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Introduction

This chapter first introduces the development of integrated smart micro-systems, aiming at health monitoring–related applications. After the introduction of the working mechanism and structural design of different energy-harvesting units, energy-storage units, and functional units, the related researches focusing on the integration and applications are further carried out. To solve the issues, including complex processing technology, poor device performance, redundant integrated design, and simple applications, integrated smart micro-systems toward health monitoring are proposed. Consequently, the motivation, purpose, and innovative contributions are briefly summarized.

1.1 Overview of Integrated Smart Micro-systems

Since the beginning of the twenty-first century, with the technological innovation of industrial production and the rapid development of Internet applications, tremendous changes have occurred in people's lifestyles. Smart lifestyle has penetrated into all aspects, such as clothing, food, housing, and transportation. It is possible to know the world well without leaving the house. The development of medical and health field is particularly noticeable.

Advances in flexible electronics, the Internet, and processing technology have provided better assistive technical means for seeking medical treatment and physical examination. The health-monitoring approach is transiting from the traditional medical model with the help of large equipment in hospital to wearable micro-systems with real-time monitoring and remote diagnosis, as shown in Figure 1.1.

Under the traditional medical model, "looking, listening, asking, and feeling the pulse" are necessary means. Doctors communicate with patients face-to-face and perform various examinations with the assistance of sophisticated medical equipment. For individuals, this is a hospital-centered diagnosis method, which takes longer time with low efficiency and cannot fully meet the needs of continuous monitoring of certain diseases. The rapid development of various types of wearable devices and flexible micro-systems allows for the opportunities to the fields of medical care and health monitoring.

Integrated Smart Micro-Systems Towards Personalized Healthcare, First Edition.
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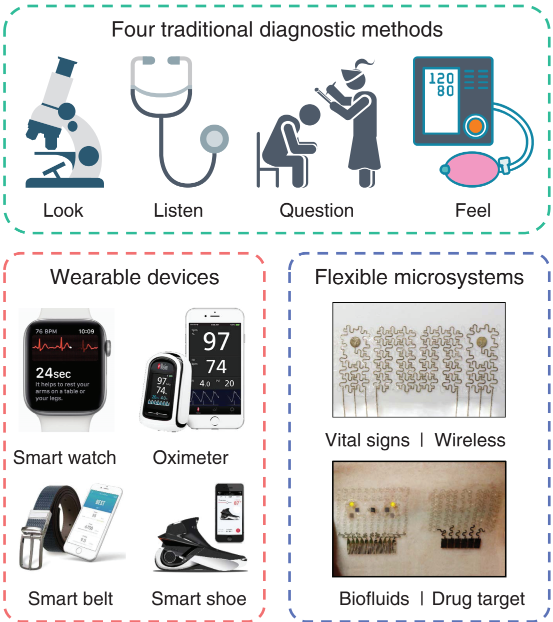

Figure 1.1 Health-monitoring approaches in the field of medical electronics. Source: Choi et al. [1]; Lee et al. [2].

1.1.1 The Progress of Portable Smart Micro-systems

The human body produces a variety of physiological signals in the daily metabolism process [3], including physical signals such as body temperature, blood pressure, biopotential, exercise information, respiratory rate, and heart rate, and chemical signals, such as pH, sodium ions, lactate, uric acid, and glucose in body fluids. These physiological signals are very critical for human health management. For example, it is feasible to monitor obstructive sleep apnea hypopnea syndrome (OSAHS) through changes in heart rate [4], and monitor the cystic fibrosis through changes of chloride ion concentration in sweat [5].

With the help of the miniaturization and intelligence of integrated circuits under Moore's law and the timely sharing of data with the development of the Internet, wearable technology has developed rapidly. A series of smart wearable devices for health monitoring are proposed, such as the new generation of Apple Watch. Authorized by the US Federal Drug Administration (FDA), it can achieve the same accuracy as the clinical electrocardiogram monitor to provide diagnosis and early warning for patients to understand their physical conditions in time.

The entire market of wearable devices is developing rapidly. In 2016, the total number of wearable devices in the global market reached 125 million units. It is estimated that by 2021, the overall number will be close to 900 million units, with an average compound annual growth rate of 23% [6]. According to IDTechEx data, the market share of the wearable health field will grow to more than US$75 billion by 2025 [7], and it will gradually develop into a patient-centered medical health model.

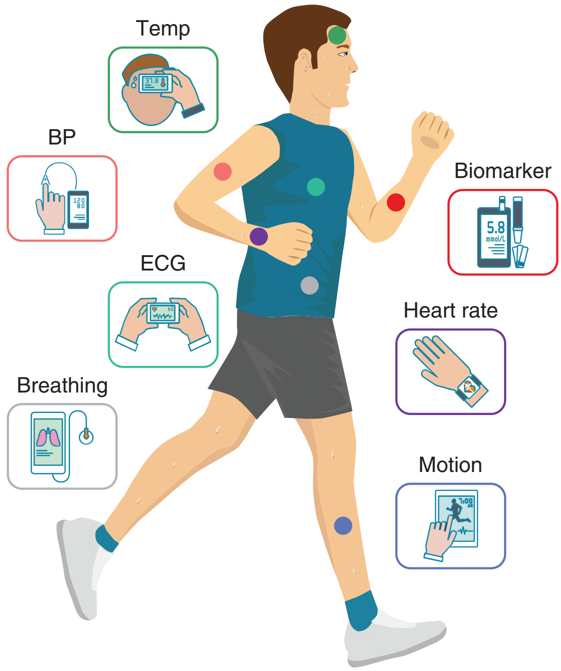

Figure 1.2 Development progress of portable health-monitoring methods. Source: Yu Song.

Figure 1.2 lists the current monitoring methods of various physiological signals. Most of these detection modules use portable and miniaturized equipment, which adopt the working modes of pre-sampling and in vitro off-line detection. It is hard to obtain real-time physiological information and perform long-term continuous monitoring. In addition, most of these commonly used wearable devices are based on silicon-based rigid materials with hard modules, which lacks in biocompatibility. Due to the mismatch of Young's modulus between the device and human skin, it is unavailable to realize skin-interfaced measurement of physiological signals directly. Meanwhile, during the normal movements, these rigid modules will be inevitably misaligned with the soft skin, resulting in the poor accuracy of detection and reduced reliability in health diagnosis. These issues greatly limit the practical applications of wearable devices in real-time monitoring of human health.

With the rapid development of material science, chemical analysis technology, and flexible fabrication process, the flexible and integrated smart micro-systems toward health monitoring have attracted huge attention [8–10]. The advantages of lightweight, soft, cheap, and durable properties enable the continuous, sensitive, and accurate monitoring of various physiological information when comfortably attached to the human skin. The further cooperation with wireless signal transmission allows for in situ detection and on-demand therapy with the assistance of big data analysis. It is feasible to achieve the ultimate goal of personalized medical care and dynamic health management based on the integrated smart micro-systems [11–13].

1.1.2 Integrated Smart Micro-systems Toward Healthcare Monitoring

The exploration of flexible bioelectronics technology and the in-depth research of flexible polymer and multifunctional nanomaterials facilitate the rapid development of integrated smart micro-systems for health monitoring, and break through the limitations of large medical equipment with poor portability and wearable devices with low sensitivity. Through the materials selection, fabrication optimization, structural design, and seamless integration, the smart micro-systems can be directly attached to the human skin to achieve accurate monitoring of various physiological signals. The schematic of specific health monitoring and remote diagnosis is shown in Figure 1.3.

On the one hand, various energy-harvesting and -storage devices can efficiently convert human mechanical energy into electrical energy [14–16] and effectively store the energy as a stable power supply [17–19]. On the other hand, through structural design and material optimization, miniaturized multimodal biosensors can continuously acquire physiological signals and provide reliable health information [20–22].

During the measurement of physiological signals, the single transmission and analysis are of vital importance. The sensor data are sent to user interface by the circuit module with Bluetooth low-energy or Wi-Fi wireless chip. Through the design of relevant applications, it is available to perform real-time signal analysis and rapid response. Doctors can acquire the key health-related parameters remotely to monitor the patients' conditions, such as respiration rate, electrocardiogram (ECG) signal, and temperature. It is feasible to answer the questions online for minor illness, conduct early warning interventions for critically ill patients, and arrange in-patient medical care in time.

The integrated smart micro-systems toward health monitoring consist of three core units: an energy-harvesting unit that converts various types of energy into electrical energy, an energy-storage unit that effectively stores electrical energy, and the functional units that transform external stimuli into electrical signals. The core units and representative devices of the integrated smart micro-systems are shown in Figure 1.4.

The coordination and integration of three units enable closed-loop smart micro-systems, which continuously acquire various physiological signals from human body, perform health status alarm with wireless data transmission and signal processing, and provide diagnosis and personalized health management with improved efficiency. The current advances and challenges of these units and applications will be discussed in detail in the following sections.

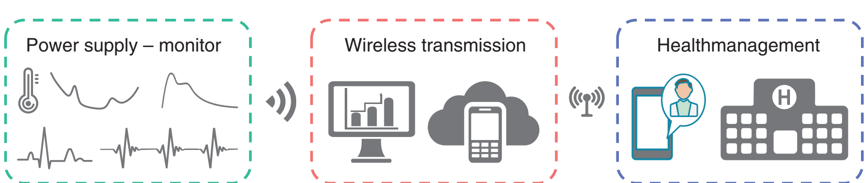

Figure 1.3 Schematic illustration of integrated smart micro-systems toward health monitoring. Source: Yu Song.

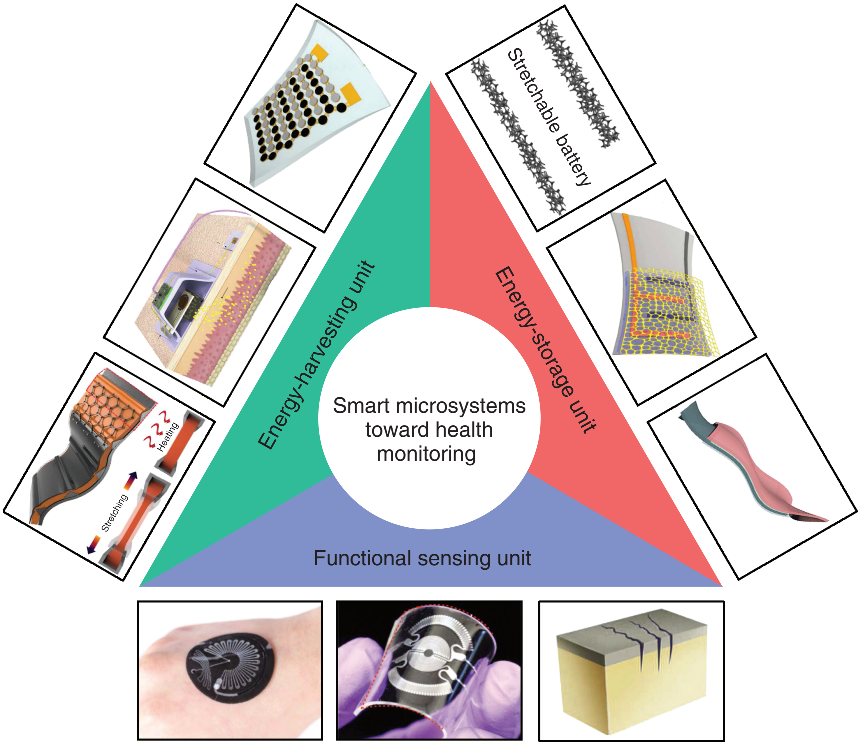

Figure 1.4 Core units and representative devices of smart micro-systems toward health monitoring. Source: Bandodkar et al. [14]. Copyright 2017, Royal Society of Chemistry. Lee et al. [15]. Copyright 2014, John Wiley & Sons. Ouyang et al. [16]. Copyright 2019, Elsevier. Liu et al. [17]. Copyright 2016, John Wiley & Sons. Zhai et al. [18]. Copyright 2019, John Wiley & Sons. Yu et al. [19]. Copyright 2017, John Wiley & Sons. Gao et al. [20]. Copyright 2017, John Wiley & Sons. Reeder et al. [21]. Copyright 2017, Springer Nature. Kang et al. [22]. Copyright 2014, Springer Nature.

