Integration designs toward new-generation wearable energy supply-sensor systems for real-time health monitoring: A minireview

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Abstract

Wearable sensing systems, as a spearhead of artificial intelligence, are playing increasingly important roles in many fields especially health monitoring. In order to achieve a better wearable experience, rationally integrating the two key components of sensing systems, that is, power supplies and sensors, has become a desperate requirement. However, limited by device designs and fabrication technologies, the current integrated sensing systems still face many great challenges, such as safety, miniaturization, mechanical stability, energy-efficiency, sustainability, and comfortability. In this review, the key challenges and opportunities in the current development of integrated wearable sensing systems are summarized. By summarizing the typical configurations of diverse wearable power supplies, and recent advances concerning the integrated sensing systems driven by such power supplies, the representative integrated designs, and micro/nanofabrication technologies are highlighted. Lastly, some new directions and potential solutions aiming at the device-level integration designs are outlooked.

KEYWORDS

energy storage devices, flexible energy supplies, health monitoring, integrated sensing systems, wearable sensors

1 INTRODUCTION

In the past decades, wearable sensing systems have witnessed great progress, showing widespread application prospects for personal healthcare, especially in the future Internet of Things times. However, due to the lack of rational designs and fabrication technologies, most of such devices have not achieved satisfactory flexibility, volume, comfortability, and power consumption yet. For a better wearable experience, developing new-generation integrated wearable sensing systems with desirable safety, flexibility, comfortability, miniaturization, and power consumption, holding a promising application prospect. In such integrated sensing systems, sensors that responsible for real-time signal collection function dependently on power supplies. The integration ways between them generally influence the wearable experience of devices. Thus, how to integrate power supplies with...
sensors as a whole, which could be an advisable breakout to solve the challenges mentioned above.

The developing integration modes for wearable sensing systems are schematically illustrated in Figure 1. In the previous wearable sensing systems, most of the power supplies and sensors are sewed on a cloth and then interconnected by unhandy external wires (Figure 1A). Such integrations are bulky and cumbersome (Figure 1B, mode 1).10-12 Afterward, with the increasing advances of devices designs and micro/nanofabrication technologies, two typical integration types are proposed. On the one hand, by sharing a joint flexible substrate, all the units of a sensing system are anchored, resulting in an integration with detachable components (Figure 1B, mode 2).13,14 In such integrations, each component is relatively independent, which is beneficial to realize their respective functions under a larger deformation. Therefore, it stands for a general integration strategy, which applies to diverse sensing systems, without the concerns on the structural compatibility between different components. However, it is hard to achieve further device-level miniaturization. On the other hand, based on the structural compatibility between power supplies and sensors, the power supplies and sensors can be integrated as a flexible all-in-one whole (Figure 1B, mode 3).4,5,15,16 Such integrations are helpful to narrow the gaps among the units, which is an effective strategy toward miniaturized designs. However, when the all-in-one sensing systems work, all the components will suffer from similar deformations simultaneously, which could easily cause some damages due to the different endurability among the components.17 In order to ensure the normal function of the respective component, the all-in-one integrations need to shrink the endurability difference among the components. Toward this goal, a complete understanding of the working properties of the typical wearable power supplies and sensors is fundamentally needed. In addition, with some advanced micro/nanofabrication technologies such as editable printing, to construct diverse planar-pattern like integrated configurations could be an approachable strategy in the near future.

Currently, the wearable power supplies for integrated sensing systems mainly are energy storage devices, energy conversion devices, and their hybrids. Among them, energy storage devices include lithium-ion batteries, Zn batteries, and supercapacitors, and so forth.1,2,18-24 Energy conversion devices primarily involve piezoelectric and triboelectric nanogenerators, and solar cells.5,19,20,25 The hybrid power supplies consist of two typical devices above.15,26-29 The noninvasive sensors for healthcare can be generally classified as tactile sensors, temperature sensors, gas sensors, sweat sensors, and so on.9,30-32 Compared with sensors, the power supplies are usually much bulkier, of which flexible miniaturization is more important.10,14 Simultaneously, the other performance indexes of power supplies such as energy density, power density, mechanical stability, and service life need to be considered as well.17

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**FIGURE 1** A, Schematic illustration showing the importance of integrated design. Reproduced with permission.35 Copyright 2017 IEEE. B, The developing integration modes, mode 1: external circuit connection; mode 2: flexible substrate-based integration; mode 3: all-in-one integration
Given the fewer studies concerning integrated systems exclusively with power supplies and sensors, herein we primarily focus on the challenges facing current integration designs and their potential solutions, aiming to develop the new-generation sensing systems with upgraded wearable healthcare experience. First, we introduce the working principles of typical flexible powering supplies to show their configurations. Here we will not introduce the sensors since they have been reviewed in some literature.33,34 Moreover, we summarize the recent advances in the integrated sensing systems, highlighting the configurations of the typical

**FIGURE 2**  A, Schematic summary of charge storage mechanisms and characteristics of electrical double layer capacitor, pseudocapacitor, and battery. Reproduced with permission.38 Copyright 2016 Nature. Schematic illustration showing the configuration of, B, lithium-ion battery (Reproduced with permission.53 Copyright Royal Society Chemistry), C, zinc ion battery (Reproduced with permission.54 Copyright 2019 Elsevier), and, D, symmetric supercapacitor (top) and a hybrid supercapacitor (bottom) (Reproduced with permission.38 Copyright 2016 Nature). E, Typical components of energy storage-type power supplies. Reproduced with permission.38 Copyright 2016 Nature. F, Representative flexible device designs. Reproduced with permission.46 Copyright 2019 Elsevier
integration modes and their typical fabrication. Based on these discussions, we further propose the integrated design requirements and outlook potentially applicable fabrication technologies toward new-generation integrated sensing systems.

