Biomedical Materials & Devices (2024) 2:669–694
https://doi.org/10.1007/s44174-023-00141-5

REVIEW

Wireless Wearable Devices and Recent Applications in Health Monitoring and Clinical Diagnosis

Mengrui Su[1] · Jiangbo Hua[1] · Xidi Sun[1] · Zhao Liu[2] · Yi Shi[1] · Lijia Pan[1]

Received: 29 September 2023 / Accepted: 26 October 2023 / Published online: 30 November 2023

Abstract
Human body contains much health information, which can reflect the basic health status and help detect diseases. However, the traditional wired transmission method greatly limits the portability and immediacy of the device. Turning the device into wireless can effectively solve the above problems. The development and research of new wireless wearable devices is urgent. This review focuses on wireless wearable devices applied in health monitoring and clinical diagnosis. Firstly, we introduce its development status and give emergent device system architecture. Then, wireless energy transmission and wireless data transmission modules are presented. Besides, this review categorizes the health information contained in the human body into three categories based on its signal states, and introduces measurement methods and existing applications. Finally, the outlook on the current challenges of wireless wearable devices is given.

Keywords Wireless technology · Wearable devices · Health monitoring

Introduction

With the continuous improvement of human living standards, people's attention to health is also increasing. To facilitate a quicker and easier assessment of one's health status, a wide range of medical devices has been developed. Most used equipments in hospitals are relatively large, such as magnetic resonance imaging instrument, computed tomography, etc. However, these devices come with drawbacks, including limited mobility and high inspection costs. The emergence of wearable devices has greatly promoted the development of this trend in order to enable people to easily know their health status in daily life without going to the hospital. Wearable devices are diverse and can be applied to various parts of the human body. For example, a wearable electrocardiogram (ECG) can capture a patient's ECG in real time and also increase the number of arrhythmias detected [1]. Wearable microscopes [2] for viewing the structure of muscle groups are also flourishing, providing medical treatment for cerebral palsy, amyotrophic lateral sclerosis, myotonic dystrophy, myasthenia gravis, stroke, and other diseases. Wearable devices have revolutionized the landscape of health monitoring and disease detection by reducing the size of these devices. With the development of wireless technology, wearable devices are further developing toward miniaturization and portability. By combining wireless technology with wearable devices, the transmission distance is no longer limited by wires, and the bulk designs can also be decreased with the omission of batteries [3, 4].

Self-powered and various wireless energy transmission technologies enable wearable devices to remove additional power devices. The participation of wireless data technologies such as Bluetooth, Radio Frequency Identification (RFID), and Near Field Communication (NFC) avoids the limitations of wires and expands the work distance of devices. For instance, in clinical applications, wireless pressure sensors have proven invaluable for monitoring

Mengrui Su and Jiangbo Hua have contributed equally to this work.

Zhao Liu
liuzhao83@gmail.com

Yi Shi
yshi@nju.edu.cn

Lijia Pan
ljpan@nju.edu.cn

1 Collaborative Innovation Center of Advanced Microstructures, School of Electronic Science and Engineering, Nanjing University, Nanjing 210093, China

2 Department of Vascular Surgery, Nanjing Drum Tower Hospital, The Affiliated Hospital of Nanjing University Medical School, Nanjing 210008, China

intracranial pressure (ICP) in patients with traumatic brain injuries [5]. With the assistance of wireless technology, real-time non-invasive monitoring of intracranial pressure can be achieved. What is more, data can be received easily. In addition, in daily health monitoring, wireless wearables are able to integrate with glasses [6], bandages [7], clothing [8, 9], gloves [10, 11], and other everyday household items. It can even be integrated with tattoos [12–14] and stickers [15, 16], effectively improving the senselessness and portability of the devices. Pregnant women can also monitor the fetal heart rate at home through a miniaturized heart rate monitor, eliminating the need for hospital visits [17]. Through wireless transmission technology, measurement results can also be synchronized in real time to the user's smartphone, greatly improving the efficiency of health monitoring and providing valuable time for disease warning.

In this review, the wireless wearables and its applications both in the daily health monitoring and clinical diagnosis are introduced (Fig. 1). Firstly, we introduce the common system architectures of wireless wearable devices and discuss the wireless power and data transfer. Introduces Bluetooth, RFID and NFC as three common wireless data communication technologies. Next, in order to present the applications in both hospital and home, we classify them by the types of the signals (chemical signals, bioelectrical signals, etc.) the devices obtain directly. In addition, this review also introduces that monitoring movements can be used to evaluate the health status and surgical recovery status of the human body. Finally, the current state of wireless wearables is summarized and the challenges and prospects are presented.

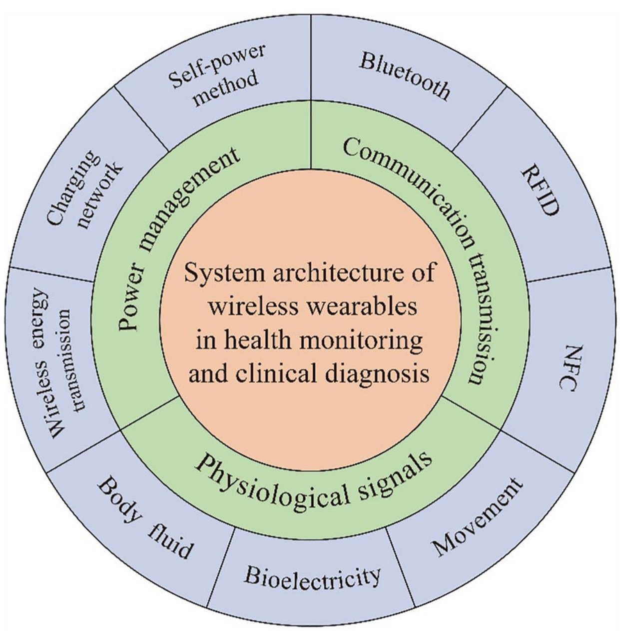


Fig. 1 The common system block diagram of a wireless health monitoring device

Designs and Technologies of Wireless Wearables

Health equipments are varied in size, from smartwatch worn on the wrist to small sensors such as e-skin which is directly attached to the skin [4, 18]. The system architecture of different devices may vary, but the modules within them may have similarities. In this session, we summarize the system architecture of wireless wearable devices firstly. Next, we introduce the modules for wireless energy and data transmission in the system. Wireless power transfer can reduce device size. What is more, we also give the technologies of wireless data transfer such as Bluetooth, RFID, and NFC, which can achieve transmission with many advantages such as low energy consumption and high fidelity.

System Architecture

After analyzing multiple health monitoring devices, we can broadly categorize the entire device system into three key components: the power management module, the information transmission module, and the signal acquisition module [19]. The power management module represents the energy conversion method of the entire system and determines the energy conversion efficiency of the devices. The information transmission module refers to the wireless communication method used in the system. This part determines the speed of information transmission, channel capacity, and other contents. The signal acquisition module is determined by the type of signal collected. To obtain different kinds of physiological signals, different technologies are required. The three modules mentioned above are often designed separately, but in order to achieve high efficiency and miniaturization of the entire system, the coordination between modules and system optimization is also crucial.

Wireless Power Transfer

In the application of electronic devices, how to power them is a very important issue. The traditional power supply methods include using batteries for power supply, or directly connecting through wires and using 220 V AC power to operate [20]. However, the methods above have many problems: the battery occupies a large volume of a device, continuous health monitoring is not possible when replacing batteries, poor mobility, etc. Wireless technology is widely used, which provides the possibility for manufacturing health monitoring devices with excellent performance such as lightweight, flexibility, sustainability, and so on [21, 22].

The following content of this session will revolve around wireless power transfer and the self-powered system.

Wireless Energy Transmission Using Electromagnetic Induction

Wireless power transfer system obtains electromagnetic radiation energy from the surrounding environment through electromagnetic induction. Typically, both the transmitting and receiving ends utilize circular coils. External devices emit electromagnetic waves through the transmitter, and the receiver receives them. The alternating source in the Tx coil generates a magnetic field, and some of the magnetic field penetrates into the Rx coil. This part of the magnetic field generates induced alternating current. With the help of a rectifier circuit, it can generate direct current power for the normal operation of the devices (Fig. 2a) [23]. The transmission efficiency is generally evaluated using the return loss coefficient, which is S11 in the S parameter [24]. The frequency with the lowest S11 value is called the resonant frequency. In general, at the resonant frequency, the wireless transmission power is the highest. Wireless energy transmission can be primarily categorized into two types: far-field and near-field [25]. The near-field coupling adopts principles such as capacitive coupling (CC), inductive coupling (IC), magnetic resonator coupling (MRC), etc. Far field transmission generally uses radio frequency (RF). In wearable devices, near-field transmission is more common, while far-field transmission is often used for large medical equipments such as magnetic resonance imaging devices. The energy supply system can also be achieved by two mutually coupled inductors. By converting sinusoidal voltage into direct current voltage through a rectifier, the device can operate which can trach short-range finger movements, expanding the application scenarios and improving the devices' degree of freedom.

Charging Network

Although one-to-one charging has already realized wireless energy transfer, there are still several issues such as restricted charging locations, limited power, and charging only one device at the same time. In order to solve these problems, many wireless charging networks also have emerged [26, 27]. By designing a wireless charging network to improve the power of energy transmission and achieve advantages such as increased transmission distance, save the space that used for power transmission, and so on. Based on wireless charging networks, researchers have also proposed the concept of omnidirectional charging [28, 29]. A practical omnidirectional wireless power transfer setup is shown in Fig. 2b [30]. Applied this technology to the sensor network, all devices worn on the human body can be charged without the need for alignment or stationary position to complete the charging process [31]. This provides great convenience for life. A noteworthy development in this field occurred on January 29, 2021, when Xiaomi unveiled the Mi Air Charge concept. The company introduced an isolated charging station equipped with five phase interference antennas capable of accurately detecting a phone's position. Then, a phase-controlled array composed of 144 antennas will directly send millimeter-wide waves to the phone through beamforming. This wireless charging technology envisions remote charging of multiple devices within a radius of several meters at a power of 5W. If the idea can be successfully implemented, then this will be the preliminary development of the previous imagination. Vigorously developing omnidirectional charging technology will provide solutions for improving the power and data transmission efficiency of wearable device systems. This provides new ideas for the next development of wireless wearable systems.

Self-Power Method

In addition to the methods mentioned in the previous text, based on the principle of energy conservation, researchers are now considering directly converting the energy generated during human's motion into electrical energy that can be used for electronic device operation [32, 33]. This method is undoubtedly a key achievement in promoting the further development of wireless wearable devices.

The human body always undergoes various energy transformations, converting biological energy into mechanical energy, thermal energy, and so on. Starner et al. once calculated that a person weighing 68 kg can generate up to 67 watts of power when walking on land [34]. According to the analysis of activity scenarios, there are many scenarios that can generate energy which can easily caught by devices: friction generates energy during arm swing [35]. Electronic devices with self-powered technology can continuously operate without external power supply, achieving long-term uninterrupted monitoring of human health [36].

In the self-power supply system of devices, the typical one is the triboelectric nanogenerators (TENGs). TENG is a powerful technology, which can get electrical energy from ambient mechanical energy through the effect of triboelectricity [37, 38]. Its operational principle is rooted in the interaction between friction and electricity. When two similar materials come into contact or undergo relative motion, charge transfer occurs between the interfaces, during which the energy required for devices operation can be obtained [39]. Wu et al. [40] developed a TENG based on the biodegradable polybutylene succinate (PBS) membrane (Fig. 2c). This device can capture small movements of the human body and convert them into electrical energy. Meanwhile, according to the experiments, it can be seen that the frequency

