IEEE Open Journal of
Circuits and Systems

Received 20 June 2021; revised 8 September 2021; accepted 9 October 2021. Date of current version 24 November 2021.

Digital Object Identifier 10.1109/OJCAS.2021.3123272

Evolving Flexible Sensors, Wearable and Implantable Technologies Towards BodyNET for Advanced Healthcare and Reinforced Life Quality

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This article was recommended by Associate Editor X. Guo.

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This work was supported in part by the National Key Research and Development Program of China at NUSRI, Suzhou, China, under Grant 2019YFB2004800 and under Project R-2020- S-002, and in part by the "Intelligent Monitoring System Based on Smart Wearable Sensors and Artificial Technology for the Treatment of Adolescent Idiopathic Scoliosis" of the "Smart Sensors and Artificial Intelligence (AI) for Health" Seed Grant at NUS Institute for Health Innovation & Technology (NUS iHealthtech) under Grant R-263-501-017-133.

ABSTRACT Recent advances in flexible electronics have offered a good opportunity in designing a variety of wearable devices for healthcare monitoring, prevention medicine, and robotic control. Wearable sensors are entering the era of digital health, with compelling functionalities in recording vital signs, physiological signals, body kinetics, and dynamic biomolecular state. Meanwhile, energy harvesters that scavenge waste energy from body motions and the ambient environment have received intense attention, which are expected to realize self-powered or energy-autonomous systems. Moving towards the inside of the body, the implantable device also plays an indispensable role in monitoring key biomedical and physiological information and effective treatment of chronic diseases. Besides, wearable robotic exoskeletons have enabled advanced functionalities of assisting or augmenting human mobilities unprecedently. These technologies and platforms will be merged, giving way to the bodyNET: a network of wearable sensors, implantable devices, and exoskeletons for improved healthcare and health outcomes. In this article, we offer a brief review of recent advances in flexible and wearable sensors and summarize the progress of self-powered wearable sensors based on piezoelectric and triboelectric nanogenerators. We also discuss the implantable devices and self-powered neuromodulation systems and offer recent works of lower-limb exoskeletons. Lastly, we present a future trend towards a comprehensive and capable bodyNET for advanced healthcare and reinforced life quality.

INDEX TERMS BodyNET, flexible electronics, healthcare, implantable electronics, nanogenerators, exoskeletons.

I. INTRODUCTION

THE PERPETUAL pursuit of superior life quality by virtue of the functionality reinforcement from external devices propel the ceaseless advancement of wearable electronics towards multifunctional wearable systems [1]–[6]. Most commercially available wearable devices are in the form of wristbands, watches, or glasses, either partially or fully composed of rigid components with flexible strips mounted on the human body. To further improve wearable comfortability and enhance interactions with humans for advanced healthcare, wearable electronics are evolving towards fully flexible, stretchable, and even self-healable platforms with the aid of significant progress in the development of functional flexible materials [7]–[11]. As the foundation of flexible and wearable electronics, flexible materials have experienced considerable advancement in the past decade to endow electronic devices with skin-like properties ranging from thinness, stretchability, biocompatibility, biodegradability, to self-healing capability [12]. Meanwhile, wearable sensors have been entering the area of digital health

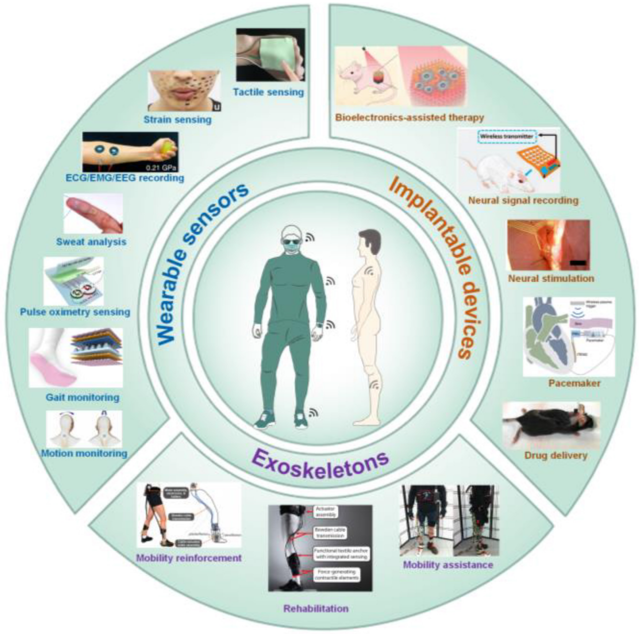

FIGURE 1. Overview of a comprehensive bodyNET incorporating different technical platforms: Wearable sensors [93]–[99], implantable devices [66], [100]–[103], and exoskeletons [104]–[106].

in diversified biomedical applications [13]–[18], enabling recording of vital signs (blood pressure, respiration rate, skin temperature, pulse, etc.) [19]–[21], physiological signals (electrocardiography (ECG), electromyography (EMG), electroencephalography (EEG), etc.) [22]–[24], body kinetics (strain, pressure, etc.) [25], [26], and dynamic biomolecular state via accessible biofluids (sweat, etc.) [27], [28], as shown in Fig. 1.

As the quantity of wearable sensors sparsely distributed around the body skyrocketing, a reliable and sustainable power source for the sensor network becomes another grand challenge towards practical applications [29]–[31]. Energy harvesting technology that utilizes the existing waste energy stemming from the human body or ambient environment then emerges as an ideal choice to supply power or to reduce the system energy consumption for future wearable electronics [32]–[36]. There are multiple types of energy sources existing around us, including solar [37], thermal [38], chemical [39], and mechanical energy [40]. Among them, mechanical energy is considered as one of the most sufficient power in a living creature that is ubiquitously available accompanied by various forms of dynamic motions [41]. By harvesting in vitro and in vivo biomechanical energy, the ultimate goal of self-sustainable sensing systems can be achieved with high-performance energy harvesters [42]–[44]. Particularly, nanogenerators (NGs) based on the piezoelectric or triboelectric effects have been receiving immense attention, which provides a possibility for us to gain useful resources from our surroundings in a low-cost, sustainable, renewable, and self-powered manner [40], [45], [46]. In the past decade, we have witnessed the rapid advancement of both piezoelectric nanogenerator (PENG) and triboelectric nanogenerator (TENG) in broad wearable applications, including kinetic energy scavenging, physiological signal motoring, motion tracking, human-machine interfacing, etc. [47]–[53].

Moving towards inside of the body, implantable electronics play a vital role in medical technologies [54]–[57], providing diversified sensing functions and therapeutic treatment locally, accurately, and directly as indicated in Fig. 1. Since the first implantable cardiac pacemaker for arrhythmia patients in the 1960s, implantable health devices have been continuously investigated and developed for disease prevention, diagnosis, and treatment [58]–[62]. For instance, implantable actuators to help underactive bladder void have been developed to meet particular clinical need [63]–[65]. In the meantime, the thriving energy harvesting technologies such as nanogenerators are pushing forward the progress of fully integrated and self-powered implantable systems, with representative efforts in the self-powered pacemakers in recent years [44], [66]–[68]. Among the implantable devices, neural interfaces that bridge the nervous system and electronics not only lead to advances in neuroscience fundamental but also unfold the potential of therapeutic targeting at the cellular level [69], [70]. Though metal-based conductors (platinum, gold, etc.) are the primary choices in clinical practice, neural interfaces implementing new flexible and soft materials, innovative fabrication processes, and novel designs have been vigorously developed [71]. On top of it, self-powered neural interfaces integrating both nanogenerators and neural interfaces have been proposed and investigated, presenting a novel electrical stimulation in closed loop with potentially higher efficiencies and reduced side effects [72]–[74].

Apart from physiological signal monitoring, wearable electronics are capable of more advanced functionalities to reinforce or assist human mobility unprecedentedly [75]–[78]. The wearable robotic exoskeleton, a robot directly serving humans by assisting or strengthen muscle movements, has become a promising platform in versatile applications such as rehabilitation, physical therapy, human capacity augmentation, and prosthetics [79]–[81]. To ensure good cooperation with the physiology and biomechanics of the human body, the exoskeleton requires accurate and multi-dimensional sensory information attained from wearable sensors as the control feedback. In such a case, the rapid progress of the diversified wearable sensors would in turn push forward the evolution of exoskeletons to a new level.

