Electronic textiles for energy, sensing, and communication

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SUMMARY

Electronic textiles (e-textiles) are fabrics that can perform electronic functions such as sensing, computation, display, and communication. They can enhance the functionality of clothing in a variety of convenient and unobtrusive ways, thus have garnered significant research and commercial interest in applications ranging from fashion to healthcare. Recent advances in materials science and electronics have given rise to variety of e-textile components, including sensors, energy harvesters, batteries, and antennas on flexible and breathable textiles substrates. In this review, we discuss recent advances in the development of e-textiles for energy, sensing, and communication. In addition, we investigate challenges in the integration of components to realize e-textile systems, and highlight opportunities enabled by innovations in materials science, engineering, and data science.

INTRODUCTION

Wearable technologies allow digital tools to be conveniently and unobtrusively integrated into our everyday lives. Electronic textiles (e-textiles) represent an important example that takes advantage of clothing as a platform for sensing, actuation, display, communication, energy harvesting, energy storage, and computation. Whereas earlier e-textile were designed based on simply attaching conventional electronic components attached onto clothing, recent advances in material science and electronics have enabled e-textiles that are able to perform a wide variety of electronic functionalities while being flexible and breathable. Such e-textiles have gained significant attention both in the industry and academia and have been demonstrated for a broad range of applications, including Internet of things (IoT), artificial intelligence (AI) (Matijevich et al., 2020), body motion tracking (Chun et al., 2018; Kim et al., 2019b), gaming (Zhou et al., 2018), pressure mapping (Lim et al., 2020), rehabilitation, healthcare (Fan et al., 2020; Li et al., 2018a; Teferra et al., 2019), smart wearables (Cameron et al., 2020; Fernández-Caramés and Fraga-Lamas, 2018; Gong et al., 2019), and smart garments (Castano and Flatau, 2014; Ou et al., 2019; Yin et al., 2018b).

E-textile-related technologies have been drawing great attention from researchers and most of the review articles on e-textiles are from the point of view of materials or methods of fabrication (Wang et al., 2021; Yong Zhang et al., 2021; Zhang et al., 2021). In this article, we present the key components needed to build independent e-textile systems and review recent progress in the development of e-textiles by their functionality: sensing, communication, and energy harvesting and storage, with emphasis on limitations and opportunities for their integration into functional systems. E-textile systems require several key components to perform basic functions with sufficient level of autonomy, including sensors for data acquisition, energy sources for system power supply and regulation, communication modules for data transmission and interfacing, and reliable interconnections that connect different modules into an integrated system. Figure 1 shows a person wearing a smart running suit that is equipped with various textile-based components. Here, the blue arrows indicate the transmission of data captured by different textile-based sensing elements. Specifically, the physical and bio/chemical data are transmitted from the sensors via conducting elements (e.g., conductive threads) to a wireless communication hub, that then send data wirelessly to a computing unit for further analysis. The red arrows indicate how the independent smart suit is powered, using either energy harvesters or energy storage devices. These components (sensor, energy harvester/storage, and communication devices as well as connection) assembly into an independent smart e-textile system, and is discussed in detail in the following sections.
SENSORS FOR E-TEXTILE SYSTEM

E-textiles can interface with large areas of the human body to capture important information about the physiological state and the environment. In this section, we will discuss various textile-based sensors that have been developed to measure physical and bio/chemical parameters.

Physical sensors

E-textiles can measure changes in the physical properties of the underlying textiles. Because they consist of woven networks of flexible fibers, textiles can easily be mechanically deformed. Furthermore, e-textiles are mainly used in smart wearables which require motion tracking of human body’s physical or mechanical movements (Roudjane et al., 2020). Thus, there are a vast number of reports on e-textiles with strain or pressure sensing capability (Islam et al., 2020; Seyedin et al., 2019).

One approach to produce textile-based sensors is to use fibers that are intrinsically conductive. As an example, highly stretchable and washable piezoresistive microfiber strain sensors were developed that can withstand 120% strain with electrical conductivity of $3.27 \pm 0.08 \text{ MS/m}$ (Yu et al., 2018). Such microfiber sensor was fabricated by encapsulating liquid metal eutectic Ga-In alloy (eGaIn) inside a tiny elastomeric microtube made of polydimethylsiloxane (PDMS) with diameter of 160 $\mu$m. Owing to

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**Figure 1. Smart e-textile system: energy, sensing, and communications**

Illustration of an independent smart e-textile system with capabilities of sensing, energy harvesting, and communication. The sensing data are wirelessly uploaded to cloud.
the small size of the sensor, it can be weaved into fabrics and even a glove as shown in Figure 2A (Yu et al., 2018). By stretching the textile, the sensor inside the fabric is elongated, thus deforming the PDMS hollow tube and displacing the liquid metal inside, which resulted in an increase of electric resistance of the sensor. In another example, a dual-core capacitive microfiber sensor was fabricated (Yu et al., 2019). This microfiber sensor is comprised of a dual-lumen elastomeric microtube filled with liquid metallic alloy, which enables continual strain perception even after being completely severed. As shown in Figure 2B (Yu et al., 2019, p.), the microfiber sensors were sewn into a fabric glove, enabling the glove to capture the gesture of the hand and monitor respiration rate based on capacitive change of ΔC/C₀.

Rather than using intrinsically conductive fibers, a number of studies focused on coating conventional textile fibers with conductive materials. For example, a wearable silk fabric based on carbonizing the pristine silk fiber was reported for stretchable strain sensing (Wang et al., 2016). The sensor showed a maximum strain of 520% and withstood 6,000 tensile cycles at 100% strain. Similar carbonization method was used in other studies on e-textiles. These include piezoresistive-type MoS₂-coated carbonized silk fabric pressure sensor (Lu et al., 2020), polyacrylne and carbon nanotubes-coated Au/nylon fiber (Zhao et al., 2020a), conductive graphene-based E-textile via bubble-exfoliation method and dip coating (Hu et al., 2020b). This popular dip coating method was used to produce resistive e-textiles by simply coating a conductive layer onto the surface of a fabric (Bi et al., 2018; Cai et al., 2017; Li et al., 2019; Lian et al., 2020; Yang et al., 2018a; Yang et al., 2020; Yang et al., 2018b). Another “all textile-based” strain sensor used an elastic fabric as a substrate with conductive yarn as the resistive sensing component weaved into the substrate in different patterns (Park et al., 2019). The sensor is reported to be able to detect bending and rotation of human joints. Other than resistive and capacitive textile-based sensors, triboelectric nanogenerators technologies can also be used for pressure sensing e-textiles. A machine-washable and breathable pressure sensor based on triboelectric nanogenerators was introduced (Zhao et al., 2020b).

Two types of yarns were designed: Cu-coated polyacrylonitrile (denoted as Cu-PAN) yarns and parylene-coated Cu-PAN (denoted as parylene-Cu-PAN) yarns. When the Cu-PAN yarns and parylene-Cu-PAN yarns are in contact with each other in a fabric, a voltage signal is produced when there is a contact area change due to applied external pressure. The study also showed that the yarns can be knitted into a piece of pressure sensing fabric glove using a knitting machine as shown in Figure 2C (Zhao et al., 2020b).

Apart from mechanical force/pressure-detectable e-textile sensors, e-textiles have also been developed to sense other physical parameters in the environment. For example, environmental humidity was reported to be detectable with a flexible humidity capacitive sensing system, in which the sensor part is composed of two copper wires with a layer of yarns in between as the dielectric layer, as illustrated in Figure 2D (Ma et al., 2019). As the yarns absorb the moisture in the atmosphere, the permittivity of the dielectric increases, leading to increase in capacitance of the textile sensor. The moisture sensing capability of e-textile can be further extended to moisture management. A double-sided synergetic Janus textile was developed for moisture/thermal management, as demonstrated in Figure 2E (Wang et al., 2020b), with one side of the textile coated with hydrophilic polymer and the other side coated with hydrophobic polymer. The difference of moisture absorption resulted in difference in textile porous size, leading to thermal managing capability. Without having any coating on the fabric, another moisture-sensing e-textile was fabricated by simply twisting the silk yarns, turning the silk into an artificial torsional silk muscle (Jia et al., 2019).

This sensor provided a reversible torsional stroke of 547° mm⁻¹ when exposed to water fog and the coiled-and-thermoset silk yarns provide a 70% contraction when the relative humidity was changed from 20% to 80%.

E-textile can also be designed to enable multiple sensing capabilities. A silk composite electronic textile combo sensor was designed for measuring both temperature and pressure (Wu et al., 2019). As shown in Figure 2F (Wu et al., 2019), the fiber sensor is composed of an external Ecoflex sealing layer, silk fibers encapsulated with CNTs and [EMIM]Tf₂N as the thermal conductive middle layer, and with polyester fibers as the supporting core. Temperature change detected by the resistance of the silk fiber middle layer achieved a sensitivity of 1.23% °C⁻¹, while the pressure sensed by the capacitance in between two contacted sensor fibers achieved sensitivity of 0.136 kPa⁻¹. By using chemical vapor deposition (CVD) method to deposit a trilayer graphene (TLG) on top of polypropylene (PP) textile, a carbon—graphene temperature sensing e-textile was reported to operate at voltage as low as 1.0 V (Rajan et al., 2020).
**Figure 2. E-textile sensors**

(A–L) Force sensing: (A) highly stretchable and wearable piezoresistive microfiber liquid-metal based sensor (Yu et al., 2018), (B) dual-core capacitive microfiber sensor for e-textile application (Yu et al., 2019), and (C) machine-knittable smart glove for pressure sensing (Zhao et al., 2020b). Moisture sensing: (D) yarn-type humidity sensor (Ma et al., 2019), and (E) smart Janus textile moisture/thermal management (Wang et al., 2020b). Temperature sensing: (F) silk composite e-textile temperature sensor (Wu et al., 2019). Light sensing: (G) WS$_2$ quantum dots on e-textile as a wearable UV photodetector (Abid et al., 2020). Biofluid sensing: (H) biosensing textile platform for chloride ion and pH sensing (Possanzini et al., 2020), and (I) integrated e-textile sensor patch for real-time and multiplex sweat analysis (He et al., 2019). Drug sensing: (J) glove-based sensor for fentanyl detection (Barfidokht et al., 2019). Chemical sensing: (K) enzyme skin-cancer biomarker sensor (Manjakkai et al., 2019). Gas sensing: (L) Colorimetric gas sensing threads for e-textile (Owyeung et al., 2019).
Other than sensing temperature and humidity, e-textile can detect wavelength of light beam. A novel photodetecting sensor was produced based on a WS\textsubscript{2} quantum dots and reduced graphene oxide (RGO) (WS\textsubscript{2}-QDs/RGO) heterostructure (Abid et al., 2020). By coating the RGO and WS\textsubscript{2} on a piece of pure cotton textile, as shown in Figure 2G (Abid et al., 2020), they were able to place the smart fabric on the back of a finger for photodetection of a 405 nm illumination source and the photoresponsivity can reach up to 5.22 mA W\textsuperscript{-1} at 1.4 mW mm\textsuperscript{-2} power density.

**Chemical/biochemical sensors**

In addition to the great effort in developing textile-based physical sensors, many chemical/bio/electrochemical sensors were being developed for the sensing of chemical biomarkers and external environmental markers that are closely associated with our daily lives. Considering the fact that most of the e-textiles are in close contact with the human skin, textile-based sensors entail intimate contact that endows easy access to various biofluids.

Shown in Figure 2H, a textile-based biofluidic sensor is produced from simple threads. After being coated with the conducting polymer poly(3,4-ethylenedioxythiophene):poly(styrene-sulfonate) (PEDOT:PSS), the thread is functionalized with nanocomposite and chemical-sensitive dye to detect chloride ion and pH level in sweat (Possanzini et al., 2020). Another flexible sweat analysis patch sensor was designed based on a silk-fabric-derived carbon textile for simultaneous detection of six health-related biomarkers in sweat—glucose, lactate, ascorbic acid, uric acid, Na\textsuperscript{+}, and K (He et al., 2019). As demonstrated in Figure 2I, the intrinsically nitrogen (N)-doped porous structured carbon textile (SilkNCT) was used (or combined with other components) as the working electrode of the electrochemical sensors (He et al., 2019). The sweat sensor patch was further integrated with signal collection and transmission components, making it possible to conduct real-time monitoring of biomarkers in sweat. Mask printing method was applied to fabricate another sweat-chemical-sensing system by printing thin layers of electrodes on the surface of a glove to measure diverse biomarkers of natural sweat, including zinc, ethanol, pH, and chloride (Bariya et al., 2020; Tang et al., 2021; Wang et al., 2018).