1.2 Three Core Units of Smart Micro-systems

The smart micro-system includes three core units, energy-harvesting unit, energy-storage unit, and functional sensing unit. Common energy harvesting units include triboelectric nanogenerators (TENGs), piezoelectric nanogenerators (PENGs), and electromagnetic generators. Energy-storage units mainly include supercapacitors, lithium-ion batteries, and fuel cells. Functional sensing units include strain sensors, temperature sensors, and electrochemical sensors. The detailed discussion is as follows.

1.2.1 Triboelectric Nanogenerator (Energy-Harvesting Unit)

Energy-harvesting devices are categorized and introduced by input energy sources, such as mechanical energy, solar energy, and thermal energy. Piezoelectric, triboelectric, and electromagnetic generators belong to the mechanical energy–harvesting

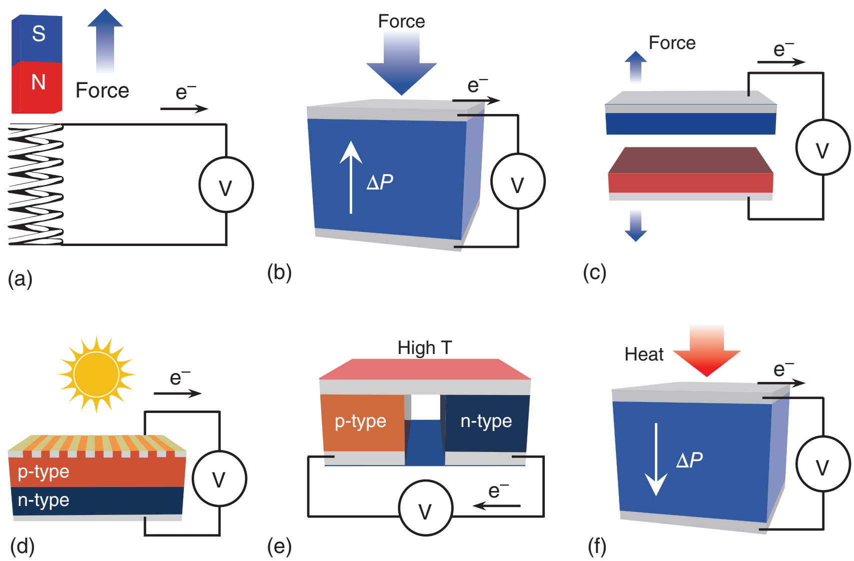

Figure 1.5 Schematic illustrations of various energy-harvesting units. (a) Electromagnetic induction, (b) piezoelectric effect, (c) triboelectric effect, (d) photovoltaic effect, (e) thermoelectric effect, and (f) pyroelectric effect. Source: Yu Song.

group; solar cells belong to the solar energy–harvesting group; thermoelectric and pyroelectric generators belong to the thermal energy–harvesting group. The detailed working mechanism is shown in Figure 1.5.

The electromagnetic energy harvester is based on the principle of electromagnetic induction [23]. When the coil and the magnet move relative to each other, the coil cuts the magnetic line to generate electromotive force and induce current in the external circuit. High-performance electromagnetic energy harvester can convert the mechanical energy into electrical energy with considerable power output, while the intrinsic large size requires specific electromagnetic materials with poor flexibility.

Piezoelectric energy harvesters are based on the piezoelectric effect of piezoelectric materials [24]. The piezoelectric effect is the conversion of mechanical energy into electric energy by breaking central symmetry of crystal structure, which generate internal potential and induce charges flow through external circuits. However, the piezoelectric energy harvester is limited by the material selectivity and specific working mode.

The other mechanical energy–based nanogenerator is the TENG, which is based on triboelectrification and electrostatic induction [25], proposed by Prof. Zhong-Lin Wang from Georgia Institute of Technology. Surface triboelectric charge polarities that form on materials are determined by the triboelectric series, and these charges induce electric flow through external circuits with specific potential differences. When two different materials come into contact, the interface of the materials transfers a charge, which results in the generation of charges with opposite polarities on the surfaces. The triboelectric potential V_T can be derived as

$$V_T = -\frac{\rho_T d}{\varepsilon_0} \tag{1.1}$$

where ρ_T is the triboelectric charge density, ε_0 is the vacuum permittivity, and d is the gap distance between two triboelectric materials. The triboelectric current I_T can be derived as

$$I_T = C_T \frac{\partial V_T}{\partial t} + V_T \frac{\partial C_T}{\partial t} \tag{1.2}$$

where C_T is the capacitance of the triboelectric nanogenerator. Therefore, both the structural design and material selection are crucial for improving the capability of the triboelectric nanogenerator.

A solar cell, or photovoltaic cell, is one of the promising green energy harvesters converting infinite solar energy into practical electricity by photovoltaic effect [26]. Work function of the p-, n-type semiconductor with electrodes is a critical factor in deciding charge transport ability and generation of voltage. The thermoelectric nanogenerator is based on the Seebeck effect [27]: the induction of electrons and holes diffusion by temperature gradient through p- and n-type semiconductors. Thus, the Seebeck coefficient determines the power performance of the output voltage of the thermoelectric nanogenerator. The other thermal energy–based nanogenerator is the pyroelectric effect–based generator, which is based on spontaneous polarization change by continuous temperature change [28]. Because every pyroelectric material has piezoelectric property, temperature change induces a pyroelectric effect, as well as a piezoelectric effect by thermal expansion of the pyroelectric material. Obviously, these energy harvesters are strongly affected by the external environment, with limited applications in flexible micro-systems.

Therefore, in the application of the wearable field, three types of energy harvesters that scavenge mechanical energy are mainly considered, electromagnetic energy harvesters, piezoelectric energy harvesters, and triboelectric energy harvesters. Among them, the TENG has great advantages in material selectivity and structural flexibility. It does not require specific permanent magnetic materials or piezoelectric materials, and various commonly used flexible polymers demonstrate good triboelectric properties.

At the same time, TENG has four basic working modes: contact–separation mode, lateral-sliding mode, single-electrode mode, and freestanding mode. For specific applications, it is feasible to develop diverse structural designs to enhance the capabilities of energy harvesting. Figure 1.6 introduces the four working modes of TENGs with corresponding charge distribution and representative works.

In 2016, Prof. Youfan Hu's group of Peking University adopted traditional weaving technology to realize a machine-washable TENG (Figure 1.6b) [29]. Taking advantages of fiber structure, the yarn experiences a contact–separation process with a maximum short-circuit current of 15.50 mA m^{-2} during the exercise. The output performance remains stable after several standardized machine-washing cycles.

In addition to harvesting energy in vertical direction, Prof. Jong Jin Park's group at Chonnam University in South Korea proposed a TENG with a continuous rotating

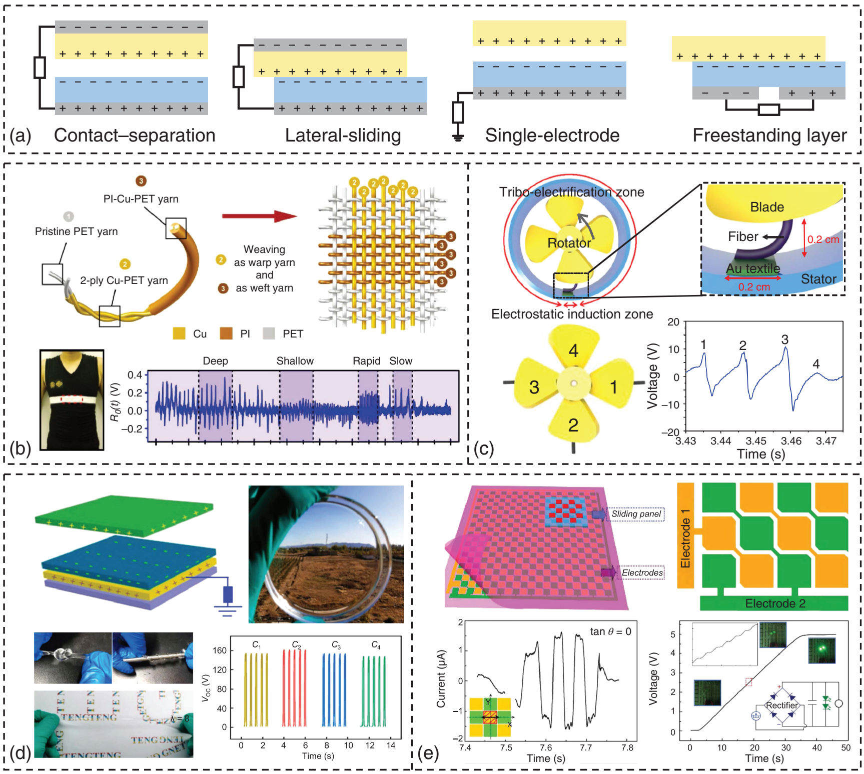

Figure 1.6 Four working modes and representative works of triboelectric nanogenerators. (a) Four working modes of triboelectric nanogenerators and corresponding charge distributions. (b) Contact–separation mode fabric TENG. Source: Reproduced with permission from Zhao et al. [29]. Copyright 2016, John Wiley & Sons. (c) Lateral-sliding mode fiber TENG. Source: Reproduced with permission from Park et al. [30]. Copyright 2017, Elsevier. (d) Single-electrode mode stretchable TENG. Source: Reproduced with permission from Jiang et al. [31]. Copyright 2021, Elsevier. (e) Freestanding layer mode checker-like TENG. Source: Reproduced with permission from Guo et al. [32]. Copyright 2015, John Wiley & Sons.

structure in 2017 (Figure 1.6c) for energy harvesting during lateral sliding process [30]. The fiber with rough surface achieves high output performance of 21.6 V and 0.6 μA, showing the advantages of flexibility and high adaptability.

To further simplify the structure of the TENG, Prof. Zhong-Lin Wang's group used hydrogel materials to prepare a single-electrode TENG in 2021 (Figure 1.6d), which shows chemical robustness and high stretchability [31]. The output performance of the TENG is nearly unaffected even under harsh environment such as overly acidic, alkaline, or saline conditions. The hydrogel is a great candidate as an excellent durable electrode material.

Meanwhile, a freestanding layer can also simplify the structure and improve the overall integration. In 2015, Prof. Chenguo Hu's group reported a checker-like interdigital electrode-based TENG (Figure 1.6e) [32]. It is available to harvest in-planar omni-directional mechanical energy, with the maximum output power density of 1.9 W m^{-2} and open-circuit voltage of 210 V, respectively.

1.2.2 Solid-State Supercapacitors (Energy-Storage Unit)

For wearable energy-storage units [33], considering practical application scenarios, liquid electrolyte remains problems, such as difficulty in encapsulation and easy leakage to harm human health. Solid-gel electrolyte is adopted, with the flexible electrodes. Common energy-storage units mainly include ion batteries and supercapacitors [34]. The working mechanism and representative devices of different energy-storage units are shown in Figure 1.7.

For the rechargeable ion battery [35], a thorough redox reaction occurs between the electrode materials and the electrolyte ions (Figure 1.7a). The ions of the electrolyte penetrate into the electrode materials and carry out repeated intercalation/deintercalation reactions. It demonstrates a high specific capacity and energy density, with a relatively low-power density instead.