As a particular branch of wireless sensor network (WSN) technologies, body sensor networks (BSNs) or sometimes referred to as body area networks are proposed to operate and connect sensors within, on, or in the vicinity of the human body for diversified human-centered applications [82]–[90]. In 2017, Chu *et al.* proposed the bodyNET where not only sensors but also screens and smart devices woven into our clothing, worn on the skin and implanted inside our body will be interconnected to form an extended network [91].

It presents an optimistic future in which we are allowed to sense and communicate with our surroundings in ways beyond our existing senses. As we are entering the era of cybernetics with a strong urge for technical health aids in our daily activities, a more comprehensive and capable body network is desired [92]. In this regard, we further broaden the concept of the bodyNET, a network incorporating wearable sensors, implantable medical devices, and powerful exoskeletons to provide healthcare monitoring, therapeutic treatment, and mobility reinforcement or assistance for the users.

In this article, we firstly present an overview of current representative wearable sensors with various functionalities and summarize the progress of self-powered wearable sensors based on the piezoelectric and triboelectric nanogenerators (Section II), and we introduced a few self-sustainable sensing systems based on nanogenerators (Section III). Then we look at the implantable medical devices with different applications including neural interfaces for different therapeutic purposes, and the self-powered neuromodulation systems combining the emerging energy harvesters (Section IV). Next, we offer recent works of exoskeletons with great prospects in rehabilitation applications (Section V). Subsequently, the future trends towards the future comprehensive and capable bodyNET for advanced healthcare and reinforced life quality as well as the possible challenges are discussed (Section VI).

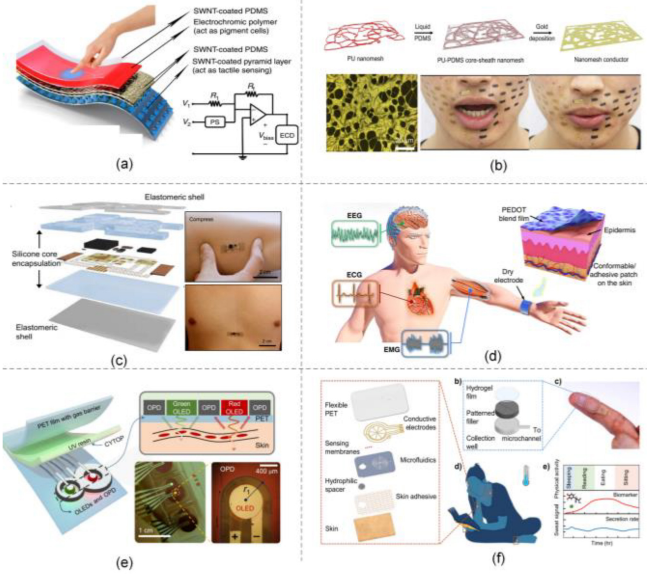

FIGURE 2. **Flexible and wearable sensors with different configurations and mechanisms to monitor various body indicators. (a) A chameleon-inspired tactile sensing electronic skin with pressure-controlled interactive color change [114]. (b) A durable nanomesh on-skin strain sensor for natural skin motion monitoring [99]. (c) An epidermal mechano-acoustic sensing system for cardiovascular diagnostics and HMIs [120]. (d) A self-adhesive dry electrode for long-term epidermal biopotential monitoring [97]. (e) An ultralow-power and reflective pulse oximetry sensing patch towards all-day health monitoring [98]. (f) A sweat-monitoring wearable patch for continuous analysis of thermoregulatory sweat at rest [96].**

II. FLEXIBLE AND WEARABLE SENSORS

Accurate and robust detection of physiological signals or vital signs requires a conformal and direct integration of the wearable sensors onto the skin. Conventional electronics are characterized by physical properties that disparate with those of the epidermis, i.e., flexible, soft, stretchable, and even self-healable, leading to an inferior sensing performance in the long term and unavoidable discomfort to the users during daily activities [107], [108]. With the flourishing development of materials equipped with new capabilities such as flexibility, stretchability, conformability, breathability, self-healing, and biocompatibility, an advanced electronic device platform has been proposed, which is termed as the "second skin" or "electronic skin" [109]–[111]. It is touted as the next interface enabling intelligent healthcare, human-machine interaction, and human sensory capability amplification to improve our life quality on a daily basis. The sensing functionalities of such wearable sensors span from basic physical sensing (i.e., pressure, strain, etc.) to chemical sensing, bio-potential signal recording, and in-depth optical sensing [112], [113]. A few representative wearable sensors with different mechanisms and detectable body indicators aforementioned will be introduced hereafter.

A. PASSIVE SENSORS

Fig. 2(a) presents a chameleon-inspired stretchable electronic skin (e-skin), which consists of a tactile sensing layer and an electrochromic layer, allowing for pressure-controlled color change similar to what the chameleon does [114]. The tactile sensing layer is composed of an elastic pyramidal-microstructured polydimethylsiloxane (PDMS) coated with single-wall carbon nanotubes (SWNTs), where the microstructures are introduced to improve the sensitivity of the tactile sensor. The integrated electrochromic device can also be used to demonstrate the applied pressure through its color change. This e-skin system holds great promise in diversified applications including smart robots, human-machine interfaces (HMIs), and artificial prosthetics. To detect minor motions on the skin, a strain sensor with excellent conformability would be required. Fig. 2(b) shows an ultrathin nanomesh strain gauge with minimal mechanical constraints on natural skin motions [99]. It is made from reinforced polyurethane-polydimethylsiloxane (PU-PDMS) nanomeshes with gold deposited on top of it to form conductive paths. This unique structure contributes to an ultralight weight of 0.12 mg/cm^2 with a tiny thickness around 430 nm. The soft and thin feature allows for a conformal attachment to the curved skin surface; meanwhile, the nanomesh configuration is highly beneficial for long-term wearing in avoiding skin inflammation by virtue of its air permeability. The developed nanomesh sensors are sensitive enough to map facial skin strain during the speech of alphabets such as "a", "u", and "o" with a sensor array on the right side of the face. This kind of imperceptible, robust, and high-performance air-permeable on-skin sensors may play an indispensable role in future wearable electronics for daily, long-term, and continuous healthcare monitoring.

In addition to the minor muscle movement, strain sensors are also applicable in monitoring body motions such as dynamic joint bending sensing [115]–[118]. The quantitative motion analysis could assist monitor motor disorders such as Parkinson's disease, showing great potential in diagnostics and assessment of motor neuron diseases [119].

Besides measuring physical parameters such as pressure and strain, wearable sensors are widely explored and developed with more advanced capabilities for in-depth healthcare monitoring. For instance, physiological mechano-acoustic signals beyond audible range provide valuable information of clinical utility. Fig. 2(c) shows a representative epidermal mechano-acoustic sensing device for cardiovascular diagnostics and HMI, which allows for a conformal integration with the skin owing to its soft, stretchable, and thin nature [120]. The overall system consists of chip-scale components as the sensing elements and serpentine copper traces as the interconnects, with all encapsulated by an elastomeric polymer to minimize the physical constraints on subtle motions. The sensing elements include a mechano-acoustic sensor leveraging miniaturized accelerometers with the operation bandwidth in the range of cardiovascular and speech, filters, a preamplifier, and removable electrodes for electrophysiology recording. The device can be attached to the sternum to record seismocardiography (SCG) that reflects heart muscle contraction and the associated blood injection, where the SCG is an important health indicator in the clinical diagnostics. On top of it, such a mechano-acoustic sensor is used as an epidermal speech recognition device mounted on the vocal cords, which has been demonstrated as the HMI in gaming and prosthesis control.

Human biopotentials such as electroencephalography (EEG) are also significant for disease diagnosis and treatment, which can be transduced through epidermal electrodes interfacing the skin electrically. On that account, the development of efficient flexible electrodes is another indispensable branch of wearable electronics that has obtained significant efforts. Fig. 2(d) shows recently reported self-adhesive dry electrodes for long-term biopotential monitoring with motion-robust characteristics [97]. This dry electrode is made of fully organic polymers including poly(ethylenedioxythiophene): poly(styrenesulfonate) (PEDOT: PSS), waterborne polyurethane (WPU), and D-sorbitol by solution processing. The composites possess excellent stretchability and conductivity, with good adhesion on both dry and wet skin, giving rise to low contact impedance and noise in both static and dynamic detection. High-quality biopotentials including EEG, ECG, and EMG can be recorded even during body movements, showing superior stability and robustness over various and complex daily conditions. The feasibility of this electrode in the clinical setting has also been investigated and demonstrated via the detection of atrial fibrillation arrhythmia features and muscle activity quantification.

