Li et al., 2019a) with permission, Copyright©2019 Elsevier Ltd.

(D) A self-powered wireless sensor node via a TENG-based direct sensory transmission mechanism. Reprinted from ref (Wen et al., 2020c) with permission, Copyright©2020 Elsevier Ltd.

(E) Self-powered iontophoretic transdermal drug delivery system driven by a wearable TENG. Reprinted from ref (Wu et al., 2020a) with permission, Copyright©2019 WILEY-VCH Verlag GmbH & Co.

(F) A self-powered face mask for air filtering with a solar panel as the feasible power source. Reprinted from ref (Zhang et al., 2020a) with permission, Copyright©2020 Springer Nature.

(G) Biofuel-powered electronic skin for multiplexed metabolic sensing and skin temperature monitoring. Reprinted from ref (Yu et al., 2020) with permission, Copyright©2020 American Association for the Advancement of Science.

(H) Self-powered implantable systems for neural stimulation, sensing, wound healing, and heart rhythm regulation. Reprinted from ref (Hwang et al., 2015; Lee et al., 2019b; Liu et al., 2019b; Long et al., 2018; Ouyang et al., 2019; Shi et al., 2016b; Wang et al., 2019c; Yao et al., 2018) with permission, Copyright©2015 The Royal Society of Chemistry, Copyright©2018 Springer Nature, Copyright©2019 Elsevier Ltd, Copyright©2019 American Chemical Society, Copyright©2015 WILEY-VCH Verlag GmbH & Co, Copyright©2018 American Chemical Society, Copyright©2018 WILEY-VCH Verlag GmbH & Co, Copyright©2019 Springer Nature.

proving the effective drug transport driven by the triboelectric output. Figure 7E also presents the concept of a pain-relief TDD system for users with ankle injuries, where the soft drug patch is attached to the ankle and TENG under the shoe. In Figure 7F, a self-powered air filter is demonstrated based on ionic liquid-polymer (ILP) composites that are irregularly coated onto a melamine-formaldehyde (MF) sponge skeleton, i.e., an ILP@MF filter (Zhang et al., 2020a). This unique structure allows polluted air to flow sufficiently through the sponge channels, which attributes to a reduced pressure drop and improved removal efficiency of particulate matter (PM) pollutants including nanoscale particles. As illustrated in Figure 7F, as the polluted air flows through the ILP@MF filter adequately, the particles are fully in contact with the ILP composites and are captured by them. The ILP@MF demonstrates remarkably high removal efficiencies of 99.59% for $PM_{2.5}$ and 99.57% for PM_{10} with an applied voltage of 3 V. For practical demonstration, wearable and self-powered face masks were designed by incorporating a lithium cell or a silicone-based solar panel as the portable power supply. A full perspiration-powered electronic skin (PPES) is reported for multiplexed metabolic sensing *in situ* in Figure 7G (Yu et al., 2020). It contains a high-performance lactate biofuel cell with a record-breaking power density (3.5 mW/cm^2 in human sweat) that is sufficient for sensing and Bluetooth low energy (BLE) functionalities. The biofuel cell displays a highly stable output performance during a 60-h continuous operation. The PPES provides real-time multiplexed sensing of body temperature and several key metabolic biomarkers (i.e., NH_4^+, urea, glucose, and pH), as well as wireless transmission to a user interface via BLE. The continuous functioning of the e-skin system is successfully validated in a human trial, and its use in metabolic and nutritional management was evaluated through supervised dietary challenges. Moreover, the PPES is demonstrated as an HMI by integrating strain sensors for muscle contraction monitoring, directing a human operator to control a robotic prosthesis wirelessly.

The establishment of the bodyNET technology platform is indispensable in demand for implanted electronics to supplement wearable electronics, further extending our senses and abilities to an unprecedented extent (Jiang et al., 2020b; Shi et al., 2019c, 2020d; Sun et al., 2019b; Zheng et al., 2020). Compared with wearable electronics, implantable devices face more challenges in terms of material biocompatibility/biodegradability, reliability, safety, adaptability, reliable power sources, well controllability, etc. (Song et al., 2019c). These challenges that remain unsolved are gaining the attention of worldwide researchers in both academia and industry. The development of implantable devices started with the demand to activate or support body functions through electrical stimulation on organs or muscles (Lee et al., 2017a; Su et al., 2019b; Wang et al., 2018a). An example would be a pacemaker, which is designed and implanted inside the human body to assist the proper function of the heart. Also, neurological diseases such as Parkinson disease, dystonia, major depression, and essential tremor could be treated with deep brain stimulation to inhibit or activate brain signals (Halpern et al., 2008; Hickey and Stacy, 2016; Vidailhet et al., 2005). As the heart of an implantable device, a stable and sustainable power source is essential for its continuous operation to diagnose, prevent, or treat diseases *in vivo*. To prolong the lifetime of the implanted devices, researchers have devoted enormous effort to develop power sources for them, including enhancing the capacity of current power sources and harvesting power from the surrounding environment or organisms. However, the capacity of power source such as conventional batteries is still limited, requiring subsequent replacement after a certain period. A variety of implanted EHs then emerged as promising methods to solve the power limitation issue (Shi et al., 2018). Compared with the wireless transfer techniques that still require an external energy source, the EHs scavenging energy from biological tissues are more desirable to ultimately eliminate the need for external power supplies. There are few types of energy sources available inside the body due to the isolation from the ambient environment. For instance, solar energy is no longer accessible inside the body, and thermal gradient/fluctuation that is usually found on-skin vanishes in the stabilized environment inside our body. Fortunately, abundant energy lies in our body during respiration, blood flow, heartbeat, and redox reaction of glucose that can be utilized. Among the implanted EHs, piezoelectric, triboelectric, and biofuel cells are widely investigated and adopted mechanisms for self-powered energy harvesting. Similar to the evolution trend of wearable EHs, we have seen the integration of the implantable/wearable EHs and neural interfaces, sensors, and other functional devices to form a self-powered system with a variety of applications (Figure 7H).