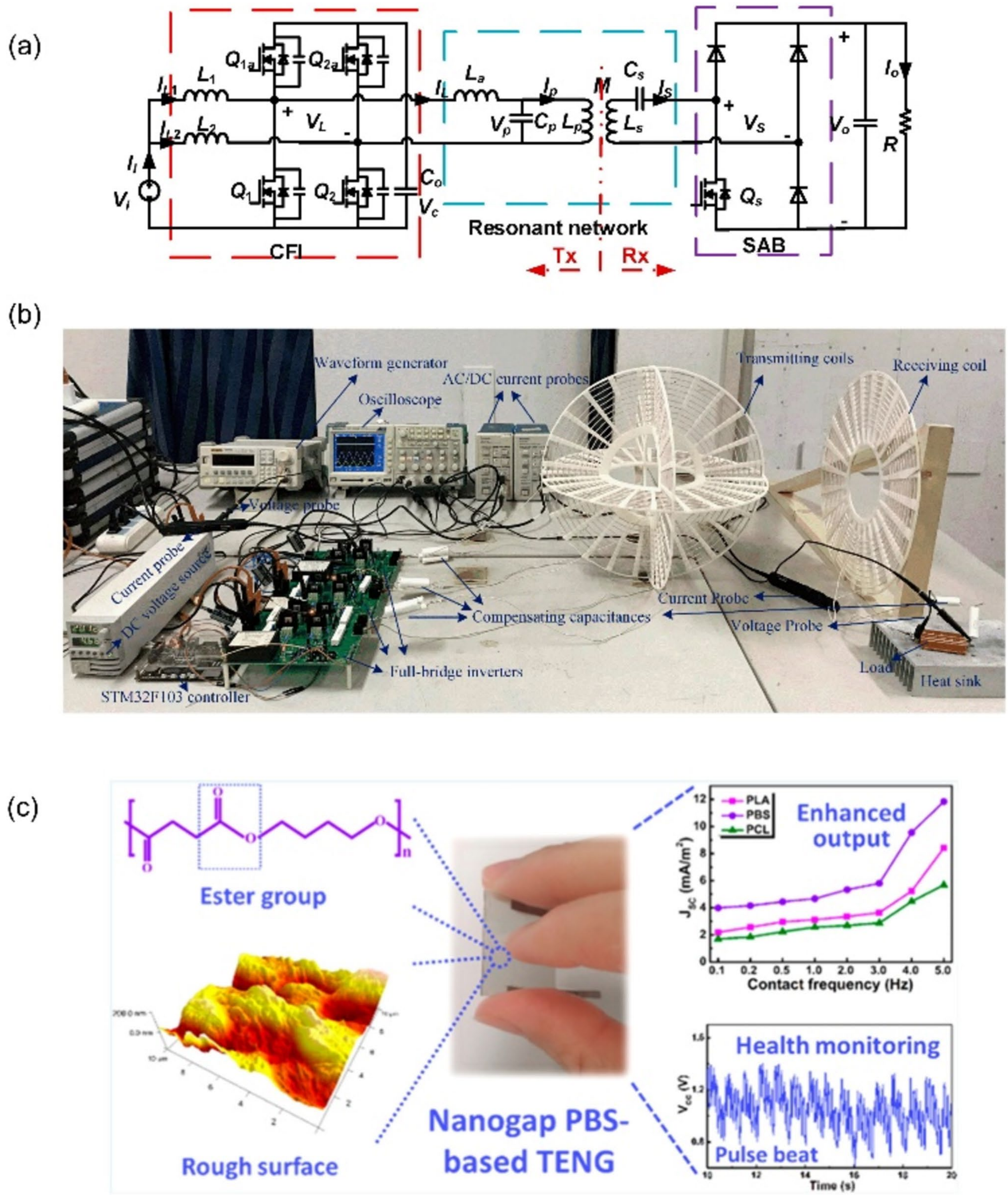


Fig. 2 **a** A circuit diagram of a power transfer system. Reprint with permission from Ref. [159]. Copyright 2018, MDPI. **b** A photo of an omnidirectional WPT system. Reprint with permission from Ref. [30]. Copyright 2018, MDPI. **c** A TENG based on the biodegradable PBS membrane. Reprint with permission from Ref. [40]. Copyright 2020, American Chemical Society

of finger contact with TENG is different, and the voltage generated is also different. After continuously touching and charging it for 480 s, the stored energy of the capacitor can reach a maximum of 102.53 J. There is also a device, whose frictional layers used magnesium zeolite/PP composite films [41]. The addition of silver zeolite increases the dielectric constant of the thin film. It can improve the performance of the generator, thereby improving conversion efficiency.

Self-powered electrical components can not only directly obtain energy from the human body, but also from the outside world, for example, the solar energy, wind energy, thermal energy, etc. [20, 42, 43]. This can ensure the normal operation of relatively high-power health monitoring equipment in adverse environments. It has shown broad application prospects in wireless wearable devices and biomedical applications as well. In order to provide higher power energy, there are also designs that combine the two types of methods mentioned above. For example, using both TENGs and solar cells to power the system, supplemented by circuits such as boost converters, to achieve design goals [19].

Wireless Data Transfer

In medical diagnosis and health monitoring systems, in addition to energy transmission, data transmission is also required. The information transmission module transmits the obtained signal to the receiver for further processing and analysis of the signal [44–47]. Common wireless transmission technologies include Bluetooth, NFC, and RFID, which can obtain data from external environment. The following session gives a minute description of these several wireless energy acquisition methods.

Bluetooth

Bluetooth is a common signal mode since many years ago. It can achieve convenient, fast, low cost, and low-power communication between devices. Bluetooth Low Energy (BLE), derived from Bluetooth 4.0, has superior performance over Bluetooth, such as lower power consumption, complexity, and cost [48]. Its core architecture is shown in Fig. 3a. The corresponding frequency band for Bluetooth is 2.4–2.485 GHz, which belongs to the Industrial Science and Medical (ISM) frequency band [49]. Bluetooth technology gives designers a lot of freedom. Developers can develop their own applications based on existing solutions, which provides the possibility to apply Bluetooth technology in various fields [50].

The fastest transmission speed of Bluetooth is 24 MB/s, and the maximum transmission distance without obstruction is 100 m [49]. Currently, there are devices for collecting electrocardiogram signals from the human body. Attach an electrode to the wrist to transmit a person's pulse signal through BLE technology [51]. In the study, the signal measured by this method was compared with the electrocardiogram signal directly obtained from the body, and it was found that the signal interference was less and the measurement was accurate. In addition to monitoring the heart, there are also various wireless sensors with Bluetooth modules that can monitor body fluids, electrolytes, gases, etc. [52–54].

With the continuous updates and improvements of Bluetooth technology from generation to generation, it has significantly improved in terms of security and stability. However, there are still many urgent issues that need to be addressed in Bluetooth technology which applied in the wearables. For example, the significant impact of obstacles on information transmission and long latency. This may affect the patient's treatment. At the same time, the low power of Bluetooth greatly limits the transmission distance [55]. So how to further improve its transmission distance of the health data while ensuring the advantage of low-power consumption is the focus of the next stage of research.

RFID

RFID refers to non-contact data communication between readers and tags, in order to achieve the goal of identifying targets. One type of this technology is shown in Fig. 3b. According to the principle, RFID can be divided into three categories: passive tags, active tags, and semi-active tags. The principle of passive tags is radio frequency signals emitted by readers, which generate induced current in the tags and then use this energy to transmit information stored in the chip. Active tags, on the other hand, actively emit a fixed frequency signal from the tag, which the reader receives and decodes before transmitting the data to the central information system for related data processing. Passive RFID does not require power to the active itself, but the transmission distance is shorter. Although active RFID can be recognized between a longer distance, it requires an external power system in operation, which lead to its larger volume. So, another data transmission method that combines the advantages of both methods has emerged, namely semi-active RFID. This foundation is also known as activation triggering technology. In most cases, this type of tags is in a dormant state and only supplies power to the part that stores data. Therefore, its power consumption is relatively low. After the tag enters the recognition range of the reader, the reader first sends a signal to activate the tag to enter the working state, and then carries out information transmission [56–58].

Due to its advantages such as miniaturization and low cost, RFID has been increasingly used by health monitoring devices in recent years [59]. Currently, it is common in clinical applications to use RFID tags to verify patient information, aiming to reduce the probability of medical accidents

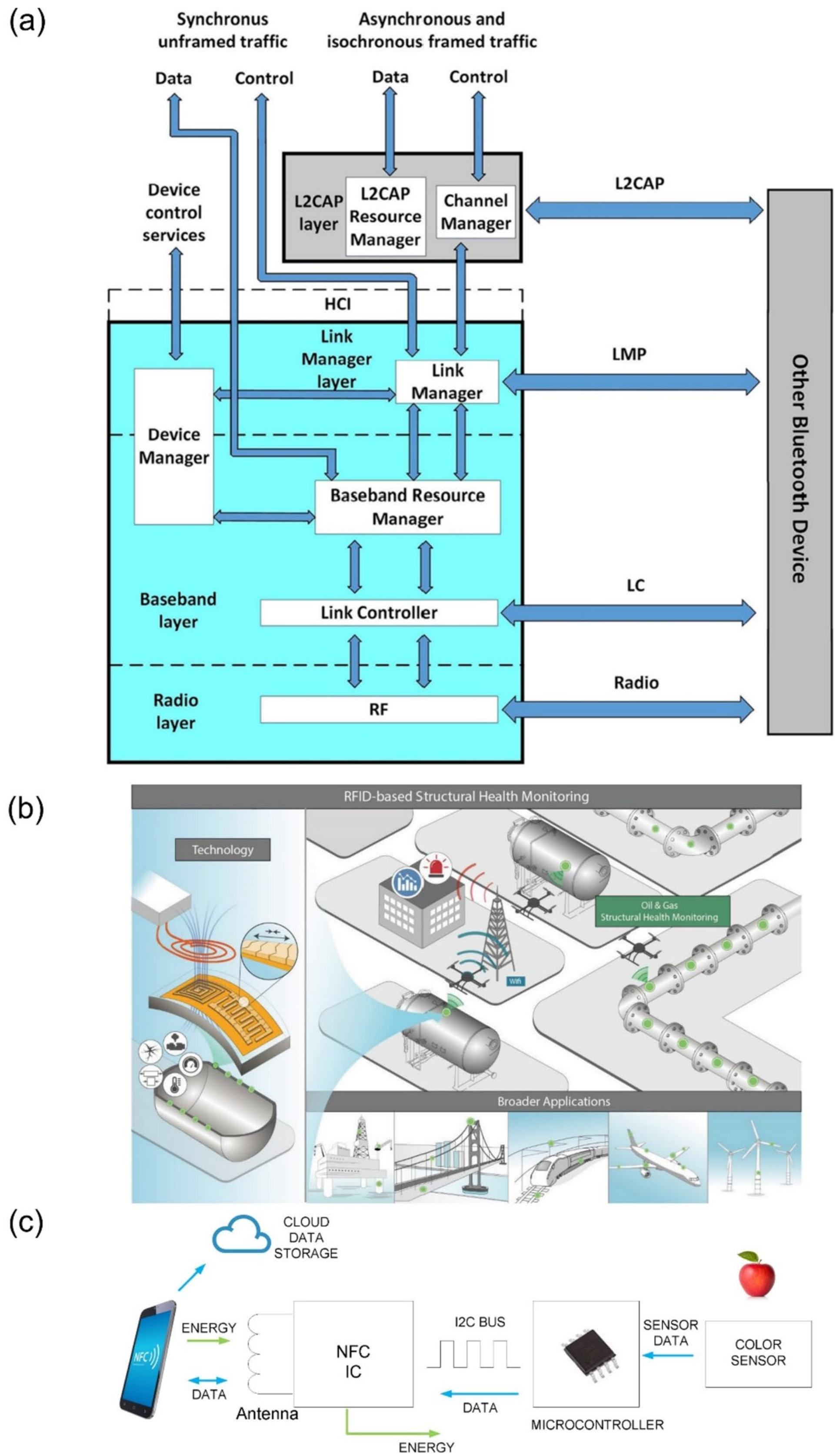


Fig. 3 **a** The core architecture of Bluetooth. Reprint with permission from Ref. [160]. Copyright 2017, Elsevier. **b** A system based on RFID technology. Reprint with permission from Ref. [161]. Copyright 2023, John Wiley & Sons. **c** A block diagram of a sensor working with NFC. Reprint with permission from Ref. [162]. Copyright 2019, MDPI

and improve the accuracy of clinical treatment [60]. As for daily health monitoring, non-invasive monitoring equipment is more convenient to use. A study has designed a device using RFID to monitor the frequency of hand tremors [61]. This device can help monitor the condition of Parkinson's disease patients. In addition to monitoring exercise, respiratory rate and heartbeat rate can also be monitored based on RFID. Attaching sensors to the chest of the human body to monitor heartbeat status, or real-time monitoring of breathing during sleep all contribute to human health management [62, 63].

The position of RFID in information transmission is beyond doubt. However, RFID technology still faces issues such as poor technical compatibility and so on. Manufacturers need to develop relevant specifications to unify standards and communication frequencies, in order to improve interoperability between devices.

NFC

NFC has now become one of the commonly used media for wireless body area networks (WBANs) [64]. NFC is a technology used for short-range information transmission as well, with a communication range of approximately 4-10 cm. The standard is also built on the 13.56 MHz RFID contactless card standard [65]. Its frequency band, like Bluetooth, belongs to the ISM band.

Integrating information transmission systems into Internet of Things (IoT) systems is currently a common practice. In the medical and healthcare industries, NFC plays a significant role. An example used NFC in the sensors is shown in Fig. 3c. From integrating chips into medical record cards to obtain patient medical records, to providing medication services, and even to mobile payments, NFC serves various stages of medical treatment [66, 67].

There are some devices that use flexible NFCs, and researchers use various materials to integrate tags onto different devices. As early as 2004, there was a case of using conductive yarn to embroider coil-shaped RFID on suits [68]. Xu et al. [69] have studied a wireless temperature sensor device, which is expected to be used for monitoring breast cancer. This device is based on a flexible NFC coil embroidered with conductive yarn. The device monitors the abnormal change of temperature, and then transmits it to the intelligent electronic device with NFC function. By reprocessing and analyzing the data, information about breast cancer can be obtained [70]. In recent years, more and more smartphones have begun to have NFC functionality, which provides the possibility for health monitoring at any time. In an ideal situation, as long as the monitoring device has NFC function, users can transmit data to smart devices anytime and anywhere, and then analyze it. This provides great convenience for medical diagnosis and health monitoring. The advantages of NFC are obvious, but it also has issues such as weak security, easy leakage of stored information, and easy cloning [71]. Researchers improve security by encrypting transmitted content, and related crypto suites such as Rabin-Montgomery cryptography have been widely used [72]. Improving the security of NFC tags will be the focus of research in the next stage.