Light-based healthcare has emerged as another promising approach to diagnostic and therapeutic purposes, with numerous devices routinely used in the clinic already. The rapid advancement in materials and mobile devices is accelerating the flourishing of both wearable and implantable photonic healthcare devices, facilitating noninvasive point-of-care testing as well as personalized medicine [121]. A typical example would be a pulse oximetry sensor, which generally comprises light sources with two wavelengths and a photodetector with its electrical signals modulated by photo absorption of oxygenated and nonoxygenated hemoglobin in blood vessels. As shown in Fig. 2(e), a reflective pulse oximetry sensing patch is presented with ultralow power consumption [98]. The layout of the pulse oximeter reveals its reflective configuration, where the light sources (a green LED and a red LED) and photodetectors are on the same plane, allowing for attachment on various pulsating body surfaces and feasibility of integration with other sensory platforms. An ideal organic photodetector wraparound layout was proposed through an optical simulation of color-sensitive light propagation related to absorption and scattering within human skin. It is worth noting that the monolithically integrated pulse oximetry sensor exhibited an ultralow operation power of only a few tens of microwatts on various body parts.

Apart from physical sensors, chemical sensors also play an important role in obtaining a comprehensive insight into an individual's physiology dynamics [122], [123]. In particular, chemical sensors that detect analytes non-invasively from accessible biofluids have been vigorously investigated to provide extra information at the molecular level. Among all the candidates for available biofluids, sweat holds great promise for wearable sensing with minimal interferences and satisfactory wearable comfort, especially for long-term monitoring. Fig. 2(f) shows a recent work of a wearable patch for continuous at-rest sweat rate monitoring [96]. To tackle the challenge of collecting resting thermoregulatory sweat with low secretion rates, microfluidics is integrated to resist evaporation and monitor sweat rate selectively. Meanwhile, a laminated hydrophilic filler is also adopted to uptake sweat into the sensing channel rapidly, reducing the sweat accumulation time in practical applications. Functionalized electrochemical electrodes and electrical electrodes are assembled inside the microchannels to detect PH, Cl^{-1}, levodopa, and sweat rates simultaneously. This sweat sensing patch has been used to measure resting sweat secretion rate on various body parts ranging from shoulder, chest, to finger thanks to its small footprint. Dynamic sweat behaviors from multiple aspects have been explored under conditions of light physical activities, glucose fluctuations, and drug administration for Parkinson's disease. Such kind of wearable patches would be an ideal platform for an individual's physiological status and medical condition monitoring on a daily basis.

B. SELF-POWERED SENSORS

As a prevailing branch of energy harvesters, nanogenerators are considered one of the most promising solutions for reliable power sources to match the human-oriented, distributed,

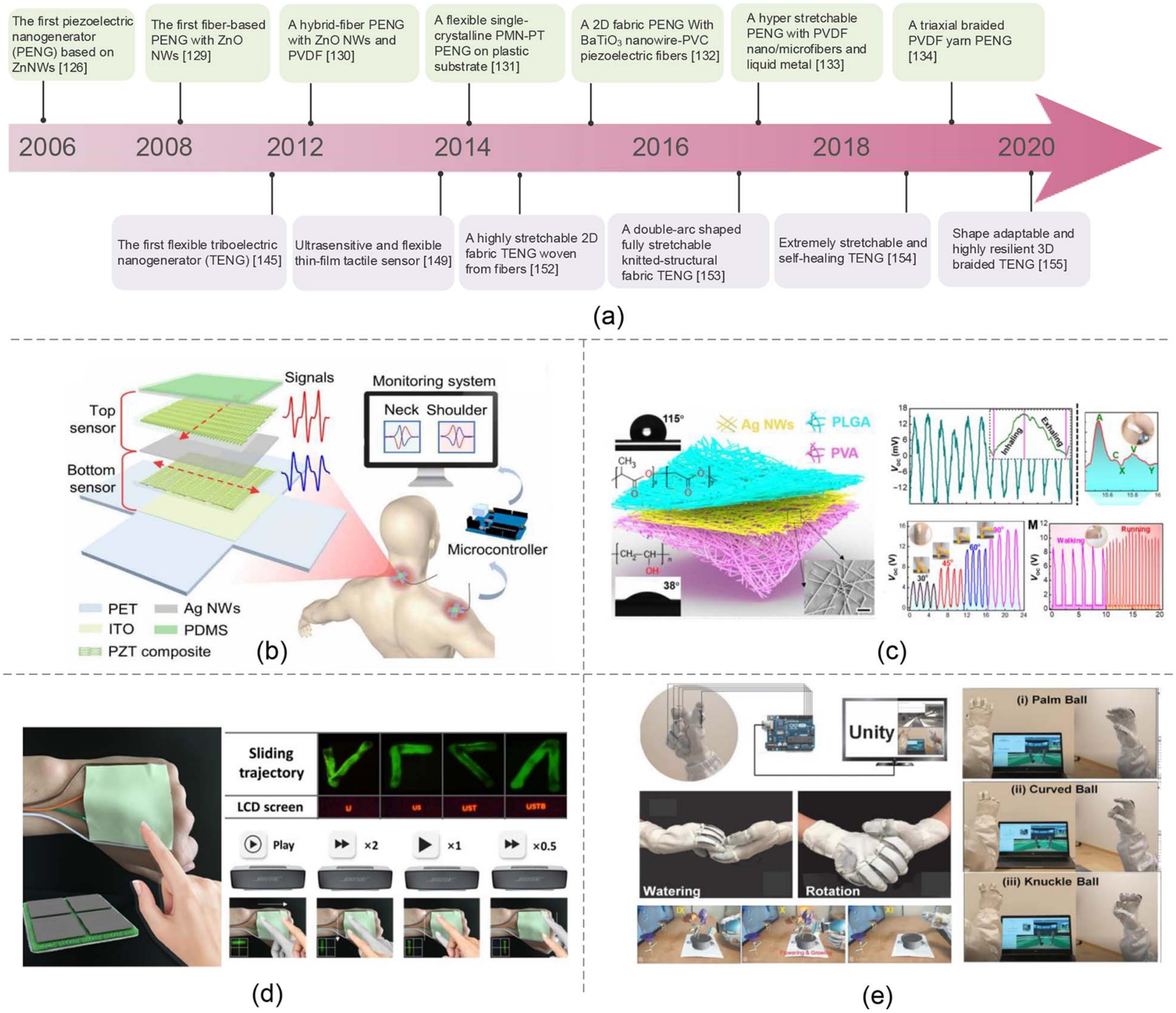

FIGURE 3. Self-powered sensors based on the PENGs and TENGs. (a) Summary of representative works of PENG and TENG since their inventions. (b) A kirigami-structured highly anisotropic piezoelectric sensor to monitor comprehensive joint motions [94]. (c) A breathable, antibacterial, and biodegradable triboelectric electronic skin based on nanofibers [137]. (d) A self-powered user-interactive electronic skin based on a proposed triboelectric-optical mode [95]. (e) A machine learning glove composed of superhydrophobic triboelectric textiles for gesture recognition in VR/AR applications [138].

and mobile sensing network [124], [125]. In addition, they can function as self-powered sensors for diversified applications, holding great promise to reduce the system power consumption, especially for future bodyNET.

1) TECHNOLOGY MILESTONES OF WEARABLE PIEZOELECTRIC NANOGENERATORS

The first piezoelectric nanogenerator (PENG) originates in 2006, proposed by Prof. Z. L. Wang with zinc oxide (ZnO) nanowires (NWs), which utilizes the piezoelectric effect to convert mechanical stress into electricity [126]. Since then, PENG has received considerable research interests with viable progress in various wearable applications, and Fig. 3(a) summarized a few milestones in this research roadmap. Textile or fibers, as the key components of clothing, are regarded as promising platforms for wearable sensors besides the well-developed epidermal platforms [50], [127], [128]. In 2008, the first fiber-based PENG was fabricated by entangling two Kevlar fibers, with both of them coated with ZnO NWs and one of them further covered by a gold layer [129]. Later, fiber-based PENGs in a single fiber were developed with a sandwiched structure. To improve the mechanical endurance and output performance, a hybrid PENG fiber was designed by integrating two piezoelectric materials (ZnO NWs and poly(vinylidene fluoride) (PVDF)) in 2012 [130]. As single-crystal piezoelectric material (1-x) $Pb(Mg_{1/3}\ Nb_{2/3})O_3$-x$PbTiO_3$ (PMN-PT) shows a superior piezoelectric coupling coefficient, a flexible thin-film PENG made of PMN-PT was developed in 2014, showing great potential for both wearable and implantable applications [131]. To improve the piezoelectric outputs of fibers, a two-dimensional fabric PENG was proposed in 2015, containing piezoelectric fibers that comprise aligned $BaTiO_3$ nanowires and polyvinyl chloride (PVC) polymer [132].