Different from the working mechanism of ion batteries, no redox reaction occurs for the electrical double-layer supercapacitors during the process (Figure 1.7b) [36]. Through the physical process of charge adsorption/desorption on the electrode surface, an interface layer is formed between the electrode and electrolyte, which shows great capacity with ideal power density and cycling stability.

In addition, during the charging process of the pseudo-capacitor [37], the surface redox reaction occurs between the electrode materials and electrolyte ions (Figure 1.7c). Such chemical reaction is highly reversible and the device shows high capacitance. However, the electrode experiences an irreversible decay after repeated redox–oxidation reaction with poor chemical stability.

Intercalation pseudo-capacitor is newly proposed model in recent years [38], where a redox reaction under a certain depth occurs at the contact interface between the electrode materials and electrolyte ions during the operation (Figure 1.7d). Although this device shows higher power density and capacitance, it requires strict crystal structure and purity of the electrode materials. The complex synthesis process and preparation conditions further limit the practical applications.

Thus, compared with various devices that store charges through chemical reactions, electrical double-layer supercapacitors have compelling advantages as follows.

First, fast charging–discharging rate and high-power density. Electrical double-layer supercapacitors rely on the physical process of charge adsorption/desorption on the electrode surface. It can achieve rapid charging or discharging in a short period, and the energy-released capacity is much greater than that of ordinary battery.

Second, reliable cycling stability. No oxidation–reduction reaction occurs in electrical double-layer supercapacitor with a simple structure. It is not prone to problems, such as irreversible consumption, material shedding, and dendritic short circuit. After long-term charging–discharging process, it still maintains a stable capacitance.

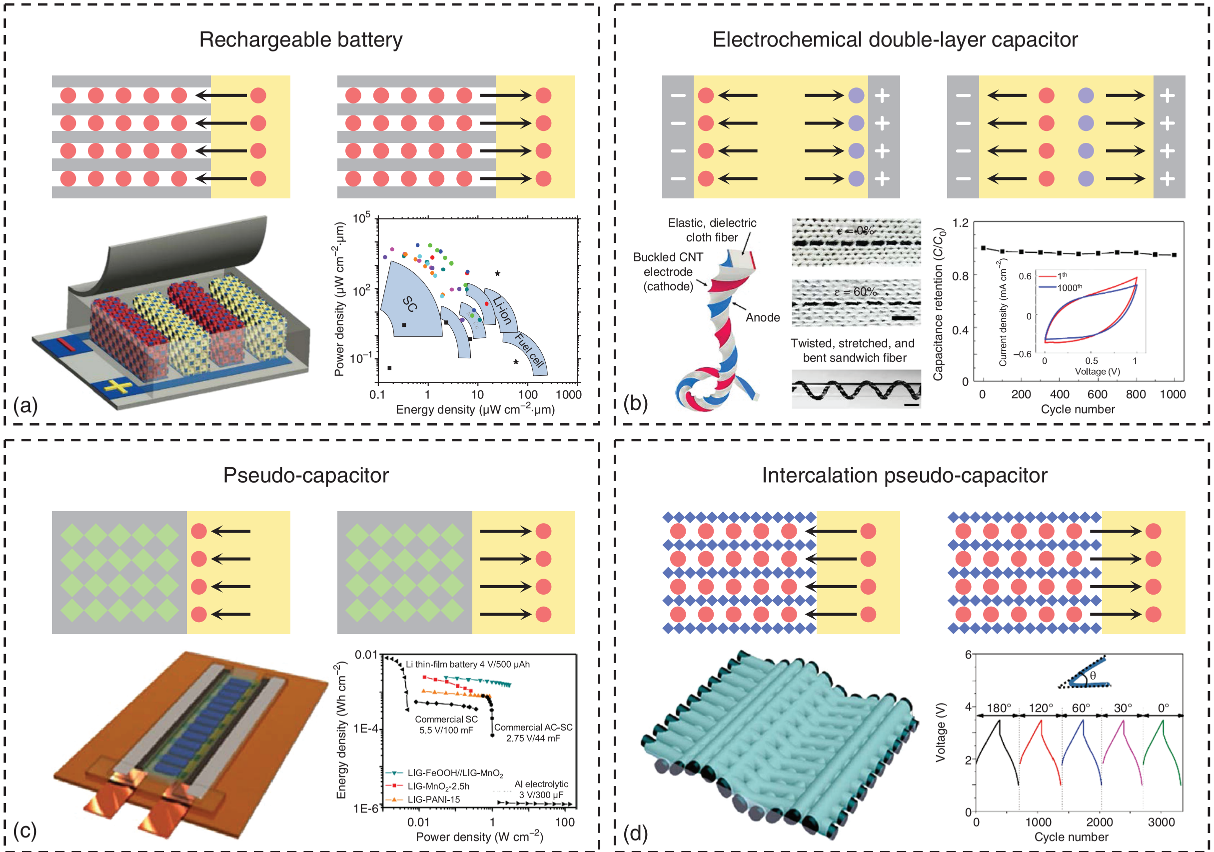

Figure 1.7 Working principles and representative works of energy-storage devices. (a) Rechargeable ion battery. Source: Pikul et al. [35]. (b) Electrochemical double-layer capacitor. Source: Choi et al. [36]. (c) Pseudo-capacitor. Source: Li et al. [37]. (d) Intercalation pseudo-capacitor. Source: Deng et al. [38].

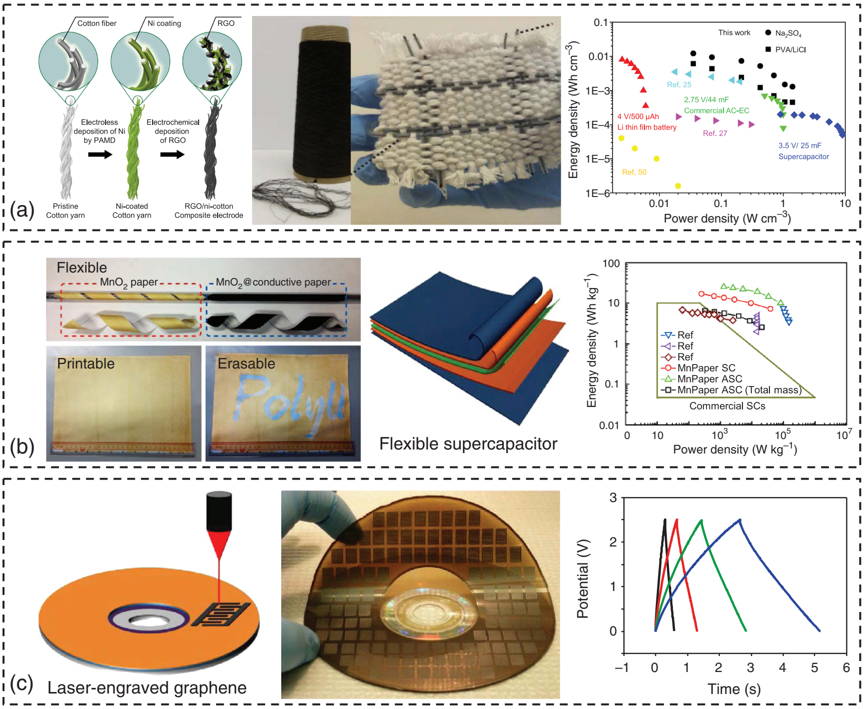

Figure 1.8 Flexible solid-state supercapacitors. (a) Fiber-shaped supercapacitor. Source: Liu et al. [42]. (b) Paper-based supercapacitor. Source: Qian et al. [43]. (c) In-plane supercapacitor. Source: El-Kady et al. [44].

Third, simple preparation process. Electrical double-layer supercapacitors mostly adopt carbon-based materials, showing great mechanical strength and conductivity at the same time. With the assistance of the large-scale preparation process and biocompatible materials, it is feasible to develop highly reliable devices.

Therefore, for the energy-storage units of the smart micro-systems, the focus is on the electrical double-layer solid-state supercapacitor (referred to as the supercapacitor) [39].

Supercapacitors have several advantages, such as the wide range of electrode selection and diverse structural design. In terms of electrodes, the materials from zero-dimensional (0D) nanoparticles, one-dimensional (1D) carbon nanotubes, two-dimensional (2D) graphene, to three-dimensional (3D) columnar graphene have unique features with great electrochemical performance [40]. For the specific applications, the supercapacitors are able to adopt different structural design, such 1D fiber, 2D planar, or 3D sponge structure [41]. Figure 1.8 demonstrates several representative works related to supercapacitors.

In 2015, Prof. Zijian Zheng's group in Hong Kong Polytechnic University proposed a one-dimensional flexible supercapacitor [42], as shown in Figure 1.8a. Through electroless deposition and electrochemical deposition, the multilayer graphene–metal composite electrode is obtained. The assembled supercapacitor shows the energy density of 6.1 mWh cm^{-3} and power density of 1400 mW cm^{-3}, respectively. With lightweight and high elasticity features, this supercapacitor exhibits great cycling stability and mechanical robustness under bending tests, which can be further adopted in bioelectronic systems.

In addition to the fiber structure, paper-based supercapacitors also demonstrate high practicability. In 2015, Prof. Jikang Yuan's group of Hong Kong Polytechnic University realized the preparation of hexagonal MnO_2 nanosheet ink based on chemical reduction method [43]. After the pretreatment with multi-walled carbon nanotubes, the MnO_2 printed paper can further be assembled into the symmetrical supercapacitor with a maximum power density of 81 kW kg^{-1}. It is feasible to realize the preparation of large-scale printable energy-storage devices based on this approach (Figure 1.8b).

Another large-scale processing method is based on the laser-engraving method. In 2013, Prof. Richard B. Kaner of the UCLA developed the graphite oxide film through the direct laser-writing method to form a large-area graphene electrode (Figure 1.8c) [44]. The cooperation of laser-engraved graphene electrode and solid-state electrolyte allows for the preparation of in-planar supercapacitor in the flexible substrate. The thickness of the device is greatly reduced, with the maximum power density of 200 W cm^{-3}.

1.2.3 Strain Sensors (Functional Sensing Unit)

Skin is the largest organ of the human body, and an ideal interface for acquiring important physiological indicators from internal organs, blood vessels, muscles, dermis, and epidermis [45]. In the muscle layer, the nerves innervate the muscle fibers to stimulate physical contraction with biological potentials [46], including electrocardiogram, electroencephalogram, and electrooculogram. In the dermis layer, the arteries provide various types of cardiovascular information [47], such as body temperature, heart rate, blood pressure, and oxygen content. In the epidermis, sweat contains various biomarkers, which provide information on human physiological conditions [48], including pH, mineral ions, lactate, and urea concentrations.

With the concept of "lab-on-the-skin," specific sensing units are developed for physiological signals. Comfortably attached among the skin, these sensing units are capable of realizing non-invasive health monitoring. The sensing units applied to different parts of human body are shown in Figure 1.9.

Among them, pressure sensors are often adopted to monitor the stress and strain, which can effectively reflect the physical signals of human body, such as heart rate, exercise information, and respiration rate. Pressure sensors are crucial in the smart micro-systems, and the working principle and representative devices of pressure sensors are discussed in Figure 1.10.

Pressure sensors are usually divided into four categories, piezoresistive, capacitive, piezoelectric, and iontronic sensors [59–62], as shown in Figure 1.10a. When the external pressure is applied, the devices experience geometrical deformations with corresponding electrical signals.