The Challenges of Wireless Technologies

As wireless technology can bring advantages such as strong mobility and high-speed information transmission, it can greatly help the health monitor device realize the long-term and real-time monitoring and extend their operation life. However, there are also related issues that need to be addressed with this technology. The first issue is that the process of wireless energy transmission can generate thermal effects, which may have certain side effects on human health [4]. At present, various countries have formulated relevant standards to specify the specific absorption rate range of wireless devices applied to the human body [73, 74]. This greatly improves the security of wireless devices. At the same time, when the wireless transmission module is integrated into the health monitoring devices, it can also cause problems such as poor fit to human body due to the lack of flexibility. Based on this, researchers consider using flexible coils to reduce the impact of the above problems on monitoring [75, 76]. In addition, in the process of information transmission, it is also very important to obtain accurate information without being disturbed by noise. Eliminating external electromagnetic interference and accurately filtering out useful information will also be the key to the next stage of research.

Applications of Wireless Wearables in Detecting Physiological Signals

The human body is a complex organism that contains various signals. Among them, physiological signals are the reflection of various information such as bioelectricity and physiological parameters in the body. Their detection and analysis are of great significance for the diagnosis and treatment of many diseases. Both chemical substances such as body fluids and electrical signals produced by various organs can be considered as physiological signals [77]. The chemical signals of the human body can be obtained from various body fluids, such as blood, sweat, tears, and so on. And electrical signals can be roughly divided into electroencephalogram signals, electrocardiogram signals, electromyogram signals, etc. In addition to the above two categories, we can also obtain information about human health status from the movement activities. The generation of multiple signals provides possibilities for clinical diagnosis of diseases and feasible solutions for more accurate detection of human health status [78, 79]. In this session, the generation and measurement mechanisms of various physiological signals will be described.

Body Fluid

Human body fluid is the blanket term of intracellular fluid and extracellular fluid. The two are distinguished by the cell membrane as the boundary. The extracellular fluid mainly includes plasma and interstitial fluid, while the intracellular fluid refers to the fluid inside the cell membrane. The body fluid contains various inorganic salts, organic substances, etc., and is the main site for cell survival and material metabolism [80, 81]. At the same time, in addition to body fluid, the fluids produced by the human body are directly secreted into the external environment [82–84]. The human status can be verdict by detecting the content of substances in the aforementioned liquids.

Blood

Blood contains various substances, such as proteins, electrolytes, organic compounds, and various blood cells. Through the analysis of the composition of these blood components, we can obtain valuable information such as oxygen saturation, heart rate variability, and the concentration of trace elements, which, in turn, aids in the early detection and monitoring of various diseases [85, 86]. Most of the information related to blood is obtained using its optical properties. Obtain the optical transparency of capillaries through an optical platform, and judge the health status of the human body based on the obtained spectral information (Fig. 4a).

In the prevention and treatment of cardiovascular diseases, dynamic monitoring of oxygen saturation is indispensable. When light passes through capillaries, the intensity of light decreases. When the hemoglobin content in the blood is different, the light energy absorbed by capillaries will also change accordingly [87]. By combining theoretical derivation, the relationship between transmitted light intensity and hemoglobin concentration can be found [88, 89]. In response to this characteristic, Chen et al. combined Bluetooth technology to manufacture a low energy consumption wearable blood oxygen monitoring device [50]. This system transmits the collected blood oxygen information to the mobile client through Bluetooth for signal processing and analysis. In this process, Discrete Saturation Transform (DST) signal extraction technology is also used to reduce the interference of useless signals. The blood oxygen information obtained through this system is not only more accurate, but also has lower power consumption than wired systems, and can achieve real-time monitoring. The importance of wireless technology has been shown. In addition to monitoring blood oxygen, Bluetooth technology can also be used to monitor blood pressure (BP). Blood pressure is very important in monitoring diabetes, atherosclerosis, coronary heart disease, and other diseases [90]. Currently, two commercial blood pressure monitors (Beurer BM 85 Bluetooth and Andersson Lifesense BDR 2.0) have emerged in the Swedish market, capable of automatic blood pressure measurement and data transmission [91]. This brings good news to hypertensive patients.

When measuring oxygen saturation, when the body moves, it will have an impact on the light path, resulting in motion artifacts [92]. The combination of flexible sensors and NFC technology can effectively solve this problem. [93]. In this study, an optical platform is attached to the fingernails to directly obtain human blood information. As Fig. 4b shows, this device uses wireless energy transmission to drive red LED, and then uses a photodetector to obtain backscattered light. In order to increase the transmission distance while ensuring the transmission power, the design uses a double-layer Cu transmission coil, and the final measured quality factor (Q) is about 16 in the 30 mm distance away from a smartphone. This flexible sensor is not only not limited by transmission lines, but also capable of long-term detection, and is only affected by the growth rate of nails.

The traceability of physiological samples in medical treatment is significant, and at critical moments, this information may be able to save lives. If not handled correctly, it may even be fatal. Previously, barcode technology was mostly used. But the barcode not only needs to be aligned during the scanning process, but also needs to be read at a very close distance, which has obvious drawbacks. After combining RFID technology, physiological data for clinical diagnosis can be more easily obtained. One of the typical examples the RFID labels used on the blood tube is shown in Fig. 4c. For example, attaching an RFID tag to the outside of a blood collection bag is used to track information about the contents [94]. As is well known, electromagnetic (EM) fields are generated during the process of information transmission and reception, which may lead to an increase in ambient temperature, leading to some side effects such as changes in blood pH and hemolysis of red cells [95]. This can cause inaccurate measurements. But using RFID technology, temperature changes are relatively small and will not bring changes to the blood. Therefore, using RFID tags is a cost-effective way of storing information in clinical applications.

Sweat

Sweat is a type of body fluid that is easily accessible from the human body. Sweat contains various substances, the most significant of which are Na^+ and Cl^- ions, as well as a small amount of substances such as urea and lactic acid

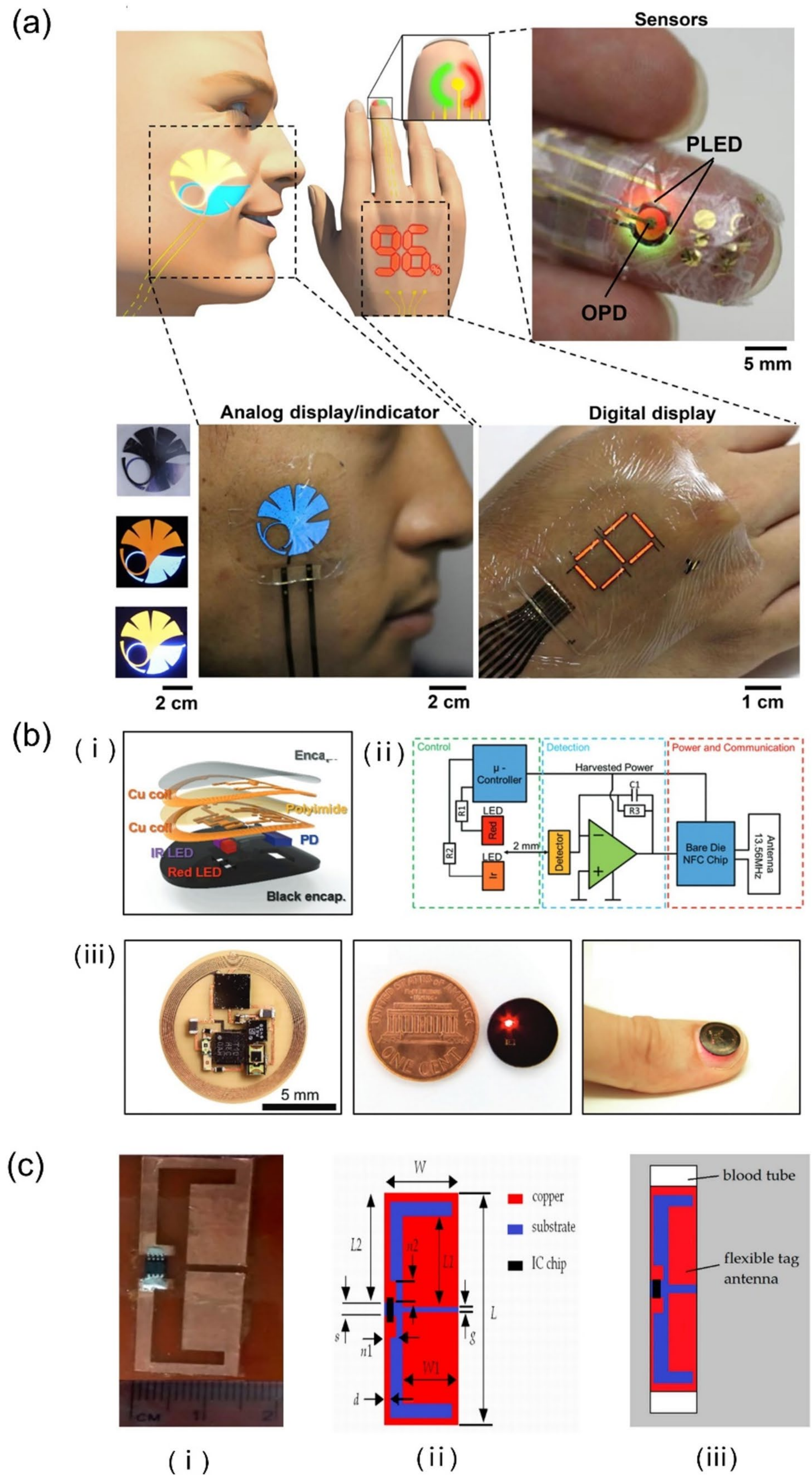
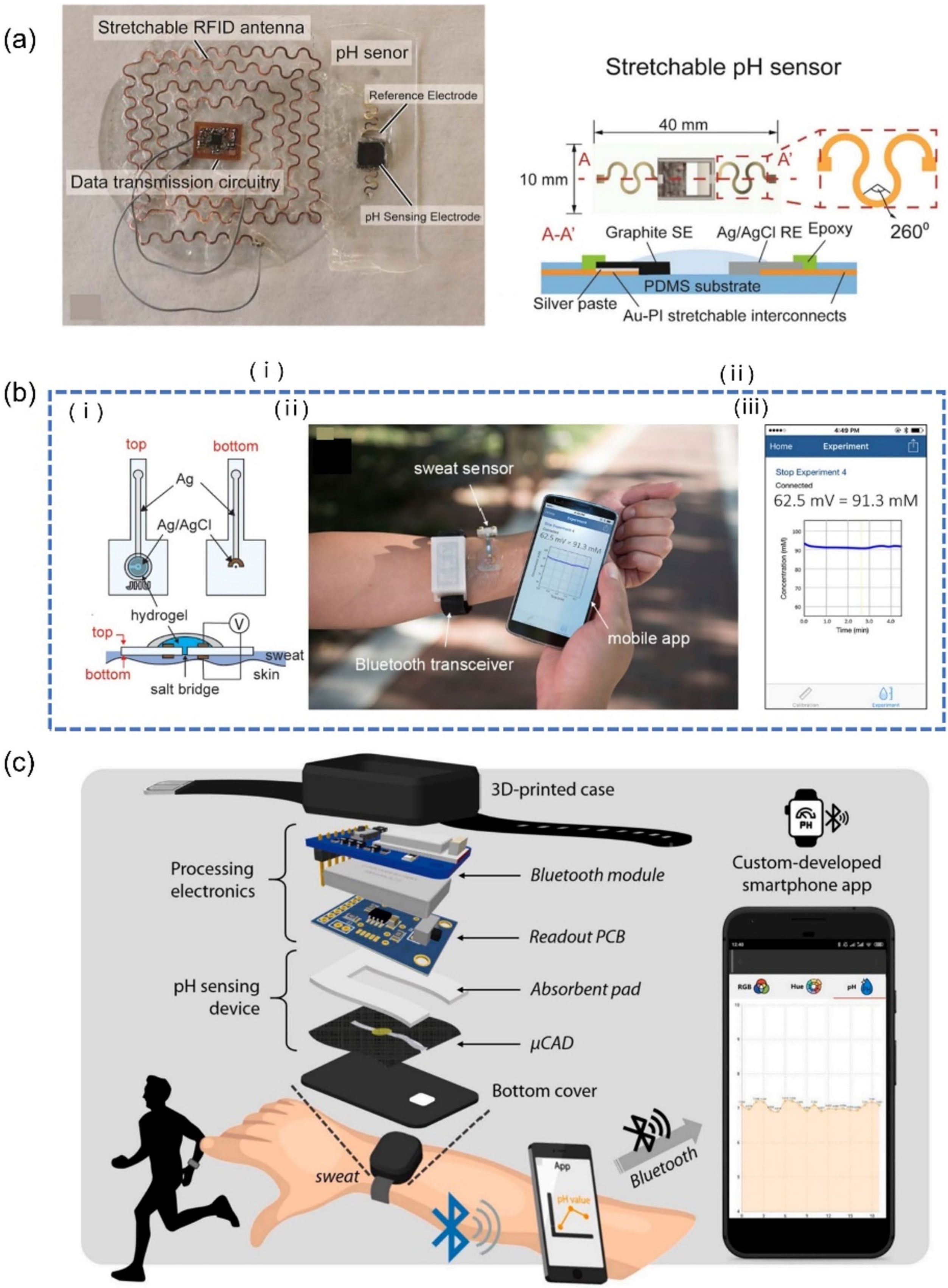


Fig. 4 **a** Some optical devices used as health monitoring sensors. Reprint with permission from Ref. [85]. Copyright 2016, AAAS. **b** A flexible device which can monitor the blood information. (i) The schematic illustration of the constituent layers. (ii) The diagram of different functional blocks. (iii) Photos of the devices and its working location. Reprint with permission from Ref. [93]. Copyright 2016, John Wiley & Sons. **c** The photos of a RFID antenna. (i) The antenna is attached to a flat surface. (ii) Its structure. (iii) It is attached to the blood tube. Reprint with permission from Ref. [163]. Copyright 2019, MDPI


(a)
Stretchable RFID antenna
pH senor
Reference Electrode
Data transmission circuitry
pH Sensing Electrode
Stretchable pH sensor
40 mm
10 mm
A
A'
260°
A-A'
Graphite SE
Ag/AgCl RE
Epoxy
PDMS substrate
Silver paste
Au-PI stretchable interconnects
(b)
(i)
(ii)
(iii)
top
bottom
Ag
Ag/AgCl
hydrogel
V
sweat
skin
salt bridge
sweat sensor
mobile app
Bluetooth transceiver
Home
Experiment
Stop Experiment 4
Connected
62.5 mV = 91.3 mM
Time (min)
(c)
3D-printed case
Processing electronics
Bluetooth module
Readout PCB
pH sensing device
Absorbent pad
μCAD
Bottom cover
Custom-developed smartphone app
sweat
App
pH value
Bluetooth
RGB
Hue
pH

◂**Fig. 5** **a** (i) A photo and (ii) a schematic diagram of a stretchable wireless sweat monitoring device. Reprint with permission from Ref. [102]. Copyright 2018, Elsevier. **b** A wearable swear sensor. (i) The schematic illustration of the sweat chloride sensor. (ii) It is connected to the smart phone. (iii) The interface of the mobile app. Reprint with permission from Ref. [101]. Copyright 2018, Elsevier. **c** An Exploded view of a sweat sensors with Bluetooth. Reprint with permission from Ref. [105]. Copyright 2021, Elsevier

[96, 97]. When detecting it, non-invasive and on-demand acquisition can also be achieved. That is, it can be obtained by iontophoresis ((Wescor Macroduct), a method approved by the Food and Drug Administration (FDA) [98].