In 2017, a hyper-stretchable PENG was developed with a high stretchability up to 300% and durability of more than 1400 times at 150% strain, composed of aligned self-similar PVDF nano/microfibers, liquid metal, and elastomers [133]. Adopting a new fabrication technique, a triaxial braided structure was proposed in a fiber-based PENG based on melt-spun PVDF fibers and silver-coated nylon yarns in 2019 [134]. Retrieving from the research roadmap, flexible and wearable PENGs have experienced prodigious development from diversified aspects, such as high-performance materials, novel structure designs, new fabrication techniques, excellent flexibility/stretchability, etc. [135], [136].

2) TECHNOLOGY MILESTONES OF WEARABLE TRIBOELECTRIC NANOGENERATORS

Triboelectric nanogenerators (TENGs) based on the coupled effect of contact electrification and electrostatic induction is another mainstay out of the nanogenerator research discipline, which has become the spotlight of wearable sensors and energy harvesters in recent years [139]–[144]. Similarly, a few characteristic milestones of wearable TENGs since its first invention are listed in Fig. 3(a).

Triboelectrification exists in our daily life ubiquitously and is known for thousands of years. However, it was mostly regarded as a negative effect and was not utilized properly. In 2012, Fan *et al.* proposed and demonstrated the first TENG prototype by stacking two polymer sheets with polyethylene terephthalate (PET) and Kapton as triboelectrification materials and gold as the electrode [145]. Since then, TENG has been receiving growing research interest worldwide in terms of its fundamental mechanisms, materials, structures, and applications [146]–[148]. Targeting wearable use, a triboelectric tactile sensor based on flexible thin-film polymers was developed in 2014, demonstrating a great promise in a variety of applications including robotics, HMI, and security [149]. As textiles have emerged as another optimistic platform for wearable electronics with intriguing advantages of light weight, softness, stretchability, breathability, and low cost, textile-based TENGs have been proposed and designed for biomechanical energy harvesting and sensing [150], [151]. In 2015, a highly stretchable two-dimensional TENG fabric prepared by weaving fibers was presented, composed of aluminum wires and PDMS tubes with nanostructured surfaces [152]. To investigate the fabric structure's influence on the triboelectric output, in 2017 Prof. S.W. Kim's team developed stretchable TENG fabrics in plain-, double-, and rib-fabric structures using fabrication techniques of the textile industry, with their stretchability and output performance comprehensively explored [153]. To endow the flexible TENG with properties of epidermal, Parida *et al.* reported an extremely stretchable and self-healable TENG enabled by highly conductive, stretchable, and healable composites based on the liquid metal and silver flakes covered by thermoplastic elastomer in 2019 [154]. Recently, a TENG-based electronic textile combining the traditional fabrication technique from the textile industry and the PDMS-coated conductive yarns was demonstrated, with a three-dimensional fiver-directional braided structure for both powering and sensing [155]. With its compelling features of flexibility, stretchability, universal availability, environmental friendliness, and cost-effectiveness, wearable TENGs have undergone immense development which could cater to the development trend of bodyNET.

Here we provide and discuss few recent progresses of wearable self-powered sensors based on the PENG or TENG for a variety of applications. Both PENG and TENG can respond to all types of mechanical stimuli arising from human body, such as pulse, in/exhaling, and movements with high sensitivity, wide dynamic range, and short response time [156]–[158]. On the grounds of these intriguing features, they are regarded as ideal candidates in self-sustainable wearable systems to record vital signals and activities.

Targeting at a specific usage scenario and driven by the demand in prevention and rehabilitation of upper extremity musculoskeletal disorders (MSDs), Hong *et al.* designed and developed a kirigami-structured anisotropic piezoelectric sensor to monitor joint motions from different aspects, as shown in Fig. 3(b) [94]. A 2D honeycomb piezoelectric kirigami is adopted as the core sensing element, which provides a high-dimensional anisotropy that contributes to the capability of discrimination of both stress amplitude and direction. As a result, this piezoelectric sensor is capable of monitoring joint motions detailing different motion modes, which is highly desired for neck and shoulder joint motion monitoring to prevent injuries from prolonged sedentary behaviors. This unique strategy of fabricating anisotropic bending sensors for joint motion monitoring would assist promote the advancement of flexible electronics in healthcare and rehabilitation.

Based on the triboelectric effect, self-powered sensors for various wearable applications have also been investigated vigorously. As shown in Fig. 3(c), a breathable, biodegradable, and antibacterial all-nanofiber TENG was proposed, which is fabricated by sandwiching AgNW with polylactic-coglycolic acid (PLGA) and polyvinyl alcohol (PVA) [137]. The micro-to-nano hierarchical porous structure has endowed the self-powered sensor with countless capillary channels for efficient thermal-moisture transfer. This self-powered sensor possesses good conformability and sensitivity, hence giving rise to the whole-body physiological signal recoding and joint movement monitoring capabilities. Fig. 3(d) presents a recently reported self-powered and user-interactive skin (SUE-skin), comprising a phosphor layer, an electrode, an insulating layer, and a PDMS substrate [95]. The SUE-skin is able to convert touch mechanical stimuli into electrical signals and visible lights simultaneously without extra power supply, based on the proposed triboelectric-optical model that induces both electrostatic induction and electroluminescence via triboelectrification. Higher pressure would generate a larger amplitude of electrical and optical signals, and the trigger pressure threshold is as low as 20 kPa. On the basis of the triboelectric-optical model, the touch stimuli can be perceived directly through the observation of human eyes and recorded by the electrical signals at the same time, making the SUE-skin highly suitable for interactive wearable devices, intelligent robots, and artificial prosthetics.

With the rapid development of artificial intelligence (AI) technology, the fusion of AI and wearable sensors becomes feasible to enhance data analytics, refine decision-making processes, and perform intelligent tasks as never before [159]–[164]. Fig. 3(e) shows a good example of combining the wearable triboelectric sensors with the cutting-edge machine learning technique, where a sensory glove was developed with superhydrophobic triboelectric textiles [138]. By only using one sensor on each finger, the smart glove is capable of recognizing multiple gestures with the aid of the convolutional neural network (CNN). Furthermore, the superhydrophobic property successfully reduced the influence from sweat, leading to an improved recognition accuracy (96.7%) compared to triboelectric textiles without superhydrophobic treatment (92.1%). The smart glove holds great prospect in diversified virtual reality (VR)/augmented reality (AR) applications, which has been utilized as a control interface in a shooting game, baseball pitching, and floral arrangement as demonstrations.

In the past several years, fruitful attempts have been made in developing wearable sensors with excellent mechanical deformability, high sensitivity, stability, self-powering capability, etc. Despite notable advances of wearable sensors have been made in terms of materials, mechanical design, and applications as summarized in Table 1, some unaddressed challenges still need ongoing attention and improvement. First, manufacturing approaches of soft and flexible materials compatible with conventional fabrication techniques are yet to be developed, such as microelectromechanical systems (MEMS) processes. Second, stretchable circuits with novel designs are needed to realize a fully deformable and conformal wearable sensing system. Meanwhile, considering the existence of rigid electronic components in current wearable systems, advanced methods to provide robust mechanical and electrical hybridization of compliant elastomer and rigid components are imperative for practical applications. Thirdly, the hybridization of different functional materials and sensory platforms for comprehensive healthcare monitoring is still in its infancy, which requires collection and analysis of multi-modality sensory information. With the rapidly developing artificial intelligence (AI) technology, we are optimistic to see the implementation of advanced data analytics such as deep learning on more complex and complete wearable sensing systems for sophisticated monitoring tasks.

TABLE 1. General features of wearable sensor, implantable devices, and exoskeletons.