2 | FLEXIBLE POWER SUPPLIES

Flexible power supplies are usually fabricated with delicate configuration designs for mechanically stable powering and desirable flexibility. Based on energy storage and conversion mechanisms, some wearable power supply units have been developed such as flexible zinc-based batteries, supercapacitors, lithium-ion batteries, and self-powered nano-generators as well as solar cells, for the powering of integrated sensing systems.5,19,20,36,37 These power supplies exhibit respective merits and disadvantages, which determine their different application scenarios. In this part, we will introduce the working principles of diverse flexible power supplies, and their performance assessment including energy density, power density, output voltage, safety, and flexible configurations, which is beneficial to understand their integration with wearable sensors (Figure 2). In addition, the challenges and opportunities facing such power supplies will be discussed carefully.

2.1 | Energy storage-type power supplies

The energy storage-type flexible power supplies are mainly rechargeable batteries and supercapacitors, which work based on Faradic or non-Faradic reactions occurring in different electrodes, respectively (Figure 2A).38-41 Among them, Faradic processes appearing in batteries can be categorized into bulky diffusion-controlled reactions and surface or near-surface (pseudo)capacitive reactions in diverse electrodes such as metal chalcogenides. Most of the Faradic processes are dominated by sluggish diffusion-controlled reactions along with minor (pseudo) capacitive behavior, which results in a relatively complete intercalation-deintercalation of metal ions. Batteries usually provide higher energy density but lower power density and limited lifespan. In addition, supercapacitors work depending on different electrodes, possessing different electrochemical processes. For carbon-based materials with a high surface specific area, supercapacitors experience a non-Faradic electrochemical double-layer ion storage process; while for metal oxides/hydroxides or polyaniline, and so forth, Faradic pseudocapacitive reactions are dominated in the supercapacitor. Compared with batteries using organic or aqueous electrolytes, supercapacitors offer a fast charging rate, higher power density, ultralong lifespan, but lower energy density.

Both lithium/zinc ion batteries and supercapacitors share a similar configuration, in which cathode (positive) and anode (negative) are separated by a separator with a filled electrolyte between them (Figure 2B-E). For example, LiFePO4 cathode and Li4Ti5O12 anode are used to construct planar flexible lithium-ion batteries, which are integrated with nanogenerator to power a smartphone for heart rate monitoring.11,28 In addition, in another case, flexible zinc ion batteries are assembled with Zn deposited on carbon nanotubes as anode and MnO2 coated on flexible current collectors as cathode, powering a strain sensor for body motion detection.15 Moreover, for achieving a higher energy density, flexible supercapacitors with pseudocapacitive electrode materials such as MnO2 and polypyrrole (PPy) are assembled to power a strain sensor.42 Due to the different electrochemical nature of metal ions and electrolyte systems, such power supplies possess a different output voltage and operation safety. Benefiting from a wide decomposition voltage of organic electrolytes, organic lithium/sodium-ion batteries can offer a 3.5~4 V output voltage with a high energy density. However, the generation of dendritic lithium in the discharge-charge and flammability of organic electrolytes are intractable barriers for highly safe use, which easily leads to serious thermal runaway caused by a short circuit.26,42 In contrast, aqueous electrolytes are nonflammable thus much safer. Currently, aqueous batteries remain hard to achieve a high energy density and output voltage because of water splitting.44,45 Additionally, as a type of important wearable power supply, the general aqueous supercapacitor is characterized by high power density but low energy density, which limits its wearable powering applications, especially for devices with a higher rated power. However, the ultralong service life and low cost of supercapacitors indeed make it advantageous over counterpart batteries for short time powering. Actually, via rational hybrid designs of supercapacitors and batteries, the respective limitations of supercapacitor and battery can be mutually compensated to some extent. Such strategies are attracting wide research attention on developing high-performance wearable power supplies with high power/energy density and long lifespan. Besides, for obtaining a higher output voltage and energy density, organic supercapacitors are also studied in the past decade, but which suffer from similar safety issues to organic batteries. To use hybrid electrolytes with organic and aqueous components for batteries or supercapacitors may be an alternative solution for high-efficiency and safe wearable powering.46 Although a wide cut-off voltage of batteries or supercapacitors can be achieved using water-in-salt electrolyte or ionic liquid electrolytes, which
is too expensive to be applied for commercialization. Among the current aqueous batteries or supercapacitors, Zn-based batteries show well-balanced energy density (100–180 Wh kg$^{-1}$) and output voltage (1.4–1.8 V), thus which are regarded as a promising choice for wearable powering.

From the perspective of wearable powering, safety issues should be considered preferentially over other performance indexes such as energy density, output voltage, and so forth. While organic lithium-ion batteries can offer a high energy density and an output voltage, the elimination of dendritic lithium remains a great challenge for their safe use in a long period. In contrast, aqueous batteries especially zinc-based systems, are extremely safe, as the zinc dendrites are stable in water. Moreover, compared with supercapacitors with high power density but low energy density, aqueous zinc batteries (eg, Zn//MnO$_2$) possess a well-balanced energy density and output voltage, enabling them promising for new-generation wearable applications. Besides, aqueous zinc-based batteries also show apparent cost advantage over other battery systems regardless of the use of zinc anode and electrolyte. As such, as typical energy storage systems, aqueous zinc-based batteries could be an important choice for scalable wearable applications in the near future. However, currently, aqueous zinc batteries with high energy and output voltage for a commercial application are limited, which still needs many studies on developing high-performance cathode materials and novel electrolyte systems. In terms of cathode materials, to develop new inorganic materials with high-potential redox couples apart from Prussian blue analogs and manganese-, cobalt-, or nickel-containing metal oxides will enrich the accessible cathode diversity. Moreover, few organic cathodes with high output voltage have been reported up to date, which could deserve much more exploration. Additionally, developing novel electrolyte systems with a wide voltage window but nonflammable could be also an alternative solution. On the other hand, Zn anode also suffers from some issues, such as dendrite formation, corrosion, and low plating/stripping columbic efficiency, which impedes the development of Zn batteries. Such issues could be solved by means of electrolyte optimization, use of Zn-based hybrid anodes or 3D Zn sponge, membranes or interfacial engineering in future research.

In short, as summarized schematically in Figure 2F, the flexibility of such power supplies can be realized based on flexible electrodes themselves or flexible substrates (current collectors, such as carbon cloth, carbon fiber, metal-coated nonconductive polymers, etc.) coated with active materials. However, self-flexible electrodes are very limited and mostly mechanically unstable, coating active material onto flexible substrates are usually needed. In order to achieve device-level whole flexibility, device designs are of significant importance, which generally include sandwich-type, fiber-type, and quasi-2D and 3D interdigitated type assembly.