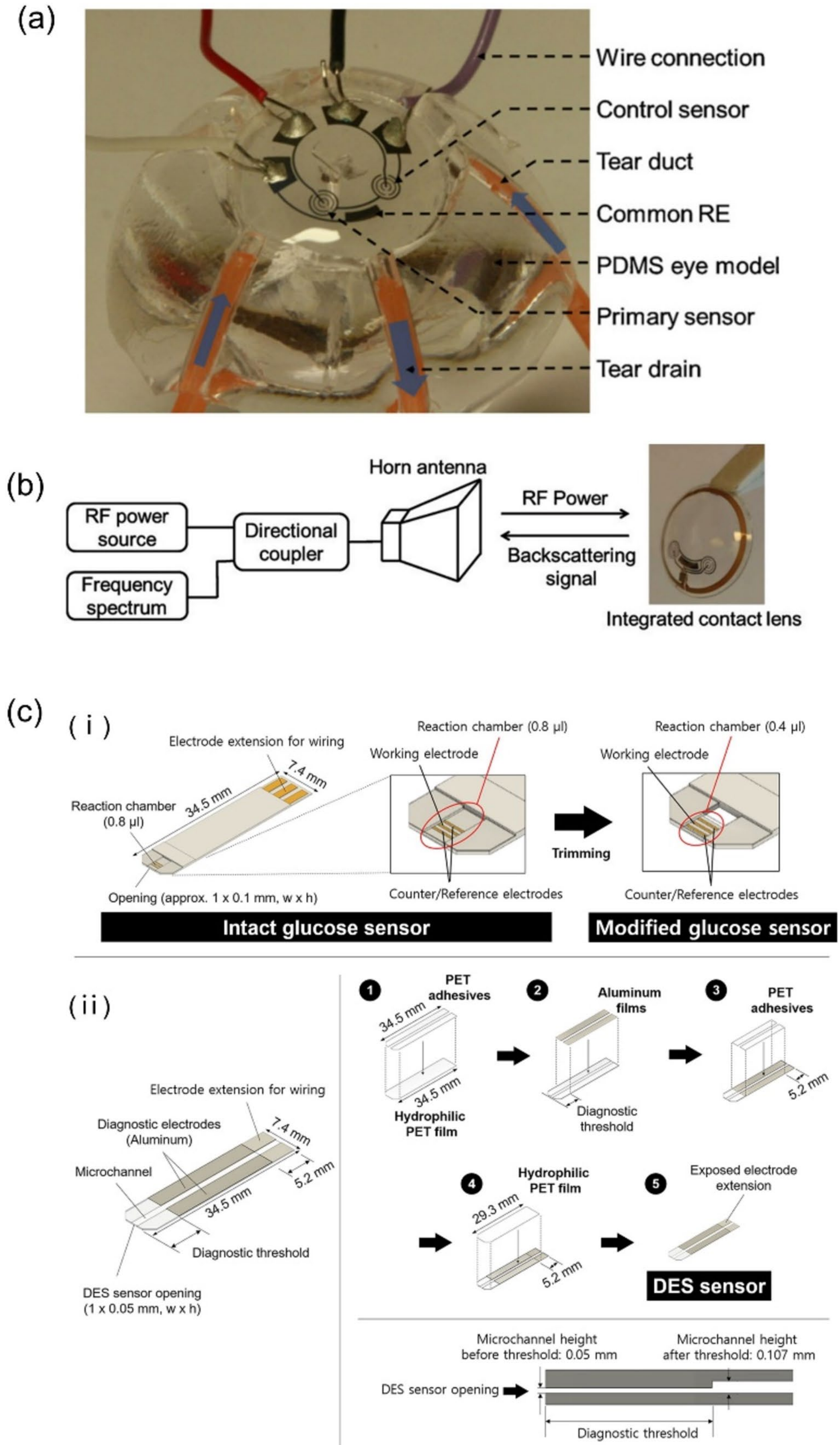
Sweat has been used in medical tests for a long time, most notably in cystic fibrosis (CF) screening [99]. Cystic fibrosis not only damages the lungs, but also negatively affects the Cl^- ion reabsorption function of the sweat glands, resulting in very high Cl^- content in the sweat of patients. Based on this, a rapid preliminary diagnosis of cystic fibrosis can be achieved through the analysis of sweat [100]. Choi et al. [101] developed a wearable sweat sensor. This sensor detects CF by checking the chlorides. This sensor has an integrated salt bridge that enables long-term and accurate detection. The monitoring result of this sensor is relatively accurate and consistent with the measurement results of traditional test in laboratories. Its Pearson correlation coefficient is $p = 0.97$. At the same time, the sensor is also connected to a smartphone through Bluetooth, allowing real-time visualization of the concentration of chloride ions in sweat. What is more, wireless monitoring can also detect the pH of sweat as Fig. 5a shows [102]. Compared to conventional testing methods, using miniaturized sensors can obtain equally accurate results from fewer test specimens, here is the sweat. This demonstrates the potential for detecting objects related to health on patients especially infants.

With the help of RFID technology, the element content in sweat can also be obtained through adhesive bandage type sensors [98]. Its photo is shown in Fig. 5b. Sensing is achieved by attaching patches to the human body. In order to improve service life and reduce size, this patch sensor adopts battery-free RFID technology, which attains power through external spiral coils (the size of the power supply coil matches the size of the patch). When the thickness of the device becomes thinner and becomes a flexible device, its fit with the human skin is greatly improved, which means that the accuracy of the device is greatly enhanced. After testing, it is found that the accuracy of the sensor can reach 96% at 50 mM NaCl.

The concentration of cortisol in sweat can reflect the magnitude of human pressure to a certain extent, and has great application prospects in sports competitions, staff in special environments, and other populations [103]. In order to ensure data security, that is, obtaining physiological information through close distances, NFC is a good solution. By combining the two above, an electrochemical sensor based on NFC has been developed [104]. This device ensures a smaller size and weight. The overall size of this device is similar to a common skin patch, and its thickness can reach the micrometer level. It integrates the sensing circuit with the power supply circuit together, and uses a rectangular resonant coil for power supply. The NFC antenna is placed on the right side of the coil to avoid crosstalk that may affect the measurement results. Electrochemical sensors convert the concentration of cortisol in sweat into changes of current, and then transmit the results to the user's mobile phone through NFC technology, in which way the users can obtain real-time information about their body. At the same time, since the device is attached to the surface of the human body through a medical-grade flexible film, this sensor also has good biocompatibility and skin adhesion, in line with the current development trend of wearable devices. A wireless wristband with Bluetooth also has these advantages (Fig. 5c) [105]. There are now also combinations of sweat sensors and textile NFC antennas [106]. Due to the special NFC antenna material, this sensor can be directly prepared on clothes, with the advantages of easy-wearing and comfortability. Intelligent textile is also a potential direction of future study. When using sweat sensors, their adhesion may be affected by the existence of sweat. How to maintain its adhesion to human skin during long-term use will also be the focus of future research.

Tears

Tears are very easily obtained body fluid. In addition to the substances such as proteins and ions that we know in tears, it has a special characteristic in clinical treatment, which is that its glucose levels are similar to those in the blood [107]. This means that tear is considered as "blood substitutes" in the field of diabetes detection [108]. The common method of measuring blood glucose requires drawing blood. Although the amount of blood required is not large, over time, multiple invasive blood-drawing on the human body can not only cause little damage to the body, but may also lead to blood infections, posing many safety hazards. Measuring glucose in tears can effectively solve the above problems. Researchers have developed a contact lens that can detect tear glucose (Fig. 6a) [108]. The device is made of transparent polyethylene terephthalate (PET) wafer with a thickness of 100 µm. Under normal circumstances, the lacrimal gland will continuously produce basal tear and then the fluid brought to various parts of the eyeball surface through the movement of the eyeball. So, when users wear contact lenses, the sensors carried on the contact lenses will be continuously immersed in tear, thereby achieving continuous monitoring of the tear glucose. In order to reduce errors, the device is equipped


(a)
Wire connection
Control sensor
Tear duct
Common RE
PDMS eye model
Primary sensor
Tear drain
(b)
Horn antenna
RF power source
Directional coupler
Frequency spectrum
RF Power
Backscattering signal
Integrated contact lens
(c)
(i)
Electrode extension for wiring
7.4 mm
34.5 mm
Reaction chamber (0.8 μl)
Opening (approx. 1 x 0.1 mm, w x h)
Reaction chamber (0.8 μl)
Working electrode
Counter/Reference electrodes
Trimming
Reaction chamber (0.4 μl)
Working electrode
Counter/Reference electrodes
Intact glucose sensor
Modified glucose sensor
(ii)
Electrode extension for wiring
Diagnostic electrodes (Aluminum)
Microchannel
7.4 mm
5.2 mm
34.5 mm
Diagnostic threshold
DES sensor opening (1 x 0.05 mm, w x h)
1 PET adhesives
34.5 mm
34.5 mm
Hydrophilic PET film
2 Aluminum films
Diagnostic threshold
3 PET adhesives
5.2 mm
4 Hydrophilic PET film
29.3 mm
5.2 mm
5 Exposed electrode extension
DES sensor
Microchannel height before threshold: 0.05 mm
Microchannel height after threshold: 0.107 mm
DES sensor opening
Diagnostic threshold

◂**Fig. 6** **a** The photos of the contact lenses. Reprint with permission from Ref. [108]. Copyright 2012, Institute of physics publishing. **b** The schematic of the wireless system. Reprint with permission from Ref. [98]. Copyright 2012, Institute of physics publishing. **c** The fabrication procedures of many sensors used for diagnosis. (i) glucose sensor, (ii) DES sensor. Reprint with permission from Ref. [112]. Copyright 2020, PLOS

with two differential sensors. In addition, to achieve wireless energy and data transmission, this device adopts radio frequency wireless power transmission. Its schematic is shown in Fig. 6b. Its operation only needs 3 μW dc power. The emergence of this design will help achieve a self-regulated insulin delivery system.

In addition to diabetes, tears can also monitor hyperlipidemia in medical diagnosis. Hyperlipidemia is one of the cardiovascular diseases, which are one of the main causes of death. According to data from the World Health Organization (WHO), in 2019, the number of deaths caused by cardiovascular diseases accounted for 38% of the total number of deaths [109]. Hyperlipidemia is a serious health risk caused by high blood lipid levels, which can lead to diseases such as atherosclerosis and coronary heart disease. The disease is commonly diagnosed by the level of total cholesterol in the plasma. According to previous studies, the cholesterol level in tear is closely related to the level in plasma [110]. Therefore, hyperlipidemia can be monitored by measuring the concentration of cholesterol in tear. Based on this, Song et al. [109] developed a contact lens for monitoring cholesterol levels in the tears of patients with hyperlipidemia. Like the study above, the present design integrates an electrochemical sensor, an antenna, and a wireless communication circuit on the lens, thus enabling full contact with the tear. The sensor is created by immobilizing cholesterol oxidase (ChOx) on a working electrode (WE), which operates enzymatic reactions with cholesterol in the tear to produce H_2O_2. The H_2O_2 is then reduced by Prussian Blue (PB) on the WE, which acts as an artificial hydrogen peroxidase. Measure the reduction potential of H_2O_2 by chronoamperometry (CA) and then the cholesterol content of the tear can be converted into the electrical signal to output. In this study, an NFC chip is used for power and data transmission. The chip transmits the electrical signals to a smartphone for real-time analysis and display. The device has the advantages of high sensitivity and stretchability, which is good news for patients with hyperlipidemia. According to the characteristics of tear, they demonstrate potential in the diagnosis of keratoconjunctivitis sicca (KCS), dry eye syndrome (DES), Alzheimer's disease (AD), and other diseases [111–113]. The schematic fabrication procedures of the sensors, which are used to help the diagnosis of these diseases above, are shown in Fig. 6c. It is clear to see that, in the future, more and more health information can be obtained by sensors through tears.