	Material properties	Mechanical design	Applications
Wearable sensors	Flexibility stretchability, conformability light-weight breathability biocompatibility self-healing etc.	Serpentine shape, hierarchical structures, Nanostructures etc.	Healthcare monitoring and diagnostics, fitness monitoring, sport/training performance tracking, etc.
Implantable devices	Flexibility Stretchability conformability light-weight biocompatibility biodegradability reliability deployability etc.	Mesh configuration, microneedles, miniaturization, etc.	Healthcare monitoring and diagnostics, cardiovascular care, neural prosthetics, drug-delivery, tissue engineering, etc.
Exoskeletons	Flexibility deformability robustness light-weight etc.	Strong structures, ergonomic and comfortable design, high maneuverability , adaptability, safety, etc.	Mobility reinforcement, Mobility restore and assistance, Rehabilitation, etc

III. SELF-SUSTAINABLE SENSING SYSTEM

The ultimate goal of self-powered sensors and energy harvesters would be the construction of self-sustainable systems that are capable of long-term autonomous operations [42], [44], [165]. The energy solutions of a bodyNET could be diversified, including but not limited to batteries, supercapacitors, wireless power transferring, and energy harvesting [29]. To address the limited lifetime issue of conventional energy storage units such as batteries, innovative power solutions such as wireless powering and self-powered energy harvested emerge as feasible approaches. Though electromagnetic power transfer is widely used for powering implantable devices, it is difficult to charge devices deep inside the body due to the dramatic decay of electric or magnetic field in biological tissues [71]. A good coil alignment is also required for adequate energy transfer efficiency. Moreover, how to power a large number of distributed sensors around or inside the body effectively stands as a grand challenge for practical implementation. In contrast, energy harvesters that scavenge power from a variety of non-limited ambient sources may be more desirable for body-orientated scenarios, especially considering the energy is available in an infinite capacity [43]. Nanogenerators that are relatively simple in device design and capable of working on low frequency regions with high efficiencies have promising applications in wearable power supplying and self-powered sensing [40], [41], [166]. Below we list a few recent self-sustainable sensing systems with the nanogenerators as the energy harvesters or sensors, or both simultaneously.

Fig. 4(a) presents a unique framework of a self-powered wireless sensor node, containing a textile-based TENG, a mechanical switch, and a coil for wireless signal

FIGURE 4. Self-sustainable and wearable sensing systems. (a) A battery-free self-powered wireless sensor node based on a triboelectric direct sensory transmission mechanism [167]. (b) A self-sustainable wearable textile system for next-generation healthcare applications [168]. (c) A deep-learning enabled smart sock based on textile-based triboelectric sensors for gait analysis and human-machine interfacing [93]. (d) An imperceptible sensing and energy harvesting patch based on ultra-flexible ferroelectric transducers and organic diodes [169]. (e) A 3D-printed motion capturing and energy harvesting hybridized lower-limb (MC–EH–HL) system for rehabilitation and sports applications [170].

transmission [167]. The switch and the TENG are operated sequentially in order to achieve instantaneous discharging of the triboelectric output, and oscillating signals will be formed in this RLC circuit upon the closing of the switch, which can be received by a nearby wireless receiver. Meanwhile, the resonant frequency of the wireless signal shifts upon different applied pressures on the TENG textile, which is more stable compared to the signal amplitude that is susceptible to environmental conditions, e.g., humidity. With this specially designed interconnection, the TENG here serves as both energy harvester and sensor at the same time, enabling self-powered active wireless sensing without any external power supplies. A more typical and general self-sustainable sensing system would comprise energy harvesters, energy management circuits, energy storage units, and sensing elements. In this configuration, the sensing capabilities can be broadened beyond physical parameters such as pressure or strain by incorporating desired sensors into the system. In Fig. 4(b), a diode-enhanced narrow-gap textile TENG (D-T-TENG) was proposed with amplified current outputs [168]. The textile-based TENG is soft, flexible, and thin, which can be seamlessly integrated with normal clothing and can generate large current outputs under various body motions. The enhanced output of D-T-TENG and an optimized charging circuit enable an improved charging speed, i.e., a 27 μF capacitor was charged up to 8 V within a minute. With the enhanced output, a Bluetooth module can work for 1 s within only 70 times of stepping of one foot, at which time the humidity and temperature value is sent to the smartphone for continuous tracking.

Recently, Zhang *et al.* developed a deep learning-enabled smart sock for both gait analysis and energy harvesting, as shown in Fig. 4(c) [93]. A textile-based triboelectric sensor with frustum-patterned surface structure was designed to obtain a wide pressure sensing range for gait signal detection. The smart sensing sock is composed of the textile-based TENGs on the bottom, which can scavenge the biomechanical energy to power up a Bluetooth temperature and humidity sensor and can detect gait events as well as gait abnormities. With a 1-D CNN structure, the smart sock can distinguish the subtle variations from the triboelectric outputs, hence enabling user identity recognition with an accuracy of 93.54% for 13 participants and user activity discrimination with an accuracy of 96.67%. On the basis of the machine learning model, a digital human system was then demonstrated to map the physical signals in the virtual space for sports monitoring, healthcare, authentication, and future smart home applications. Moving forward, a more intelligent and capable self-powered sensor network can be envisioned with the ongoing effort in terms of sensor technology and AI algorithms, paving the way for the future Artificial Intelligence of Things (AIoT). Fig. 4(d) shows a comprehensive and ultra-flexible energy harvesting device (UEHD) integrating ultra-flexible ferroelectric polymer transducers (UFPTs) with P(VDF:TrFE)$_{70:30}$, a diode-based rectifier, and a storage capacitor, with all of them fabricated on a thin parylene substrate (just 1 μm) [169]. The UEHD features imperceptibility, excellent conformability, and high sensitivity hence can function as a wireless e-health patch for pulse rate detection and blood pressure recording. Besides, it is able to serve as a biomechanical energy harvester via the combined rectifiers and thin-film capacitor, with average output power up to 0.25 mW cm^{-3} at 2 Hz.

Fig. 4(e) shows a motion capturing and energy harvesting hybridized lower-limb (MC-EH-HL) system, consisting of a sliding block-rail piezoelectric generator (S-PEG) for low-frequency biomechanical energy harvesting and a ratchet-based triboelectric nanogenerator (R-TENG) for motion sensing [170]. The particularly designed S-PEG on the lower-limb contains 20 piezoelectric bimorphs, which contributes to a high output power and charging speed. Meanwhile, the bidirectional R-TENG can be attached to multiple lower-limb joints for real-time monitoring. A self-sustainable IoT system was demonstrated based on the S-PEG, power management circuit, energy storage unit, microcontroller, and wireless transmission module. The collected sensory information holds great promise in multiple application scenarios including rehabilitation monitoring, human-machine interface, and VR gaming.

With the persistent efforts in the development of nanogenerators as well as energy harvesters in other forms, we have witnessed their evolution trend towards more powerful and sophisticated systems targeting diversified applications [29]. To further boost up the energy harvesting capability and maximize the energy utilization for practical uses, hybridized energy harvesting systems with two or more working mechanisms have been proposed to collect multiple forms of energy, such as solar, mechanical, biochemical, etc. [32]. Moving forward, the multi-source energy harvesters would be an effective approach to deal with non-consistent, insufficient, and sometimes random energy sources around our body, which could push forward the future realization of the bodyNET unprecedentedly.

IV. IMPLANTABLE MEDICAL DEVICES

Flexible electronics have dramatically reformed the sensors, enabling human biological signal monitoring not only on the skin but also inside the body. Real-time nitric oxide (NO) measurement in physiological environments is critical for monitoring neurotransmission, cardiovascular systems, inflammatory responses, etc. Fig. 5(a) presents a flexible and degradable electrochemical NO sensor that is operated wirelessly, with a low detection limit (3.97 nmol), a wide sensing range (0.01-100 μM), and anti-interference features [171]. The transient NO sensor consists of a bioresorbable substrate, ultrathin gold nanomembrane electrodes, and a biocompatible poly(eugenol) film as the selective membrane. The entire NO device can degrade completely after 8 weeks of in vivo implantation with no apparent inflammation or toxicity. Real-time NO concentration monitoring with wireless control and data transmission is realized both in vitro (chondrocytes and organs of rats and rabbits) and in vivo (heart and join cavity regions).