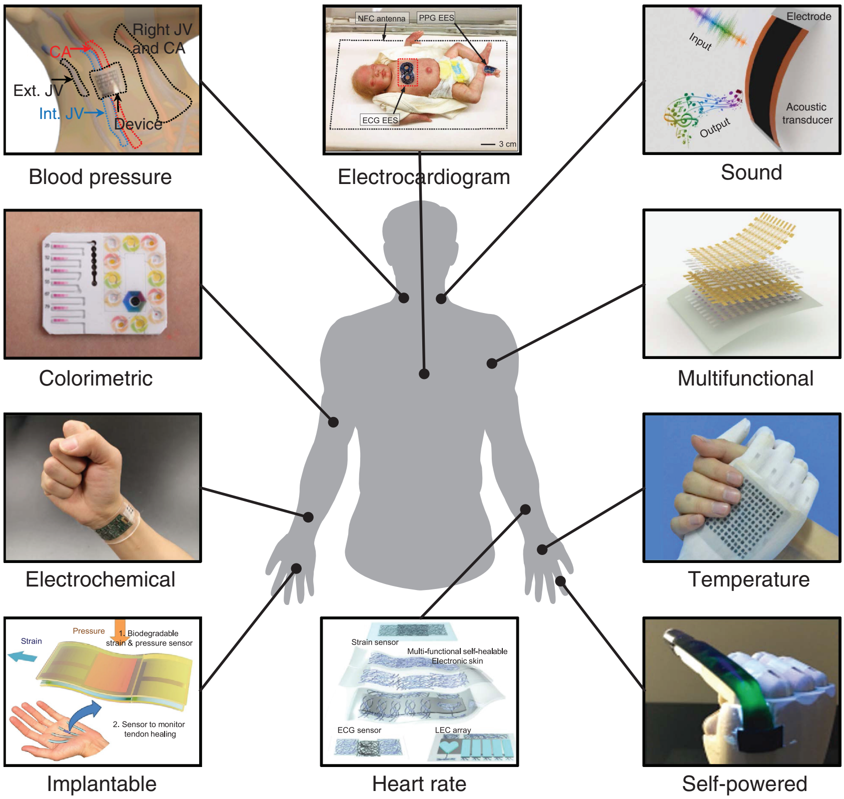

Figure 1.9 "Lab-on-the-skin" for real-time monitoring of various physiological signals. Source: Bu et al. [49]. Copyright 2018, John Wiley & Sons. Wang et al. [50]. Copyright 2018, Springer Nature. Tao et al. [51]. Copyright 2017, Springer Nature. Zhang et al. [52]. Copyright 2015, Springer Nature. Hua et al. [53]. Copyright 2018, Springer Nature. Boutry et al. [54]. Copyright 2018, Springer Nature. Son et al. [55]. Copyright 2018, Springer Nature. Chung et al. [56]. Copyright 2019, AAAS. Choi et al. [57]. Copyright 2019, American Chemical Society. Gao et al. [58]. Copyright 2016, Springer Nature.

- Piezoresistive sensors: the change of internal conductive networks induces a resistance response with simple structure and reliable performance.
- Capacitive sensors: the change of gap between two electrodes causes a capacitor response. Such devices have high sensitivity, while they are susceptible to signal interference with poor reliability.
- Piezoelectric sensors: the potentials between two electrodes change stably, while they are highly dependent on the embedded piezoelectric materials.
- Iontronic sensors: the number of charges attracted by the electrical double-layer changes with high stability, while it is not suitable for large-scale preparation with toxicity.

Therefore, the piezoresistive sensors with simple preparation process have stable performance and are widely used in the real-time monitoring of physiological signals.

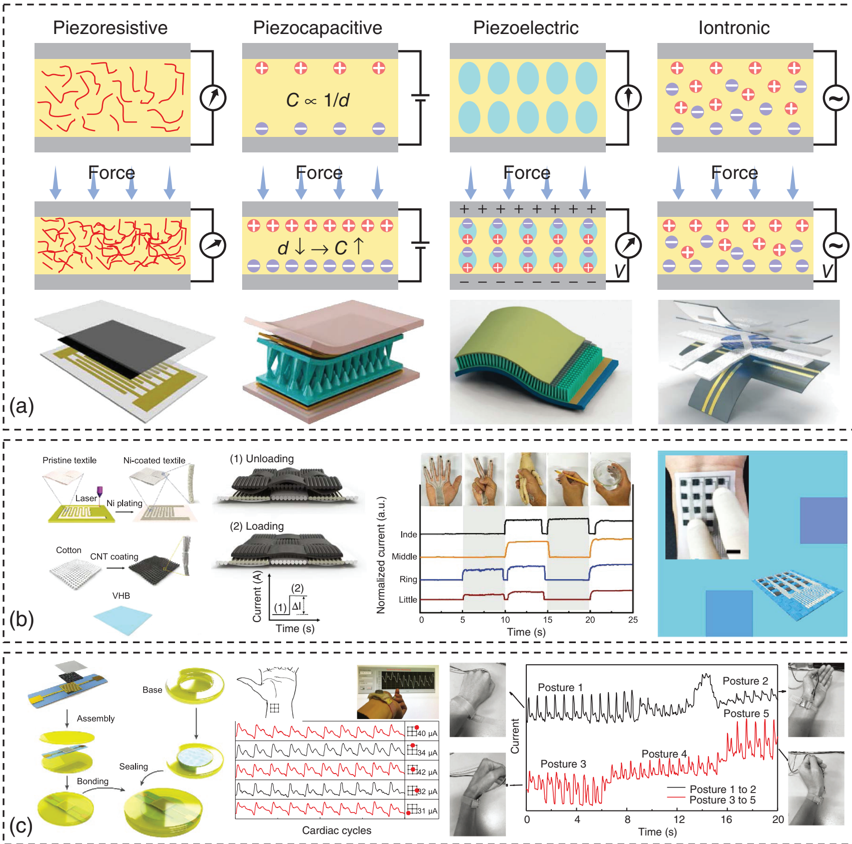

Figure 1.10 Classification and representative works of strain sensors. (a) Structure and working principles of four kinds of strain sensors. Source: Nie et al. [59]. Chen et al. [60]. Gong et al. [61]. Niu et al. [62]. (b) Large-area textile piezoresistive sensor. Source: Liu et al. [63]. (c) Liquid capsule piezoresistive sensor. Source: Fan et al. [64].

To realize the compatible integration of piezoresistive sensors with human body, in 2017, Prof. Zhong-Lin Wang's group proposed a fabric-based pressure sensor array (Figure 1.10b), which can be prepared by depositing nickel and carbon nanotubes through a mask-assisted method [63]. The obtained piezoresistive sensor has ultra-high sensitivity (14.4 kPa^{-1}) with low detection limit (2 Pa) and fast response time (24 ms). It is feasible to detect real-time pulse signals and realize large-area sensing and spatially tactile positioning, showing great potentials in the fields of smart textiles and human–machine interaction.

In addition, for long-term monitoring of physiological signals, piezoresistive sensors are capable of working stably under different states. In 2018, Prof. Shiqi Chen's group developed a liquid capsule-based sensing platform [64], as shown in Figure 1.10c. The flexible capsule, with great comfortability and adhesion, can achieve continuous and accurate tracking of heart rate and blood pressure under different wrist positions. The stable monitoring of physiological signals allows for the diagnosis and prognosis of cardiovascular diseases.

In summary, three core units of micro-systems for human health monitoring are well discussed. The energy-harvesting unit adopts the TENG, which are able to scavenge low-frequency motion energy from human body; the energy-storage unit adopts the supercapacitor, with stable electrochemical performance; the functional unit focuses on the piezoresistive sensor for monitoring physical signals, and electrochemical sensor for monitoring chemical signals in sweat. However, the working capability of a single unit is hard to meet the requirements of multifunctional practical applications. The combination of multiple units through the structural design and process optimization is crucial to the development of integrated smart micro-systems.

1.3 The Progress of the Integration of Smart Micro-systems

Due to the limitations of material processing, it is difficult to realize seamless integration of three units among the same substrate. Such approach decreases the overall integration and reliability with mutual interference. The integration of two key units is a feasible approach to expand the system dimension and application range. Figure 1.11 introduces the exploration of integration methods in three directions.

The self-charging power unit is capable of converting mechanical energy from human body to stored electrical energy directly [65]. On one hand, it can significantly reduce the energy dissipation during the transmission, and on the other hand, it is beneficial to the energy conversion from mechanical energy into chemical energy. The integration of TENG and supercapacitor enables the self-charging power unit, realizing the energy harvesting and storage simultaneously.

Self-driven monitor patch adopts various functional sensing units [66], such as piezoresistive sensors, to perform measurements of physiological signals from human body. During the operation, stable voltage supply is desired to stably drive the sensor, while the external circuit will not only increase the complexity of the system, but also bring the problems, such as signal crosstalk. Through the designed structure and optimized performance, the in situ energy supply is a feasible approach to address the challenges. The integration of supercapacitor and the functional sensor allows for a stable and reliable self-driven monitor patch to achieve the goal of long-term monitoring.

Self-powered sensing platform adopts TENG for the energy conversion from mechanical energy into electrical energy and the functional sensor to acquire physiological information in electrical signal [67]. On one hand, the TENG itself serves as an active sensor, and on other hand, the collected energy from TENG is able to drive the functional sensor stably to obtain a self-powered sensing platform. The self-powered sensing platform is battery-free, showing advantages of continuous monitoring of health status.

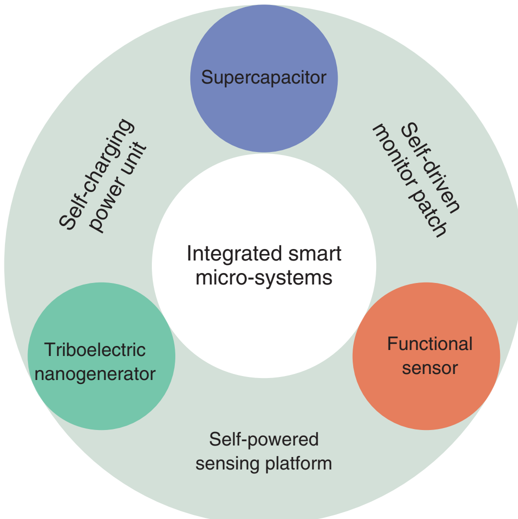

Figure 1.11 Exploration direction of integrated micro-systems. Source: Yu Song.

1.3.1 Self-Charging Power Unit

For self-charging power units, the selection of energy-harvesting unit and energy-storage unit is of vital importance. TENG has diverse working modes with a wide selection of materials, which can be easily integrated with other devices through the structural design. The supercapacitor shows great performance and flexibility, and the structure can be optimized for specific applications. The electrical energy collected by the TENG can be effectively stored in the supercapacitor through the rectifier bridge. Such integrated energy supply mode has attracted huge attention, and Figure 1.12 summarizes several representative self-charging power units.

The development of self-charging power units for human-related applications mainly includes two parts. First, considering the wearing comfort and energy-harvesting modes, fabric electrodes are adopted to realize the large-area preparation of TENGs to efficiently scavenge human mechanical energy. Second, the reasonable integration of TENG and supercapacitor with new features allows for the multi-dimensional energy harvesting and storage.

For fabric-based self-charging power unit, Prof. Zhonglin Wang's group proposed a self-charging power cloth in 2016 [68]. Through the simple manufacturing method, fiber-shaped supercapacitors are prepared, which can be further integrated with a fabric TENG within the same fabric, allowing the effective storage of the intermittent energy collected during the human movement (Figure 1.12a).

To further realize large-scale processing, Prof. Chenguo Hu's group used industrial weaving method to integrate fabric TENG and fiber-shaped supercapacitor into a textile substrate in 2018 (Figure 1.12b) [69]. Such self-charging power textile exhibits excellent flexibility and mechanical robustness, showing broad prospects in the field electronic textiles.