While smart wearable sensors can sense chemicals in our biofluids and provide critical information regarding the health status of our body, they can also be applied for detection of foreign chemicals for environmental, forensic, or military applications. For example, a wearable electrochemical glove-based sensor was reported to conduct rapid and on-site detection of fentanyl, in order to prevent drug abuse (Barfidokht et al., 2019). In this device, the flexible electrochemical sensors were integrated on the fingertips of the glove using screen printing method. The electrochemical sensor for fentanyl is based on its irreversible oxidation on the composite electrode which consists of multi-walled carbon nanotubes (MWCNT) and ionic liquid (shown in Figure 2J) (Barfidokht et al., 2019). The glove sensor can detect fentanyl in both liquid and powder forms with a detection limit of 10 \textmu M using square-wave voltammetry. Similarly, electrochemical sensors for other chemicals based on textile have been developed for the detection of nerve agents, pollutants, or explosives (Bandodkar et al., 2013; Goud et al., 2021; Malzahn et al., 2011).

Chemicals under human skin can also be detectable with a bandage-based sensor with minimally invasive microneedles for skin melanoma screening (Ciui et al., 2018). In another study, a textile-based potentiometric electrochemical pH sensor was reported with thick film graphite composite as the sensitive electrode and Ag/AgCl as the reference electrode. Both electrodes were printed on cellulose-polyester blend cloth and the sensor was able to measure pH ranging from 6.0 to 9.0 (Manjakkal et al., 2019). The wearable electrochemical sensors can even detect tyrosinase (TYR) enzyme skin-cancer biomarker with the catechol substrate. As illustrated in Figure 2K, in the presence of TYR, catechol will be oxidized into benzoquinone, which can be detected amperometrically (Manjakkal et al., 2019).

Instead of sensing chemicals in liquid or solid forms, wearable sensors can also sense chemical in its gaseous form. Shown in Figure 2L is a colorimetric gas-sensing e-textile fabricated by applying optically responsive dyes on the thread substrate, before being put into the acetic acid for cleaning and PDMS for physical entrapment of the dye (Owyeung et al., 2019). Three types of dyes were tested: 5,10,15,20-Tetraphenyl-21H,23H-porphine manganese (III) chloride (MnTPP), methyl red (MR), and bromothymol blue (BTB) for sensing two volatile gases, ammonia and hydrogen chloride. The concentration of gases was tested from 50 to 1000 ppm.

Table 1 compiles the sensor type, material used, fabrication method used, flexibility, and washability and other information of the physical textile sensors. In terms of material, most of the sensors consists of at least one flexible substrate (fabric, cotton, or yarn, etc.), providing the sensor with a physical flexible property;
another inevitable part of these sensors is the conductive component (carbon, eGaIn, etc.), which will allow electrical signal to pass within or on the surface of the substrate. Thus, we can see that some of the sensors share similar fabrication methods, especially (strain or pressure) sensors. Dip coating is one of the most popular ways to produce for sensors, as by using this method, one can easily coat a conductive/functional layer on a normal piece of fabric or textile. However, with different functional components, specifications such as sensitivity, range, and cycle life of different sensors can differ a lot. Table 2 shows the compilation of different bio/chemical sensors. It can be seen that these types of sensors comparatively are more complex than physical sensors. In order to obtain the chemical sensing capability, electrodes are necessary to perform different level of chemical reaction on a flexible substrate. Thus screen printing or mask printing is very popular for being able to coat a tiny piece of electrode on the substrate. It is noticeable that the novel 2D carbon-based materials significantly contribute to the fast development of e-textile sensors. Among these materials, Graphene, RGO, MWCNT, and Mxene are most commonly used by researchers. In e-textile sensors, 2D carbon-based materials are not only able to perform as the conducting or sensing component in a sensor but also the small size or low thickness characteristics ensuring the flexibility of the e-textile sensors.

**Table 1. Summary of e-textile physical sensors including the sensor type, material, fabrication method, and washability**

| Sensor type | Material | Fabrication | Washability | Ref. |
|-------------|----------|-------------|-------------|------|
| Pressure    | eGaIn + PDMS + fabric | Microfiber fabrication | Yes | (Yu et al., 2018) |
|             | MoS2 + Carbon + silk | Coating | Yes | (Lu et al., 2020) |
|             | Graphene + Polymer + Cu particles | Printing and dyeing | Yes | (Hu et al., 2020b) |
|             | Mxene + cotton + Pt tape | Dip coating | Yes | (Li et al., 2019) |
|             | AgNW + cotton | Dip coating | Yes | (Lian et al., 2020) |
|             | Cu-PAN yarn + parylene-Cu-PAN yarn | Coating + weaving | Yes | (Zhao et al., 2020b) |

| Strain      | eGaIn + PDMS + fabric | Microfiber fabrication | Yes | (Yu et al., 2019) |
| Carbon + silk | Coating | Yes | (Wang et al., 2016) |
| Pen ink + Cupra fabric (CF) | Dip coating | Yes | (Bi et al., 2018) |
| rGO + nylon/PU fabric, | Dip coating | Yes | (Cai et al., 2017) |
| CNT + cotton | Dip coating | Yes | (Yang et al., 2018a) |
| Carbonic pigment ink + Polyamide fabrics | Dip coating | Yes | (Yang et al., 2020) |
| rGO + textile | Dying | Yes | (Yang et al., 2018b) |
| Conductive yarn + textile | Weaving | | (Park et al., 2019) |

| Moisture    | Copper wire + yarn | Wrapping | | (Ma et al., 2019) |
| Silk        | Twisting | | | (Jia et al., 2019) |

| Moisture thermal | Hydrophilic polymer + hydrophobic polymer | Polymer Coating | | (Wang et al., 2020b) |

| Temperature pressure | Ecoflex + silk + CNT + [EMIM]Tf2N + polyester fibers | Encapsulating | | (Wu et al., 2019) |

| Temperature | Graphene + polypropylene textile | CVD | | (Rajan et al., 2020) |

| Light | WS2 quantum dots + rGO | Chemical coating | | (Abid et al., 2020) |

**ENERGY FOR E-TEXTILE SYSTEM**

The operation of various e-textile sensing modules and the downstream data processing, transmission, and interfacing will have to rely on a compatible energy system. In a self-sustainable independent e-textile system, wearable energy harvesters scavenge energy from various sources and energy storage modules.
regulate the harvested energy and enhance system reliability. In this section, we discuss the commonly employed strategies in developing various energy harvesters and storage devices, and the integration thereof. The specific requirements to meet the standards of an e-textile module and their current limitations are also summarized.

**Textile-based energy harvesters**

As the power source for an energy independent autonomous system, the performance of energy harvesters determines the admissible functionality of the system. To fully utilize the diverse sources of energy, energy harvesters based on different energy generation mechanisms have been developed, harvesting solar or thermal energy from the surrounding environment (Chen et al., 2016; Ding et al., 2020; Elmoughni et al., 2019; Hashemi et al., 2020; Hinckley et al., 2021; Pu et al., 2016b; Wen et al., 2016, 2020), or the bioenergy associated from the human activities and metabolism (Bandodkar, 2017; Bandodkar and Wang, 2016; Dong et al., 2019; Jeerapan et al., 2016; Lund et al., 2018; Xiong and Lee, 2019; Zhang et al., 2015b). In general, we can classify the energy harvester commonly seen in e-textile systems into two types: the ones that harvest environmental energies, namely, solar cells that harvest via photovoltaic effect and thermoelectric generators (TE) that harvest by exploiting the Seebeck effect (Bell, 2008); and the ones that harvest from the human body itself, namely, piezoelectric nanogenerators (PENG) and triboelectric generators (TENG) that harvest biomechanical energy from the movements of human body, and biofuel cells (BFC) that generate electricity using microbial or enzymatic redox reactions fueled by metabolites in human biofluids (Dong et al., 2019; Jeerapan et al., 2020; Pang et al., 2017; Ryu et al., 2019). Other types of wearable energy harvesters have also been proposed based on motion-powered electromagnetic generators (Quan et al., 2015; Zhang et al., 2015a; Zhang et al., 2019), breathing-powered pyroelectric generators (Li et al., 2020a; Thakre et al., 2019; Xue et al., 2017), or antenna-based electromagnetic radiation harvesters (Abadal et al., 2014), but are less relevant to the scope of this review and are not discussed here. In general, we can classify the energy harvester commonly seen in e-textile systems into two types: the ones that harvest environmental energies, namely, solar cells that harvest via photovoltaic effect and thermoelectric generators (TE) that harvest by exploiting the Seebeck effect (Bell, 2008); and the ones that harvest from the human body itself, namely, piezoelectric nanogenerators (PENG) and triboelectric generators (TENG) that harvest biomechanical energy from the movements of human body, and biofuel cells (BFC) that generate electricity using microbial or enzymatic redox reactions fueled by metabolites in human biofluids (Dong et al., 2019; Jeerapan et al., 2020; Pang et al., 2017; Ryu et al., 2019). Other types of wearable energy harvesters have also been proposed based on motion-powered electromagnetic generators (Quan et al., 2015; Zhang et al., 2015a; Zhang et al., 2019), breathing-powered pyroelectric generators (Li et al., 2020a; Thakre et al., 2019; Xue et al., 2017), or antenna-based electromagnetic radiation harvesters (Abadal et al., 2014), but are less relevant to the scope of this review and are not discussed here. In general, the fabrication of the textile-based energy harvesters can be differentiated into the yarn/wire/thread-based devices that constitute the e-textile system from a “bottom-up” approach, and the ones that are directly fabricated onto fabrics/textiles in a “top-down” approach. The material and characteristics of examples discussed below were summarized in Table 3.

The fabrication of textile-based solar cells requires extensive material and structural engineering to obtain the desired flexible and wearable form factors. Opposed to traditional silicon-based photovoltaic materials, textile-based solar cells that rely on novel organic photovoltaic (OPV), dye-sensitized, and perovskite materials can be fabricated by solution compatible processes due to their thin-film nature which enables flexibility (Hatamvand et al., 2020; Li et al., 2015; Liu et al., 2018; Qiu et al., 2016; Xu et al., 2020). As shown in Figures 3A, one of the most common strategies of integrating solar cells on textile is through the functionalization of fibers and yarns, which can thereafter be woven or sewn into the fabric (Chen et al., 2016; Table 2. Summary of e-textile bio/chemical sensors including the sensor type, material, fabrication method, and washability reported in the literature

| Sensor type | Material | Fabrication | Ref. |
|-------------|----------|-------------|------|
| Biofluid (sweat) | PEDOT:PSS + thread | Dying | (Possanzini et al., 2020) |
| | nitrogen-doped porous structured carbon textile | Carbonization | (He et al., 2019) |
| | Au + nitrile | Mask printing | (Bariya et al., 2020) |
| | Ag + Ecoflex + Porous PVA Hydrogel + poly (ethylene terephthalate) (PET) | Mask printing | (Tang et al., 2021) |
| | MWCNT + Nitrile + Ag/AgCl | Mask printing | (Wang et al., 2018) |
| Chemical | MWCNT + ionic liquid | Screen printing | (Barfidokht et al., 2019) |
| | Spandex + SEBS + Ag/AgCl | Screen printing | (Goud et al., 2021) |
| | Ag/AgCl + synthetic rubber neoprene | Screen printing | (Malzahn et al., 2011) |
| | microneedles + carbon + bandage | Screen printing | (Cui et al., 2018) |
| | graphite composite + Ag/AgCl + catechol substrate | Printing | (Manjakkal et al., 2019) |
| | MntTPP + MR + BTB + PDMS | Dying | (Owyang et al., 2019) |
Li et al., 2015). Typical solar cells generate power with density up to hundreds of μW/cm² from outdoor lighting, and their voltage and current can be adjusted upon changing its serial or parallel connections. Another fabrication strategy involves the direct deposition of the photovoltaic material onto textile substrates, which involves various thin and thick-film deposition techniques such as screen printing, dip coating, or spray coating (Figures 3B) (Arumugam et al., 2016). The as-fabricated solar cells are intimately integrated with the textile and flexible (Figures 3C) (Arbab et al. 2016).