### 2.2 Energy conversion-type power supplies

#### 2.2.1 Piezoelectric and triboelectric nanogenerators

Given that energy storage-type power supplies cannot be independent of static power sources to realize charging, how to solve the off-grid charging becomes meaningful exploitation. As typical self-powered power supplies, diverse nanogenerators can function by converting ambient mechanical energy to electric energy based on different conversion mechanisms. Besides, flexible solar cells enabled by converting solar energy into electric energy also were reported for wearable powering.

However, the working property dependent on solar sunshine limits their wide wearable application indoor scenarios. Hence, to combine rechargeable power supplies, especially nanogenerators with self-powered power supplies is an alternative solution for off-grid charging.

Flexible nanogenerators for wearable powering mainly include piezoelectric nanogenerators (PENGs) and triboelectric nanogenerators (TENGs), which work based on piezoelectric materials (ZnO, certain ceramic and polymer piezoelectric materials, etc.), and triboelectric materials (carbon nanotubes, graphene, polydimethylsiloxane, etc.). In terms of PENGs, under external force, the central symmetry of crystal structure in these piezoelectric materials is broken, resulting in the generation of a piezoelectric potential (Figure 3A). The piezoelectric potential drives electrons to flow along an external circuit. Based on diverse flexible substrates (carbon fiber, polydimethylsiloxane, polyethylene terephthalate, etc.), typical flexible PENGs encompassing fiber-type, wave-type, and micrograting-type designs can be achieved (Figure 3B-D). For example, based on piezoelectric zinc oxide nanowires grown radially around textile fibers, a fiber-type PENGs can convert low-frequency vibration/friction energy into electricity. By twisting two fibers and plucking the nanowires rooted in them with respect to each other, the mechanical energy is converted into electricity because of a coupled piezoelectric-semiconductor process. In addition, by printing piezoelectric ceramic zirconate titanate onto prestretched elastomeric substrates, as-obtained nanogenerators can form buckled ribbons with engineered wavelengths and amplitudes. Such design not only accommodates order-of-magnitude larger poststrains compared to the fiber dimension while maintaining high outputs.
with their flat counterparts, but also enhances the piezoelectric performance. Moreover, by a laser lift-off process, a flexible and lightweight micrograting-type PENG is fabricated on a plastic substrate, which delivers an output voltage of \(~200\) V and current signals up to \(150\) µA cm\(^{-2}\) in periodical bending/unbending cycles. In general, with a delicate integration of piezoelectric potential, PENGs can provide an output voltage as high as \(1.26\) V and electric current as high as \(28.8\) nA, thus which show wide prospects in wearable powering. Additionally, TENGs are composed of two polymer films with different electron-withdrawing ability (Figure 3E). On the backside of each film, metal was deposited as an electron highway. Once the films come into contact with friction, an equal amount but opposite charges appear at the surfaces of films, forming an electric potential. Via contact and separation between films, the resultant alternative potential can boost electrons to flow back and forth in the external load. Similar to PENGs, the flexibility of TENGs is mostly realized based on flexible substrates. The typical flexible designs include micrograting-type, checker-type, and fiber-type configurations, in which the metal circuits are tailored into diverse patterns as current collectors (Figure 3F,G). For example, based on polymer thin films that have complementary linear electrode arrays, the as-fabricated TENG effectively produces sufficient enough electricity for powering regular electronics.

**FIGURE 3** A, Atomic model and piezoelectric properties (top) of the wurtzite-structured ZnO, and piezoelectric potential distribution in a ZnO nanowire under axial strain (bottom). Reproduced with permission. Copyright 2016 Wiley-VCH. B, Typical fiber-type (Reproduced with permission). Copyright 2008 Nature Publishing Group), C, wave-type (Reproduced with permission). Copyright 2011 ACS publication), and, D, micrograting-type piezoelectric nanogenerators (Reproduced with permission). Copyright 2014 Wiley-VCH). E, Configuration of the first flexible triboelectric nanogenerator. Reproduced with permission. Copyright 2012, Elsevier. F, Typical micro-grating-type (Reproduced with permission) and, G, checker-type (Reproduced with permission). Copyright 2014, Wiley-VCH) and, G, checker-type (Reproduced with permission). Copyright 2015, Wiley-VCH) triboelectric nanogenerators.
when a relative slide occurs between two contacting surfaces. In another case, based on checker-like interdigital electrodes with a sandwiched polyethylene terephthalate thin film, the as-fabricated TENG can harvest 2D translation kinetic energy in all directions. The design can effectively avoid direct friction between metal electrodes and sliding panel, greatly increasing the operating life of the generator. With rational integration, such flexible TENGs can yield an output voltage of up to 3.3 V with a power density of 10.4 μW cm⁻³.

For the off-grid power supplies including various nanogenerators and solar cells, the energy conversion efficiency is the key issue. In spite of great progress achieved, a low energy conversion efficiency remains the intractable challenge for such energy conversion devices, impeding their wide wearable application. Compared with PENGs, TENGs deliver a relatively higher energy conversion efficiency (14.9%–70.6%), making them more suitable as off-grid wearable power supplies. Moreover, the feature of noncontinuous powering in the nanogenerators also limits their application to some extent. Although solar cells can output electricity continuously, which is also unstable due to the dependence on the sunshine intensity and a lower power conversion efficiency (~23%). Therefore, developing high-efficiency energy conversion devices is still urgently needed for off-grid powering applications to date.