In addition to health monitoring, active treatments such as bioelectronics-assisted therapy are imperative for disease control in the healthcare domain [54]. For instance, hyperthermia treatment can raise the temperature of the local environment of a tumor, resulting in the change of the physiology of diseased cells and finally leading to apoptosis [172], [173]. An ultrathin 2D inorganic ancient pigment Egyptian blue (EB) nanosheets (NSs) decorated 3D-printing scaffold enabling photonic hyperthermia of osteosarcoma is constructed, as shown in Fig. 5(b) [100]. Photothermal therapy (PTT) features high spatial-temporal precision and minimal invasiveness, which has received extensive attention lately. The EB NSs exhibits superior absorption in the second NIR light biowindow and high photothermal-conversion characteristic, accordingly the scaffolds were investigated comprehensively under 1064 nm laser irradiation. Notably, mRNA sequencing results unveiled that the scaffold-based PTT treatment enriched both cancer metabolism- and bone development-associated gene terms, demonstrating promising clinical translation prospects in the osteosarcoma elimination and subsequent osteogenesis. Drug delivery as another therapeutic tool assisted by the cutting-edge bioelectronics has also been studied extensively to deliver pharmaceutical compounds to desired tissues, organs, cells, and subcellular organs [174]–[177]. They are designed to improve aqueous solubility and chemical stability, increase pharmacological activity, and reduce side effects of therapeutic drugs. Fig. 5(c) shows an implantable miniaturized device with electrode-embedded optical fibers for both immunotherapeutics delivery and tumor impedance measurement capabilities over a few weeks [103]. The implantable miniaturized optical fiber device (IMOD) contains a tubular optical fiber with a thin chemical-resistant layer bearing two copper microelectrodes embedded for impedance measurement. It not only allows drug release through the outer drug-containing layer of the fiber but also can be loaded with hydrophilic molecules through the inner channel. It is

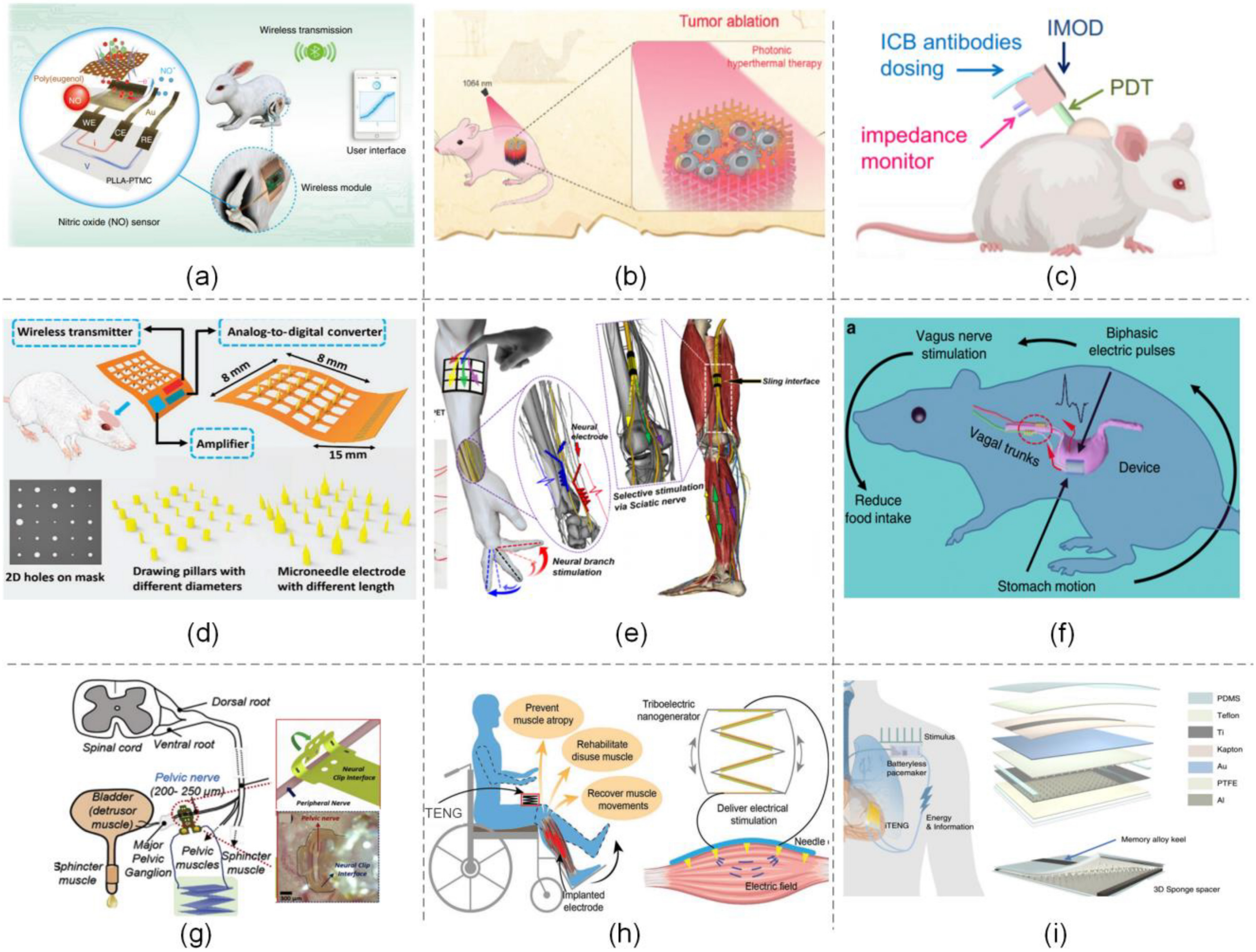

FIGURE 5. Implantable medical devices and self-powered neural stimulation systems. (a) A flexible, biologically degradable and wirelessly operated electrochemical sensor for real-time nitric oxide monitoring [171]. (b) An ultrathin 2D inorganic ancient pigment Egyptian blue decorated 3D-printing scaffold for photonic hyperthermia of Osteosarcoma [100]. (c) An implantable optical fiber for immunotherapeutics delivery and tumor impedance measurement [103]. (d) A flexible 3D electrode mesh for wireless brain-computer interface prostheses [101]. (e) A battery-free neuromodulating system for peripheral nerve stimulation enabled by a TENG [102]. (f) A self-powered vagus nerve stimulation device for effective weight control [189]. (g) Mechano-neuromodulation of autonomic pelvic nerves using a TENG and flexible neural clip for underactive bladder [190]. (h) A self-powered direct muscle stimulation system for rehabilitation treatment associated with muscle function loss with a stack-layer TENG [191]. (i) A fully implanted symbiotic pacemaker based on an implantable triboelectric nanogenerator [66].

discovered in various tumor models that the combination of local immune checkpoint blockade antibodies delivery and photodynamic therapy via IMOD cures or delays tumor growth, and elicits anti-tumor immune responses. On top of it, the impedance measurement can be utilized to visualize treatment outcomes, rendering its potential for on-demand delivery of potent immunotherapeutics without exacerbating toxicities.

Meanwhile, advanced bioelectronics on flexible and soft platforms are developed to record biological signals and to stimulate organs or the nervous systems [23], [57], [178]. The core enabling technologies for neuroscience and neuroengineering research lies the emerging field of the neural interface, which provides a direct connection to the biological tissues for electrical or optical recording and interfering neural functionalities [179]–[183]. Some diseases related to neural signaling can be potentially treated by neural interfaces through observing and modulating relevant neural signals. The neural interfaces can be employed for different biological tissues, ranging from central nervous system (CNS) including brain and spinal cord, peripheral nervous system (PNS) such as numerous nerves on different body parts, to muscles. The ever-increasing knowledge of neural signaling mechanisms makes electrical stimulation a powerful tool to treat neurological, neurodegenerative, and neuromuscular conditions. For instance, stimulating spinal cord is applied to restore ambulation capabilities of patients with spinal cord injury [184], [185]. Brain recording has been employed to decode motor intentions and decipher complicated speech, and deep brain stimulation has also been included in some well-established neuromodulation protocols for the treatment of Parkinson's disease, epilepsy, and dystonia [186]–[188].

Fig. 5(d) shows a flexible 3D microneedle electrode on a flexible mesh substrate for wireless brain-computer interface prostheses, which is fabricated using a drawing lithography technology from biocompatible materials [101]. Using the designed 2D patterns on a mask, the microneedle electrode profile can be controlled to access different layers inside the brain. Both the mesh structure and flexibility give rise to a good conformability to the curved brain without shear force induced on the tissue. The *in vivo* tests on rats demonstrated the successful penetration into the brain and neural signal recording from the exposed contact at the end of the microneedle electrode array.