TEs made of various organic and inorganic thermoelectric materials have been used for harvesting energy from the temperature gradient between human body and the surrounding environment. As the temperature gradient ranges from 5 to 20 K between the human body and the surrounding, a single cell can only generate an extremely low voltage. TEs using n-type and p-type thermoelectric materials can be connected in serial to increase voltage and power (usually in the order of 10–10² mV, 10⁻¹–10³ pW). The power of TE varies with the load, with its ideal load equal to the internal resistance of the device. In addition to the serial connection, the direction of each p-n junction must be parallel with the temperature gradient, thus the design of the harvester requires skillful spatial arrangement. As shown in Figures 3D, the p-type material (PEDOT:PSS) and the n-type material (Poly[Na(NiETT)]) were arranged in a hexagonal layout and connected with a Hilbert curve to reach high fill factor of 30%, and the interconnections were printed to sequentially connect the n-type and p-type thermoelectric materials in series (Elmoughni et al., 2019).

Alternatively, the thermoelectric material can be extruded into fibers with segments of p-type materials (CNT) and n-type materials (PEI-CNT), which were weaved into textile to establish a hierarchical structure of p-n junctions and generate >80 pW power per square of textile (Figures 3E) (Ding et al., 2020).

PENG and TENG bioenergy harvesters scavenge energy produced by the human movements and metabolism, and hence do not rely on the external environment and can generate power on-demand. Invented by Wang et al., in 2006 (Wang and Song, 2006), PENGs scavenge energy from mechanical deformation of piezoelectric materials that induce charge separation within the material (Figures 3F) (Wang and Song, 2006). A wearable PENG based on inorganic materials such as ZnO and lead zirconate titanate (PZT), or organic materials such as poly(vinylidene fluoride-co-trifluoroethylene) PVDF-TrFE is able to generate nW-μW power with several to tens of V alternating voltage from daily human movements (Khan et al., 2012; Lee et al., 2012; Mokhtari et al., 2020; Wu et al., 2012). As an example, shown in Figures 3G, the piezoelectric PVDF which is melt-spun into microfibers and weaved into textile generates power from its bending, twisting, and pulling (Lund et al., 2018). TENGs harvest energy from the relative motion between two materials that have different electron affinities (Fan et al., 2012). The energy harvesting using TENG has a variety of configurations to harvest energy from vertical contact-separation or from lateral sliding, harvesting the charge movement between either one electrode and ground or between two electrodes (Figures 3H) (Dong et al., 2019). As all materials have a certain affinity to electrons, the selection of materials

| Harvester type | Material/Type | Fabrication | Features | Max power | Ref |
|---------------|--------------|-------------|----------|-----------|-----|
| Solar         | Cu, ZnO, Dye, Cu, PBT wire | Chemical plating/electroplating | Flexible | 0.4 mW | (Chen et al., 2016) |
|               | PCBM, Perovskite, PEDOT: PSS, CNT | Printed/coated (top down) | Flexible | 12.69 mA/cm² Jsc, 0.82 V Voc | (Jung et al., 2018) |
| BFC           | GOx + BOD on SWCNT-PEDOT: PSS yarn | Bi-scrolled yarn (bottom up) | Flexible | 1.5 mW/cm² | (Kwon et al., 2014) |
|               | LOx + Ag₂O on MWCNT | Printed, drop casting (top down) | Flexible, stretchable | 250 µW/cm² | (Chen et al., 2019; Lv et al., 2018) |
| PENG          | Carbon black, PVDF, polyethylene fiber | Melt-spin (bottom up) | Flexible, washable | 8 µW | (Lund et al., 2018) |
|               | PZT, Ag nanoparticles | Printed, die pressed (top down) | Flexible, washable | 0.45 µW/cm³ | (Almusallam et al., 2017) |
| TENG          | Cu/PtFE strips | Cut strips, woven (bottom up) | Flexible | 0.8 mW | (Chen et al., 2016) |
|               | Ni/Parylene | Electroless/chemical vapor deposition (top down) | Flexible, washable | 4 mW | (Pu et al., 2016b) |
| TEG           | SWCNT, PEI yarn | Colloidal gelation extrusion | Flexible, washable | 0.1 µW | (Ding et al., 2020) |
|               | PEDOT:SS, Na(NiETT), PVDF | Printed (top down) | Flexible, washable | 0.5 nW | (Elmoughni et al., 2019) |
Figure 3. Constituents of wearable energy systems

(A) Yarn-based photovoltaic cells and its integration into a solar-based textile (Chen et al., 2016; Li et al., 2015).
(B) Printed, sprayed, and embedded solar cell using textile substrate (Arumugam et al., 2016). (C) Textile fabric-based dye sensitized solar cell (Arbab et al., 2016).
(D) Printed and hot-pressed thermoelectric devices on textile substrate (Elmoughni et al., 2019).
(E) Yarn-based thermoelectric device and the assembly of the yarns into textile (Ding et al., 2020).
(F) Charge generation methods of piezoelectric materials (Dong et al., 2019).
(G) Yarn-based triboelectric materials weaved into textiles (Lund et al., 2018).
(H) Four modes of charge generation in triboelectric nanogenerators (Dong et al., 2019).
(I) Printed piezoelectric generator (Paosangthong et al., 2019; Wen et al., 2019).
(J) Illustration of the charge-generation mechanism of biofuel cells (Yin et al., 2021a).
(K) Yarn-based glucose biofuel cells (Kwon et al., 2014).
is rather unlimited, with common negative electrode materials selected from electron-rich materials such as PTFE, PVC, PE, PP, and PS, and common positive electrode materials selected from positively charged materials such as aluminum, nylon, and cellulosic materials (Fan et al., 2012). The triboelectric materials can be deposited onto flexible substrates such as textiles or fabricated into yarn-type materials that directly weaves into textiles (Figures 3I), and thus harvest energy from body movements (Chen et al., 2016; Paosangthong et al., 2019; Wen et al., 2019). Similar to PENGs, the power generated from the TENGs are in alternating high voltage (tens to hundreds of volts) and requires regulation before the generated energy can be harvested and stored.

BFC, a promising wearable energy harvester, collects energy form metabolites in human biofluids, such as glucose, urea, alcohol, and lactate. As lactate has the highest concentration in sweat, BFCs based on lactate have been widely studied (Bandodkar and Wang, 2016; Chen et al., 2019; Jeerapan et al., 2020). The lactate-based BFCs rely on enzyme catalytic oxidation reaction to convert lactate into pyruvate on the bioanode, which is complemented by oxygen reduction reaction on the cathode catalyzed by Pt or BCo (Figures 3J) (Jeerapan et al., 2020; Jia et al., 2014; Yin et al., 2021a). As the BFC operates based on the availability of lactate in sweat, high-intensity exercise is usually required to generate significant amount of sweat. Different from PENG and TENG-based harvesters, the sweat can be stored in reservoirs or hydrogels for subsequent use, hence allowing energy harvesting even after movement stops. The BFC can be fabricated into yarn form factor, or printed onto textile substrates, and integrated onto shirts or garments to harvest energy from human perspiration (Figures 3K–3L) (Jeerapan et al., 2016; Kwon et al., 2014).

Textile-based energy storage devices

The energy storage device on wearable e-textile systems can be generally classified into two types: batteries and supercapacitors, both relying on the storage of charges in electrochemical cells. In general, the battery stores energy based on the redox conversion of the anode and cathode materials or the intercalation and deintercalation of cations that shuttles between the anode and cathode hosts. The supercapacitors store energy based on surface reactions on capacitive and pseudocapacitive electrodes, and rely on high surface area materials for non-faradaic double-layer charge adsorption (e.g. CNT, graphene, and Mxene) and desorption and highly reversible redox materials (e.g. conductive polymers, Prussian blue analogs, and TMD) (Borenstein et al., 2017; Hu et al., 2020a; Ke and Wang, 2016; Manjakkal et al., 2020). The batteries feature high capacity and energy density, with slower reaction rate, whereas the supercapacitors support higher power density due to its high reaction rate, high cycle life, yet has lower energy density compared to batteries.

Wearable Li-ion batteries have been developed with good flexibility and stretchability endowed by structural innovations (Xu et al., 2013; Yin et al., 2018a). However, they are prone to overheating and explosion and are deemed less suitable for wearable applications. In contrast, Zn-based batteries are much safer, easy to fabricate, and have variability in form factors (Li et al., 2018b, 2018c; Mo et al., 2020; Parker et al., 2017). Paring with oxygen in the air or the oxides of Mn, Ag, and Ni as cathode, a wide selection of batteries that are flexible, stretchable, and wearable has been developed in printable, planar configuration or in wire or yarn configuration, readily to be integrated with wearable electronics (Figures 3M–3N) (Kumar et al., 2017; Li et al., 2018b, 2018c). Printable Zn-based batteries have achieved areal capacity up to 54 mAh/cm² and current of up to tens of mA, demonstrating the ability to steadily power various kinds of microcontrollers and integrated systems with display and sensing functionalities (Yin et al., 2021c). High capacitance supercapacitors have also been developed that can supply instant high power to electronics and be rapidly recharged. Conductive polymer (e.g. PEDOT-PSS, PPy, and PANi) or 2D-material-coated yarns can be used to fabricate textile supercapacitors with hierarchical structures (Figures 3O) (Anasori et al., 2017; Qu et al., 2016; Sun et al., 2016; Xu et al., 2017). Similarly, such capacitive or pseudocapacitive materials can be formulated into printable inks to print on textile, which can be combined with special structures (e.g. serpentines) for structural stretchability or with elastomeric binders which endows intrinsic stretchability (Figure 3P) (Pu et al., 2016a).
Integration of textile-based energy devices

With the development of various textile-based energy harvesters and storage devices, integrating different kinds of energy devices is a promising method to achieve unprecedented performance. Specifically, integrating different energy storage mechanisms enables both high power density and high energy density (Forouzandeh et al., 2020; Zuo et al., 2017). As examples, Figures 4A and 4B show several kinds of textile-based battery-supercapacitor hybrid devices based on VO2 and Ni-Co selenide, respectively (Sahoo et al., 2019; Wang et al., 2020a). These devices allow rapid charge and discharge due to the use of highly redox-reversible pseudocapacitive transition metal oxides and dichalcogenides, and able to maintain relatively high energy density.

Likewise, the hybridization of energy harvester has also been widely explored (Chen et al., 2016; Lee et al., 2016; Li et al., 2020b; Ryu et al., 2019; Xu et al., 2021; Yin et al., 2021a). The integrations have been demonstrated on harvesters with similar working mechanisms, such as PENGs and TENGs (Song et al., 2018; Zhang et al., 2015b; Zhu et al., 2019), and harvesters with different working mechanisms, such as TENGs and photovoltaic materials (Chen et al., 2016; Pu et al., 2016b). As Figures 4C–4D show, a textile-based hybrid harvester integrates solar cells and TENGs to scavenge energy from two different sources, which enhances the system reliability when one of the energy sources is unavailable (Chen et al., 2016; Pu et al., 2016b).

To further enhance system reliability, energy storage devices are integrated with energy harvesters. Energy sources for wearable harvesters are highly irregular and uncontrollable, thus the storage units are required to store or output energy on-demand. Furthermore, the storage units are able to discharge at high current which the harvesters alone cannot supply, allowing utilization of high-power electronics on e-textiles. As shown in Figures 4E–4G, examples such as integrating solar cells, TENG, and BFC with supercapacitors on textile were explored, respectively (Chai et al., 2016; Lv et al., 2018; Pu et al., 2015; Wen et al., 2016). Such integration allows the energy harvested under sunlight or during movements to be stored for later use after the supply of sunlight, movements, or sweat stopped, hence extended the operation time of any electronics that may be powered by these harvesters.