Other Body Fluid

In addition to blood and sweat, there are several types of body fluids that can provide human health information, such as saliva, etc.

Like tear, saliva can also be able to be a "blood substitute" in the detection of certain substances such as proteins and so on [114]. Compared to blood, apart from easy to be collected, saliva also has other advantages, for example, it can be collected without stimulation [115]. According to research, saliva has great development prospects in the treatment of schizophrenia [116]. Because drugs exhibit different effects on different patients, and the amount of medication is particularly important in treating mental illnesses. The amount of medication may directly affect the treatment effect, in which case developing personalized treatment plans is a good solution. A current study has designed a smart wireless saliva drug monitoring system [116]. With the assistance of a Bluetooth module, when the user puts the smart lollipop in his or her mouth, the drug can be detected as the sucking process. And then transmit the data to the smartphone for the real-time pharmaceutical investigation. According to the test experimental results, it can be seen that the results of this smart lollipop are not only highly consistent with clinical results, but also have a shorter turnaround time. This device only takes two minutes, far exceeding the 18 min of clinical test. Not only will this device not lead to invasive harm to the patient, it will also avoid contravention from patients suffering from mental illness. This facilitates the treatment of mental illness.

The interstitial fluid is the fluid between cells. Here the cells exchange substances, in other words, the interstitial fluid is the site of cellular metabolism. This fluid has the special property of being coagulation-free, so it has more accurate results than blood in some tests [117]. Due to the specificity of interstitial fluid, it is often monitored using microneedles or even microneedle arrays [118]. The information visualization can be achieved through the wireless transmission module, BLE. This module transmits the data obtained to the wearers' mobile app, which means it can realize long-term monitoring. At the same time, the wireless module can provide power for operation by charging coils.

Bioelectricity

Bioelectricity displays in the forms of a potential or polarity change produced by organs, tissues, and cells of living organisms. It is an electrical phenomenon that actively generated by or acts on cells to affect their phenotype. Bioelectricity can be collected to study the physiological processes of organisms, which can be classified as electroencephalogram (EEG), electrocardiogram (ECG), electromyography (EMG), and so on. Bioelectricity is a great indicator of the change of physical condition, the physiologic activities in the bodies, etc. [119, 120]. When combined with wireless technologies, they can facilitate the use of the monitoring devices directly and achieve real-time access to get the human signals by vitro devices, which benefits the diagnosis and treatment of diseases.

EEG

EEG is a graph formed by connecting electrodes with scalp by conductive gel and recording the changes of spontaneous biological potential in the brain [121, 122]. Due to the relatively weak potential change, it is generally necessary for the signals to be recorded in conjunction with amplifiers, etc. [123]. The diagram of the EEG signal acquisition process is shown in Fig. 7a. In order to better study the human brain nerves and help the patients with suspected non-convulsive seizures, cognitive impairment, etc., the Brain–computer interface (BCI) system based on EEG has become increasingly prevalent in recent years. By utilizing the information of EEG, it can be used to monitor the anesthesia status of elderly patients during surgery [124], which can effectively reduce the possibility of postoperative mental disorder in elderly patients [125]. The use of this device for adjuvant treatment after surgery can reduce the probability of postoperative delirium by 38%. And it can help evaluate attention, just like Fig. 7b shows. Although the technology is relatively mature nowadays, these applications require more accurate and handy measurement of EEG. What is more, a study has confirmed that it is preferable to doing long-term EEG for several hours instead of just twenty minutes [126]. Wireless technology has demonstrated its unique advantages.

Figure 7c shows a block diagram of an embedded EEG system. In the process of measuring EEG, because the electrode is attached to the scalp, the existence of hair will produce error on the results. In order to reduce this error, EEG measurement by ear has been put forward, which is named as in-ear EEG. At present, the existing in-ear EEG used in clinic is mostly based on wet electrodes, that is, electrodes with hydrogel [127]. This kind of monitoring equipment contacts the electrode with the scalp through the hydrogel as the adhesive. However, the hydrogel will become dry with the service time goes on, resulting in problems such as the reduction of signal-to-noise ratio (SNR) [128]. So, the emergence of devices which work based on the dry electrodes has effectively solved these problems. Besides, there is a cap with an eight-channel EEG amplifier based on dry electrode. Dry electrodes are formed by benign metal, such as stainless steel. Instead of add electrolyte between the skin and electrode, the in-ear EEG devices couple the signal directly from the skin to the substrate by the insulating electrode with a thin dielectric surface layer [128]. Kaveh et al. [129] create a wireless user-generic in-ear EEG recording platform. The device uses polymer resin for 3D printing to create an earpiece that fits the shape of a human ear, and then solder the circuit board onto it. The EEG signals are obtained through the contact between the electrodes and the skin by the earpiece. And then WANDmini, a neural recording system rely on Bluetooth, transmits the data to a laptop. By this device, alpha rhythm, eye-blinks, and the auditory steady-state response (ASSR) can be recorded. This can help detect the users' stress by the devices put in ears. And it even can be used in the smart phones, which means voice assistants can be activated by blink.

In addition to the precision equipments that only exist in the laboratory at present, many commercial headworn wireless EEG monitoring equipments have been developed. Although its affect in clinical medicine is limited, it plays a positive role in the estimation of human health in daily life. Muse-Interaxon (https://choosemuse.com/muse-2/.) has launched several wireless headbands which can monitor EEG. For example, in this company's products, Muse-2 device is a typical representative. It has seven sensors, two on the forehead, two behind the ears, and the left three as reference sensors. The user wears it on their head, and the device senses the brain activity through active sensor technology and then sends data to their phone or computer through Bluetooth. With these data, it is possible to monitor a person's mental state and even evaluate their attention level, which has great development prospects in fatigue monitoring and drowsiness detection [130]. The purpose of conducting the monitoring mentioned above is to analyze and improve human sleep quality and focus level, thereby achieving the ultimate goal of optimizing the quality of human's life. Daily health monitoring will be the future development trend. So now there are many headworn devices, breaking through the previous situation where there were only wristband devices. Starting from a headworn device, making the device lightweight and comfortable is a key issue that needs to be addressed. Using flexible electrons may be a good method to solve these problems.

ECG

ECG shows the electrical activity of the heart, which can reflect the heart condition, such as atrial tachycardia, atrial fibrillation, and ventricular tachycardia [131–133]. The generation of electrocardiogram signals is shown in Fig. 8a, and a normal electrocardiogram generally consisted of P-wave, T-wave, PR interval, etc. [134]. Traditional methods require attaching electrodes to the patient and transmitting the information to the receiver through troublesome wires. These approaches reduce the mobility of devices and affect the

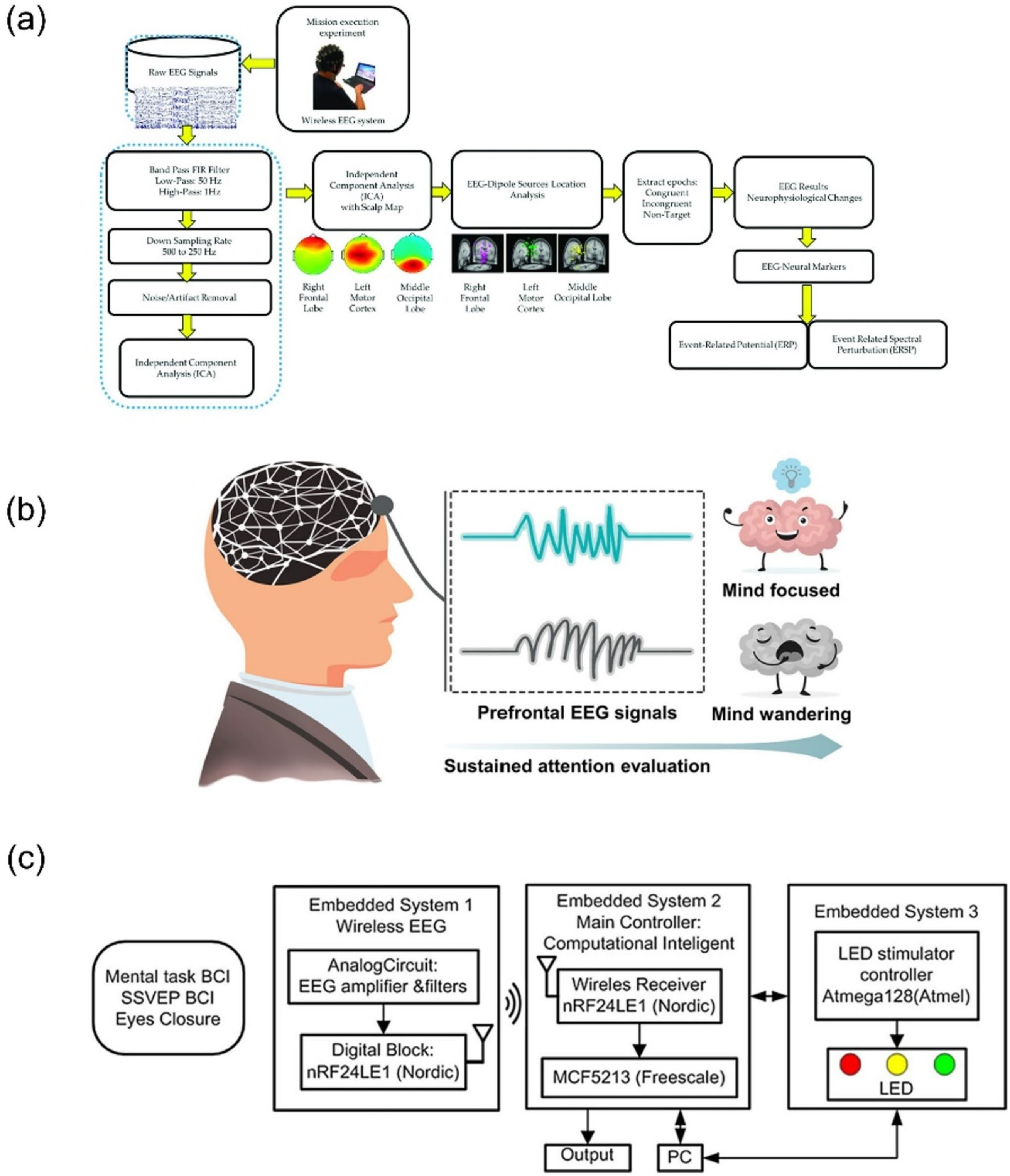
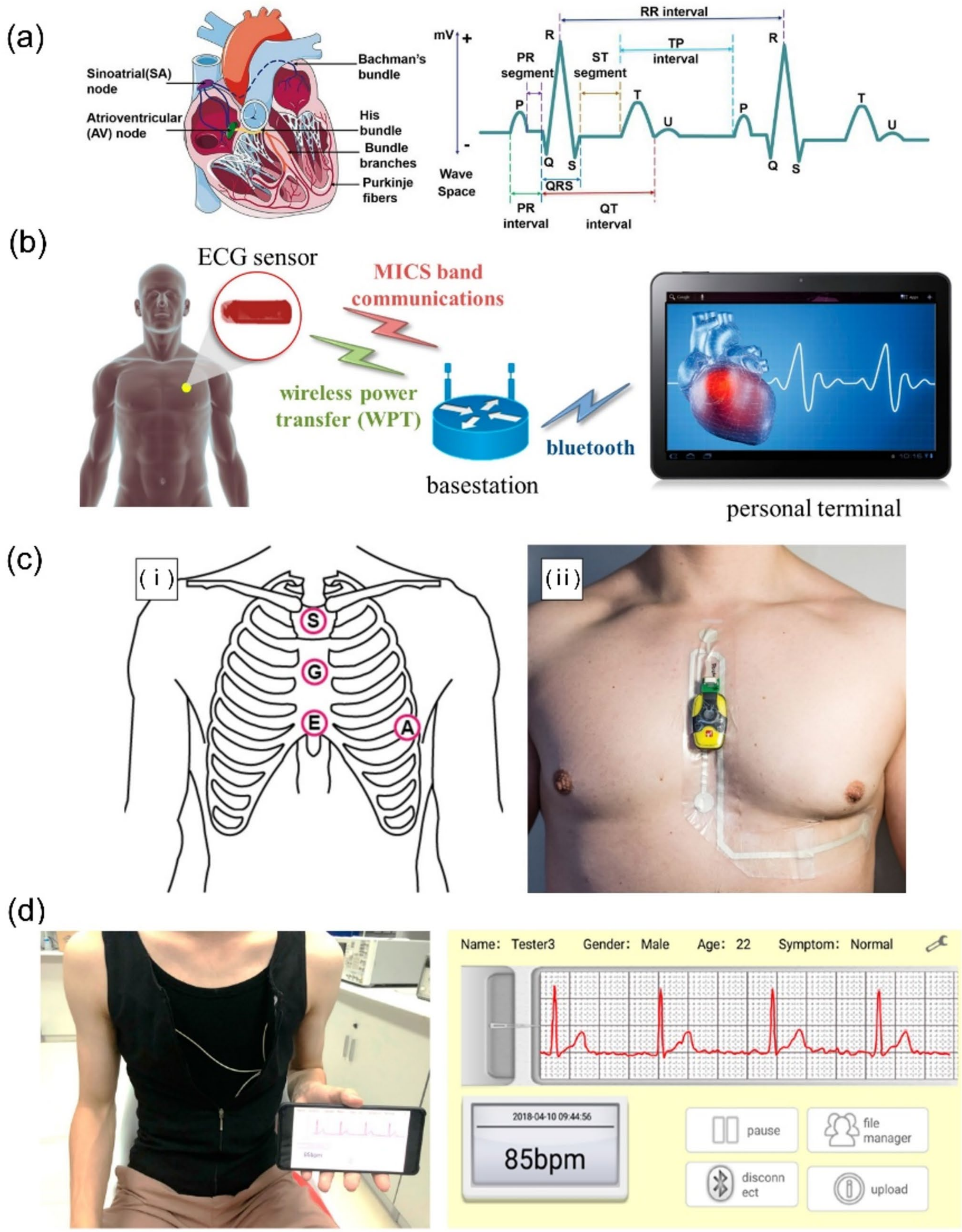