**FIGURE 4**

A. Typical structure (left) and operational principle (right) of planar DSSCs. Reproduced with permission. Copyright 2019 Elsevier. B. Schematic and equivalent circuit of an MWFF-DSSC(6) with six working electrodes and one counter electrode. Reproduced with permission. Copyright 2015 Elsevier. C. Schematic of the PSC stack composed of PET substrate, PEDOT:PSS hole selective electrode, perovskite, PTCDI or PCBM electron-transport layers, Cr/Cr₂O₃ layer, low-resistivity metals, and PU capping layer. D. Photograph of the horizontal stabilizer with integrated solar panel. Scale bar, 2 cm. Reproduced with permission. Copyright 2015 Nature Publishing Group. E. Schematic showing the architecture of the double-twisted fibrous perovskite solar cells. Reproduced with permission. Copyright 2015 Wiley-VCH. F. Schematic of the superhydrophobic electrodes and mechanism for generating electricity. G. Stability testing of different devices. Reproduced with permission. Copyright 2018 Elsevier.
2.2.2 Solar cells and water-voltage cells

Solar cells have witnessed a great development, from the first-generation crystalline Si-based type to the second-generation thin-film type, and to the third-generation dye/quantum dots-sensitized, polymer-based, and the emerging perovskites-based types. Among them, the widely reported types for wearable powering include dye-sensitized solar cells (DSSCs) and perovskite solar cells.

As schematically illustrated in Figure 4A, the typical planar DSSCs consist of a dye-sensitized semiconductor photoanode coated on a flexible conductive substrate, a counter electrode made by coating thin catalyst on a transparent conductive substrate, and an electrolyte consisting of iodine-based redox couple ($I^-/I_3^-$). The semiconductor film needs to absorb dye to form a valid photoanode in advance. After assimilating photon energy, the dye molecules are excited to generate electrons, and injected into the semiconductor, and then diffuse to the conductive substrate. Simultaneously, owing to the loss of electrons, such dye molecules turn to oxidized state ($D^+$), which is reduced by iodides ($I^-$) with the formation of oxidized tri-iodides ($I_3^-$). Subsequently, the photo-excited electron moves to the counter electrode via the external circuit. During the process, the tri-iodides diffusing to the counter electrode can accept the electron from external wire, and be reduced to iodides by the catalyst. Such reactions constitute a circle, realizing a continuous powering.

Besides the general planar configuration, DSSCs can be typically designed into fiber-like structure with multi-working electrodes (MWFF-DSSC[x], x = 1, 2, 3, 4, 5, and 6). Figure 4B shows an MWFF-DSSC(6), which contains a Pt microwire counter electrode and six Ti microwire working electrodes. The Ti microwires had been treated by two-step anodization, resulting in a hybrid structure covered with TiO$_2$ nanotube arrays. Such TiO$_2$ arrays were sensitized with dye molecules in advance. Then six Ti microwires and a sole Pt microwire surrounding by them were parallely inserted into a flexible plastic capillary tube, consisting of an MWFF-DSSC(6) after electrolyte injection. Compared with other MWFF-DSSC(x)s (x = 1, 2, 3, 4, or 5), the MWFF-DSSC(6) exhibited obviously higher conversion efficiency. The conversion efficiency can be further enhanced when the TiO$_2$ arrays were treated in a niobium isopropoxide solution. More importantly, such conversion efficiency did not suffer a substantial loss under bending.

Another type of promising photoelectricity converter is the newly-emerging perovskite solar cell (PSC). Different from the DSSCs, PSCs can function well without the help of dyes. This mainly benefits from the intrinsic merits of perovskites, such as lower recombination and higher migration rates of phono-excited electrons and holes, offering a longer diffusion distance and lifespan of carriers. So far, a high conversion efficiency of $\sim$23%, long-term stability, and modular manufacturing of PSCs have been achieved. As shown in Figure 4C, the typical PSC device is a sandwich architecture composed of anode/perovskite/cathode, thus which can be fabricated with roll-to-roll production technology. Compared with other organic photovoltaic absorbers, perovskites exhibit much better mechanical flexibility and durability, enabling them more suitable for the wearable powering application. Figure 4D demonstrates the feasibility of ultrathin perovskite solar foils for aeronautic applications with lab-scale models. Impressively, two 4 $\times$ 8 solar modules can power a d.c. electrical motor with propeller when integrated onto a curved hull of a lighter-than-air dirigible. The solar modules on 1.4 $\mu$m foil based on 64 individual cells can output 75 mW at maximum power point under simulated AM 1.5 solar irradiance. In order to meet the requirements of more complicated deformation from body or clothes, the flexible PSCs can also be fabricated with typical coaxial fiber-like architecture (Figure 4E). The double-twisted PSCs are fabricated on the basis of carbon nanotube fibers, on which perovskite and silver nanowire layers are deposited. Such architectures show a good interfacial adhesion under stress with a maximum conversion efficiency of 3.03%, which could endure more than 1000 bending cycles with negligible degradation.

In the past few years, water-voltage cells are proposed and attracting growing attention, which are defined as the energy-harvesters by water. When the water is evaporated on the surface of certain materials such as graphene, carbon nanotubes, MoS$_2$, and so forth, considerable energy absorbed from the ambient environment can be directly converted to electricity. Such mechanism will enlighten to develop various applications, holding a great promise in the future. However, it seems that few researches on adopting water-voltage cells for wearable powering are reported so far. Most recently, a redox-induced electric generator from a water droplet is presented for wearable powering (Figure 4F,G). Such a generator consists of a hydrophobic cathode Cu wire, a superhydrophobic anode Zn wire, and a superhydrophobic TiO$_2$ substrate. It actually works dependently on the oxygen-reduction-reaction of water and oxidation of Zn occurred on the surface of cathode and anode, respectively. Via redox-induced electricity from three water droplets, the as-fabricated wearable generator can directly power a wearable watch or a temperature sensor.
2.3 Hybrid power supplies combining energy conversion with energy storage

While PENGS and TENGs can work anytime and anywhere, their imperfection is visible as they only provide short-time and impulse-like powering, which is unable to power continuously. Thus, to assemble hybrid power supplies that combine energy storage devices and nanogenerators is necessary for a stable wearable powering.