Implementing these concepts, many self-powered, autonomous systems that incorporate energy harvesters, storage, power management circuits, data acquisition, and transmission electronics have recently been reported (Song et al., 2020; Yin et al., 2021a; Yu et al., 2020). Many works utilize a similar power utilization system, which stores the energy generated in capacitors or supercapacitors, and releases such stored energy in pulses to power microcontrollers or system-on-chips to perform the data acquisition-processing-transmission cycle within a few hundred milliseconds. System powered by BFC arrays or TENG has been reported to transmit sensing data of glucose, urea, temperature, or pH of sweat to cell phones without any external power supply (Song et al., 2020; Yu et al., 2020). Alternatively, e-textile system that

Table 4. Selected examples of various textile-based energy harvesters fabricated via top-down and bottom-up strategies

| Storage type | Material | Fabrication | Features | Capacity | Example |
|--------------|----------|-------------|----------|----------|---------|
| Li-ion battery | Graphite, LiCoO2 | Chemical plating/electroplating | Flexible, washable | 25 mAh/m | (He et al., 2021) |
| | Li4Ti5O12, LiFePO4, denka black | Electroless deposition, Slurry coating | Flexible | 13 mAh | (Lee et al., 2013) |
| Zn battery | MnO2, CNT, Zn | Coated yarn (bottom-up) | Flexible, stretchable | 1.5 mAh/cm | (Li et al., 2018c) |
| | Ag2O, Zn, Super-P | Printed, drop casting (top down) | Flexible, stretchable | 2.5 mAh/cm² | (Kumar et al., 2017) |
| Supercapacitors | Reduced graphene oxide (rGO), Ni, Polyester | Melt-spun (bottom up) | Flexible | 13 mF/cm | (Pu et al., 2015) |
| | COOH-CNT/MnO2-CNT, PEDOT:PSS | Printed (top down) | Flexible, stretchable | ~100 mF/cm² | (Lv et al., 2018) |

Table 4 summarizes the key characteristics, structure, and fabrication of selected examples as discussed above.
combines several harvesters and storage devices has been explored, aiming to establish a microgrid-on-shirt, and display the sensing result using electrochromic display directly, hence further removing the need for external mobile devices (Yin et al., 2021a; 2021b). Currently, as the energy scavenged from the harvesters is still limited in microwatt range, the functionality of the integrated systems is rather limited, compatible to only open-circuit potentiometric-based sensors. The integrated system also relies on inconvenient power input, such as exercises or direct sunlight, thus impeding the practicality of the device. Further improvement in the increasing power of on-body harvester while reducing the requirement for energy input is needed to truly expand the practicality and reliability of such self-powered systems.

**WIRELESS COMMUNICATION FOR E-TEXTILE SYSTEM**

Over the past decades, developments in materials and fabrication methods have yielded a wide range of sensors that can be implanted in the body (Stuart et al., 2021), attached on the skin (Tricoli et al., 2017), and integrated into textiles (Hatamie et al., 2020) to acquire physiological signals. Textiles, as the second human skin, provide a unique platform for integrating wireless functionality (Heo et al., 2018; Shi et al., 2020).
and eventually establishing a digital communication network that wirelessly interconnects these sensors with the digital world (Xie et al., 2020). Unlike direct wiring method that is widely used in clinical and research settings, such a wireless communication network enables continuous health monitoring without temporal and spatial restraint (Cao et al., 2009; Cui et al., 2019; Liang and Yuan, 2016). In this section, we will introduce the mechanism of wireless communication, integration of wireless module with textiles, textile antennas, and textile-based body sensor networks. We briefly summarize typical materials, fabrication methods, and features of textile-integrated wireless modules in Table 5.

Wireless communication transfers information between two or multiple devices through electromagnetic field (“RFID Handbook,” 2010). Near-field communication (NFC) and Bluetooth are the most widely used approaches. In these wireless technologies, the reader antenna generates a time-varying magnetic field, which develops a time-varying electric field by electromagnetic induction, and mutual dependence of these time-varying fields generates a chain effect of electric and magnetic fields in space. In the near-field, at where the distance between the reader and the transponder is within the wavelength of electromagnetic field, wireless interconnection is achieved through inductive coupling (Figure 5A). In the far field, such interconnection is established through backscatter coupling at where a small proportion of emitted electromagnetic field reflected by the responder is received by the reader antenna (Figure 5B). The transponder microprocessor converts the data stream to switch on and off the load resistor connected with the antenna, which affects the inductive coupling or backscatter coupling and eventually transmit the data to the reader (“RFID Handbook,” 2010).

Advancement on CMOS technology has enabled minimization of electronics and incorporation of wireless modules into tiny chips with millimeter dimensions. Integrating embedded chips and passive components directly on textile remains a challenge and requires innovation on electronic materials and fabrication methods. Alternatively, a flexible printed circuit board (PCB) is used to assemble all electronics and then physically attached or adhered on textile (Mishra et al., 2018; Niu et al., 2019). The wireless module can be further connected with sensors wirelessly or wired. In the wireless approach, the sensor is part of the passive LC circuit and converts the sensing signal to resonant frequency shift or magnitude variation (Figure 5C) (Nie et al., 2019; Niu et al., 2019). As there is no physical connection, the sensor can not only be on textile (Nie et al., 2019) but also on skin and even implanted in deep tissue (Boutry et al., 2019; Yeon et al., 2019). The LC circuit can be free of fragile silicon-integrated circuits and completely soft, offering a conformal skin-mimicking interface. However, the inductive coupling between the wireless module and sensor may be affected by surrounding environment such as moisture, human touch, and relative motion, and thus eventually affect data accuracy (Huang et al., 2016; “RFID Handbook,” 2010). The wired method is generally used to connect the wireless module with textile-integrated sensors (Figure 5D) (Kassal et al., 2018; Mishra et al., 2018). These textile-integrated systems are wearable version of bench-top devices and able to employ most conventional methods such as electrochemical, electrical, and optical measurement to detect various kinds of physiological and biochemical signals (Kassal et al., 2018).

Even though minimization makes wearable electronics to be less obtrusive for users, miniaturizing antennas, the critical component for wireless communication, generally deteriorates antenna performance. Instead, textile antenna, which is composed of a textile conductive element and another textile material acting as substrate, is a promising candidate for constructing unobtrusive wearable communication network (Ali et al., 2020; Alonso-Gonzalez et al., 2019; Kennedy et al., 2009; Roh et al., 2010). Utilizing textile

| Table 5. Typical textile-integrated modules for wireless communication |
|---------------------------------|-----------------|----------------|-----------------|------------------|
| **E-textile for wireless communication** | **Material** | **Fabrication** | **Features** | **Ref** |
|---------------------------------|-----------------|----------------|-----------------|------------------|
| Textile attached modules | Metal on polymer substrate | Printing, etching | Flexible | (Mishra et al., 2018; Niu et al., 2019) |
| Textile antennas | Metal nanomaterial | Printing, coating Embroidery | Flexible | (Lin et al., 2020) |
| Body networks | Conductive fabric | Laser cutting | Flexible, washable | (Tian et al., 2019) |
material enables antennas to be thin, lightweight, flexible, robust, inexpensive, and easily integrated into a garment, thus making the textile antennas comfortable for wear and durable for long-term usage (Figure 5E) (Ali et al., 2020; Xu et al., 2019). Antenna performances such as radiation pattern, gain, resonant frequency, and bandwidth are significantly affected by material characteristics (Brebels et al., 2004; Koski et al., 2014; Salvador et al., 2012). For instance, antenna bandwidth and efficiency are significantly affected by permittivity and thickness of the dielectric substrate. In general, textiles present a very low dielectric constant with relative permittivity close to one as they are very porous materials. As the porous structure can be easily deformed by bending and stretching, and can facilitate air exchange with moisture under the effect of environmental temperature and humidity, the textile’s permittivity may change dynamically and result in unstable antenna performance. The textile conductive threads generally have much lower electrical conductivity compared with metal tracks, resulting in high power loss and low antenna efficiency (Salvador et al., 2012). Innovation in material, fabrication process, and antenna design could enable textile antenna performance similar to that of conventional metal antenna and even maintain performance under various circumstances such as mechanical deformation and harsh environmental factors (Figure 5F) (Kiourti and Volakis, 2015; Lilja et al., 2012; Wang et al., 2012, 2014).

Near-field-enabled clothing relies on inductive coupling to establish wireless power and data connectivity around the human body (Figure 5G) (Lin et al., 2020). Specifically, the near-field-enabled clothing is fabricated by using computer-controlled embroidery to integrate low-cost conductive threads in textiles with near-field-responsive inductor patterns. By placing devices near to these patterns, the time-varying magnetic field generated by the reader such as smartphone can be transferred to other connected patterns with meter-scale distance from the hub (proximity to the reader) and then to the respective sensor nodes. Metamaterial textiles which are clothing structured with conductive textiles can support surface-plasmon-like modes at communication frequencies and thus provide a platform for the propagation of radio waves around the body (Figure 5H) (Tian et al., 2019). When standard wireless devices are placed near metamaterial textiles, their interconnection can be achieved through the propagation of wireless signals as surface waves instead of wireless signals radiating into the surrounding space. Both the near-field-enabled clothing and metamaterial textiles transfer the wireless signal across conductive textile other than over air, enabling the network to operate with high efficiency. The physical localization of wireless signals on body surface ensures the networks immune to interference and inherently secure. In contrast with prior efforts to integrate wireless modules into textiles, the near-field-enabled clothing and metamaterial textiles do not incorporate fragile silicon-integrated circuits or require physical connectors with nearby devices, they are entirely fabric-based and are robust to daily wear.

**CONDUCTORS FOR E-TEXTILES**

Electrical conductor that can be integrated on textiles, term textile conductor, is a critical component to interconnect discretely distributed modules around human body and form an independent e-textile system (Mulatier et al., 2018; Wang and Facchetti, 2019). Textile conductors should not only have high electrical conductivity as metal conductors to form a power bus and data network but also maintain conventional textile properties to enable durable and comfortable wearing, thus require innovation on both material and fabrication methods.
Integrating conductive threads

Coating conductive material

Before washing

After washing

Washability

Conductivity (S cm⁻¹)

Stretchability

Permeability
Several methods have been developed to fabricate textile conductors and can be classified into two categories. One is to integrate conductive threads on textile by using conventional textile methods such as knitting, weaving, sewing, and embroidering (Figure 6A) (Ismar et al., 2020; Mohamadzade et al., 2019; Roh, 2017, 2018; Sanchez et al., 2021; Tsolis et al., 2014). The conductive threads include commercially available yarn such as metal-plated, metal filament, and stainless-steel yarns, and polymer threads functionalized with nanomaterial such as nanowires, nanoparticles, and carbon material. While these integration processes are completely solvent-free and compatible with the conventional textile fabrication equipment and largely maintain textile properties, they generally only achieve millimeter-scale pattern resolution, and the threads are subjected to serious mechanical deformation during fabrication.

The other method is to functionalize textiles with conductive material through printing, coating, or deposition (Figure 6B) (Andrew et al., 2018; Jin et al., 2017; Mohamadzade et al., 2019; Wang and Facchetti, 2019). As textiles are 3D porous structures consisting of a network of interconnected fibers or yarns, these methods create conductive paths on the textiles by filling the voids or the network with conductive ink, paste, or precursor, followed by thermal curing or reaction to form metal composite/coating. While the metal conductive paths can achieve high electrical conductivity, they generally stiffen the textile, block moisture, and are vulnerable to crack or delamination under mechanical deformation.

To implement textile conductors on durable and comfortable wearing, innovation of material and fabrication methods should enable textile conductors with several distinct properties. The textile conductors should maintain high electrical conductivity under repeatable mechanical deformation as they are subjected to stretching, bending, and washing frequently. Pure metallic conductors such as metallic filament yarns generally have low yield point, and thus susceptible to breakage under bending/washing (Figure 6C) (Hardy et al., 2020). Metallic composites consist of conductive fillers added into a polymer matrix to increase the yield strain, which confers the conductor’s stretchability at the cost of decreased electrical conductivity (Figure 6D) (Jin et al., 2017; Lee et al., 2015; Matsuhisa et al., 2015, 2017). Achieving high electrical conductivity with robustness remains a key challenge for textile conductors. To maintain wearable comfortability of textile, the textile conductor should also be lightweight, breathable, and flexible. As such, the textile should maintain its 3D porous structure after functionalized with conductive materials (Figure 6E) (Kim et al., 2019a; Wu et al., 2018). Finally, the textile conductors should have an insulating layer to protect the wearer and prevent the circuit from effects of temperature, sweat, moisture, and accidental splash (Yin et al., 2018b).

CONCLUSIONS

Owing to their considerable potential for wide application in various fields, e-textile systems have attracted much attention from researchers. These applications include physical, chemical, and biological sensing, energy harvesting, storage, and data interfacing with other smart devices. Studies conducted on e-textiles include washability, nontoxicity, biocompatibility, and mechanical performance, all of which are crucial toward practical applications. Nevertheless, limitations still exist in e-textile systems that impede their development as commercial consumer products.