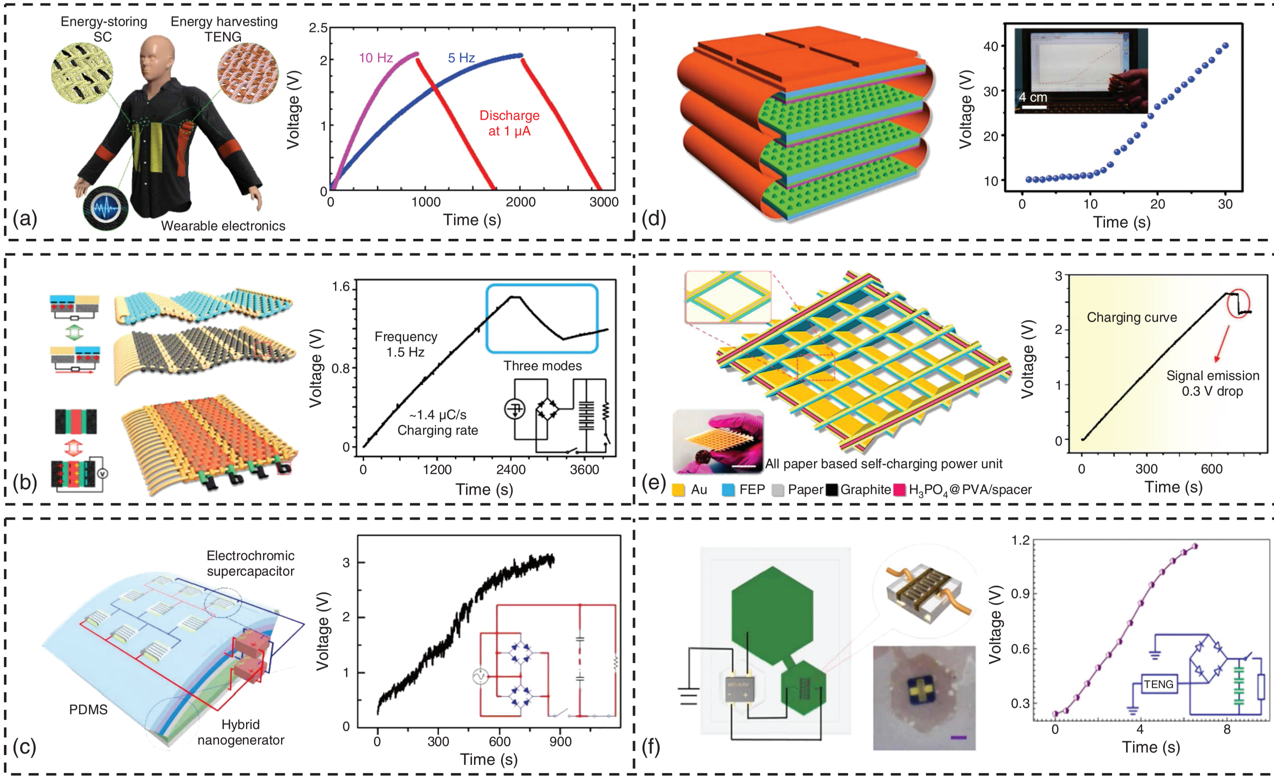

Figure 1.12 Self-charging power units. (a–c) Wearable textile, and (d–f) structural design. Source: Reproduced with permission from Pu et al. [68]. Copyright 2016, John Wiley & Sons. Chen et al. [69]. Copyright 2018, Elsevier. Qin et al. [70]. Wang et al. [71]. Guo et al. [72]. Wang et al. [73].

The hybridization of TENG and other energy-harvesting devices further expand the practical applications and improve the performance. In 2018, Prof. Zhong-Lin Wang's group proposed a concept of hybridized self-charging power unit (Figure 1.12c), by collecting mechanical energy efficiently [70]. The integration of hybrid nanogenerators and micro-supercapacitors array enables the self-charging power package capable of indicating the charging state with color change. With simple and cost-effective fabrication, it greatly promotes the development of self-charging power units.

In addition, the exploration of the integrated structure of the self-charging energy unit is also significant. In 2015 and 2017, Prof. Zhong-Lin Wang's group developed two self-charging power units (Figure 1.12d,e), adopting a multilayer plastic structure and an ultralight cut-paper structure, respectively [71, 72]. With stacked structure, the TENGs of the former one can achieve multiple cycles of energy harvesting during one compressing process. The supercapacitor is encapsulated on the top surface with stable mechanical performance. The latter one uses paper-cutting technology to combine multiple TENGs with supercapacitors with great mechanical capability. Using environment-friendly materials, the output performance is further enhanced through the serial or parallel connection with potential applications.

Another structural strategy is to encapsulate both TENG and supercapacitor together. In 2017, Prof. Zheng You's group introduced a bionic flexible stretchable TENG with supercapacitor (Figure 1.12f) [73]. Such all-in-one integration strategy not only ensures the stability of the unit but also reduces signal interference, which is crucial for the development of flexible electronics.

1.3.2 Self-Driven Monitor Patch

Through the calibration and optimization, various functional sensors are used for monitoring physiological information in electrical signals, such as stress, concentration, and temperature. Reliable power supply method is highly desired to reduce the external noise and signal distortion. It is feasible to adopt supercapacitor as energy-storage unit to directly drive functional sensors continuously. Figure 1.13 introduces several self-driven monitor patches for different physiological signals.

Considering the multi-dimensional structure of supercapacitors and multimodal signals of functional sensors, the self-driven monitor patches are divided into three categories according to the materials and structures. These approaches are closely related and enrich the overall functionality and diversity.

The first approach is an all-in-one structural design based on similar characteristics of active materials. In 2019, Prof. Jeong Sook Ha's group proposed a dynamic stretchable fabric system [74]. With general nanocomposite materials, supercapacitor and strain sensor are developed in different directions of extension to monitor the physiological signals (Figure 1.13a). Supercapacitor demonstrates great performance and mechanical stability under deformations, such as static and dynamic strains, while strain sensor demonstrates several advantages, including high sensitivity, good repeatability, and fast response time. After comfortably attached among

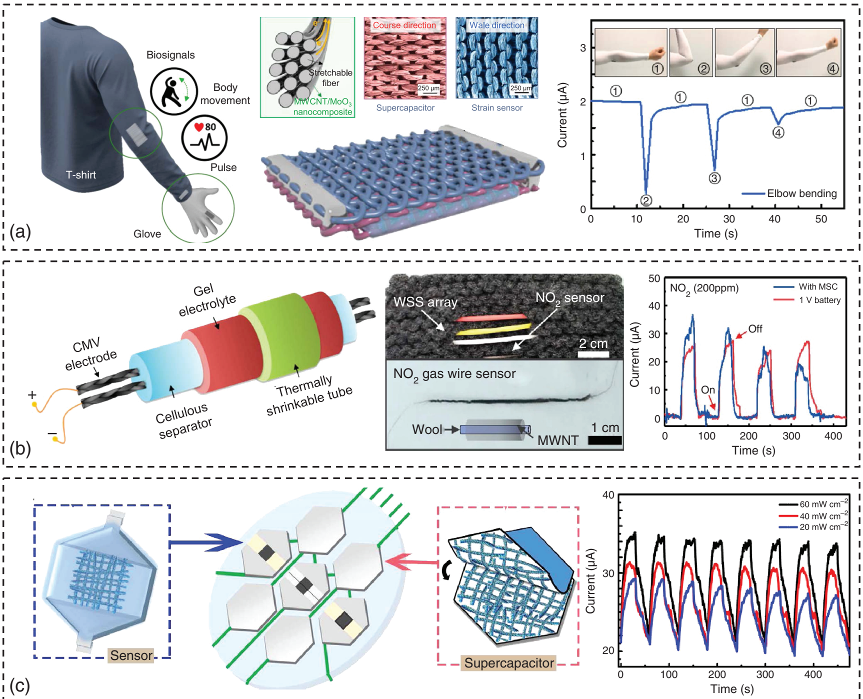

Figure 1.13 Self-driven monitor patches. (a) All-in-one structural design. Source: Park et al. [74]. (b) Multifunctional sensing. Source: Kim et al. [75]. (c) Multimodal planar structure. Source: Ai et al. [76].

human skin, this all-in-one patch is able to realize accurate reading of joint movement and heartbeat for real-time health monitoring.

The second approach is the combination of units with similar structure. In 2017, Prof. Jeong Sook Ha's group developed a high-performance flexible fiber-shaped supercapacitor to drive various fiber-shaped sensors [75]. The supercapacitor with fiber electrodes has a wide potential window and high specific capacitance ($10.6\,mF\,cm^{-2}$). As shown in Figure 1.13b, various sensors for the detection of ultraviolet light and nitrogen dioxide are prepared based on the same yarn material, which can be directly woven on the surface of clothes. It is easily replaceable according the practical requirements, enabling real-time monitoring of various signals.

The third approach is the fully integrated multimodal planar structure with new features. In 2017, Prof. Guozhen Shen's group developed a multifunctional self-driven electronic skin, which integrates four micro-supercapacitors with three functional sensors in the same substrate (Figure 1.13c) [76]. Through electrospinning process, the prepared nanofibers can be modified with different active materials for specific devices. Using micro-supercapacitor as stable power supply, the pressure sensor is used to monitor physiological information, such as heart rate and sound, the photoelectric detectors are used for brightness recognition, and the gas sensor focuses on the detection of volatile organic compounds. The multimodal monitoring of this self-driven electronic skin has potential applications in the field of flexible electronics.

1.3.3 Self-Powered Sensing Platform

While efficiently collecting mechanical energy, the TENG can respond to various mechanical stimuli. Using the output of the TENG as a sensing signal, it can realize the development of a self-powered sensing platform without external energy supply. Since the freestanding-layer mode is similar to the lateral-sliding mode, the TENG mainly adopts the contact–separation mode, the single-electrode mode, and the lateral-sliding mode to detect three mechanical signals, including small strain, stress position, and stretching ratio, respectively. Several corresponding self-powered sensing platforms are shown in Figure 1.14.

Aiming at detecting small strains on the skin, in 2017, Prof. Zhong-Lin Wang's group proposed a contact-mode TENG strain sensor using negative Poisson ratio auxetic materials (Figure 1.14a) [77]. Such auxetic foams can expand in all directions when they are stretched in a single direction. The TENG could sense different types of motions applied onto the foam, such as pressing, bending, and twisting. Therefore, it shows promising applications to monitor human body movements on the finger, elbow, and knee as a self-powered human body system for human–machine interaction.

For the identification and judgment of stress position, in 2019, Prof. Zhong-Lin Wang's group proposed a flexible and durable wood-based TENG for big data analysis of sports [78], as shown in Figure 1.14b. Based on a simple and efficient chemical treatment method, the strength of natural wood is greatly improved, with excellent flexibility and durability. The prepared single-electrode TENG can achieve a transferred charge density of $36\,\mu C\,m^{-2}$ with advantages of being lightweight and ultrathin, and showing low-cost performance. The arrayed TENG can be further adopted for the development of a table tennis–positioning sensor platform to realize speed judgment, motion trajectory tracking, and big data analysis. It works well for the judgment of the side ball and expands the application in the field of smart sports.

To realize the detection of the lateral stretching ratio, in 2017, Prof. Haixia Zhang's group prepared a digitalized self-powered strain gauge based on the lateral-sliding TENG (Figure 1.14c) [79]. With different working mechanism, this device is different from the traditional resistive or capacitive sensors. The grating-shaped TENG analyzes the stretching ratio with the number of periodic signals with high precision and high sensitivity, instead of the analogue value of the output. When attached to joint, such as elbows, it is available to realize real-time monitoring of joint motion with signal processing, providing new approaches for posture reconstruction and artificial limb assistance.