Conventionally, electrical circuits and components are required to generate electrical pulses for therapeutic purposes. Recently, nanogenerators have been explored as alternatives to support the operation of implantable medical devices such as pacemakers and neural interfaces [55], [71]. This strategy could allow the development of advanced features for implantable devices, such as extended life and miniaturization with improved comfort. Herein a few self-powered implantable systems combining the nanogenerators and neural interfaces for a variety of applications will be introduced. Fig. 5(e) presents a water/air hybrid TENG (WATENG) connected to flexible sling interfaces for peripheral nerve stimulation [102]. The TENG output was amplified by a suspended dielectric thin film in this WATENG from mV level to tens of volt, which is high enough to induce plantar flexion and dorsiflexion through tibial and common peroneal nerve branches. In the meantime, the muscle activation amplitude can be directly controlled by the applied force on the WATENG. It is also demonstrated that the special triboelectric output waveform is more efficient in nerve stimulation than square waveforms with better linear control. Fig. 5(f) shows an implantable battery-free vagus nerve stimulation system that is responsive to the spontaneous stomach peristalsis [189]. It comprises a biocompatible TENG attached to the stomach surface that produces biphasic electric pulses when the stomach moves, which can stimulate vagus afferent fibers for reducing food intake and weight control. This strategy was successfully demonstrated on rats, with 38% weight loss within 15 days and without a further rebound. In Fig. 5(g), mechano-neuromodulation of autonomic pelvic nerves was demonstrated for underactive bladder by integrating a stacked TENG with a flexible neural clip interface [190]. The effect of stimulation frequency on neuromodulation was investigated while monitoring changes in bladder pressure and the micturition occurrence in *in vivo* experiments, revealing that a too low frequency may not be sufficient to evoke bladder contraction. The results indicate that this technology could potentially be employed to restore bladder function in the future.

In contrast to the peripheral nerves where lots of nerve fibers are packed tightly, skeletal muscles generally are with larger sizes and enable easier operations. However, muscles are constituted of distributed motoneurons, which typically require a larger stimulation current as compared to the low stimulation threshold of peripheral nerves and the brain. Wang *et al.* designed a self-powered system of a stacked-layer TENG and a multiple-channel epimysial electrode to directly stimulate rat's tibias anterior (TA) muscle with penetrating spikes, as shown in Fig. 5(h) [191]. The stacked-layer configuration successfully produced large currents and direct TA muscle activation was demonstrated by the triboelectric output. The stimulation efficiency was further investigated and optimized through changing electrode arrangements with different spatial positions. It is also validated that the long-pulse width and low-current amplitude of TENG output can effectively avoid synchronous motoneuron recruitment at the stimulation electrodes, hence contributing to a more stable activation profile.

Recently, in vivo energy harvesting and internal charging through the natural body activities and physiological environment with nanogenerators have been reported towards self-sustainable implantable medical devices and systems [44], [192]. They hold great potential to extend operation time of the devices inside the body and hence can reduce or avoid high risks accompanied by repeated surgeries. In Fig. 5 (i), an implantable TENG is integrated with a power management circuit and a pacemaker, forming a self-powered symbiotic pacemaker system for correcting sinus arrhythmia and preventing deterioration [66]. The TENG ingests energy from the beating heart, which is stored in the capacitor of the power management unit. A switch can be turned on by a magnet, which serves as wireless passive trigger to drive the pacemaker unit produce electrical pacing pulses and control the cardiac contraction rate. 0.495 μJ energy can be harvesting from each cardiac cycle, which is higher than the pacing threshold energy of both pig (0.262 μJ) and human (0.377 μJ).

Grounded on the advancement of flexible materials and mechanical designs, implantable medical devices have undergone tremendous improvement allowing for demonstrations in various applications, as summarized in Table 1. In spite of the viable progress in this field, there still are bottlenecks to be addressed prior to the implementation in practical applications. First of all, medical-grade biocompatibility is essential for the commercialization of implantable medical devices. Material selection especially for device encapsulation is of vital importance to guarantee no notable cytotoxicity and to minimize the foreign body response, which could be verified by large-scale clinical trials. Meanwhile, clinical grades of accuracy and stability beyond laboratory-scale demonstration are yet to be achieved for practical use. In addition, device integration and further system optimization to provide specific sensing or therapeutic functions for particular disease models are needed. Towards this goal, miniaturization of individual components, advanced interconnection configurations, and improve encapsulation techniques should be achieved. In consideration of long-term reliable utility, intimate coupling of the body and device should be maintained even upon dynamic body movements, which require further reduction of the mechanical mismatch at the interfaces between electronic entities and biological tissues.

FIGURE 6. **Lower-limb exoskeletons and prosthesis to restore or augment walking performance. (a) A modular exoskeleton for incomplete and complete spinal cord injured individuals [198]. (b) An untethered exoskeleton with real-time biofeedback for walking performance augmentation in individuals with cerebral palsy [104]. (c) A soft robotic exosuit for post-stroke gait assistance and rehabilitation [105]. (d) A powered above-knee prosthesis with volitional control for gait assistance of above-knee amputees [106]. (e) A exoskeleton manipulator with bidirectional triboelectric sensors for enhanced multiple degree of freedom motion sensing [199].**

V. REINFORCED LIFE QUALITY WITH FLEXIBLE SENSORS AND ROBOTIC EXOSKELETONS

Aside from bioelectronics for therapy and rehabilitation, robotic exoskeleton that integrates sensing, control, and computer science can also directly serve humans by assisting or enhancing human activities [193]. Among them, exoskeletons for the lower extremity have been widely developed to apply torques to the biological joints, in order to augment healthy individuals or assist those with impaired ambulation capabilities [194]–[197]. These systems generally are based on the robotic mechanism which comprises rigid links, joints, and actuators, running in parallel with the lower limb to provide gait training or rehabilitation. A bunch of research institutes and enterprises have carried out research work in the theory and applications, and achieved several milestones.

Spinal cord injuries (SCI) would cause a reduced or completely lost mobility of an individual, in which case a wearable exoskeleton could be helpful in assisting gait and improving patients' quality of life. Fig. 6(a) shows a lower limb modular exoskeleton for people with a spinal cord injury, which is equipped with 8 powered joints and 4 passive joints connected in rigid framing components [198]. A backpack module is essential for the whole system as it contains batteries, power management circuit, and control computer. Based on the impairment level of the patient, the exoskeleton can be customized with an ankle-knee configuration or the ankle-knee-hip configuration, to deliver appropriate and safe force to the wearer. Testing results have also validated the positive effects from that SCI individuals with an incomplete lesion walked faster compared to walking without the exoskeleton. More importantly, the exoskeleton can help those who have lost their ambulation ability restore the walking capability with the support of crutches.

Impaired walking function and pathological gait patterns are widely found among the elderly or individuals with relevant diseases such as cerebral palsy (CP). Unlike patients suffering from SCI, they still possess the ability to walk individually but with abnormal gait patterns that are associated with slow walking speed, reduced ground clearance/step length, and increased energy cost. They generally suffer from a reduced ankle strength in plantarflexion for push-off and dorsiflexion for ground clearance, which can be assisted and improved by ankle exoskeletons. Fig. 6(b) presents an untethered ankle exoskeleton to provide ankle assistance for CP patients [104]. It comprises a waist-mounted motor, Bowden cables to transmit force, and an ankle assembly structure. Resistive pressure sensors were embedded on the foot pad to identify stance and swing phases, with which adaptive plantar-flexor torque can be delivered to the ankle. The step lengths as biofeedback were provided to the participants when they walked with ankle assistance, which was demonstrated as an effective gait training strategy for individuals with moderate-to-severe plantar-flexor impairment. Improvements in lower limb posture and moments to baseline were observed immediately with such biofeedback provided to the participants.

For people who still retain their ability to walk, rigid exoskeletons may not be essential to restore more walking behaviors. Soft robotic exosuits that are made from flexible and garment-like textiles then have emerged as a promising alternative for the relevant patients. A variety of approaches can be utilized to deliver assistance during walking. Prof. C. Wash's team has been dedicating to developing exosuits for gait rehabilitation for a long time, and they have successfully demonstrated a few prototypes to assist mobility-impaired patients or enhance healthy subjects by reducing metabolic rate [200], [201]. In Fig. 6(c), one of their recent exosuit prototypes that integrate actuators, Bowden cables, functional textile anchors, and force generating contractile elements is presented [105]. In contrast to the exoskeletons containing mostly rigid components and frames, the soft exosuit is closer to a normal garment that can be conformably wrapped around the lower extremity. Assistive forces were transmitted to the ankle through the Bowden cables connected to the shoe insole. They have evaluated the overground walking speed, distance, and energy expenditure of post stroke individuals in terms of statistical exosuit-induced changes. Both improvement on the walking speed and distance indicates that post-stroke patients can benefit from plantarflexor and dorsiflexor assistance provided by the soft exosuit.