Limitations of e-textile sensors

Firstly, the quality and repeatability of e-textile sensors are difficult to control. Compared with ordinary electronics, the dimension of electronics in e-textiles are comparatively smaller, so that flexibility and wearability can be achieved. However, the small size of these fibers or thin layers of coating may make the high quality and repeatability difficult to achieve. Most of the reported smart e-textiles are produced in lab and only at the “proof of concept” stage, without taking quality and repeatability of the sensor into consideration.

Secondly, there is lack of mass production capability. Most of the smart e-textiles are produced in lab by hand. On the other hand, most of these e-textiles are produced either using expensive materials or with complicated fabrication method, which may lead to high production cost and less acceptable by the market. Thus, mass production capability is difficult to achieve for most of the laboratory produced e-textiles.
Thirdly, there is lack of standardization. Even for the same application, different e-textile sensors may have different testing range, resolution, cycle life, hysteresis, and other aspects owing to different materials used, fabrication methods, and working mechanism behind different e-textiles. As such, it is difficult to evaluate or compare the different e-textiles. In order to make e-textile commercially available in the future, standard evaluation system is necessary at least for e-textile with mainstream production methods.

Furthermore, the functionality of some e-textile sensors, especially for bio/chemical sensors, relies highly on reactants that have been integrated in the textile. This may lead to the issue that once the reactants have depleted to a certain level, these e-textile sensors will lose the sensing capability before the reactants are being replenished.

In addition, lacking of compatible technologies may also hinder the development of e-textile sensors. Most of the reported e-textiles are mainly focused on one single component, sensor, energy harvester, or connection. However, every single component cannot work by itself but requires other compatible technologies to support it. For example, some of the e-textiles sensors may require high power energy device, which may not be currently available in the e-textile market. In order to use these e-textile sensors, a bulky battery may need to be connected to the sensor, thus affecting the flexibility and wearability of e-textiles.

**Limitations of e-textile energy harvesters and storage systems**

Energy harvesting still remains the most significant bottleneck for the energy self-sufficiency of the wearable electronics ecosystem, as the energy generated for practical use is only able to power electronics in very limited applications. We envision future developments in novel materials (e.g. 2D materials, conductive polymers, and high-entropy alloys), fabrication methods, and device structures in existing e-textile energy harvesters to bring improvements in performance, wash-durability, and stretchability. Furthermore, as more energy harvesting mechanisms are explored, energy harvesting system that works in more diverse environment and scenarios may be made available to diversify the energy input to e-textile systems.

Current energy storage is limited by their energy density, power density, and cycle life (Yin et al., 2021c). Hence, the functionality of e-textile systems is limited not only by their performance but also their need for frequent recharge. Although some attention has been directed to incorporate energy harvesters in wearable systems, their power is generally limited, and no harvesters are yet commercially available for use in e-textiles. Nevertheless, the concept of wearable microgrid has been proposed recently, advocating the critical budgeting of energy and power in e-textile systems to enhance the practicality and reliability of wearable energy systems, and its development will rely on multidisciplinary collaboration to make it a success (Yin et al., 2021a; 2021b).

**Limitations of e-textile communication systems**

Textiles have been demonstrated as a unique platform for integrating wireless functionalities and bridging the human body with surrounding physical world without temporal and spatial constraints. To enable public acceptance of wireless e-textiles as conventional clothing, several key challenges still remain and need to be overcome.

Firstly, material and manufacturing innovations are required to seamlessly integrate wireless functionalities into conventional textiles to achieve both high performance on wireless communication and durability/comfortability for wearing. For example, textile conductive materials are the basic elements for textile antennas. However, current textile conductive materials are either limited to low electrical conductivity, which seriously affected the wireless powering transfer efficiency, or low mechanical robustness, which causes e-textiles to lose their functionalities during daily wearing or washing.

Secondly, novel wireless technologies are required to build a secure wireless network between multiple devices distributed on textiles, skin, and even inside the body. Such a network would enable continuous monitoring of physiological signals that are once invisible and achieve clinical quality data outside the hospital. Power and data must be transmitted reliably across those devices during daily activities without temporal and spatial constraints. The network should also be highly secured against eavesdropping to maintain personal data privacy.
To sum up, e-textile is a unique platform that can provide tremendous value to applications such as personalized healthcare, robotics, virtual/augmented reality, and human-machine interface. There are tremendous opportunities in building innovative e-textile products that can revolutionize our lifestyles and eventually the way people conceptualize clothing and textiles. As such, the potential is there for e-textile to become a disruptive technology. However, to develop a complete e-textile product, researchers need to focus not only on the development of individual components but also on the seamless integration of these different components into a complete system with compatible form factors that confer comfort and wearability. We just need to continually engage industrial collaborators and investors to eventually transform lab-ready prototypes into commercially viable products.

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DECLARATION OF INTERESTS

The authors declare no conflict of interest.

REFERENCES

Abadal, G., Alda, J., and Agusti, J. (2014). Electromagnetic Radiation Energy Harvesting – The Rectenna Based Approach. In ICT - Energy - Concepts Towards Zero - Power Information and Communication Technology. G. Fagas, L Gammaitoni, D. Paul, and G.A. Berin, eds (IntechOpen).

Abid, Sehrawat, P., Julien, C.M., and Islam, S.S. (2020). WS2 quantum dots on e-textile as a wearable photodetector: how well reduced graphene oxide can serve as a carrier transport medium? ACS Appl. Mater. Interfaces 12, 39730–39744. https://doi.org/10.1021/acsami.0c08028.

Ali, S.M., Sovuthy, C., Imran, M.A., Socheatra, S., Abbasi, Q.H., and Abidin, Z.Z. (2020). Recent advances of wearable antennas in materials, fabrication methods, designs, and their applications state-of-the-Art. Micromachines 11, 888. https://doi.org/10.3390/mi11100888.

Almusallam, A., Luo, Z., Komolafe, A., Yang, K., Robinson, A., Torah, R., and Beeby, S. (2017). Flexible piezoelectric nano-composite films for kinetic energy harvesting from textiles. Nano Energy 33, 146–156. https://doi.org/10.1016/j.nanoen.2017.01.037.

Alonso-Gonzalez, L., Ver-Hoeve, S., Vazquez-Antuna, C., Fernandez-Garcia, M., and Andres, F.L.H. (2019). Multifunctional fully textile-integrated RFID tag to revolutionize the internet of things in clothing [wireless corner]. IEEE Antennas Propagation Mag. 61, 104–110. https://doi.org/10.1109/MAP.2019.2907910.

Anasori, B., Lukatskaya, M.R., and Gogotsi, Y. (2017). 2D metal carbides and nitrides (MXenes) for energy storage. Nat. Rev. Mater. 2, 1–17. https://doi.org/10.1038/natrevmats.2016.98.

Andrew, T.L., Zhang, L., Cheng, N., Bairma, M., Kim, J.J., Allison, L., and Hoxie, S. (2018). Melding vapor-phase organic chemistry and textile manufacturing to produce wearable electronics. Acc. Chem. Res. 51, 850–859. https://doi.org/10.1021/acs.accounts.7b00604.

Arbab, A.A., Sun, K.C., Sahito, I.A., Memon, A.A., Choi, Y.S., and Jeong, S.H. (2016). Fabrication of textile fabric counter electrodes using activated charcoal doped multi walled carbon nanotube hybrids for dye sensitized solar cells. J. Mater. Chem. A 4, 1495–1505. https://doi.org/10.1039/c5ta08858e.

Arumugam, S., Li, Y., Senthilarasu, S., Torah, R., Kanibolotsky, A.L., Inigo, A.R, Skabara, P.J., and Beeby, S.P. (2016). Fully spray-coated organic solar cells on woven polyester cotton fabrics for wearable energy harvesting applications. J. Mater. Chem. A 4, 5561–5568. https://doi.org/10.1039/C5TA03389F.

Bandodkar, A.J. (2017). Review—wearable biofuel cells: past, present and future. J. Electrochem. Soc. 164, H3007–H3014. https://doi.org/10.1149/2.0031703jes.

Bandodkar, A.J., O’Mahony, A.M., Ramirez, J., Samek, I.A., Anderson, S.M., Windmiller, J.R., and Wang, J. (2013). Solid-state Forensic Finger sensor for integrated sampling and detection of gunshot residue and explosives: towards ‘Lab-on-a-finger’. Analyst 138, 5288–5295. https://doi.org/10.1039/C3AN01179H.

Bandodkar, A.J., and Wang, J. (2016). Wearable biofuel cells: a review. Electroanalysis 28, 1188–1200. https://doi.org/10.1002/ean.201600019.

Barfizdkht, A., Mishra, R.K., Seenivasan, R., Liu, S., Hubble, L.J., Wang, J., and Hall, D.A. (2019). Wearable electrochemical glove-based sensor for rapid and on-site detection of fentanyl. Sens. Actuators B Chem. 296, 1256422. https://doi.org/10.1016/j.snb.2019.04.053.

Barya, M., Li, L., Ghattamaneni, R., Ahn, C.H., Nyein, H.Y.Y., Tai, L.C., and Javey, A. (2020). Glove-based sensors for multimodal monitoring of natural sweat. Sci. Adv. 6, eabb8308. https://doi.org/10.1126/sciadv.abb8308.

Bell, L.E. (2008). Cooling, heating, generating power, and recovering waste heat with thermoelectric systems. Science 321, 1457–1461. https://doi.org/10.1126/science.1158899.

Bi, S., Hou, L., Zhao, H., Zhu, L., and Lu, Y. (2018). Ultrastensive and highly repeatable pen ink decorated cuprammonium rayon (cupra) fabrics for multifunctional sensors. J. Mater. Chem. A 6, 16556–16565. https://doi.org/10.1039/C8TA04809F.

Borenstein, A., Hanna, O., Attias, R., Luski, S., Brousse, T., and Aurbach, D. (2017). Carbon-based composite materials for supercapacitor electrodes: a review. J. Mater. Chem. A 5, 12653–12672. https://doi.org/10.1039/C7TA00863E.

Boutry, C.M., Beker, L., Kaizawa, Y., Vassos, C., Tran, H., Hinckley, A.C., Pfattner, R., Niu, S., Li, J., Claverie, J., et al. (2019). Biodegradable and flexible arterial-pulse sensor for the wireless monitoring of blood flow. Nat. Biomed. Eng. 3, 47–57. https://doi.org/10.1038/s41551-018-0336-5.

Brebels, S., Ryckaert, J., Combe, B., Donnay, S., De Raedt, W., Beyne, E., and Mertens, R.P. (2004). SOP integration and codesign of antennas. IEEE Trans. Adv. Packaging 27, 341–351. https://doi.org/10.1109/TADVP.2004.829922.

Cai, G., Yang, M., Xu, Z., Liu, J., Tang, B., and Wang, X. (2017). Flexible and wearable strain sensing fabrics. Chem. Eng. J. 325, 396–403. https://doi.org/10.1016/j.cej.2017.05.091.

Cao, H., Leung, V., Chow, C., and Chan, H. (2009). Enabling technologies for wireless body area

iScience 25, 104174, May 20, 2022 19
networks: a survey and outlook. IEEE Commun. Mag. 47, 84–93. https://doi.org/10.1109/MCOM.2009.5350373.

Carneiro, M. R. de Almeida, A. T., and Takahashi, M. (2020). Wearable and comfortable e-textile headband for long-term acquisition of forehead EEG signals. IEEE Sens. J. 20, 15107–15116. https://doi.org/10.1109/JSEN.2020.3009629.

Castano, L. M., and flatsau, A. B. (2014). Smart fabric sensors and e-textile technologies: a review. Smart Mater. Struct. 23, 053001. https://doi.org/10.1088/0964-1726/23/5/053001.

Chai, Z., Zhang, N., Sun, P., Huang, Y., Zhao, C., Fan, H. J., Fan, X., and Mai, W. (2016). Tailorable and wearable textile devices for solar energy harvesting and simultaneous storage. ACS Nano 10, 9201–9207. https://doi.org/10.1021/acsnano.6b05293.

Chen, J., Huang, Y., Zhang, N., Zou, H., Liu, R., Tao, C., Fan, X., and Wang, Z.-L. (2016). Micro-cable structured textile for simultaneously harvesting solar and mechanical energy. Nat. Energy 1, 16138. https://doi.org/10.1038/nenergy.2016.138.

Chen, X., Yin, L., Lu, J., Gross, A. J., Le, M., Gutierrez, N. G., Li, Y., Jeerapan, I., Goud, K. Y., Tian, Z. Q., and Lin Wang, Z. (2012). Tailorable thermoelectric generator for body heat harvesting and simultaneous storage. Adv. Funct. Mater. 22, 1905785. https://doi.org/10.1002/adfm.2011095785.