Figure 7H(i-iv) lists some representative works that incorporate nanogenerators with neural interfaces for different scenarios. In Figure 7H(i), a flexible PENG on a plastic substrate converting tiny mechanical deformations into electricity directly stimulated a certain area of the mouse brain via a bipolar stimulation electrode (Hwang et al., 2015). The activation of the primary motor cortex of a living mouse with the flexible PENG is verified by the immediate bending of the right forelimb. This preliminary test indicates the feasibility of self-powered deep brain stimulation enabled with nanogenerators. Figure 7H(ii) presents an implanted self-powered vagus nerve stimulation device, which comprises a biocompatible and flexible TENG attached on the surface of the stomach with the TENG electrodes directly connected to the vagus nerve (Yao et al., 2018). The TENG generates biphasic pulses when the stomach wall moves, stimulating the vagus nerve to reduce food intake. This correlated vagus nerve stimulation system could serve as an effective therapeutic strategy for patients with obesity concerns. Integrating a flexible neural clip interface with a triboelectric neurostimulator, mechano-neuromodulation of autonomic pelvic nerves for rats' bladder function was also demonstrated in Figure 7H(iii) (Lee et al., 2019b). Clear bladder contractions and micturition events were evoked with stimulation of more than 50 BPM. Besides, chronic implantation of the clip interface was performed, and the bladder modulation can be successfully evoked even after 16 days without any damage to the pelvic nerve. Muscle stimulation, when compared with nerve stimulation, generally requires a much larger current to induce effective stimulation as there are fewer neurons innervating the bulk muscle fibers. Wang et al. have successfully demonstrated electrical muscle stimulation through a multi-channel intramuscular electrode, which is powered by a stack-layered TENG (Wang et al., 2019c). The multiple channels of the electrode enable the mapping of sparsely distributed motoneurons in the muscle tissue, contributing to a highly efficient muscle stimulation even with a small triboelectric current (35 μA). This self-powered system could be potentially used for the future rehabilitation approach of muscle function loss.

Apart from nerve and muscle stimulations, the implanted systems with other functionalities have also been developed. Shi et al. developed a piezoelectric and triboelectric hybrid nanogenerator to construct a packaged self-powered system (PSNGS), as shown in Figure 7H(v) (Shi et al., 2016b). Universal outlet connectors and viable inner connections are designed for the system, contributing to a "plug and play" mobile power source. The whole system is packaged by PDMS for waterproof implantation, and its stability has been validated by submerging the whole device in normal saline for 12 h. To demonstrate the capability of the power unit, an implanted temperature sensor is connected to the PSNGS for body temperature monitoring of a rat. Figure 7H(vi) illustrates an electrical bandage to accelerate skin wound healing that is powered by an external TENG (Long et al., 2018). The TENG can convert the kinetic energy of rat respiration into AC voltage signals, generating an electric field on the skin wound to enhance skin regeneration. The accelerated healing process is confirmed through animal studies, where a full-thickness rectangular wound is closed rapidly within 3 days, when compared with 12 days of the normal healing process. This physical treatment strategy not only can help to lower the discomfort or pain level but also could impose an effect on other diseases as well. The nanogenerator itself can serve as the self-powered sensor for physiological monitoring on the body and inside the body. Figure 7H(vii) shows a miniaturized and self-powered endocardial pressure sensor (SEPS) to monitor endocardial pressure (EP) in real-time (Liu et al., 2019b). The SEPS is based on a multi-layered TENG integrated with a surgical catheter for minimally invasive implantation, which converts the kinetic energy of blood flow within the heart chamber into electricity. The measured output of the device can indicate physiological cardiovascular status, including EP, ventricular premature contraction, and ventricular fibrillation. The encapsulation layer demonstrates superior blood compatibility, attributing to ultra-low risks of evoking a hemolytic reaction and coagulation cascade. The SEPS was implanted into an adult Yorkshire swine's heart with a minimally invasive surgery to demonstrate real-time biomedical monitoring as shown in Figure 7H(vii). The developed implanted TENG can be integrated with a symbiotic pacemaker to correct sinus arrhythmia and prevent deterioration as well (Ouyang et al., 2019). The interconnected symbiotic system ingests energy from the body to maintain operation; in the meantime, the body receives electrical stimulation from the pacemaker to regulate cardiac physiological activities. The TENG can harvest 0.495 μJ energy from each cardiac cycle, which is higher than the pacing threshold energy of humans (0.377 μJ) and pigs (0.262 μJ). Besides, the remarkable mechanical durability of the TENG has also been demonstrated over 100 million mechanical stimuli cycles.