In summary, there are three strategies to improve the performance and application of integrated smart micro-systems. The self-charging power unit adopts a fabric structure or an integrated structure for simultaneous energy harvesting and storage; the self-driven monitor patch is based on general materials and fabrication process to achieve multimodal signal detection; self-powered sensing platform uses TENGs

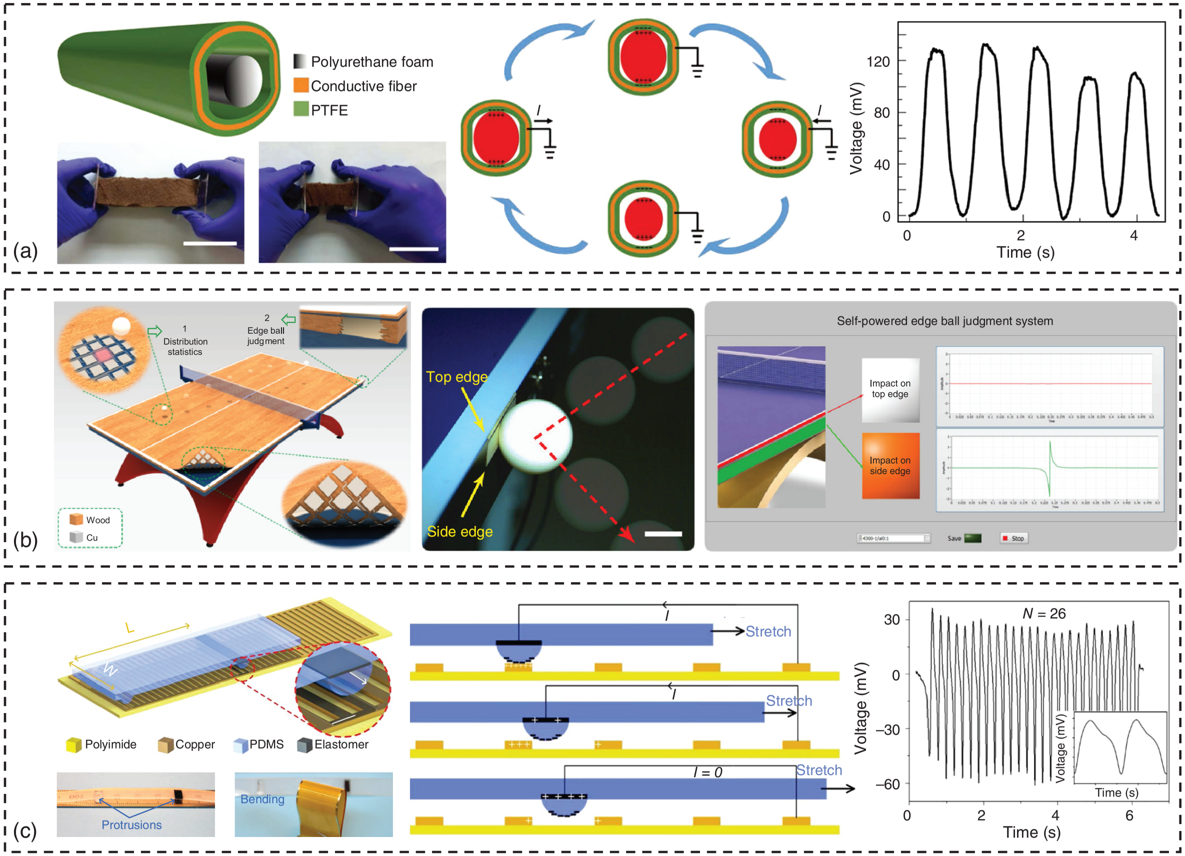

Figure 1.14 Self-powered sensing platforms. (a) Subtle skin deformation. Source: Reproduced with permission from Zhang et al. [77]. Copyright 2017, John Wiley & Sons. (b) Pressure position recognition. Source: Reproduced with permission from Luo et al. [78]. Copyright 2019, Springer Nature. (c) Lateral stretching judgement. Source: Reproduced with permission from Su et al. [79]. Copyright 2017, Elsevier.

in different working modes to transform the mechanical stimuli into the electrical outputs as the active mechanical sensing. Further practical application in the field of health monitoring is crucial for the development of integrated smart micro-systems.

1.4 The Progress of Applications of Integrated Smart Micro-systems

The integrated smart micro-systems, with the coordination of multiple devices, realize human-centered closed-loop health management from physiological signal monitoring, wirelessly human–machine interaction, to real-time diagnosis-assisted drug delivery. With the flexible and malleable materials, application-oriented structural design, and wireless signal transmission, the smart micro-systems show broad prospects in the field of medical care. The integrated smart micro-systems are discussed from three aspects, real-time health monitoring, multifunctional human–machine interaction, and assisted precision therapy.

1.4.1 Real-Time Health Monitoring

The various kinds of physiological signals can be mainly divided into two categories, biochemical signals and biophysical signals, with corresponding sensor structure. For temperature sensing, the resistor with temperature coefficients is normally used; for ECG signals, three-electrode configuration is adopted; for pulse signals, strain sensor with high sensitivity is preferred. In terms of real-time health monitoring, three strategies are proposed, including chemical sensing for biofluids, multimodal physical and chemical information monitoring, and network detection of physical signals. Figure 1.15 introduces the representative works of integrated smart micro-systems.

For the monitoring of various biomarkers in biofluids, in 2016, Prof. Ali Javey's group proposed a fully integrated multiplexed sensor array for reliable in situ perspiration analysis [58], as shown in Figure 1.15a. Considering the complex environment of sweat, the multiplexed sensor array can simultaneously measure the metabolites (glucose, lactic acid) and electrolytes (sodium ions, potassium ions) of sweat, further calibrated by the temperature sensor. Through the signal processing and wireless transmission by the flexible circuit module, it is feasible for continuous monitoring of health status during controllable exercise. This non-invasive multi-channel monitoring is essential for personalized diagnosis and early warning.

Besides specific analysis of chemical signals, Prof. Somayeh Imani's group developed a physical–chemical hybrid patch in 2016 (Figure 1.15b) [80]. With large-scale screen-printing technology, chemical sensor for monitoring lactate in sweat and physical sensor for detection of ECG signal are prepared together with lower noise crosstalk. During human movement, the ECG signal is similar to result collected by the commercial device, and the chemical sensor achieves selective response to the lactate in sweat with high sensitivity. The cooperation of these hybrid sensors

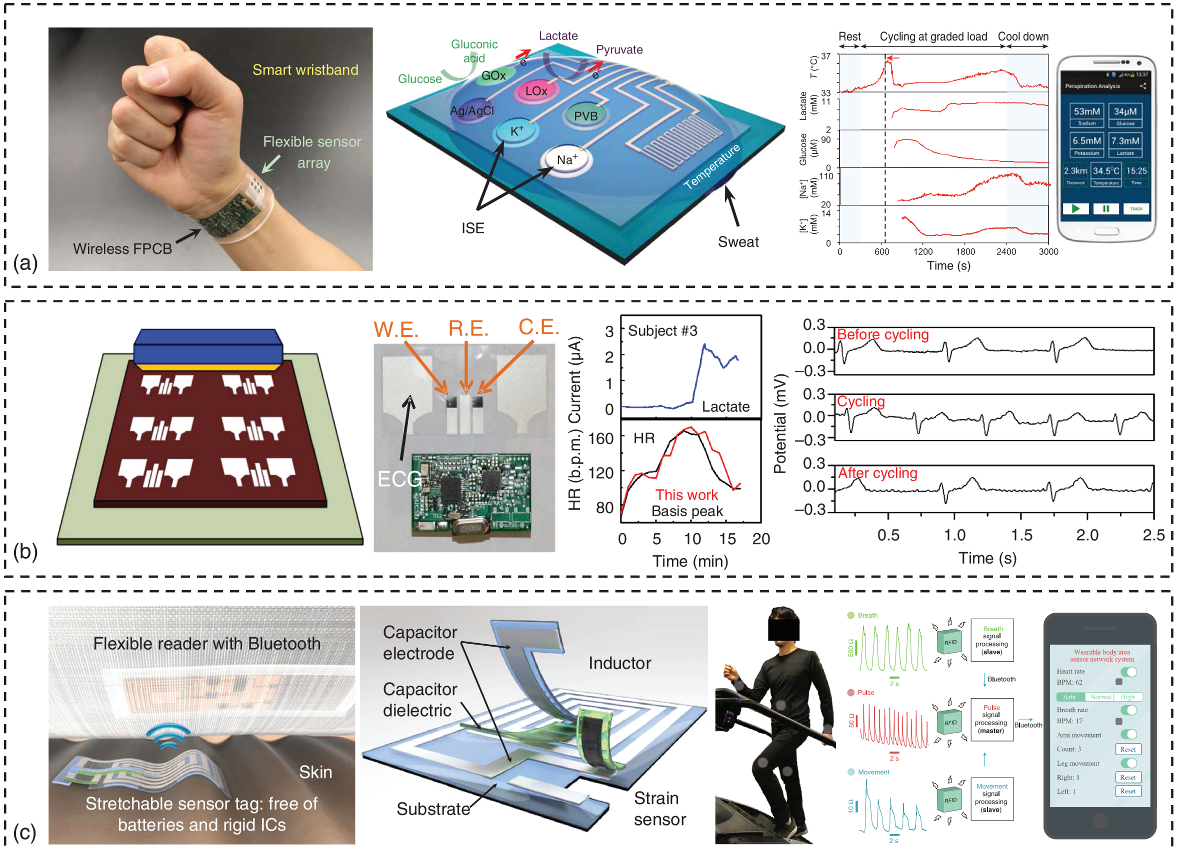

Figure 1.15 Real-time health monitoring. (a) Multiplexed sweat chemical signal detection. Source: Gao et al. [58]. (b) Multimodal physical–chemical information sensing. Source: Imani et al. [80]. (c) Network body physical indicator monitoring. Source: Niu et al. [81].

enables reliable tracking for human status, providing more comprehensive and reliable health information.

After realizing the local physiological signal monitoring, whole-body network monitoring is also important. In 2019, Prof. Zhenan Bao's group proposed a body network system with stretchable sensors attached to various parts of human body (Figure 1.15c) [81]. In cooperation with the passive radio frequency identification technology, it can acquire through the flexible circuit and still maintains functions even under the deformation of 50%. The skin-like conformal interface allows for the continuous measurement of physiological signals, including heart rate, respiration rate, and movement information, with the visual readout. Such integrated smart micro-system shows excellent and reliable performance for the next generation of real-time health monitoring and clinical study.

1.4.2 Multifunctional Human–Machine Interaction

To achieve effective communication between humans and smart systems in a computer environment, human–machine interaction that can monitor physical activities, health conditions, and emotional fluctuations is indispensable, through various smart homes or portable electronics. Among them, various types of sensors play an important role. Based on functional units with different characteristics, the integrated smart micro-system serves as a human–machine interaction medium to meet different application requirements, including virtual reality with feedback, remote control for posture recognition, and multifunctional prosthesis assistance, as shown in Figure 1.16.

Aiming at the application of skin-interfaced virtual reality and real-time feedback, in 2019, Prof. John Rogers's group used a thin and soft structure to realize the epidermally programmable virtual reality system, providing a large-scale tactile actuator array under wireless operation [82], as shown in Figure 1.16a. The light elastic layer serves as a reversible and soft adhesive interface with skin. The silicone encapsulation layer contains a wireless control system and an actuator array. And a stretchable fabric is coated with a silicon film showing good air permeability, as a substrate with toughness. Compared with eyes and ears, the skin can enhance the experience for the interaction, as the programmable communication interfaces and input channels, showing potential applications in prosthetic tactile feedback and game entertainment.