Chun, K. S., Bhattacharya, S., and Thomas, E. (2018). Detecting eating episodes by tracking jawbone movements with a non-contact wearable sensor. Proc. ACM Interact. Mob. J. 20, 1905785. https://doi.org/10.1145/3191736.

Fan, F. R., Tian, Z. Q., and Lin Wang, Z. (2012). Flexible triboelectric generator. Nano Energy 1, 328–334. https://doi.org/10.1016/j.nanoen.2012.01.004.

Fan, W., He, Q., Meng, K., Tan, X., Zhou, Z., Zhang, G., Yang, J., and Wang, Z.-L. (2020). Machine-knitted washable sensor array textile for precise epidermal physiological signal monitoring. Sci. Adv. 6, eaaay2840. https://doi.org/10.1126/sciadv.ay2840.

Fernández-Camáis, T. M., and Fraga-Lamas, P. (2018). Towards the internet of smart clothing: a review on IoT wearables and garments for creating intelligent environments. Electronics 7, 405. https://doi.org/10.3390/electronics7120405.

Forouzandeh, P., Kumaravel, V., and Pilai, S. C. (2020). Electrode materials for supercapacitors: a review of recent advances. Catalysts 10, 969. https://doi.org/10.3390/catal10050969.

Gong, Z., Xiang, Z., OuYang, X., Zhang, J., Lau, N., Zhou, J., and Chan, C. C. (2019). Wearable fiber optic technology based on smart textile: a review. Materials 12, 3511. https://doi.org/10.3390/ma12033511.

Goud, K. Y., Sandhu, S. S., Teymourian, H., Yin, L., Tostado, N., Rauhild, F. M., Harvey, S. P., Moores, L. C., and Wang, J. (2021). Textile-based wearable solid-contact flexible fluoride sensor toward biodetection of G-type nerve agents. Biosens. Bioelectron. 182, 112312. https://doi.org/10.1016/j.bios.2021.112312.

Hardy, D. A., Rahemtulla, Z., Satharasinghe, A., Shihadi, A., Oliveira, C., Anastassopoulos, I., Nashed, M. N., Kajtazov, M., Komolafe, A., Torah, R., et al. (2020). Wash testing of electronic yarn. Materials 13, 1228. https://doi.org/10.3390/ma13051228.

Hashemi, S. A., Ramakrishna, S., and Aberle, A. G. (2020). Recent progress in flexible–wearable solar cells for self-powered electronic devices. Energy Environ. Sci. 13, 685–743. https://doi.org/10.1039/C9EE03046H.

Hatamie, A., Angoi, S., Kumar, S., Pandey, C. M., Simchi, A., Willander, M., and Malhotra, B. D. (2020). Review—textile based chemical and physical sensors for healthcare monitoring. J. Electrochem. Soc. 167, 035746. https://doi.org/10.1149/1.1851171.

He, J., Lu, C., Jiang, H., Han, F., Shi, X., Wu, J., Wang, L., Chen, T., and Wang, J., et al. (2021). Scalable production of high-performing woven lithium-ion fiber batteries. Nature Energy 7, 14069. https://doi.org/10.1038/s41560-020-04640-9.

Heo, J. S., Eom, J., Kim, Y.-H., and Park, S. K. (2019). Recent progress of textile-based wearable electronics: a comprehensive review of materials, devices, and applications. Small 15, 1703034. https://doi.org/10.1002/smll.201703034.

Hindley, A. C., Andrews, S. C., Dunham, M. T., Sood, A., Barako, M. T., Schneider, S., Toney, M. F., Goodson, K. E., and Bao, Z. (2021). Achieving high thermoelectric performance and metallic transport in solvent-sheared PEDOT:PSS. Adv. Electron. Mater. 7, 2001190. https://doi.org/10.1002/aelm.202001190.

Hu, M., Zhang, H., Hu, T., Fan, B., Wang, X., and Li, Z. (2020a). Emerging 2D MXenes for supercapacitors: status, challenges and prospects. Chem. Soc. Rev. 49, 6666–6693. https://doi.org/10.1039/D0CS0175A.

Hu, X., Huang, T., Liu, Z., Wang, G., Chen, D., Guo, Q., Yang, S., Jin, Z., Lee, J.-M., and Ding, G. (2020b). Conductive graphene-based E-textile for highly sensitive, breathable, and water-resistant multimodal gesture-distinguishable sensors. J. Mater. Chem. A 8, 14778–14787. https://doi.org/10.1039/D0TA04915H.

Huang, Q., Dong, L., and Wang, L. (2016). LC passive wireless sensors toward a wireless sensing platform: status, prospects, and challenges. J. Microelectromech. Syst. 25, 822–841. https://doi.org/10.1109/JMEMS.2016.2602298.

Islam, G. M. N., Ali, A., and Collie, S. (2020). Textile sensors for wearable applications: a comprehensive review. Cellulose 27, 6103–6131. https://doi.org/10.1007/s10570-020-03215-5.

Ismar, E., Tao, X., Rault, F., Dassonville, F., and Cochran, E. (2020). Towards embroidered circuit board from conductive yarns for E-textiles. IEEE Access 8, 155329–155336. https://doi.org/10.1109/ACCESS.2020.3019759.

Jeerapan, I., Sempionatto, J. R., Pavinatto, A., You, J.-M., and Wang, J. (2016). Stretchable biofuel cells as wearable textile-based self-powered sensors. J. Mater. Chem. A 4, 18342–18353. https://doi.org/10.1039/C6TA03583G.

Jeerapan, I., Sempionatto, J. R., and Wang, J. (2020). On-body bioelectronics: wearable biofuel cells for bioenergy harvesting and self-powered biosensing. Adv. Funct. Mater. 30, 1906243. https://doi.org/10.1002/adfm.201906243.

Jia, T., Wang, Y., Dou, Y., Liu, Y., de Andrade, M. J., Wang, R., Fang, S., Lu, J., Yu, Z., Qiao, R., et al. (2019). Moisture sensitive smart yarns and textiles from self-balanced silk fiber muscles. Adv. Funct. Mater. 29, 1808241. https://doi.org/10.1002/adfm.201808241.

Jia, W., Wang, X., Imani, S., Bandodkar, A. J., Ramirez, J., Mercier, P. P., and Wang, J. (2014). Wearable textile biofuel cells for powering electronics. J. Mater. Chem. A 2, 18184–18189. https://doi.org/10.1039/C4TA04796F.

Jin, H., Matsushita, N., Lee, S., Abbas, M., Yokota, T., and Someya, T. (2017). Enhancing the performance of stretchable conductors for E-textiles by controlled ink permeation. Adv. Mater. 29, 1605848. https://doi.org/10.1002/adma.201605848.

Jung, J. W., Bae, J. H., Ko, J. H., and Lee, W. (2018). Fully solution-processed indium tin oxide-free textile-based flexible solar cells made of an...
organic-inorganic perovskite absorber toward a wearable power source. J. Power Sour. 402, 327–332. https://doi.org/10.1016/j.jpowsour.2018.09.038.

Kassal, P., Steinberg, M.D., and Steinberg, I.M. (2018). Wireless chemical sensors and biosensors: a review. Sens. Actuators B: Chem. 266, 228–245. https://doi.org/10.1016/j.snb.2018.03.074.

Ke, Q., and Wang, J. (2016). Graphene-based materials for supercapacitor electrodes – a review. J. Materiomics 2, 37–54. https://doi.org/10.1016/j.jmatr.2016.01.011.

Kennedy, T.F., Fink, P.W., Chu, A.W., Champagne, N.J., Lin, G.Y., and Khayat, M.A. (2009). Body-worn E-textile antennas: the good, the low-mass, and the conformal. IEEE Trans. Antennas Propagation 57, 910–918. https://doi.org/10.1109/TAP.2009.2104602.

Khan, A., Ali Abbas, M., Hussain, M., Hussain Ibupoto, Z., Wissting, J., Nur, O., and Willander, K. (2012). Piezoelectric nanogenerator based on zinc oxide nanorods grown on textile cotton fabric. Appl. Phys. Lett. 101, 195306. https://doi.org/10.1063/1.4766921.

Kim, I., Shaharir, H., Ingram, W.F., Zhou, Y., and Jur, J.S. (2019a). Inkjet process for conductive patterning on textiles: maintaining inherent stretchability and breathability in knit structures. Adv. Funct. Mater. 29, 1807573. https://doi.org/10.1002/adfm.201807573.

Kim, K., Jung, M., Jeon, S., and Bae, J. (2019b). Robust and scalable three-dimensional spacer geometrical-accuracy embroidery process for wearable electronics. Adv. Mater. 31, 5753–5761. https://doi.org/10.1002/adma.201803860.

Li, B., Xiao, G., Li, F., Qiao, Y., Li, C.M., and Lu, Z. (2016a). A flexible humidity sensor based on silk fabrics for human respiration monitoring. J. Mater. Chem. C 6, 4549–4554. https://doi.org/10.1039/C6TC0238J.

Li, H., Han, C., Huang, Y., Huang, Y., Zhu, M., Pei, Z., Xue, Q., Wang, E., Wang, L., Zhang, T., et al. (2018b). An extremely safe and wearable solid-state zinc ion battery based on a hierarchical structured polymer electrolyte. Energy Environ. Sci. 11, 941–951. https://doi.org/10.1039/C7EE03232C.

Li, H., Koh, C.S.L., Lee, Y.H., Zhang, Y., Phan-Quang, G.C., Zhu, L., Chen, Z., Sim, H.Y.F., Lay, C.L., et al. (2020a). A wearable solar-thermal-pyroelectro-harvesting fabric with high power output using modified rGO–PEI and polarized PVDF. Nano Energy 73, 104723. https://doi.org/10.1016/j.nanoen.2020.104723.

Li, H., Liu, Z., Liang, G., Huang, Y., Huang, Y., Zhu, M., Pei, Z., Xue, Q., Wang, E., Wang, L., et al. (2018c). Waterproof and tailorable elastic rechargeable yarn zinc ion batteries by a cross-linked polyacrylamide electrolyte. ACS Nano 12, 3140–3148. https://doi.org/10.1021/acsnano.7b09003.

Li, H., Zhang, X., Zhao, L., Jiang, D., Xu, L., Liu, Z., Wu, Y., Hu, K., Zhang, M.-R., Wang, J., et al. (2020b). A hybrid biofuel and triboelectric nanogenerator for bioenergy harvesting. Nano-Micro Lett. 12, 50. https://doi.org/10.1007/s40820-020-0232-6.

Li, R., Xiang, X., Tong, X., Zou, J., and Li, Q. (2015). Wearable double-twisted fibrous perovskite solar cell. Adv. Mater. 27, 3831–3835. https://doi.org/10.1002/adma.201501333.

Li, T., Chen, L., Yang, X., Chen, X., Zhang, Z., Zhao, T., Li, X., and Zhang, J. (2019). A flexible pressure sensor based on an MXene–textile network structure. J. Mater. Chem. C 7, 1022–1027. https://doi.org/10.1039/C8TC04893B.

Lian, Y., Yu, H., Wang, M., Yang, X., Li, Z., Yang, F., Wang, Y., Tai, H., Liao, Y., Wu, J., et al. (2020). A multifunctional wearable E-textile via integrated nanowire-coated fabrics. J. Mater. Chem. C 8, 8399–8409. https://doi.org/10.1039/DOTC00372G.

Liang, T., and Yuan, Y.J. (2016). Wearable medical monitoring systems based on wireless networks: a review. IEEE Sens. J. 16, 8168–8189. https://doi.org/10.1109/JSEN.2016.2597312.

Lija, J., Salonen, P., Kaija, T., and de Maagt, P. (2012). Design and manufacturing of robust textile antennas for harsh environments. IEEE Trans. Antennas Propagation 60, 4130–4140. https://doi.org/10.1109/TAP.2012.2207035.

Lim, S.J., Bae, J.H., Han, J.H., Jang, S.J., Oh, H.J., Lee, W., Kim, S.H., and Ko, J.H. (2020). Foldable and washable fully textile-based pressure sensor. Smart Mater. Struct. 29, 055010. https://doi.org/10.1088/1361-665X/ab5827.

Lin, R., Kim, H.-J., Achavananthadith, S., Kurt, S.A., Tan, S.C.C., Yao, H., Tee, B.C.K., Lee, J.K.W., and Ho, J.S. (2020). Wireless battery-free body sensor networks using near-field-enabled clothing. Nat. Commun. 11, 444. https://doi.org/10.1038/s41467-020-14311-2.