In the past few years, some typical cases have witnessed the feasibility of hybrid power supplies. For example, a self-cleaning hybrid power system composed of a hydraulic TENG (H-TENG) embedded fiber supercapacitors was reported (Figure 5), where the impulse output power of H-TENG can be stored by the cascade supercapacitors after rectification. The corresponding equivalent circuit clearly exhibits the configuration of the hybrid power supply (Figure 5B). By such a hybrid design, the flexible fiber-like supercapacitors embedded in the H-TENG achieved a high energy density of up to $8 \times 10^{-4}$ Wh cm$^{-3}$ and a power density of 0.09 W cm$^{-3}$. In addition, separable and all-in-one hybrid power systems with combined TENGs and flexible lithium-ion batteries were also reported. For

![Diagram of hybrid power supplies](https://example.com/diagram.png)

**FIGURE 5** A, Schematic illustration of a self-powered system integrating TENG and supercapacitors, B, corresponding equivalent circuit, and, C, galvanostatic charge-discharge curves at a current of 100 $\mu$A in different bending states. Reproduced with permission. Copyright 2018 Wiley-VCH. D, Equivalent circuit of self-powered system integrated with flexible lithium ion battery and TENG and corresponding optical photos. Reproduced with permission. Copyright 2015 Wiley-VCH. E, Schematic discharging processes of a hybrid solid lithium ion battery with a TENG. Reproduced with permission. Copyright 2017 Wiley-VCH. F, Schematic self-powered textile integrated with solar cell, TENG and supercapacitor, G, corresponding equivalent circuit, and, H, optical photo of real scenario. Reproduced with permission. Copyright 2016 Nature publishing group.
instance, a hybrid power system-combining textile TENG and flexible lithium-ion battery were presented, where Ni-cloth belts connected together and parylene-cloth belts act as two electrodes of TENG, respectively. Such hybrid power supply is separable, its equivalent circuit and optical photos are shown in Figure 5D, by which a heartbeat meter strap worn at the chest can be powered by the hybrid power system.11 Recently, Liu et al presented an all-in-one hybrid power supply by internally integrated a solid Li-ion battery with a TENG, delivering a peak output power of 7.4 mW under a loading resistance of 7 MΩ (Figure 5E).28 Besides, multifunctional hybrid power systems combining diverse energy conversion devices and energy storage units were constructed as well, which enable reasonable energy harvesting for efficient energy storage.29 As schematically shown in Figure 5F, a double-layered hybrid power system integrated with fiber-like TENG, solar cell, and supercapacitor embodied well such configurations, its corresponding equivalent circuit and the optical photo showing real application scenarios verified the rationality of such designs (Figure 5G-H).

In brief, while different power supply units possess respective merits, their limitations are also apparent, such as short-term off-grid operation of energy storage devices and short-time impulse-like powering of energy conversion devices. Hence, for a continuous wearable powering, it is difficult to be achieved only relying on a certain single energy storage device or energy conversion device. As such, to combine energy conversion devices with energy storage devices as multifunctional power supplies, has been currently regarded as the most reliable strategy toward sustainable and stable wearable applications. In terms of the hybrid power supplies, future research should focus on the integration designs between more safe energy storage devices (eg, aqueous batteries) with a proper trade-off of energy/power density and nanogenerators with higher energy conversion efficiency. Besides, aiming at some special outdoor wearable scenarios, to develop novel hybrid power supplies of high-efficiency solar cells and high-performance flexible batteries matters as well.

3 INTEGRATED WEARABLE SENSING SYSTEMS FOR HEALTH MONITORING

The real-time health monitoring by wearable sensing systems is an effective approach for personal healthcare, especially for patients who suffer from heart cerebrovascular diseases such as myocardial infarction and acute heart disease, and so forth. Typically, a complete sensing system consists of a sensor, power supply, microcontroller, and data transmission unit (Figure 6A-E).10 Via a complex sensing array integrated with multifunctional non-invasive sensors, a series of key physiological parameters such as body temperature, heart rate, and various metabolites can be obtained. Such data can be transmitted by blue-tooth to personal cell phone, and then shared on cloud server for timely disease diagnosis or prevention (Figure 6D-E).35 Power supply, as the driving force of the sensing systems, was detached from the whole sensing system in the past years, which is impedimental to obtain a good wearable experience and comfortability (Figure 6B). Hence, a rational integration of sensing system with power supply is needed for stable powering, ergonomics, and device miniaturization (Figure 6F-H). Currently, the integration can be realized usually by two accessible approaches based on: (a) whole flexible substrates but with separate units6,13,14, (b) rational all-in-one device designs sharing joint substrates.15,16 In the following parts, we will review the recent advances concerning the two integration types, and discuss their merits and disadvantages.

3.1 Integrated sensing systems with separable power supplies and sensors

In the wholly flexible substrate-based integrated sensing systems, all the units are immobilized independently. The integration between power supplies and sensors is generally achieved by an integrated circuit interconnection. Benefiting from the flexibility of substrate, when applied under certain deformations such as strain or stretching, the sensing systems can sustain a stable operation without damages.

Recently, Ha et al reported a wireless-chargeable and body-attachable multifunctional integrated sensing system with separate microscale supercapacitors and sensor units, which can work at a uniaxial strain up to 50%.14 In their work, the individual sensors, micro-supercapacitors (MSC), and power receiver were dry-transferred onto flexible Ecoflex substrate, respectively. An external wireless power receiver was used to receive energy from radio frequency (RF) power source for the charge of nine parallel-connected arrays of MSCs. Galinstan liquid metal was used for the interconnection of diverse units. Such design minimized the strain of the sensing system under deformation, such as human body movement or uniaxial stretching (Figure 7A-E). The MSCs array delivered a capacitance retention of 99% over 200 cycles, ensuring a stable powering of the sensor system under mechanical deformation. With a graphene-based strain sensor, repeated body motion, voice, swallowing of saliva, and the carotid artery pulse can be successfully detected. To obtain a comprehensive signal, a carbon nanotubes/SnO₂
A nanowire hybrid film sensor was used to detect both NO2 gas and UV light. Such a multifunctional sensing system integrated with MSCs array shows a great prospect for personal health monitoring.