Fig. 7 **a** The flow diagram of EEG signal acquisition and preprocessing. Reprint with permission from Ref. [164]. Copyright 2021, MDPI. **b** The application of EEG used in sustained attention evaluation. Reprint with permission from Ref. [134]. Copyright 2020, MDPI. **c** A block diagram of a wireless embedded EEG system. Reprint with permission from Ref. [165]. Copyright 2017, Springer Nature


(a)
Sinoatrial(SA) node
Atrioventricular (AV) node
Bachman's bundle
His bundle
Bundle branches
Purkinje fibers
mV
Wave Space
RR interval
R
PR segment
ST segment
TP interval
P
Q
S
T
U
QRS
PR interval
QT interval
(b)
ECG sensor
MICS band communications
wireless power transfer (WPT)
basestation
bluetooth
personal terminal
(c)
(i)
S
G
E
A
(ii)
(d)
Name: Tester3 Gender: Male Age: 22 Symptom: Normal
2018-04-10 09:44:56
85bpm
pause
file manager
disconn ect
upload

◂**Fig. 8** **a** The generation mechanism of electrocardiogram (ECG) signal and a typical cardiac cycle. Reprint with permission from Ref. [134]. Copyright 2020 MDPI. **b** The diagram of a wireless ECG monitoring devices. Reprint with permission from Ref. [137]. Copyright 2019 MDPI. **c** (i) The locations of the electrodes and (ii) a picture of a volunteer attached by these electrodes. Reprint with permission from Ref. [166]. Copyright 2019, John Wiley & Sons. **d** The app displayed in an Android-based smart phone. Reprint with permission from Ref. [167]. Copyright 2019, MDPI

miniaturization of instruments. With the developments of wireless transmission technology, inductive coupling and other technologies are becoming increasingly applied in the ECG monitoring, providing an opportunity for the emergence of portable measuring instruments [135]. Without the limit of wires, it is possible to achieve continuous monitoring and even early warning for cardiovascular diseases such as strokes, arrhythmias, heart attacks, and so on [136].

Lee et al. [137] developed wireless charging implanted ECG monitoring system, which can not only sense the ECG signals, but also can check the voltage level of the cell and the temperature of the implantable device. As the diagram shows in Fig. 8b, a sensor is implanted to get the ECG signal in the subcutaneous fat. Then it transmits the information to a base station. This base station collects the ECG signals and also transfers the power to the in-body device when it detects the device in the low battery voltage level. Through Bluetooth, a personal terminal can get connection to the base station, in which case the users can know the personal health status of chronic disease, arrhythmia. This device can achieve communication at a distance of 2.4 m and achieve an energy transmission efficiency of 30%. This wireless system helps achieve the 24/7-monitoring, even in the place where there is no electricity at all because of the existence of battery.

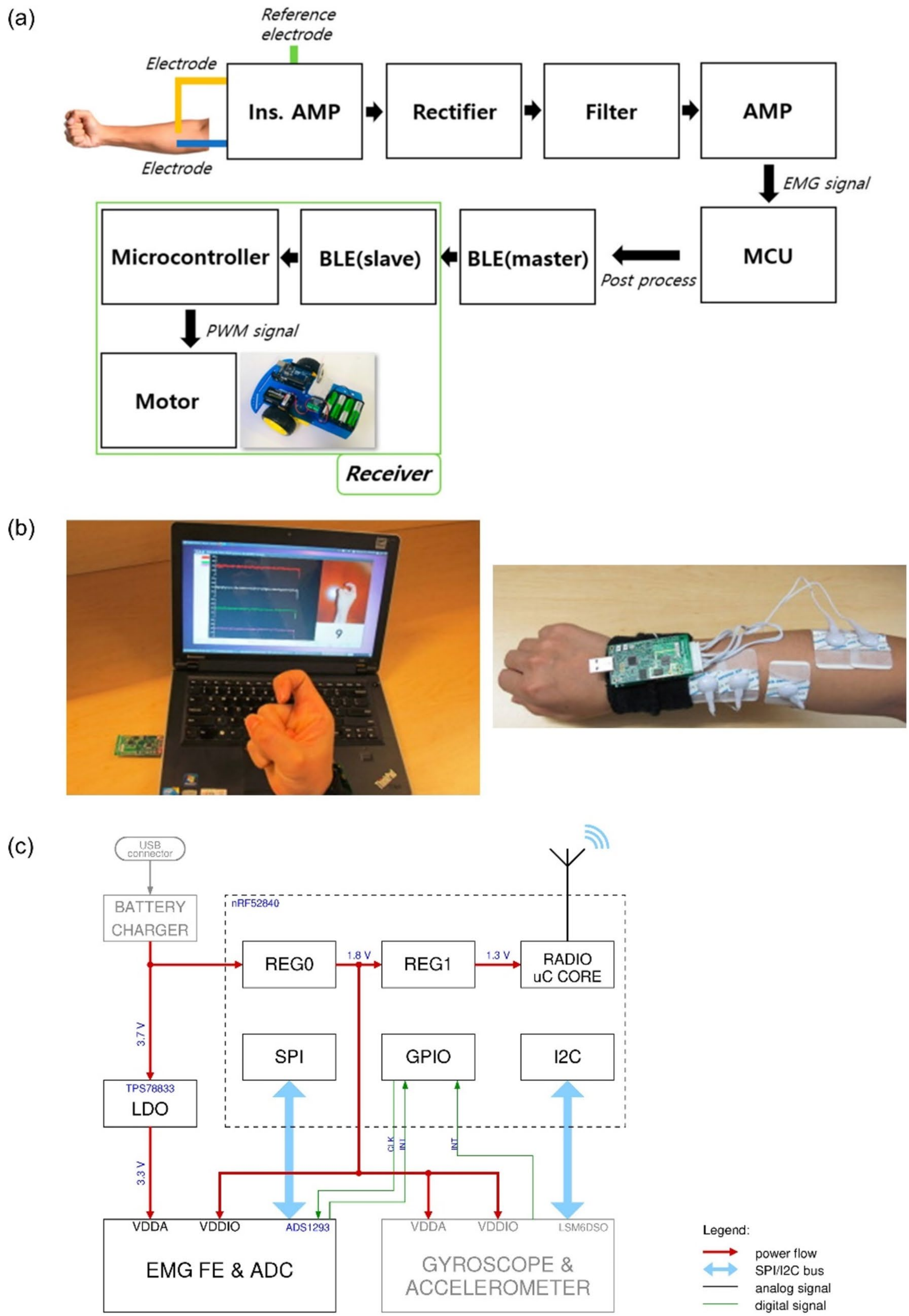
In addition to acquiring ECG signals, improving the comfort of the measurement process and reducing the number of sensors have become a current study direction. Attaching electrodes to the human body can get accurate information (Fig. 8c). Wannenburg et al. [138] use two active electrodes and one reference electrode to get the ECG signals. The active electrode has an active buffer stage, which can preprocess the signals to decrease the electromagnetic interference (EMI). Then with utilization of Bluetooth as well, or with GZLL protocol, measurement result can be transferred to the remote server for calculating HRV, RR, and related features. This measurement method reduces the number of sensors required for measurement through ingenious circuit design, greatly reducing users' discomfort while ensuring the accuracy.

Currently, Smart Home has been put into deep research as IoTs technology has become an important research direction. Recent years, Smart Home began to focus on monitoring the health of the human body. At present, remote ECG Monitoring Systems have been able to realize monitoring the health state of people who wear portable devices [139]. The wearable devices are equipped with a Wireless Sensor Networks (WSNs) and can transmit the measured ECG signals to an ECG server and then to the hospital for analysis. The presence of this system can effectively warn of abnormalities and provide some health protection for patients in advance. The above monitored content can be displayed in real-time on smartphones or other smart devices, as shown in Fig. 8d.

EMG

When a muscle contracts, it produces a weak electric current, which can be measured using electrodes, and the resulting curve is called EMG. In medical diagnosis, EMG can help doctors to do noninvasively monitoring. EMG is a handy access to assess the function status of skeletal muscles. A Block diagram of the EMG sensor structure is shown in Fig. 9a. For example, muscle volume can be determined by EMG, which is contributed to determine the recovery situation after related surgeries, such as volumetric muscle loss (VML) transplantation surgery [140]. EMG also allows medical determination of the functional status of peripheral nerves, neurons, the muscles themselves, and other issues. In this case, EMG has a greater role in the field of biomedical health technology for the elderly and disabled. Nowadays, two measurement methods are commonly applied to get the EMG: intramuscular EMG and surface EMG (sEMG). Intramuscular EMG requires needles or wires inserted to the muscles to detect the signals, while the sEMG can record the activity of muscles on the skin [141, 142]. Considering the accessibility and the risk, sEMG is focused on to develop.

Since EMG is often acquired by attaching the sensor directly to the surface of the human skin, flexible electronics are more commonly used in this type of measurement device. Flexible electronics has the properties of soft and stretchable, which allow the wearable sensors to be more durable and be applied to more scenes. Based on the microfabrication applied to the semiconductors, a stretchable electrode patch was manufactured to monitor the EMG [143]. This device can get up to 50% stretching, which can reach the maximum tensile deformation of skin. Meanwhile, with the wireless module fixed on the leg, this system can transmit the EMG signals to the PC in short time. This device can monitor the muscles and nerves of the human body, while greatly reducing the discomfort of wearing external objects. In addition to the above applications, the EMG signal can also help detect gestures as Fig. 9b shows. The use of EMG to assist disabled people to overcome communication barriers is also very meaningful. With the configuration of wireless transmitter, an electrode module developed for EMG can transform small movements into Braille [144]. The wireless electrodes are attached on the flexor carpi ulnaris muscle


(a)
Reference electrode
Electrode
Electrode
Ins. AMP
Rectifier
Filter
AMP
EMG signal
MCU
Post process
BLE(master)
BLE(slave)
Microcontroller
PWM signal
Motor
Receiver
(b)
(c)
USB connector
BATTERY CHARGER
nRF52840
REG0
1.8 V
REG1
1.3 V
RADIO uC CORE
3.7 V
SPI
GPIO
I2C
TPS78833
LDO
3.3 V
CLK
IN1
INT
VDDA
VDDIO
ADS1293
EMG FE & ADC
VDDA
VDDIO
LSM6DSO
GYROSCOPE & ACCELEROMETER
Legend:
power flow
SPI/I2C bus
analog signal
digital signal

◂**Fig. 9** **a** A Block diagram of an EMG sensor structure. Reprint with permission from Ref. [168]. Copyright 2019, MDPI. **b** An EMG recognition system with its software. Reprint with permission from Ref. [169]. Copyright 2013, Elsevier. **c** The architecture of a wireless EMG measurement module. The USB battery charger and the accelerometer/gyroscope blocks are gray because they have been replaced by BLE in this device. Reprint with permission from Ref. [170]. Copyright 2021, MDPI

to detect the fingers' move, and then convert the small move into signals for inputting the characters. Compared with other electrical signals, EMG has more promising applications. The use of EMG in conjunction with ECG can control a robotic hand, which enables the simulation of human operation [145]. Using multichannel to collect information can also improve the accuracy of measurement.

In commercial product, many EMG acquisition systems are costly, so achieving low-cost measurement is a research direction many people working on. By the wireless technology, the size of devices can be optimized for portable applications. However, multichannel measurement is uneasy. Yang et al. [146] designed a low-cost eEMG acquisition system which can be conducting multichannel measure with high-sampling, and its work architecture is shown in Fig. 9c. Combining with a Wi-Fi module, the EMG signals can be transferred to a host for further analysis. This system can be used in the commercial EMG detection device to realize lower cost.

Movement

In clinical applications, except monitoring vital signs, it is sometimes of significance to monitor the movement status of the human body in real time, especially for infants and the elderly. Different behaviors exhibit different signals, as shown in Fig. 10a. In the process of this application, the key points are transforming behaviors and actions into signals for transmission.