Summary and future perspectives

With the rapid development of wearable electronics and WSN, reliable, portable, and sustainable power sources have become a critical challenge that has attained intense attention both from academia and industry. The flourishing energy harvesting technologies have shed light on the realization of self-sustainable systems by scavenging waste energy from the ambient environment, in the form of vibration, light, heat, etc. Wearable EHs targeting for a single source have been relatively well developed, including the well-investigated TENGs and PENGs, EMGs, solar cells, TEGs, and biofuel cells. To improve the energy conversion efficiency of single-source EHs, hybrid EHs incorporating two or three conversion mechanisms have been proposed, which, in most of the cases, are mechanical EHs. The energy harvesting technology is now entering the era of multi-source EHs, whereby the device is capable of scavenging various forms of energy, including but not limited to mechanical, thermal, solar, and biochemical energy to maximize the energy utilization for a practical environment. This would be an effective approach to deal with unstable, insufficient, and sometimes random input energy sources in our surroundings. Moving forward, we have witnessed the integration of the EHs with functional components (e.g., power management circuits, energy storage units, sensors) to form wearable self-sustainable systems for diversified applications. On top of that, self-sustainable implanted systems have also been developed to supplement wearable systems, providing advanced capabilities of *in vivo* sensing, neural stimulation, and even disease treatment to push forward the eventual realization of the future bodyNET applications.

Despite the viable progress in developing hybrid EHs with the ability to scavenge single-type energy or multi-form energy sources, several challenges remain to be solved on the road to self-sustainable bodyNET. First and foremost, the output performance of the hybrid EHs needs to be further improved to meet the demands of processing circuits, wireless transmission modules, and functional components (e.g., sensors). Fundamental materials' innovation and structural designs' advancement will be the two significant directions toward the output enhancement, like exploring and applying materials with larger electronegativity difference for TENGs and materials with higher energy efficiency for solar cells. Second, mechanical durability is also a considerable challenge for current EHs. For higher output power, wearable EHs aiming at harvesting biomechanical energy typically are designed to be put on the location with large acceleration, force, or deformation, which also makes devices easy to be broken. The robustness of the hybridized structure and the inner parts that inevitably endure stretching, friction, and collision must be further optimized to sustain a long-time operation. Structure optimization, including applying serpentine or kirigami structures, and fabrication optimization, like applying coating metal electrodes other than sticking metal layers, could be two possible strategies. Besides, current progress in hybridized EHs is mainly based on structural hybridization, in which case the electric outputs from each component are integrated through external power management circuits. However, the escalated configuration complexity and device size, along with the increased conversion mechanisms for different energy sources, have become one of the major challenges to be tackled. More compact structures need to be designed in consideration of the distinctive requirements of different EHs to induce a minimal deterioration in the output performance resulting from the integration. Moreover, taking the PETNG devices as an example, better and more efficient ways to integrate different energy conversion mechanisms rooted in their fundamental principles should be explored to let them work closely and further enhance each other rather than just simply combine them into a device. Additionally, more combinations of energy conversion mechanisms should be investigated and developed. For instance, little research has looked into simultaneously harvesting biochemical energy (e.g., sweat) and body heat, which are closely correlated when people are exercising. Last, as wearable devices, some ponderable aspects require further improvement, including wear comfort, washability, and the ability for large-scale production.

For those hybrid EHs from multiple sources, customized power management circuits corresponding to different configuration combinations are in urgent demand for highly efficient systems. Meanwhile, energy storage units with superior stabilities are the prerequisites of self-sustainable systems for long-term operation. Aside from sole structural integration, the coupling effects between different conversions are also worthy of a thorough investigation to create positive feedback between EHs. Although the majority of the hybrid EHs adopt distinctive materials for converting different energy sources, it would be desirable to develop multifunctional materials that possess various properties simultaneously. In this way, system integration can be further improved. A single multifunctional material can avoid structure complexity caused by conventional hybridized approaches where distinctive energy conversion materials are physically integrated into a complicated configuration. In spite of the compelling merits of hybrid EHs, we have seen little research of implanted hybrid EHs due to the higher requirement on the packaging, mechanical property, reliability, and biocompatibility/biodegradability. We wish to see the prosperous future development of hybrid EHs for self-sustainable and fully implanted systems to pave the way for bodyNET.

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Author contributions

T.H., X.G., and C.L. conceived the idea designed the structure. C.L. supervised the project. T.H. and X.G. wrote the first draft of the manuscript. All the authors commented, edited, and revised the final manuscript.

Declaration of interests

The authors declare that there is no conflict of interest regarding the publication of this article.

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