Liu, P., Gao, Z., Xu, L., Shi, X., Fu, X., Li, K., Zhang, B., Sun, X., and Peng, H. (2018). Polymer solar cell textiles with interlaced cathode and anode fibers. J. Mater. Chem. A 6, 19947–19953. https://doi.org/10.1039/C8TA06510A.

Lu, W., Yu, P., Jian, M., Wang, H., Wang, H., Liang, X., and Zhang, Y. (2020). Molybdenum disulfide nanosheets Aligned vertically on carbonized silk fabric as smart textile for wearable pressure-sensing and energy devices. ACS Appl. Mater. Interfaces 12, 11825–11832. https://doi.org/10.1021/acsami.9b12068.

Lund, A., Rundquist, K., Nilsson, E., Yu, L., Hagström, B., and Müller, C. (2018). Energy harvesting textiles for a rainy day: woven piezoelectric textiles based on melt-spun PVDF microfibres with a conducting core. NPJ Flexible Electronics 2, 1–9. https://doi.org/10.1038/s41528-018-0022-4.

Lu, J., Jeerapan, I., Tehrani, F., Yin, L., Silva-Lopez, C.A., Jang, J.-H., Joshua, D., Shah, R., Liang, Y., Xie, L., et al. (2018). Sweat-based wearable energy harvesting-storage hybrid textile devices. Energy Environ. Sci. 11, 3431–3442. https://doi.org/10.1039/C8EE02792G.

Ma, L., Wu, R., Patil, A., Zhu, S., Meng, Z., Meng, H., Hou, C., Zhang, Y., Liu, Q., Yu, R., et al. (2019). Full-textile wireless flexible humidity sensor for human physiological monitoring. Adv. Funct. Mater. 29, 1904549. https://doi.org/10.1002/adfm.201904549.

Malzahn, K., Windmiller, J.R., Valdés-Ramírez, G., Schoning, M.J., and Wang, J. (2011). Wearable electrochemical sensors for in situ analysis in marine environments. Analyst 136, 2912–2917. https://doi.org/10.1039/C1AN11918B.

Manjakkal, L., Dang, W., Yogeswaran, N., and Daihaya, R. (2019). Textile-based potentiometric electrochemical pH sensor for wearable applications. Biosensors 9, 14. https://doi.org/10.3390/bios9100104.

Manjakkal, L., Pullanchiyodan, A., Yogeswaran, N., Hosseini, E.S., and Daihaya, R. (2020). A wearable supercapacitor based on conductive PEDOT:PSS-coated cloth and a sweat electrolyte. Adv. Mater. 32, 1907254. https://doi.org/10.1002/adma.201907254.

Matijevich, E.S., Scott, L.R., Volgyesi, P., Derry, K.H., and Zelik, K.E. (2020). Combining wearable sensors, machine learning and biomechanics to estimate tibial bone force and damage during running. Hum. Movement Sci. 74, 102690. https://doi.org/10.1016/j.humov.2020.102690.
Matsuhashi, N., Inoue, D., Zalar, P., Jin, H., Matsuba, Y., Itoh, A., Yokota, T., Hashizume, D., and Someya, T. (2017). Printable elastic conductors by in situ formation of silver nanoparticles from silver flakes. Nat. Mater. 16, 834–840. https://doi.org/10.1038/nmat4904.

Matsuhashi, N., Kaltenbrunner, M., Yokota, T., Jinno, H., Kuribara, K., Sekitani, T., and Someya, T. (2015). Printable conductive spin-coating inks with a high conductivity for electronic textile applications. Nat. Commun. 6, 7461. https://doi.org/10.1038/ncomms8461.

Mishra, R.K., Martin, A., Nakagawa, T., Barfodkht, A., Lu, X., Sempionatto, J.R., Lyu, K.M., Karajic, A., Musameh, M.M., Kyritsis, I.L., and Wang, J. (2018). Detection of vapor-phase organophosphate threats using wearable conformable integrated epidermal and textile wireless biosensor systems. Biosens. Bioelectron. 101, 227–236. https://doi.org/10.1016/j.bios.2017.10.044.

Mo, F., Liang, G., Huang, Z., Li, H., Wang, D., and Zhuo, C. (2020). A review of fiber-shaped batteries with a focus on multifunctionality, scalability, and technical difficulties. Adv. Mater. 32, 1902151. https://doi.org/10.1002/adma.201902151.

Mohamadzade, B., Hashmi, R.M., Simorangkir, R.B.V.B., Gharei, R., Ur Rehman, S., and Abbasi, Q.H. (2019). Recent advances in fabrication textile methods for flexible antennas in wearable devices: state of the Art. Sensors 19, 2312. https://doi.org/10.3390/s19102312.

Mokhari, F., Cheng, Z., Raad, R., Xi, J., and Foroughi, J. (2020). Piezoelectric textile smart fabrics: a review on recent advances and future outlook for wearable technology. J. Mater. Chem. A 8, 9496–9522. https://doi.org/10.1039/D0TA0027E.

Mulatier, S. de, Nasreldin, M., Delattre, R., Ramuz, M., and Djenizian, T. (2018). Electronic circuits integration in textiles for data processing in wearable technologies. Adv. Mater. Tech. 3, 1700320. https://doi.org/10.1002/admt.201700320.

Nie, B., Huang, R., Yao, T., Zhang, Y., Mao, Y., Liu, C., Liu, J., and Chen, X. (2019). Textile-based wireless pressure sensor array for human-interactive sensing. Adv. Funct. Mater. 29, 1808786. https://doi.org/10.1002/adfm.201808786.

Niu, S., Matsuhashi, N., Beker, L., Li, J., Wang, S., Wang, J., Jiang, Y., Yan, X., Yun, Y., Burnett, W., et al. (2019). A wireless body area sensor network based on stretchable passive tags. Nat. Electronics 2, 361–368. https://doi.org/10.1038/s41928-019-0286-2.

Ou, J., Oran, D., Haddad, D.D., Paradiso, J., and Ishii, H. (2019). SensorKnit: Architecting textile sensors with machine knitting. 3D Print. Addit. Manuf. 6, 1–11. https://doi.org/10.1089/3dp.2018.0122.

Owyeung, R.E., Panzer, M.J., and Sonkusale, S.R. (2019). Colorimetric gas sensing washable threads for smart materials. Sci. Rep. 9, 5607. https://doi.org/10.1038/s41598-019-42054-8.

Pang, S., Gao, Y., and Choi, S. (2017). Flexible and stretchable biobatteries: monolithic integration of membrane-free microbial fuel cells in a single textile layer. Adv. Energy Mater. 8, 1702261. https://doi.org/10.1002/ente.201702261.

Paosangthong, W., Torah, R., and Beeby, S. (2019). Recent progress on textile-based triboelectric nanogenerators. Nano Energy 55, 401–423. https://doi.org/10.1016/j.nanoen.2018.10.036.

Park, S., Ahn, S., Sun, J., Bhatia, D., Choi, D., Yang, K.S., Bae, J., and Park, J.-J. (2019). Highly bendable and rotational textile structure with prestrained conductive sewing pattern for human joint monitoring. Adv. Funct. Mater. 29, 1808369. https://doi.org/10.1002/adfm.201808369.

Parker, J.F., Chervin, C.N., Pala, I.R., Machler, M., Burz, M.F., Long, J.W., and Rolison, D.R. (2017). Rechargeable nickel-Zn batteries: an energy-dense, safer alternative to lithium-ion. Science (New York, N.Y.) 356, 415–418. https://doi.org/10.1126/science.aak9997.

Possanzini, L., Decataldo, F., Mariani, F., Gualandi, I., Tessarollo, M., Scavetta, E., and Fraboni, B. (2020). Textile sensors platform for the selective and simultaneous detection of chlorine ion and pH in sweat. Sci. Rep. 10, 17180. https://doi.org/10.1038/s41598-020-74337-w.

Pu, X., Li, L., Song, H., Du, C., Zhao, Z., Jiang, C., Cao, G., Hu, W., and Wang, Z.L. (2015). A self-charging power unit by integration of a textile triboelectric nanogenerator and a flexible lithium-ion battery for wearable electronics. Adv. Mater. 27, 2472–2478. https://doi.org/10.1002/adma.201500311.

Pu, X., Liu, M., Li, L., Han, S., Li, X., Jiang, C., Du, C., Luo, J., Hu, W., and Wang, Z.L. (2016a). Wearable textile-based in-plane microsupercapacitors. Adv. Energy Mater. 6, 1601254. https://doi.org/10.1002/aenm.201601254.

Pu, X., Song, W., Liu, M., Sun, C., Du, C., Jiang, C., Huang, X., Zou, D., Hu, W., and Wang, Z.L. (2016b). Wearable power-textiles by integrating fabric triboelectric nanogenerators and fiber-shaped dye-sensitized solar cells. Adv. Energy Mater. 6, 1601048. https://doi.org/10.1002/aenm.201601048.

Qu, Q., Li, Y., Guo, S., Yang, J., Deng, J., and Peng, H. (2016). Fiber-shaped perovskite solar cells with high power conversion efficiency. Small 12, 2419–2424. https://doi.org/10.1002/smll.201600326.

Qu, G., Cheng, J., Li, X., Yuan, D., Chen, P., Chen, X., Wang, B., and Peng, H. (2016). A fiber supercapacitor with high energy density based on hollow graphene/conducting polymer fiber electrode. Adv. Mater. 28, 3646–3652. https://doi.org/10.1002/adma.201600889.

Quan, T., Wang, X., Wang, Z.L., and Yang, Y. (2015). Hybridized electromagnetic-triboelectric nanogenerator for a self-powered electronic watch. ACS Nano 9, 12301–12310. https://doi.org/10.1021/acsnano.5b03598.

Rajan, G., Morgan, J.J., Murphy, C., Torres Alonso, E., Wade, J., Ott, A.K., Russo, S., Alves, H., Cracium, M.F., and Neves, A.I.S. (2020). Low operating voltage carbon-graphene hybrid E-textile for temperature sensing. ACS Appl. Mater. Interfaces 12, 29661–29667. https://doi.org/10.1021/acsami.0c08397.

Rajani, V., Mhaskar, P., Chang, Y., Zhi, C., and Tao, X. (2020). Batteries and supercapacitors: fundamentals, applications, and future outlook. Mater. Horiz. 7, 415–418. https://doi.org/10.1039/D9MH00745H.

Rana, S., Zhang, L., Wang, X., and Ren, M. (2020). Wearable piezoelectric and triboelectric nanogenerators for mechanoelectric energy harvesting. Adv. Mater. 32, 1901958. https://doi.org/10.1002/adma.201901958.

Song, J., Liu, S., Zhang, L., Yang, B., Shu, L., Yang, Y., Ren, M., Wang, Y., Chen, J., Chen, W., et al. (2020). Smart textile-integrated microelectronic systems for wearable applications. Adv. Mater. 32, 1900746. https://doi.org/10.1002/adma.201900746.

Song, J., Yang, B., Zeng, W., Peng, Z., Lin, S., Li, J., and Tao, X. (2018). Highly flexible, large-area, and facile textile-based hybrid nano-generator with cascaded piezoelectric and triboelectric units for mechanoelectric energy harvesting. Adv. Mater. Technol. 3, 1800016. https://doi.org/10.1002/admt.201800016.
Song, Y., Min, J., Yu, Y., Wang, H., Yang, Y., Zhang, H., and Gao, W. (2020). Wireless battery-free wearable sweat sensor powered by human motion. Sci. Adv. 6, eay9842. https://doi.org/10.1126/scadv.ay9842.

Sun, H., Nie, S., Li, Y., Jiang, Y., Sun, X., Wang, B., and Peng, H. (2016). Large-area supercapacitor textiles with novel hierarchical conducting structures. Adv. Mater. 28, 8431–8438. https://doi.org/10.1002/adma.201602987.

Tang, W., Yin, L., Dempster, S., Ewan, J.-M., Teymourian, H., and Wang, J. (2021). Touch-based stressless cortisol sensing. Adv. Mater. 33, 2000865. https://doi.org/10.1002/adma.202000865.

Tefera, M. N., Kourbelis, C., Newman, P., Ramos, J. S., Hobbs, D., Clark, R. A., and Reynolds, K. J. (2015). Electron textile electrocardiogram monitoring in cardiac patients: a scoping review protocol. JBI Evid. Synth. 13, 17–156. https://doi.org/10.11124/JBISRIR-2017-003630.