Monitoring sports not only matters for people engaged in the sports industry, but also increasingly common in daily life. Real-time monitoring can effectively reduce the risk of sudden illnesses while also can prevent injuries caused by excessive exercise [147]. Through electrospinning technology, wireless sensors can be integrated into clothes. For example, by preparing a textile capacitor above the knee, the degree of knee bending can be monitored. This technology is beneficial for monitoring the recovery after knee surgery [148]. As Fig. 10b shows, the readers in the trousers can track various motions' kinds of knees and then display in a smartphone app. In the context of monitoring the physical activity of newborns, this technology proves invaluable for assessing their activity levels and overall health. Wireless devices can reduce the limitations of measuring instruments on the movement of the baby, while also allowing parents to hold their child, even when the baby has to be connected to devices for their disease [149]. Aggarwal et al. [150] come up with an investigational device which can continuously monitor the baby with heart rate, oxygen saturation, respiratory rate, and body temperature (Fig. 10c). With this device worn on the newborn babies' foot, the four vital parameters mentioned above can be measured and then relayed to a central station for the easy-supervision remotely conducted by the doctors or nurses through the BLE communication module. The device can also upload data to the cloud for storage, ensuring seamless data storage within 24 h when the signal connection is weak. Cough, respiration, and other indicators are very common in clinical practice. Through analysis of these indicators, we can help diagnose chronic obstructive pulmonary disease (COPD) and other diseases [151, 152]. Through wireless wearable measurement systems which is a low-power radio module, muscle movements, such as the intercostal, collarbone, and neck muscles can be measured in order to record coughing and breathing [153]. With the help of accelerometer and gyroscope, and then doing the data processing and analysis, the displacement angles of the abdomen and chest can be calculated. Thereby it is possible to obtain parameters such as breathing and coughing cycles. In order to get more accurate data and eliminate some interference, filters are indispensable. As shown in the article, the sensor nodes are attached to the human body. Based on this, comparing the measurement performance of sitting and walking shows that this device not only has robustness, but also can transmit data to the base station for analysis while ensuring low energy consumption.

In addition to the obvious movements, there are also many weak signals in the human body that are helpful for clinical monitoring. A typical weak signal is the pulse signal of the human body. Blood contracts from the left ventricle of the heart and is squeezed into the aorta, then flows throughout the body. During this process, a pulse is generated. The interval and strength of pulse can reflect the health status of the human body and are very important physiological signals. Traditional Chinese medicine in China has been using this information for disease diagnosis for a long time [154, 155]. The key difficulty in measuring the human pulse signal is that the signal is relatively weak, so the sensitivity of pressure sensors is required to be high. Researchers have improved the sensitivity of the sensing interface through various methods, such as using electrospinning microstructure array films [156], adding polydimethylsiloxane (PDMS) passivation layers [157], and so on.

Challenges and Conclusions

We review the wireless wearables and its applications in this article. When the data are ready to be processed and analyzed, many wireless technologies are used to transfer

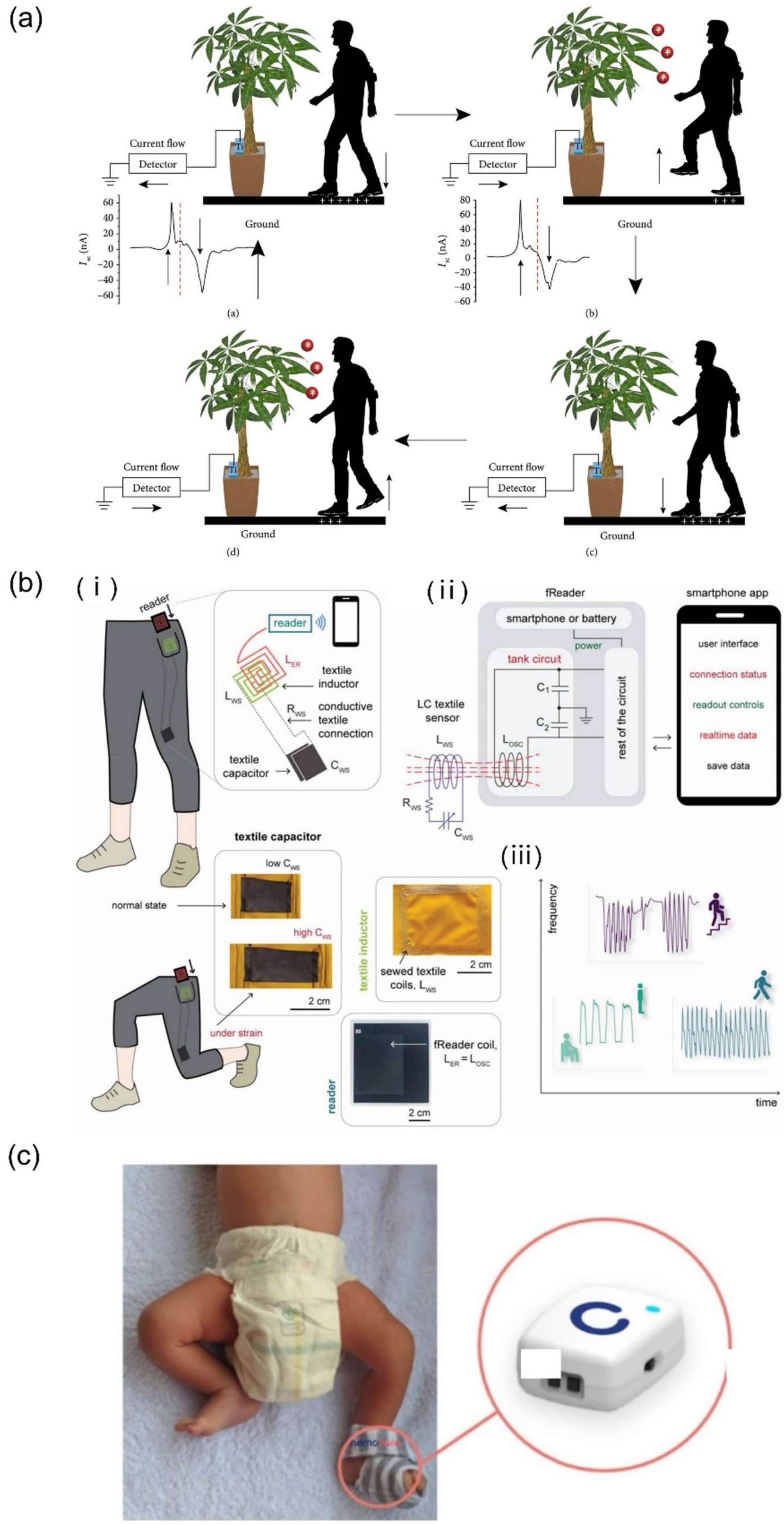


Fig. 10 **a** Different movements exhibit different signals. Reprint with permission from Ref. [171]. Copyright 2021, AAAS. **b** The sensing system of motion-tracking. (i) The scheme of a smart trousers. (ii) The readout process between the sensors and the smartphone. (iii) Different activities recorded different signals. Reprint with permission from Ref. [148]. Copyright 2023 John Wiley and Sons. **c** Movements monitoring devices designed for baby. Reprint with permission from Ref. [150]. Copyright 2023 Springer Nature

the power and data. Wireless power transfer can reduce the size of the device, while self-power can fully utilize energy produced by human. With the continuous innovation and improvement of technology, portable wearable devices have brought many conveniences to people, enabling them to monitor health at all time and use non-invasive methods to achieve medical diagnosis. Wireless power transmission modules are an integral part. Although its presence makes the equipment easier to use, it also introduces a lot of error into the measurement results. According to the principle of wireless transmission, the presence of electromagnetic interference cannot be avoided [158]. In addition, according to research, there is currently no system for quantitative analysis and evaluation of the issue mentioned above. This will also become a key focus of research and development in the next stage.

The information which reflects the state of human health can be obtain in many ways such as body fluid, bioelectricity, and movements. Some diseases can be diagnosed by the types and levels of substances contained in body fluid. Thus, it can help to better carry out clinical medical treatment. There is also movements monitoring, which provides significant assistance for daily health monitoring. Many existing health monitoring wearable devices are based on rigid circuit boards. Although rigid devices are durable, they have drawbacks such as low comfort and limited application scenarios. Flexible equipment will be an important development goal in the future. The preparation and optimization of flexible sensors are the key to solving this problem. The toughness of the device can be improved by using stretchable electrodes on a stretchable substrate, thereby improving the skin adhesion and biocompatibility of the device. On the basis of flexible devices, the accuracy and diversity of measurement results will be greatly improved.

Although there are issues that need to be addressed, many researchers are currently working together to promote the technological innovations. We believe that through efforts, wireless wearable devices will blend in all aspects of medical diagnosis and daily life in the future, bringing irreplaceable contributions to human health.

Acknowledgements This research was supported by the National Key Research and Development program of China under Grant No. 2021YFA1401103; China National Funds for Distinguished Young Scientists under Grant 61825403; the National Natural Science Foundation of China under Grants 61921005, 61674078, and 82370520; and the Nanjing Scientific & Technological Talents Program.

Funding Funding was provided by the National Key Research and Development Program of China (2021YFA1401103), China National Funds for Distinguished Young Scientists (61825403), the National Natural Science Foundation of China (61921005, 61674078, 82370520), and Nanjing Scientific & Technological Talents Program.

Data Availability Manuscript has no associated data.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

1. M.V. Perez, Getting smart about wearable ECG interpretation in the clinic. Clin. Electrophysiol. **8**, 792–794 (2022). https://doi.org/10.1016/j.jacep.2022.03.018
2. J.C. Williams, P.J. Campagnola, Wearable second harmonic generation imaging: the sarcomeric bridge to the clinic. Neuron **88**, 1067–1069 (2015). https://doi.org/10.1016/j.neuron.2015.12.009
3. Q.H. Abbasi, H. Heidari, A. Alomainy, Wearable wireless devices. Appl. Sci. **9**, 2643 (2019). https://doi.org/10.3390/app9132643
4. Y.-G. Park, S. Lee, J.-U. Park, Recent progress in wireless sensors for wearable electronics. Sensors **19**, 4353 (2019). https://doi.org/10.3390/s19204353
5. Y. Li, M. Zhao, Q. Wei, J. Yu, J. Chen, D. Chen, J. Wang, Wireless passive intracranial pressure sensor based on vacuum packaging. IEEE Sensors J. **20**, 11247–11255 (2020). https://doi.org/10.1109/JSEN.2020.2998786
6. K. Kim, S.-W. Jung, Interactive image segmentation using semi-transparent wearable glasses. IEEE Trans. Multimed. **20**, 208–223 (2018). https://doi.org/10.1109/TMM.2017.2728318
7. B. Ciui, A. Martin, R.K. Mishra, B. Brunetti, T. Nakagawa, T.J. Dawkins, M. Lyu, C. Cristea, R. Sandulescu, J. Wang, Wearable wireless tyrosinase bandage and microneedle sensors: toward melanoma screening. Adv. Healthc. Mater. **7**, 1701264 (2018). https://doi.org/10.1002/adhm.201701264
8. L. Manjakkal, A. Pullanchiyodan, N. Yogeswaran, E.S. Hosseini, R. Dahiya, A wearable supercapacitor based on conductive PEDOT: PSS-coated cloth and a sweat electrolyte. Adv. Mater. **32**, 1907254 (2020). https://doi.org/10.1002/adma.201907254
9. H.E. Lee, D. Lee, T.-I. Lee, J.H. Shin, G.-M. Choi, C. Kim, S.H. Lee, J.H. Lee, Y.H. Kim, S.-M. Kang et al., Wireless powered wearable micro light-emitting diodes. Nano Energy **55**, 454–462 (2019). https://doi.org/10.1016/j.nanoen.2018.11.017
10. X. Chen, L. Gong, L. Wei, S.-C. Yeh, L. Da Xu, L. Zheng, Z. Zou, A wearable hand rehabilitation system with soft gloves. IEEE Trans. Ind. Inf. **17**, 943–952 (2021). https://doi.org/10.1109/TII.2020.3010369
11. Z. Li, Y. Ma, K. Zhang, J. Wan, D. Zhao, Y. Pi, G. Chen, J. Zhang, W. Tang, L. Lin et al., Air permeable vibrotactile actuators for wearable wireless haptics. Adv. Funct. Mater. **33**, 2211146 (2023). https://doi.org/10.1002/adfm.202211146
12. R.K. Mishra, A. Barfidokht, A. Karajic, J.R. Sempionatto, J. Wang, J. Wang, Wearable potentiometric tattoo biosensor for on-body detection of G-type nerve agents simulants. Sens. Actuators B **273**, 966–972 (2018). https://doi.org/10.1016/j.snb.2018.07.001
13. T. An, D.V. Anaya, S. Gong, L.W. Yap, F. Lin, R. Wang, M.R. Yuce, W. Cheng, Self-powered gold nanowire tattoo triboelectric sensors for soft wearable human-machine interface. Nano Energy **77**, 105295 (2020). https://doi.org/10.1016/j.nanoen.2020.105295
14. V. Kedambaimoole, N. Kumar, V. Shirhatti, S. Nuthalapati, S. Kumar, M.M. Nayak, P. Sen, D. Akinwande, K. Rajanna, Reduced graphene oxide tattoo as wearable proximity sensor. Adv. Electron. Mater. **7**, 2001214 (2021). https://doi.org/10.1002/aelm.202001214
15. B. Gao, A. Elbaz, Z. He, Z. Xie, H. Xu, S. Liu, E. Su, H. Liu, Z. Gu, Bioinspired kirigami fish-based highly stretched wearable biosensor for human biochemical-physiological hybrid