In another recent example, Zhao et al reported a fully integrated self-powered smartwatch for noninvasive and continuous monitoring of glucose levels (Figure 7F-H).26 The smartwatch was driven by integrated hybrid power supplies consisting of flexible photovoltaic cells and Zn-MnO2 rechargeable batteries. An electrochemical sensor for sweat glucose monitoring, a printed circuit board (PCB) controlling module and an electronic ink (E-ink) display were used for direct and real-time monitoring. Among them, the sensor was connected with hybrid power supplies by circuit wire to realize the integration. In the integrated sensing system, the photovoltaic cells were responsible for the charge of the batteries, thereby powering for the operation of the whole system encompassing real-time signal processing and data display. By using quasi-solid-state aqueous Zn-MnO2 batteries with high capacity, long lifespan, and desirable mechanical stability, the safety issue facing traditional flexible lithium-ion batteries can be eliminated. Based on a highly sensitive and stable glucose sensor, reliable sweat glucose monitoring was achieved. By the flexible design of power supplies and sensors, such a smart watch...
can be comfortably worn on the wrist for an on-body sweat glucose real-time and continuous monitoring. The self-powered sweat glucose monitoring system shows a good application potential for daily healthcare.

Although the substrate-based integration has achieved a series of progress, such integration cases remain unsatisfactory for an excellent wearable experience. On the one hand, the integration cannot utilize the space between adjacent parts on the flexible substrate, which is not beneficial to further miniaturize the wearable devices. On the other hand, such integrated systems cannot reduce the use of connected wires at a high limit, which could result in additional energy consumption. Therefore, from the perspectives of miniaturization and lowering energy consumption, to develop a more rational integrated configuration should be necessarily needed. Additionally, to ensure a good interconnected stability among separable units, the circuit wires should possess excellent flexibility and conductivity, such as liquid Ga-based alloy metal. In terms of the wire assignment, the mature integrated circuits can be taken as a reference to achieve a good operational stability. Besides, the mutual

**FIGURE 7** Integrated sensing systems with separable power supplies and sensors: A, photograph of stretchable system, which consists of a RF power receiver, a MSC array, strain sensor, and UV/NO₂ gas sensor; B, circuit diagram of integrated system; C, MWNT/SnO₂ NW hybrid film sensor for NO₂ gas and UV light detection; D, photograph of FGF sensor attached on skin of neck; E, saliva swallowing detection curve (left), resistance vs hand motion (middle), detection of NO₂ under dynamic stretching up to 50% (right). Reproduced with permission.²⁴ Copyright 2016, Wiley-VCH. F, system-level block diagram of the self-powered smartwatch; G, schematic illustrations of the self-powered smartwatch; H, images of the smartwatch on a subject’s wrist and separate components. Reproduced with permission.²⁶ Copyright 2019, American Chemical Society
interference among the separable units need to be avoided, which directly influences the accuracy and responsively of sensing information. To obtain the goal, proper gaps should be reserved among the separable units to keep from their possible deformation intercontact. Moreover, the interfaces and flexibility of adjacent units need to be rationally designed with a good match, thereby reducing the risk of mutual interference.  

**FIGURE 8** Fiber-like all-in-one sensing systems: (A, B), schematic illustrations of the fabrication of the stretchable fiber-shaped Zn-MnO$_2$ battery and dye-sensitized solar cells; C, schematic illustration of the structure of the fully solar-powered coaxial-fiber stretchable sensing system for energy harvest, storage, and utilization; D, galvanostatic charge-discharge curves collected at different current densities; E, change in relative resistance of fiber-like all-in-one sensing system as a function of time, insets are optical photographs showing the movements of the back of a person wearing the device. Reproduced with permission. Copyright 2019, Elsevier. F, Stretchability representation and the cross section view of the all-in-one stretchable coaxial-fiber strain sensor self-supported by an integrated supercapacitor; G, galvanostatic charge-discharge curves at different current densities of the as-assembled supercapacitor, and, H, the corresponding volumetric capacitances as a function of current density; I, change in relative resistance under cyclic stretching over 10 000 cycles, (J, K), change in relative resistance as a function of time for arm movements and neck movements. Reproduced with permission. Copyright 2019, Elsevier
3.2 Integrated sensing systems consisting of all-in-one power supplies and sensors

Different from the flexible substrate-based integrated sensing system mentioned above, the all-in-one design represents a higher level of integration, which is beneficial to fabricate more miniaturized sensor devices. In such devices, power supplies and sensors are rationally integrated into a whole, which can be realized with diverse shapes such as fiber-shape and planar structures, and so forth. Although the all-in-one systems show some merits over separate integrated systems, only a few relevant cases have been reported so far, it could result from the relatively complex fabrication. In the following part, we will introduce two typical all-in-one integration designs, including fiber-shape and planar configurations.

3.2.1 Fiber-shape all-in-one integrated sensing systems

As one of the typical examples, Zhang et al recently reported a coaxial fiber-shape stretchable sensing system with ultra-endurance, which was driven by hybrid power supplies. With an especial coaxial design, solar cells, an aqueous Zn-MnO2 battery, and a stretchable strain sensor were integrated simultaneously, realizing energy harvest, storage, and utilization (Figure 8A-E). By wrapping ultralight multiwalled carbon nanotubes/thermal plastic elastomer composite on a prestretched rubber fiber, the strain sensor was fabricated. Especially, through storing the converted electricity from harvested solar energy in the battery, a stable and continuous powering of sensing operation can be obtained, featuring a green and safe energy application. The effective strain range of the system is up to ~180%, with a high gauge factor of 12.4 in the strain range 0%-40% and 65.77 for 50%-160%, which is high enough for a wearable health monitoring sensing. Very recently, Pan et al reported a stretchable coaxial-fiber integrated sensing system driven by an asymmetric microsupercapacitor with a maximum working voltage of 1.8 V (Figure 8F-K). In the integrated system, the supercapacitor was constructed around an elastic fiber with manganese dioxide and polypyrrole deposited on aligned carbon nanotube sheets as the positive and negative electrode, respectively (Figure 8F). By wrapping a carbon nanotube/thermal plastic elastomer composite film around the supercapacitor, a coaxial strain sensor was obtained. Benefiting from the unique configuration design, the power supply exhibits a high volumetric energy density up to 1.42 mWh cm−3, and an outstanding flexibility with 85.1% capacitance retention after stretching for 6000 cycles at a strain of 200%. Such a strain sensing system shows an excellent stability and durability at repeatedly unloading/loading of 40% applied strain for 10 000 cycles at stretchable sensing applications (Figure 8I). When applied to monitor a series of body motions such as arm and neck motions, the integrated sensing system can recognize the real-time actions of various muscles or joints with good sensitivity and stability (Figure 8J-K). These studies demonstrate a conceptual design for the integration of sensors with energy storage devices for the new-generation wearables.