The accurate recognition of motion mode enables the remote control by robotic arm. In 2020, Prof. Woon-Hong Yeo's group introduced all-printed, nanomembrane hybrid electronics using multiple nanomaterials to construct high-performance wearable sensors and wireless circuits (Figure 1.16b) [83].

The biocompatible, high-aspect ratio nanomaterial offers excellent conformal lamination on human skin for high-fidelity recording of EMG. The mechanical stretchability of the sensor and the flexibility of the circuit allow the whole patch to endure the multimodal strain during the wearable applications. The wearable all-printed, nanomembrane hybrid electronics integrated with machine-learning method shows a successful detection of all finger motions with an accuracy of about

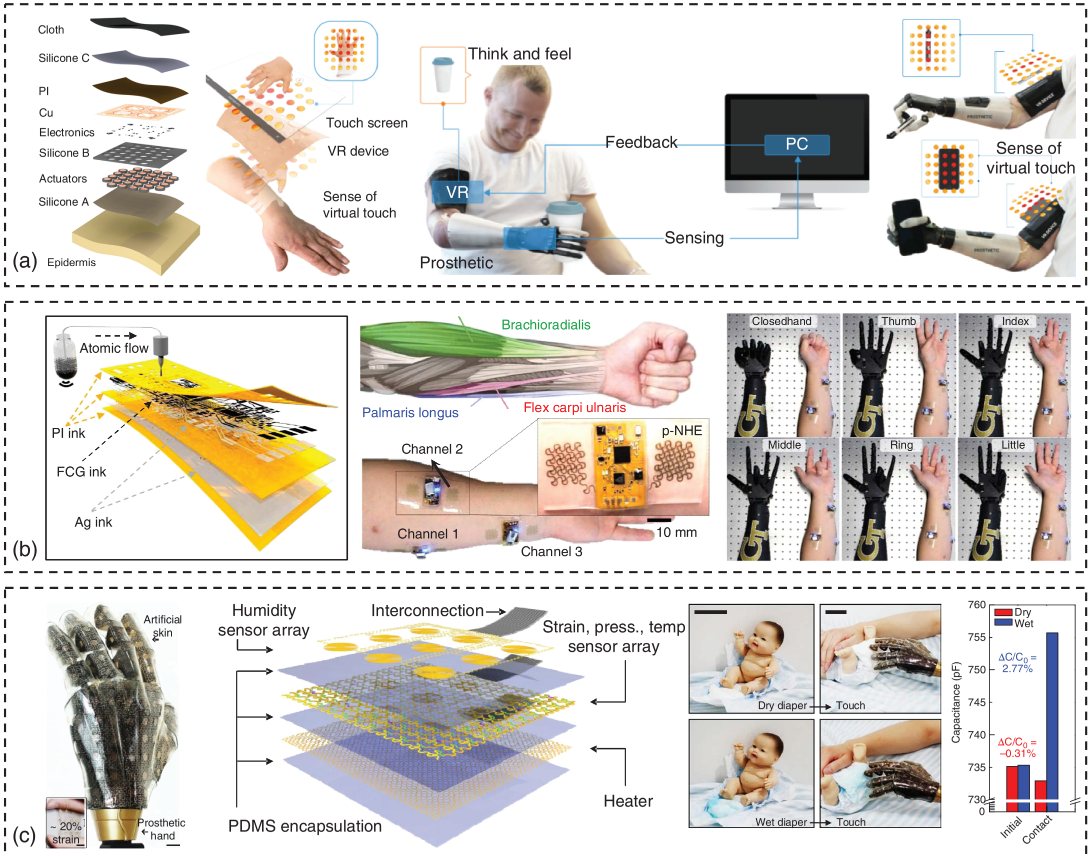

Figure 1.16 Multifunctional Human–Machine Interaction. (a) Virtual reality with dynamic feedback. Source: Reproduced with permission from Yu et al. [82]. Copyright 2019, Springer Nature. (b) Remote operation of posture recognition. Source: Reproduced with permission from Kwon et al. [83]. Copyright 2020, Springer Nature. (c) Prosthetic assistance for multimodal sensing. Source: Reproduced with permission from Kim et al. [84]. Copyright 2014, Springer Nature.

99%. This approach can enhance the collaboration between human and machine for future biofeedback-enabled prosthetic development and enhanced rehabilitation training.

The multifunctional sensor array can realize prosthesis-assisted monitoring. In 2014, Prof. Dae Hyeong Kim's group proposed an ultrathin silicon nanobelt as smart artificial electronic skin [84], including strain, pressure, and temperature sensor array, humidity sensor, heaters, and stretchable electrode arrays for nerve stimulation (Figure 1.16c). The multi-layer composite sensor design has high temporal and spatial sensitivity with mechanical reliability, significantly improving the capability to perceive external environment. The stretchable humidity sensor and heater can realize skin humidity perception and body temperature regulation, and the electrical stimulation module can stimulate specific nerves to relieve inflammation. The development of the multifunctional electronic skin provides reliable technical support for emerging fields such as assisted smart prosthetics.

1.4.3 Assisted Precision Therapy

On the basis of health monitoring and human–machine interaction, precision therapy is the last step for personalized health management of the entire smart micro-system. The real-time monitoring of physiological signals provides informative data, and human–machine interaction allows for online diagnosis. Both jointly lay the foundation for precision therapy, which is helpful for early disease control and postoperative rehabilitation. Based on different methods and applications, assisted precision therapy is mainly divided into three types for specific diseases: epidermal drug delivery, implantable nerve regeneration, and self-activated electrical stimulation, as shown in Figure 1.17.

During the monitoring of the physiological signals for disease diagnosis, in situ real-time drug delivery is also desired. In 2016, Prof. Dae Hyeong Kim's group developed an integrated patch for non-invasive sweat glucose monitoring and in situ therapy by microneedles (Figure 1.17a) [2]. The cooperation of the sensor design and absorption layer structure enables reliable sweat sampling and analysis, with real-time calibration of pH, temperature, and humidity, to achieve accurate reading of glucose. On the abnormal condition of glucose in the human body, the drug is controllably released to perform multi-stage and precision therapy, providing a closed-loop approach for non-invasive health management of diabetes and related diseases.

Besides various chronic diseases, peripheral nerve injury is also a common traumatic disease. The rapid recovery of neurological function remains challenging in the field of public health. In 2018, Prof. John Rogers's group proposed a wirelessly programmable stimulation platform for peripheral nerve (Figure 1.17b) [85]. It is composed of fully bioabsorbable and biocompatible circuit components and substrates for enhanced nerve regeneration and functional recovery of injured nerve tissue. Nerve treatment surgery wraps the nerve stimulator around the sciatic nerve. The modulation of the transmission power allows for controllable electrical stimulation pulses. The effect of nerve regeneration and muscle function recovery

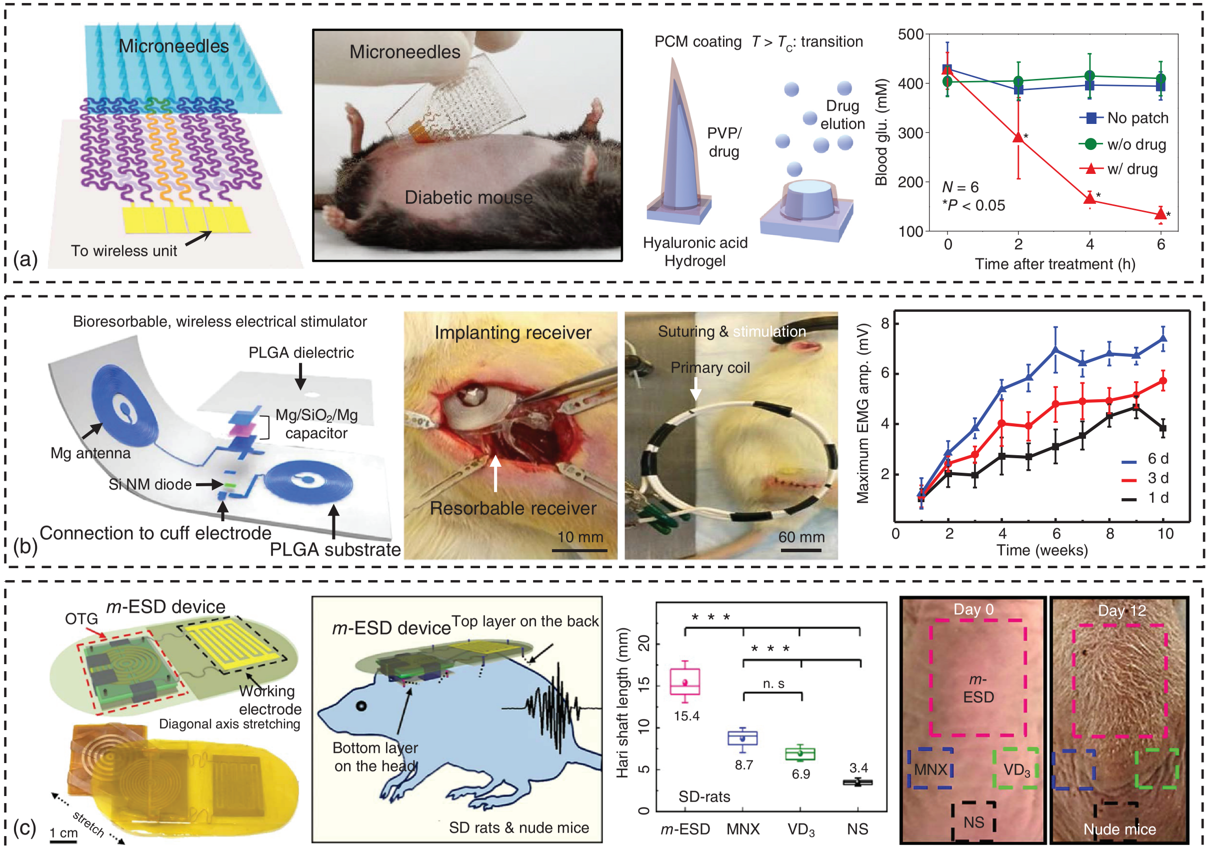

Figure 1.17 Assisted precision therapy. (a) Epidermal drug delivery. Source: Reproduced with permission from Lee et al. [2]. Copyright 2016, Springer Nature. (b) Implantable nerve regeneration. Source: Reproduced with permission from Koo et al. [85]. Copyright 2018, Springer Nature. (c) Self-activated electrical stimulation. Source: Reproduced with permission from Yao et al. [86]. Copyright 2018, American Chemical Society.

is significantly promoted, and this non-drug effective therapy can be used for fixed-point nerve injury repair.

Implantable electrical stimulation requires clinical surgery, and the power supply mode will limit the continuous operation. Realizing self-activated epidermal electrical stimulation is a potential therapy approach. In 2019, Prof. Xudong Wang's group designed a motion-driven self-activated electrical stimulation device, which consists of a TENG that harvests energy from all directions and a pair of interdigital electrodes that provide a spatially distributed electric field [86], as shown in Figure 1.17c. Compared with traditional medical treatment, the device can be directly attached to the skin surface to convert biomechanical energy into electrical stimulation signals, which carries out higher density of new hair follicles and faster hair growth, achieving the goal of painless and non-invasive precision therapy. This strategy of self-activated electrical stimulation provides a non-pharmacologically feasible solution to solve the problem of hair loss that influences hundreds of millions of people worldwide by using integrated smart micro-systems.