There is an important and ongoing research area of assistive robotic devices, in which passive or powered prostheses in amputees, tetraplegics, or stroke patients are designed and developed to restore the capability of extremities such as lower limbs [80], [202]. Generally, powered prostheses leverage controllers that are well tuned to replicate normal movement pattern of non-amputee individuals, aiming at mimicking the missing biological limb. As opposed to the conventional passive prostheses, powered prostheses are capable of adjusting joint movements actively with battery-supported servomotors, which requires the recognition of the amputee's intent regarding locomotion modes. Fig. 6(d) shows a typical powered above-knee prosthesis comprising a powered knee joint and a passive ankle joint, where the knee motion was driven by a motor via a ball screw [106]. The system utilizes the EMG signal from the user's residual limb muscles and mechanical measurements (knee joint, knee angular velocity, and ground reaction force) of the prosthetic pylon to interpret the user's intent for different activities (e.g., level ground walking, ramp ascent, etc.). In this study, it has been found out that not all recognition errors in this volitional prosthesis control affect the individual's gait stability, which might assist the future design of the powered above-knee prostheses that are robust and reliable for practice. Looking forward, the flexible sensors and flexible electronics will further advance the designs and functions of exoskeletons and exosuits. Recently, Zhu et al. proposed a triboelectric bi-directional (TBD) sensor as a universal solution to customized exoskeletons to detect all moveable joints of human upper limbs, as shown in Fig. 6(e) [199]. Based on the triboelectric sliding sensing mode, the TBD sensor can monitor bidirectional rotation angles with the outputs from a single grating pattern. A set of customized exoskeleton arms embedded with the TBD sensors are developed, allowing for multiple joint motion detection with multiple degrees of freedom (DOFs). Various upper-limb movements including shoulder rotation, wrist twists, and bending motions are detected and further utilized to control a virtual character and a robotic arm in real-time. The good merge between the exoskeleton structure and the triboelectric rotation sensor presents a future where the fine line between the two disciplines of research would gradually fade away, giving way to an optimized exoskeleton system with advanced sensing and actuating capabilities simultaneously. Therefore, the future robotic prosthetics, exoskeletons, and exosuits will largely benefit the elderly and individuals with impaired mobilities, providing natural mobility and dexterity to the missing or paralyzed extremity.

Powered exoskeletons are gaining growing attention in both rehabilitation and assistance fields (Table 1), yet there are still a few roadblocks standing in the way of an ideal prototype [81]. First and foremost, considering the complex human kinematics, inter-subject variability, and the common assumption that human joints are perfect pivot joints when designing and constructing exoskeleton frames, a proper and correct alignment between exoskeletons and anatomical joints becomes a grand challenge [203]. Misalignments of human and exoskeleton joints may cause undesired forces that could compromise safety and comfort of the wearer, and limit the patient's natural movement as well as responses to the rehabilitation process. Besides the physical interaction between the user and exoskeleton, a cognitive interaction for information exchange is of vital importance for an effective and consistent mechanical power transfer too. On that account, proper sensor designs and configurations are required to monitor correct kinematics and kinetic information, which is especially imperative to decide when to deliver mechanical assistances at appropriate levels according to the user's intent. We are optimistic to see the merge of the thriving wearable/implantable sensing technologies and the exoskeleton platforms in the near future, with them reciprocally affected by each other and bring on more user-friendly mobility assistance systems.

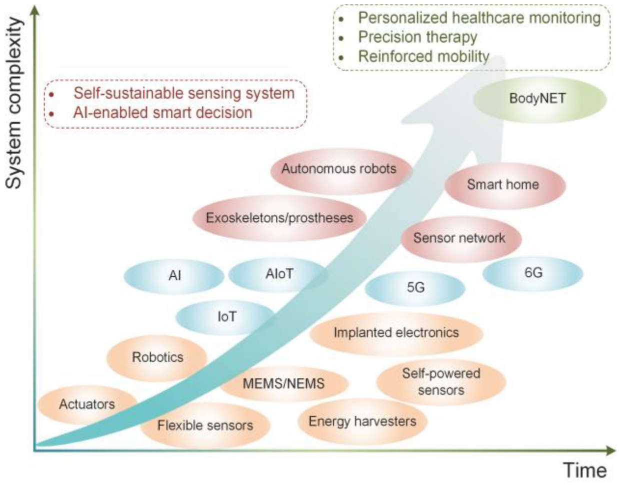

FIGURE 7. An overview of technology evolution from discrete components and platforms to a comprehensive and capable bodyNET for personalized healthcare monitoring, precision therapy, and reinforced mobility.

VI. FUTURE PERSPECTIVE

The emerging field of flexible electronics has acquired tremendous attention in modern society, and its rapid development also has laid the foundation of other disciplinary research areas and paves the way for a comprehensive bodyNET in the near future, as sketched in Fig. 7. Over the past decades, we have witnessed the thriving advancement of flexible sensors for reliably monitoring key biomedical and physiological information as well as daily activities. Meanwhile, energy harvesters and self-powered sensors have arisen as promising alternatives and supplementations in the construction of a bodyNET, which could give rise to self-sustainable sensing systems with energy autonomy and pro-longed life spans. Beneficial from the substantial progress in flexible electronics and MEMS/NEMS technologies, implantable devices for sensing, neural signal recording/modulating, and actuating have been widely developed as well. Flexible sensors and actuators, in the meantime, can offer transformational opportunities for soft robotics that are able to interface with humans seamlessly for assistance and augmentation, such as exoskeletons and prosthetic limbs. As we are entering the era with advanced wireless communication (5G, 6G, IoT) and AI technology, a variety of sensors can form an artificial intelligence of things (AIoT) network with a cloud server to collect, store, and analyze data for smart decisions [143], [147]. Supported by these enabling technologies and platforms, complex and multifunctional systems with innovative characteristics would be feasible, such as body sensor networks on the skin and inside the body, exoskeletons/prostheses, functional autonomous robots, and smart homes. Moving forward, these multidisciplinary research outcomes would be merged together to better serve humans, forming revolutionary bodyNET, a network interconnecting wearable devices, implantable devices, and exoskeletons. Equipped with these compelling features, the bodyNET shows remarkable prospects in personalized healthcare monitoring, precision therapy, and reinforced mobility, leading to an immensely improved life quality as never before.

While there is substantial progress in the field of wearable/implantable electronics and assistive exoskeletons, a few associated challenges still remain to be addressed on the way to a comprehensive bodyNET. Firstly, the characteristics and feasibility of the functional units are generally validated individually, and integration of various different sensors or platforms has rarely been investigated. To form a network with good consistency and stability, antennas and RF devices suitable for on-body and in-body communication should be investigated and characterized, aiming at reducing energy consumption and meeting coexistence constraints. Effective methods to process the growing amount of and heterogeneous data should also be developed, considering the type and volume of data in a bodyNET would grow tremendously beyond the capability of commonly used software tools. Data security of the bodyNET is also a vital concern in practical scenarios, which could be protected by advanced transmission techniques [127]. Besides, wider applications and distributions of the bodyNET require adequate social awareness and acceptance, in which case the privacy of personal data shall be well protected against external intruders.

VII. SUMMARY

Overall, flexible electronics have demonstrated a growing impact in the area of wearable/implantable devices, robotics, and energy harvesters in the past decade. The superior deformability, stretchability, light-weight, and high sensitivity have enabled multimodal healthcare monitoring in terms of physiological signals, vital signs, and dynamic motions both on the body and inside the body. The emerging nanogenerators are regarded as promising tools in realizing self-powered systems to provide long-term and continuous health supervision. With the synergistic development of materials and manufacturing techniques, implantable bioelectronics becomes an attractive platform for therapeutic applications such as chronic disease management. In particular, the integration of implantable neural interfaces and nanogenerators has shed light on future self-powered therapeutic electronics. At the intersection of wearable sensors and robotics lies the assistive exoskeletons, which have been demonstrated in restoring mobilities of the elderly and individuals with impaired muscle functions and reducing the metabolic energy cost of healthy subjects. In a foreseeable future, these evolving technologies would assist each other and form a comprehensive bodyNET to extend our senses and abilities, enabling advanced healthcare and reinforced quality of life.

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