Although a series of merits of fiber-shape integration such as miniaturization, breathability, and easy fabrication, current studies only addressed the basic configuration design, where certain key issues still need urgently to be concerned. For example, for a stable and accurate sensing, how to match the stretchability and avoid the mutual effect between sensors and power supplies, is of significant importance. Moreover, if such configuration could apply to other sensing systems more than stain sensors for diverse sensing applications, which needs much more explorations. In addition, the integrations with other configurations should also be developed to meet diverse application scenarios.

3.2.2 Planar all-in-one integrated sensing systems

Apart from the fiber-shape all-in-one sensing system mentioned above, planar configuration is also an important all-in-one integration design. For instance, Park et al recently reported a dynamically stretchable supercapacitor-driven integrated sensing system for the detection of various biosignals (Figure 9A,B). In the system, strain sensors and supercapacitors were constructed based on fabrics with different textile directions. The supercapacitor was assembled with MWCNT/MoO3 nanocomposite electrodes and non-aqueous gel electrolyte along the course direction of the fabric, delivering good stability and high performance under dynamic and static deformation. Along the wale direction of the fabric, the fabricated strain sensor shows a high sensitivity of 46.3 under a strain of 60%, a fast response time of 50 ms, and high stability over 10 000 cycles of stretching/releasing. By a back-to-back package between supercapacitor and strain sensor, as-obtained all-in-one textile sensing system can be sewed into cloth to detect strain from joint movement and the wrist pulse in real-time. Most recently, Wang et al designed a planar all-in-one sensing patch integrating piezoresistance sensor and micro-supercapacitor with the porous CNT-PDMS elastomer (Figure 9C,D). By virtue of piezoresistivity of porous structure and electrochemical performance of elastomer, the sensor exhibited high sensitivity...
(0.51 kPa$^{-1}$) and wide detection range as a functional fraction, while the micro-supercapacitor delivered excellent areal capacitance and cycling stability after 6000 cycles, respectively. By a back-to-back assembly, the obtained sensing patch can be easily attached to the epidermal skin for joint and muscle monitoring. Such sensing patch could also be applied as a 3D touch for user identification and safety communication via feature parameter collection and signal decoding. When packaged as a sensing patch matrix, static pressure sensing and dynamic tactile trajectory can be achieved. Besides, based on flexible substrates, Li et al. fabricated a planar-structured all-in-one strain sensing system by integrating a supercapacitor and a strain sensor.16 3D multilevel porous graphite foams (MPGs) and mechanically robust MPG/Mn$_3$O$_4$ composites (MPGMs) were used in the system. The MPGMs can endure 1000 bending cycles with only 1.5% resistance change, which were applied as free-standing electrodes for supercapacitors. Moreover, a planar-structured flexible strain sensor was fabricated using ultrathin single graphene-PDMS composites, showing excellent ultra-sensitivity and durability. The integration of the supercapacitor and strain sensor was realized by packaging them together with PDMS. By virtue of excellent performance stability of supercapacitor under mechanical deformation and ultra-sensitivity of strain sensor, the integrated sensing system can be conformed to human skin for coarse and fine motions detection such as finger folding and heart beating. Such a piece of flexible integrated sensing system with an area of 2 cm$^2$ can work for more than 8 minutes when the supercapacitor was charged to 1.0 V.
Similar to coaxial fiber-shape integration, the all-in-one planar integration is also helpful to realize miniaturization and possible low energy-consumption of wearable devices. However, due to a usual bigger area of such a planar integration, compared with coaxial fiber-shape configuration, its breathability could be weakened greatly. Hence, breathability should be rationally considered for a fast heat dissipation. Compared with the above mentioned flexible substrate-based integration, all-in-one integration imposes a higher requirement on flexibility and interfacial match of adjacent modules. On the one hand, due to a direct intercontact, the adjacent modules need possess a highly compatible flexibility, ensuring their normal function without mutual interference. On the other hand, the interfacial match also needs to be rationally guaranteed, thereby eliminating the disassembly or damage among integrated units. In this aspect, it could be well realized by standardized design technology such as auto CAD or other modeling software. Besides, current studies mainly addressed the integration of strain sensing systems, other integrated sensing systems should be designed for a comprehensive sensing application in future studies.

**FIGURE 10** A, Schematic illustration of diverse printing technologies for the fabrication of flexible electronic device. Reproduced with permission.79 Copyright 2017, Wiley-VCH. (B, D), Schematic illustration of, B, printed lithium-ion battery (Reproduced with permission.83 Copyright 2015, American Chemical Society), C, printed supercapacitor (Reproduced with permission.89 Copyright 2019, Nature publishing group), and, D, printed Zn-Ag2O battery (Reproduced with permission.81 Copyright 2016, Wiley-VCH). E, Schematic illustration showing the brief history of printable electronic devices for sensor applications. Reproduced with permission.82 Copyright 2016, Wiley-VCH. F, Fully printed wearable sensing systems based on a flexible substrate. Reproduced with permission.84 Copyright 2019, Wiley-VCH
4 | EMERGING FABRICATION TECHNOLOGIES FOR WEARABLE INTEGRATED SENSING SYSTEMS

Among various micro/nanofabrication technologies, diverse printings have been emerging as promising technologies for the fabrication of integrated sensing systems. Such printings can be generally classified into template and template-free approaches (Figure 10A). Among them, template printings include screen-printing, imprinting, gravure printing, and flexography, which are very useful for the scalable production of flexible pattern-like devices. The template-free printings comprise mainly of inkjet and 3D printing, which function by locally and controllably dispensing the ink onto the substrate by a template-free means. So far, template-free printings have achieved great progress in the advanced dispensing technologies, which can print more intricate and high-resolution architectures. Compared with templated printing, template-free printings show a great versatility for the fabrication of complex systems.