In summary, on the basis of the accurate physiological signal monitoring and wireless data analysis, integrated smart micro-systems are expanding their application in the medical field in three directions: multimodal real-time health monitoring, realizing reliable analysis of physical signals and chemical signals, to provide comprehensive information of human health status; multifunctional human–machine interaction, improving the communication and connection between the human and machines, to broaden the sensing dimension of human skin; multi-field assisted precision therapy, performing closed-loop health management with point-to-point drug delivery and electrical stimulation. With the advent of flexible electronics, dynamic sensing, and interdisciplinary technology, there is plenty of room for the further development of the integrated smart micro-systems.

1.5 Scope and Layout of the Book

As discussed above, the integrated smart micro-system has made certain breakthroughs in the fields of health monitoring, human–machine interaction, and precision therapy. However, there are still remaining challenges, including complex fabrication process, insufficient device performance, and redundant structural design. To realize the coordination of multiple devices and form a closed-loop smart micro-system for health monitoring, the following three problems need to be fully addressed.

First, processing technology compatible with multiple materials should meet the needs of integrated smart micro-systems. For the fabrication process, it is desired to expand the functional characteristic with the assistance of diverse substrates, such as flexibility, stretchability, and compressibility. The specific devices are prepared by modulating the parameter. For material selection, new features are introduced. For example, traditional stretchable materials are usually non-conductive, while the conductive materials are rigid with limited stretchability. Taking advantage of the synthetic effect of different materials, the devices with high performance are developed through the introduction of novel fabrication and complementary materials.

Second, the integrated structural design should realize the functions of integrated smart micro-systems. For the selection of three kinds of units, the energy-harvesting unit should efficiently scavenge low frequency and irregular mechanical energy from the human body. The energy-storage units focus on the enhancement of electrochemical performance and cycling stability. And the functional sensing units with soft and biocompatible materials can realize the monitoring of human physiological signals. The structural design and seamless integration allow for the development of the self-charging power unit, self-driven monitor patch, and self-powered sensing platform. The effective combination from energy harvesting, energy storage to functional sensing, enables the real-time monitoring of multimodal physiological information.

Third, the working mode should be suitable for the applications of integrated smart micro-systems. Combined with flexible circuits, it is feasible to realize the seamless connection with integrated smart micro-systems, to expand the dimensions of applications. For physiological signal monitoring, the multimodal sensing platform can achieve signal acquisition, data processing, wireless transmission, real-time reading, and early warning. For human–machine interaction, smart micro-systems provide the platform to realize the signal transmission and in situ feedback, with the help of malleable and soft materials. For assisted precision therapy, through the calibration of multimodal physiological signals, multi-stage and targeted disease diagnosis and health management are performed based on the development of data analysis and cloud interaction.

This research aims at a flexible, highly efficient, and stable integrated smart micro-system for health monitoring. It conducts research from four aspects with process, device, integration, and system, focusing on multi-dimensional process optimization, multi-functional device innovation, multi-dimensional integration, and smart applications of integrated micro-systems.

1.5.1 Scope of the Book

Figure 1.18 introduces the four key problems to be solved in this research and the logical relationship between them. In view of this, the main scope of the book is as follows.

First, the large-scale integrated processing of flexible materials. Processing technology is the cornerstone of smart micro-systems. Improving processing efficiency and optimizing processing accuracy are crucial to ensure the operation of the system. For the single process, it is necessary to overcome the limitation of substrate selection and cooperate to expand the functional characteristics; for the general process, it is available to realize the diversity of processing methods according to the needs of different devices; for the integrated process, large-scale multi-scale processing is development through parameter control.

Second, high-performance and high-efficiency multifunctional devices. The devices are the basic parts of the entire system, and the performance of the devices

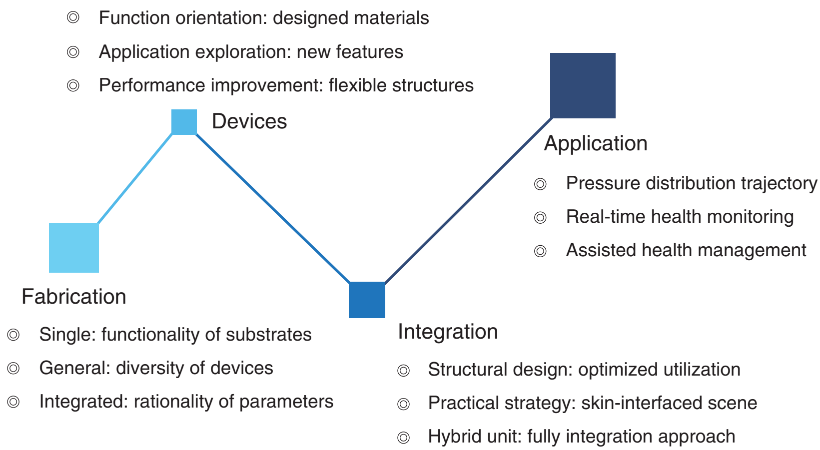

Figure 1.18 Scope of the integrated smart micro-systems. Source: Yu Song.

determines the capability and dimensions of the system. The actual function of the device should be considered first to select specific functional materials; secondly, the properties of the device should be enriched, such as stretchability and compressibility, to break through the limitations of applications; finally, it is essential to improve the performance of the device, through dimensional parameter optimization and flexible structural design, to obtain stable and reliable devices.

Third, the flexible, reasonable, and compatible integration strategy. Integrated design is the framework of smart micro-systems, and the integration degree reflects the rationality and reliability of the overall system. First, reasonable structural design should be used to improve the space utilization and material utilization of the device; second, for the skin-interfaced applications, the integrated unit and homogenized module are beneficial to expand the integration and stability of the system; Finally, for the ultimate goal of the closed-loop system, it is feasible to adopt a fully integrated design to realize the complete flow of signal acquisition, processing, and transmission.

Fourth, representative health-monitoring system applications. Application is the demonstration of the comprehensive capability of smart micro-systems. Based on the single device, the developed sensor array can identify static stress distribution and dynamic trajectory; then a multi-channel sensing platform that combines physical and chemical signals is designed to achieve real-time monitoring of multimodal physiological signals; finally, with the help of flexible circuit module, it can achieve interactive data transmission and analysis, and conduct dynamic closed-loop health management.

In summary, this research focuses on a series of problems in the field of integrated smart micro-systems, especially for health monitoring. Starting from the optimization of the fundamental process, reasonable processing methods suitable for different materials and devices are developed to enrich the device features and improve the performance. The collaborative operation of multiple devices is further proposed with the structural designs and integration strategies. Applications are introduced

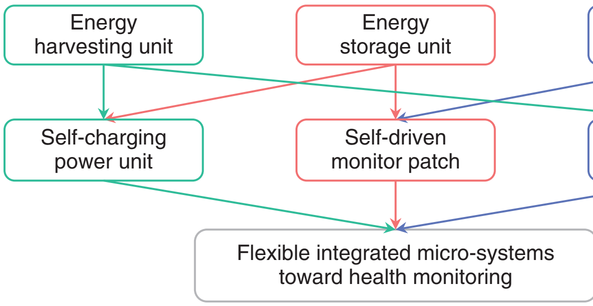

Figure 1.19 Layout of the integrated smart micro-systems. Source: Yu Song.

in detail, from single function, multimodal monitoring, to fully integrated dynamic management.

1.5.2 Layout of the Book

The research framework of this book is shown in Figure 1.19, aiming at the flexible and integrated smart micro-systems for health monitoring. The energy-harvesting unit collects energy for the energy-storage unit, and drives the functional sensor unit to monitor physiological signals. The cooperation with flexible circuit modules of signal processing and wireless transmission enables the establishment of a complete micro-system. Specifically, starting from the material process and structural design, three types of devices are studied separately, which are suitable for energy-harvesting units, energy-storage units, and functional units to achieve device optimization and performance improvement; the integration of the two devices allows for the development of the sandwiched self-charging power unit, the all-in-one self-driven monitor patch, and the fully integrated self-powered sensing platform. The obtained multimodal sensing system with flexible circuit module performs real-time physiological signal monitoring, and realizes personalized health management and assisted medical care.

The layout of this book is briefly introduced as follows

Chapter 1 – Introduction: This chapter summarizes the current progresses and advances of flexible integrated smart micro-systems, including working mechanism, structural dimensions, and characteristic advantages. Aiming at health monitoring, this chapter also analyzes the existing problems with following prospects.

Chapter 2 – Core Units of Smart Micro-systems: For energy harvesting during human motions, TENGs with single-electrode and freestanding modes are developed, showing improved harvesting capabilities when cooperated with energy management circuits. For the energy-storage devices, supercapacitors, based on the carbon nanotube “drop-drying” method with different substrates, demonstrate reliable performance with cycling stability. In terms of the piezoresistive sensors, the porous structure of electrodes achieves high sensitivity and stable electrical response to the external mechanical stimuli, realizing real-time monitoring of human movements, such as muscle contraction, joint bending, and other modalities.

Chapter 3 – Sandwiched Self-charging Power Unit: With a single-step wrinkle-processing method, the output performance of the TENG is significantly improved; based on the carbon nanotube penetration theory, a flexible super-capacitor is obtained, which has good mechanical strength and cycle stability. The sandwiched self-charging power unit is further assembled, where the parallel-connected TENGs are attached among both lower and upper surfaces of the encapsulated supercapacitor to improve the overall space utilization. The charged self-power charging power unit can drive the electrochromic device to realize the application of smart display and visual warning as a novel power supply approach.

Chapter 4 – All-in-one Self-driven Monitor Patch: Utilizing the general processing technology for conductive elastomer with optimized parameters, both the micro-supercapacitor for energy storage and piezoresistive sensor for functional sensing are prepared successfully. Through the mechanical and electrical analysis, it is feasible to modulate the performance of the piezoresistive sensor. Based on the laser-patterning and electrolyte-transferring process, the micro-supercapacitor shows reliable electrochemical performance. The assembled self-driven monitor patch adopts a stacked all-in-one structure, which greatly improves the integration degree and shows prospects in motion rebuilding, human–machine safety communication, arrayed static position distribution, and dynamic trajectory recognition.

Chapter 5 – Fully Integrated Self-powered Sweat-Sensing Platform: During the exercise, the TENGs efficiently scavenge mechanical energy and biochemical sensors reliably monitor the biomarkers of the secreted sweat. The combination of TENGs and biochemical sensors with power management module enables self-powered signal acquisition and wireless transmission. Both the TENG and power management circuit are based on the flexible printed circuit board technology, which reduces the power consumption with high efficiency. The biochemical sensor, in cooperation with microfluidic structure, performs continuous sampling and dynamic update of sweat. The motion-powered fully integrated sweat sensor platform shows broad prospects in the medical management and assisted health monitoring.

Chapter 6 – Multimodal Sensing Integrated Health-monitoring System: Based on the all-laser-engraving method, a multimodal sensing system is developed. The laser-engraved graphene can detect chemical signals of uric acid and tyrosine in sweat, and serve as the temperature and strain sensors to acquire biophysical signals. The microfluidic structure provides a chamber for the detection between the sweat and chemical sensors with dynamic update. The further integration with flexible circuit module realizes continuous multimodal physiological signal monitoring at different parts of human body. At the same time, as an important biomarker of gout disease, uric acid can be dynamically and continuously measured through the integrated health monitoring system, which is of great significance for personalized health management for chronic diseases.

Chapter 7 – Summary and Perspectives: The research work present in this book is summarized in this chapter, and the challenges and prospects are also discussed.

Abbreviations

0D	zero-dimensional
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
ECG	electrocardiogram
FDA	federal drug administration
OSAHS	obstructive sleep apnea hypopnea syndrome
TENG	triboelectric nanogenerator
PENG	piezoelectric nanogenerator

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