Thakre, A., Kumar, A., Song, H.-C., Jeong, D.-Y., and Ryu, J. (2016). Pyroelectric energy conversion and its applications—flexible energy harvesters and sensors. Sensors 19, 2170. https://doi.org/10.3390/s19072170.

Tian, X., Lee, P. M., Tan, Y. J., Wu, T. L. Y., Yao, H., Zhang, M., Li, Z., Ng, K. A., See, B. C. K., and Ho, J. S. (2019). Wireless body sensor networks based on metamaterial textiles. Nat. Electron. 2, 243–251. https://doi.org/10.1038/s41928-019-0257-7.

Tricoli, A., Nasiri, N., and De, S. (2017). Wearable and miniaturized sensor technologies for personalized and preventive medicine. Adv. Funct. Mater. 27, 1605271. https://doi.org/10.1002/adfm.201605271.

Tsolis, A., Whittow, W. G., Alexandridis, A. A., and Vardavouli, J. C. (2014). Embroidery and related manufacturing techniques for wearable antennas: challenges and opportunities. Electronics 3, 314–338. https://doi.org/10.3390/ electronics3030314.

Wang, B., and Facchetti, A. (2019). Mechanically flexible conductors for stretchable and wearable E-skin and E-textile devices. Adv. Mater. 31, 1901408. https://doi.org/10.1002/adma.201901408.

Wang, C., Li, X., Gao, F., Jian, M., Xia, K., Wang, Q., Xu, Z., Ren, T., and Zhang, Y. (2016). Carbonized silk fabric for ultrastretchable, highly sensitive, and wearable strain sensors. Adv. Mater. 28, 6640–6648. https://doi.org/10.1002/adma.201605172.

Wang, C., Song, Z., Wan, H., Chen, X., Tan, Q., Gao, Y., Liang, P., Zhang, J., Wang, H., Wang, Y., et al. (2020a). Ni-Co selenide nanowires supported on conductive wearable textile as cathode for flexible battery-supercapacitor hybrid devices. Chem. Eng. J. 400, 125955. https://doi.org/10.1016/j.cej.2020.125955.

Wang, H., Zhang, Y., Liang, X., and Zhang, Y. (2021). Smart fibers and textiles for personal health management. ACS Nano 15, 12497–12508. https://doi.org/10.1021/acs.nanolett.0c0320.

Wang, L., Wang, L., Zhang, Y., Pan, J., Li, S., Sun, X., Zhang, B., and Peng, H. (2018). Weaving sensing fibers into electrochemical fabric for real-time health monitoring. Adv. Funct. Mater. 28, 1804546. https://doi.org/10.1002/adfm.201804546.

Wang, Y., Liang, X., Zhu, H., Xin, J. H., Zhang, Q., and Zhu, S. (2020b). Reversible water transportation diode: temperature-Adaptive smart Janus textile for moisture/thermal management. Adv. Funct. Mater. 30, 1907851. https://doi.org/10.1002/adfm.201907851.

Wang, Z. L., and Song, J. (2006). Piezoelectric nanogenerators based on zinc oxide nanowire arrays. Science 312, 242–246. https://doi.org/10.1126/science.1124005.

Wen, D.-L., Deng, H.-T., Liu, X., Li, G.-K., Zhang, X.-R., and Zhang, X.-S. (2020). Wearable multi-sensing double-chain thermoelectric generator. Microsyst. Nanoeng. 6, 1–13. https://doi.org/10.1038/s41378-020-0179-4.

Wen, D.-L., Liu, X., Deng, H.-T., Sun, D.-H., Qian, H.-Y., Brugger, J., and Zhang, X.-S. (2019). Printed silk-paper-based triboelectric nanogenerators for multi-functional wearable sensing. Nano Energy 66, 104123. https://doi.org/10.1016/j.nanoen.2019.104123.

Wen, Z., Yeh, M.H.M.-H., Guo, H., Wang, J., Zi, Y., Xu, W., Deng, J., Zhu, L.L., Wang, X., Hu, C., et al. (2016). Self-powered textile for wearable electronics by hybridizing fiber-shaped nanogenerators, solar cells, and supercapacitors. Sci. Adv. 2, e1600997. https://doi.org/10.1126/sciadv.1600997.

Weng, W., Yang, J., Zhang, Y., Li, Y., Yang, S., Zhu, L., and Zhu, M. (2020). A route toward smart system integration: from fiber design to device construction. Adv. Mater. 32, 1902301. https://doi.org/10.1002/adma.201902301.

Wu, R., Ma, L., Hou, C., Meng, Z., Guo, W., Yu, W., Yu, R., Hu, F., and Liu, X.Y. (2019). Silk composite electronic textile sensor for high space precision 2D combination temperature-pressure sensing. Small 15, 1901558. https://doi.org/10.1002/smll.201901558.

Wu, W., Bai, S., Yuan, M., Qin, Y., Wang, Z.L., and Lin, M., Liang, D., and Luo, Q. (2017). A wearable pyroelectric nanogenerator and self-powered breathing sensor. Nano Energy 38, 147–154. https://doi.org/10.1016/j.nanoen.2017.05.056.

Yang, M., Pan, J., Xu, A., Luo, L., Cheng, D., Bai, G., Wang, J., Tang, B., and Wang, X. (2018a). Conductive cotton fabrics for motion sensing and heating applications. Polymers 10, 568. https://doi.org/10.3390/polym10060568.

G.-Z. Yang, ed. (2014). Body Sensor Networks, 2nd ed. (Springer-Verlag). https://doi.org/10.1007/978-1-4471-6374-9.

Yang, S., Li, C., Chen, X., Zhao, Y., Zhang, H., Wen, N., Fan, Z., and Pan, L. (2020). Facile fabrication of high-performance pen ink-decorated textile strain sensors for human motion detection. ACS Appl. Mater. Interfaces 12, 19873–19881. https://doi.org/10.1021/acsami.9b12534.

Yang, Z., Zhang, Y., Han, Y., Yang, Y., Ling, J., Jian, M., Zhang, Y., Yang, Y., and Ren, T.-L. (2018b). Graphene textile strain sensor with negative resistance variation for human motion detection. ACS Nano 12, 9134–9141. https://doi.org/10.1021/acsnano.8b03919.
Yeom, P., Kim, M.-G., Brand, O., and Ghoovanloo, M. (2019). Optimal design of passive resonating wireless sensors for wearable and implantable devices. IEEE Sens. J. 19, 7460–7470. https://doi.org/10.1109/JSEN.2019.2915219.

Yin, L., Kim, K.N., Lv, J., Tehrani, F., Lin, M., Lin, Z., Moon, J.-M., Ma, J., Yu, J., Xu, S., and Wang, J. (2021a). A self-sustainable wearable multi-modular E-textile bioenergy microgrid system. Nat. Commun. 12, 1542. https://doi.org/10.1038/s41467-021-21701-7.

Yin, L., Kim, K.N., Trifonov, A., Podhajny, T., and Wang, J. (2021b). Designing wearable microgrids: towards autonomous sustainable on-body energy management. Energy Environ. Sci. https://doi.org/10.1039/D1EE03113A.

Yin, L., Scharf, J., Ma, J., Doux, J.-M., Redquest, C., Le, V.L., Yin, Y., Ortega, J., Wei, X., Wang, J., and Meng, Y.S. (2021c). High performance printed AgO-Zn rechargeable battery for flexible electronics. Joule 5, 228–248. https://doi.org/10.1016/j.joule.2020.11.008.

Yin, L., Seo, J.K., Kurniawan, J., Kumar, R., Lv, J., Xie, L., Liu, X., Xu, S., Meng, Y.S., and Wang, J. (2018a). Highly stable battery pack via insulated, reinforced, buckling-enabled interconnect array. Small 14, 1800938. https://doi.org/10.1002/smll.201800938.

Yin, Z., Jian, M., Wang, C., Xia, K., Liu, Z., Wang, Q., Zhang, M., Wang, H., Liang, X., Liang, X., et al. (2018b). Splash-Resistant and light-weight silk-sheathed wires for textile electronics. Nano Lett. 18, 7085–7091. https://doi.org/10.1021/acs.nanolett.8b03085.

Yong Zhang, Y.Z., Lu, H., Liang, X., Zhang, M., and Liang, H. (2021). Silk materials for intelligent fibers and textiles: potential, progress and future perspective. Acta Physico-Chimica Sinica. https://doi.org/10.3866/PKU.WHXB202103034.

Yu, L., Feng, Y., S/O M Tamil Selven, D., Yao, L., Soon, R.H., Yeo, J.C., and Lim, C.T. (2019). Dual-core capacitive microfiber sensor for smart textile applications. ACS Appl. Mater. Interfaces 11, 33347–33355. https://doi.org/10.1021/acsami.9b10939.

Yu, L., Yeo, J.C., Soon, R.H., Yeo, T., Lee, H.H., and Lim, C.T. (2018). Highly stretchable, wearable, and washable piezoresistive microfiber sensors. ACS Appl. Mater. Interfaces 10, 12773–12780. https://doi.org/10.1021/acsami.7b19823.

Yu, Y., Nassar, J., Xu, C., Min, J., Yang, Y., Dai, A., Doshi, R., Huang, A., Song, Y., Gehlhar, R., et al. (2020). Biofuel-powered soft electronic skin with multiplexed and wireless sensing for human-machine interfaces. Sci. Robotics 5, eaaz7946. https://doi.org/10.1126/scirobotics.aaz7946.

Zeng, W., Shu, L., Li, Q., Chen, S., Wang, F., and Tao, X.-M. (2014). Fiber-based wearable electronics: a review of materials, fabrication, devices, and applications. Adv. Mater. 26, 5310–5336. https://doi.org/10.1002/adma.201400633.

Zhang, K., Wang, X., Yang, Y., and Wang, Z.L. (2015a). Hybridized electromagnetic–triboelectric nanogenerator for scavenging biomechanical energy for sustainably powering wearable electronics. ACS Nano 9, 3521–3529. https://doi.org/10.1021/nn507455f.

Zhang, M., Gao, T., Wang, J., Liao, J., Qiu, Y., Yang, Q., Xue, H., Shi, Z., Zhao, Y., Xiong, Z., and Chen, L. (2015b). A hybrid fibers based wearable fabric piezoelectric nanogenerator for energy harvesting application. Nano Energy 13, 298–305. https://doi.org/10.1016/j.nanoen.2015.02.034.

Zhang, S.L., Jiang, Q., Wu, Z., Ding, W., Zhang, L., Alsharifeef, H.N., and Wang, Z.L. (2019). Energy harvesting-storage bracelet incorporating electrochemical microsupercapacitors self-charged from a single hand gesture. Adv. Energy Mater. 9, 1900152. https://doi.org/10.1002/aenm.201900152.

Zhao, J., Fu, Y., Xiao, Y., Dong, Y., Wang, X., and Lin, L. (2020a). A naturally integrated smart textile for wearable electronics applications. Adv. Mater. Tech. 5, 1900781. https://doi.org/10.1002/admt.201900781.

Zhao, K., Ouyang, B., Bowen, C.R., Wang, Z.L., and Yang, Y. (2020b). One-structure-based multi-effects coupled nanogenerators for flexible and self-powered multi-functional coupled sensor systems. Nano Energy 71, 104632. https://doi.org/10.1016/j.nanoen.2020.104632.

Zhou, Z., Li, Y., Cheng, J., Chen, S., Hu, R., Yan, X., Liao, X., Xu, C., Yu, J., and Li, L. (2018). Supersensitive all-fabric pressure sensors using printed textile electrode arrays for human motion monitoring and human–machine interaction. J. Mater. Chem. C 6, 13120–13127. https://doi.org/10.1039/C8TC02716A.

Zhu, M., Shi, Q., He, T., Yi, Z., Ma, Y., Yang, B., Chen, T., and Lee, C. (2019). Self-powered and self-functional cotton sock using piezoelectric and triboelectric hybrid mechanism for healthcare and sports monitoring. ACS Nano 13, 1940–1952. https://doi.org/10.1021/acs.nano.8b08329.

Zuo, W., Li, R., Zhou, C., Li, Y., Xia, J., and Liu, J. (2017). Battery-supercapacitor hybrid devices: recent progress and future prospects. Adv. Sci. 4, 1600539. https://doi.org/10.1002/advs.201600539.