Due to the unique merits of printing technologies, such printing technologies have been widely used for the fabrication of various energy devices, involving pattern-like lithium-ion batteries, supercapacitors, Zn$_2$O batteries, nanogenerators, solar cells, and so on (Figure 10B-D). Additionally, such printing technologies are also used for the fabrication of diverse wearable sensors for temperature, strain, gas, sweat, and so forth (Figure 10E). Undoubtedly, such printing technologies possess excellent compatibility, which will revolute the manufacturing of wearable devices in the near future. Although amounts of effort have been devoted to the fabrication of various devices, most of them are aimed to fabricate a single device. In terms of the printable integration of power supplies and sensors, there are still fewer studies reported to date.

Recently, Lin et al. firstly reported a fully integrated and self-powered sensor system by inkjet printing (Figure 10F). In such a sensing system, with various functional inks, all the units including amorphous silicon solar cell-supercapacitor hybrid power supplies, SnO$_2$ gas sensor, and Ag interconnects, were printed onto a whole flexible substrate. Such integration is of substrate-based integration type, in which the harvested solar energy can be stored in supercapacitors to power the sensing system. The whole system is designed with a planar configuration for the integration, including both planar supercapacitors and sensors with interdigitated-type electrodes.

Currently, while the substrate-based integration has been realized by a full inkjet printing, all-in-one integrated system using printing technologies has not been reported yet, which is expected to be realized in future research. Besides the gas sensing system, other integrated sensing systems should be developed as well. Since the printing technologies for integrated fabrication remain in their infancy stage, more exploitations on the design of functional inks and device configurations are needed to carry out for wide wearable applications.

Apart from above mentioned various printing technologies, the adoption of micro/nanoelectromechanical systems (MEMS/NEMS) fabrication technologies should be taken into account as well. In the past decades, MEMS/NEMS technologies have undergone a rapid progress in industrials and academia, which mainly benefits from their excellent compatibility with various novel manufacturing technologies such as micro/nanopatterning, additive printing, and so forth. With the integrated merits from various micro/nanofabrication technologies, MEMS/NEMS are expected to be massively applied in the fields of biomedical engineering, personal healthcare, Internet of Things, and so on. Particularly, for a complete integrated sensing system, all the components including multiple sensors, power supplies, circuit wires, microprocessors, data transmission, and so forth, should be orderly organized. Currently, MEMS/NEMS technologies still suffer from the key challenges such as the construction of standardized operation, reproducibility improvement, cost decrease, and so forth. Along with the development of MEMS/NEMS, the intractable bottlenecks of wearable integrated sensing systems such as scalable fabrication, low power consumption, miniaturization, high stability, and so forth, could be solved well.

5 | SUMMARY AND OUTLOOK

Wearable powering for healthcare sensing systems have witnessed great research progress from initial nonflexible, bulky external wire interconnection, to wholly flexible substrate-based integrated power, and then to advanced all-in-one integrated powering. Such progress has paved the way for next-step improvements of sensing systems, such as further miniaturization, lowering power consumption, and enhancing wearable comfort. In this review, we have introduced the working properties of several typical wearable power supplies for integrated wearable sensing, including energy storage devices and their hybrids with energy conversion devices. By reviewing the recent advances of integrated sensing systems, we summarized the general integration type by making all the units share a whole flexible substrate, and typical all-in-one integration designs including fiber-shape and planar configurations. In addition, taking
emerging printing technologies as examples, typical printable fabrications of integration were reviewed, and the future research directions were pointed out as well. Such new designs and fabrications are expected to boost the application of new-generation wearable detectors for real-time healthcare. Nevertheless, most of the current integrations remain far away from being perfection for future commercial applications. Based on the current bottleneck issues for the wearable integrated sensing system, more research efforts should be focused on the following aspects in the future (Figure 11).

Firstly, to integrate durable energy storage devices with higher safety and energy density with sensors. Currently, most of the power supplies for wearable sensing systems are supercapacitor or lithium-ion batteries, and their hybrids with energy conversion devices, which suffer either low energy density or undesirable safety. In contrast, highly safe batteries such as aqueous Zn-based batteries, while have been developed with excellent flexibility, durability, and appropriate energy density, are still less reported for integrated sensing applications. 

Hence, more studies on the integrated powering application of highly safe energy storage systems should be committed to addressing the issue toward safe and stable sensing systems.

Secondly, to design diverse all-in-one integration with multifunctional sensors. Compared with flexible substrate-based integration, all-in-one integrations are more beneficial to realize the key indexes such as miniaturization, low power consumption, and ergonomics. However, current several reported all-in-one integration designs are only limited to stretchable strain sensors, by which the signals obtained are not adequate for complex healthcare. Thus, to build all-in-one sensing systems based on various sensors such as temperature, sweat, and gas, and so forth, could be a profound research direction.

Thirdly, to design the all-in-one integration with diverse configurations by advanced micro/nanofabrication techniques. So far, the all-in-one integration reported is limited to two types, that is, coaxial fiber-like and planar configurations. Such designs are still hard to meet diverse sensing scenarios. Given the excellent compatibility of some advanced printing technologies
(screen-printing, 3D/inkjet printing, and laser writing, etc.) with the fabrication of energy devices and sensors, many efforts are needed to be devoted to exploiting their utilization for the all-in-one integration. With such technologies, the existing wearable pattern-like designs could be copied for miniaturized, energy-efficient, and comfortable sensing applications.

Lastly, to establish a systematic evaluation standard concerning the key performance parameters of integrated sensing systems. Despite many studies on integrated sensing systems performed, most of them only focused on the performance measurement of either power supplies or sensors. So far, no report has systematically evaluated the performance indexes of such integrated sensing systems well, including sensing accuracy, reproducibility, power consumption specification, and so forth. Thus, the next-step efforts should be devoted to conducting the relevant studies for a more standardized evaluation of integrated sensing systems.

Overall, such integrated sensing systems with power supplies and sensors should be designed with the complex considerations of safety, stability, sustainability, miniaturization, energy-efficiency, and comfortability, toward a better wearable experience.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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