monitoring. Adv. Mater. Technol. **3**, 1700308 (2018). https://doi.org/10.1002/admt.201700308
16. T.R. Ray, M. Ivanovic, P.M. Curtis, D. Franklin, K. Guventurk, W.J. Jeang, J. Chafetz, H. Gaertner, G. Young, S. Rebollo et al., Soft, skin-interfaced sweat stickers for cystic fibrosis diagnosis and management. Sci. Transl. Med. (2021). https://doi.org/10.1126/scitranslmed.abd8109
17. P. Porter, F. Muirhead, J. Brisbane, B. Schneider, J. Choveaux, N. Bear, J. Carson, K. Jones, D. Silva, C. Neppe, Accuracy, clinical utility, and usability of a wireless self-guided fetal heart rate monitor. Obstet. Gynecol. **137**, 673–681 (2021). https://doi.org/10.1097/AOG.0000000000004322
18. G.S. Cañón Bermúdez, D. Makarov, Magnetosensitive E-skins for interactive devices. Adv. Funct. Mater. **31**, 2007788 (2021). https://doi.org/10.1002/adfm.202007788
19. W. Yan, C. Ma, X. Cai, Y. Sun, G. Zhang, W. Song, Self-powered and wireless physiological monitoring system with integrated power supply and sensors. Nano Energy **108**, 108203 (2023). https://doi.org/10.1016/j.nanoen.2023.108203
20. K. Xie, B. Wei, Materials and structures for stretchable energy storage and conversion devices. Adv. Mater. **26**, 3592–3617 (2014). https://doi.org/10.1002/adma.201305919
21. C. Wu, L. Han, Y. Dong, M. Guo, R. Wang, J. Si, Wireless battery-free flexible sensing system for continuous wearable health monitoring. Adv. Mater. Technol. **8**, 2201662 (2023). https://doi.org/10.1002/admt.202201662
22. T. Sakata, M. Hagio, A. Saito, Y. Mori, M. Nakao, K. Nishi, Biocompatible and flexible paper-based metal electrode for potentiometric wearable wireless biosensing. Sci. Technol. Adv. Mater. **21**, 379–387 (2020). https://doi.org/10.1080/14686996.2020.1777463
23. K. Lee, S.H. Chae, Power transfer efficiency analysis of intermediate-resonator for wireless power transfer. IEEE Trans. Power Electron. **33**, 2484–2493 (2018). https://doi.org/10.1109/TPEL.2017.2698638
24. S.H. Gupta, A. Sharma, M. Mohta, A. Rajawat, Hand movement classification from measured scattering parameters using deep convolutional neural network. Measurement **151**, 107258 (2020). https://doi.org/10.1016/j.measurement.2019.107258
25. M.F. Mahmood, S.L. Mohammed, S.K. Gharghan, A. Al-Naji, J. Chahl, Hybrid coils-based wireless power transfer for intelligent sensors. Sensors **20**, 2549 (2020). https://doi.org/10.3390/s20092549
26. W.-Y. Lai, T.-R. Hsiang, Wireless charging deployment in sensor networks. Sensors **19**, 201 (2019). https://doi.org/10.3390/s19010201
27. Z.J. Lee, G. Lee, T. Lee, C. Jin, R. Lee, Z. Low, D. Chang, C. Ortega, S.H. Low, Adaptive charging networks: a framework for smart electric vehicle charging. IEEE Trans. Smart Grid **12**, 4339–4350 (2021). https://doi.org/10.1109/TSG.2021.3074437
28. Z. Zhang, B. Zhang, Angular-misalignment insensitive omnidirectional wireless power transfer. IEEE Trans. Ind. Electron. **67**, 2755–2764 (2020). https://doi.org/10.1109/TIE.2019.2908604
29. J. Feng, Q. Li, F.C. Lee, M. Fu, Transmitter coils design for free-positioning omnidirectional wireless power transfer system. IEEE Trans. Ind. Inf. **15**, 4656–4664 (2019). https://doi.org/10.1109/TII.2019.2908217
30. Z. Ye, Y. Sun, X. Liu, P. Wang, C. Tang, H. Tian, Power transfer efficiency analysis for omnidirectional wireless power transfer system using three-phase-shifted drive. Energies **11**, 2159 (2018). https://doi.org/10.3390/en11082159
31. W.M. Ng, C. Zhang, D. Lin, S.Y. Ron Hui, Two- and three-dimensional omnidirectional wireless power transfer. IEEE Trans. Power Electron. **29**, 4470–4474 (2014). https://doi.org/10.1109/TPEL.2014.2300866
32. Y. Zhang, Z. Zhou, Z. Fan, S. Zhang, F. Zheng, K. Liu, Y. Zhang, Z. Shi, L. Chen, X. Li et al., Self-powered multifunctional transient bioelectronics. Small **14**, 1802050 (2018). https://doi.org/10.1002/smll.201802050
33. W. Li, K. Lin, L. Chen, D. Yang, Q. Ge, Z. Wang, Self-powered wireless flexible ionogel wearable devices. ACS Appl. Mater. Interfaces (2023). https://doi.org/10.1021/acsami.2c19744
34. T. Starner, Human-powered wearable computing. IBM Syst. J. **35**, 618–629 (1996). https://doi.org/10.1147/sj.353.0618
35. M. Lee, C.-Y. Chen, S. Wang, S.N. Cha, Y.J. Park, J.M. Kim, L.-J. Chou, Z.L. Wang, A hybrid piezoelectric structure for wearable nanogenerators. Adv. Mater. **24**, 1759–1764 (2012). https://doi.org/10.1002/adma.201200150
36. Z. Lou, L. Li, L. Wang, G. Shen, Recent progress of self-powered sensing systems for wearable electronics. Small **13**, 1701791 (2017). https://doi.org/10.1002/smll.201701791
37. J. Shao, T. Jiang, Z. Wang, Theoretical foundations of triboelectric nanogenerators (TENGs). Sci. China Technol. Sci. **63**, 1087–1109 (2020). https://doi.org/10.1007/s11431-020-1604-9
38. L. Wang, Z. Fei, Z. Wu, Y. Ye, Y. Qi, J. Wang, L. Zhao, C. Zhang, Y. Zhang, G. Qin et al., Wearable bending wireless sensing with autonomous wake-up by piezoelectric and triboelectric hybrid nanogenerator. Nano Energy **112**, 108504 (2023). https://doi.org/10.1016/j.nanoen.2023.108504
39. S.S. Kwak, H.-J. Yoon, S.-W. Kim, Textile-based triboelectric nanogenerators for self-powered wearable electronics. Adv. Funct. Mater. **29**, 1804533 (2019). https://doi.org/10.1002/adfm.201804533
40. Y. Wu, Y. Luo, J. Qu, W.A. Daoud, T. Qi, Nanogap and environmentally stable triboelectric nanogenerators based on surface self-modified sustainable films. ACS Appl. Mater. Interfaces **12**, 55444–55452 (2020). https://doi.org/10.1021/acsami.0c16671
41. G.Q. Gu, C.B. Han, J.J. Tian, C.X. Lu, C. He, T. Jiang, Z. Li, Z.L. Wang, Antibacterial composite film-based triboelectric nanogenerator for harvesting walking energy. ACS Appl. Mater. Interfaces **9**, 11882–11888 (2017). https://doi.org/10.1021/acsami.7b00230
42. H. Wu, Y. Huang, F. Xu, Y. Duan, Z. Yin, Energy harvesters for wearable and stretchable electronics: from flexibility to stretchability. Adv. Mater. **28**, 9881–9919 (2016). https://doi.org/10.1002/adma.201602251
43. F.R. Fan, W. Tang, Z.L. Wang, Flexible nanogenerators for energy harvesting and self-powered electronics. Adv. Mater. **28**, 4283–4305 (2016). https://doi.org/10.1002/adma.201504299
44. K. Chang, M. Guo, L. Pu, J. Dong, L. Li, P. Ma, Y. Huang, T. Liu, Wearable nanofibrous tactile sensors with fast response and wireless communication. Chem. Eng. J. **451**, 138578 (2023). https://doi.org/10.1016/j.cej.2022.138578
45. Z. He, Y. Wang, H. Xiao, Y. Wu, X. Xia, S. Li, J. Liu, K. Huang, F. Wang, J. Shang et al., Highly stretchable, deformation-stable wireless powering antenna for wearable electronics. Nano Energy **112**, 108461 (2023). https://doi.org/10.1016/j.nanoen.2023.108461
46. H. Park, K. Kim, S.-J. Kweon, O. Gul, J. Choi, Y.S. Oh, I. Park, M. Je, A wireless and wearable body-pressure-monitoring system for the prevention of pressure-induced skin injuries. IEEE Trans. Biomed. Circuits Syst. (2023). https://doi.org/10.1109/TBCAS.2023.3288126
47. Y. Lan, Y. Yang, Y. Wang, Y. Wu, Z. Cao, S. Huo, L. Jiang, Y. Guo, Y. Wu, B. Yan et al., High-temperature-annealed flexible carbon nanotube network transistors for high-frequency wearable wireless electronics. ACS Appl. Mater. Interfaces **12**, 26145–26152 (2020). https://doi.org/10.1021/acsami.0c03810
48. S. Mohammadi, K. Ismail, A.H. Ghods, Investigating Wi-Fi, bluetooth, and bluetooth low-energy signal characteristics for integration in vehicle-pedestrian collision warning systems.

Sustainability **13**, 10823 (2021). https://doi.org/10.3390/su131910823
49. B.W. An, J.H. Shin, S.-Y. Kim, J. Kim, S. Ji, J. Park, Y. Lee, J. Jang, Y.-G. Park, E. Cho et al., Smart sensor systems for wearable electronic devices. Polymers **9**, 303 (2017). https://doi.org/10.3390/polym9080303
50. Q. Chen, L. Tang, A wearable blood oxygen saturation monitoring system based on bluetooth low energy technology. Comput. Commun. **160**, 101–110 (2020). https://doi.org/10.1016/j.comcom.2020.05.041
51. J. Jung, S. Shin, M. Kang, K.H. Kang, Y.T. Kim, Development of wearable wireless electrocardiogram detection system using bluetooth low energy. Electronics **10**, 608 (2021). https://doi.org/10.3390/electronics10050608
52. W. Gao, S. Emaminejad, H.Y.Y. Nyein, S. Challa, K. Chen, A. Peck, H.M. Fahad, H. Ota, H. Shiraki, D. Kiriya et al., Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis. Nature **529**, 509–514 (2016). https://doi.org/10.1038/nature16521
53. Z. Sonner, E. Wilder, J. Heikenfeld, G. Kasting, F. Beyette, D. Swaile, F. Sherman, J. Joyce, J. Hagen, N. Kelley-Loughnane et al., The microfluidics of the eccrine sweat gland, including biomarker partitioning, transport, and biosensing implications. Biomicrofluidics **9**, 031301 (2015). https://doi.org/10.1063/1.4921039
54. S.-J. Choi, S.-J. Kim, I.-D. Kim, Ultrafast optical reduction of graphene oxide sheets on colorless polyimide film for wearable chemical sensors. NPG Asia Mater. **8**, e315–e315 (2016). https://doi.org/10.1038/am.2016.150
55. C. Liu, Y. Zhang, H. Zhou, A comprehensive study of bluetooth low energy. J. Phys. (2021). https://doi.org/10.1088/1742-6596/2093/1/012021
56. A. Kiourti, RFID antennas for body-area applications: from wearables to implants. IEEE Antennas Propag. Mag. **60**, 14–25 (2018). https://doi.org/10.1109/MAP.2018.2859167
57. G. Valentine, L. Vojtech, M. Neruda, Design of solar harvested semi active RFID transponder with supercapacitor storage. AEEE **13**, 344–349 (2015). https://doi.org/10.15598/aeee.v13i4.1485
58. H. Shan, J. Peterson Iii, S. Hathorn, S. Mohammadi, The RFID connection: RFID technology for sensing and the internet of things. IEEE Microw. **19**, 63–79 (2018). https://doi.org/10.1109/MMM.2018.2863439
59. J. Zhang, G. Tian, A. Marindra, A. Sunny, A. Zhao, A review of passive RFID tag antenna-based sensors and systems for structural health monitoring applications. Sensors **17**, 265 (2017). https://doi.org/10.3390/s17020265
60. B. Aslam, U.H. Khan, M.A. Azam, Y. Amin, J. Loo, H.A. Tenhunen, A compact implantable RFID tag antenna dedicated to wireless health care. Int J. Microw. Comput. Aided Eng. **27**(5), e21094 (2017). https://doi.org/10.1002/mmce.21094
61. Y. Zhang, S. Chen, Y. Zhou, Y. Fang, C. Qian, Monitoring bodily oscillation with RFID tags. IEEE Internet Things J. **6**, 3840–3854 (2019). https://doi.org/10.1109/JIOT.2019.2892000
62. H. Abdelnasser, K.A. Harras, M. Youssef, UbiBreathe: a ubiquitous non-invasive WiFi-based breathing estimator, in *Proceedings of the 16th ACM International Symposium on Mobile Ad Hoc Networking and Computing* (2015)
63. N. Patwari, L. Brewer, Q. Tate, O. Kaltiokallio, M. Bocca, Breathfinding: a wireless network that monitors and locates breathing in a home. IEEE J. Sel. Top. Signal Process. **8**, 30–42 (2014). https://doi.org/10.1109/JSTSP.2013.2287473
64. A. Scidà, S. Haque, E. Treossi, A. Robinson, S. Smerzi, S. Ravesi, S. Borini, V. Palermo, Application of graphene-based flexible antennas in consumer electronic devices. Mater. Today **21**, 223–230 (2018). https://doi.org/10.1016/j.mattod.2018.01.007
65. N.K. Singh, Near-field communication (NFC). ITAL (2020). https://doi.org/10.6017/ital.v39i2.11811
66. E. Sutjiredjeki, N.C. Basjaruddin, D.N. Fajrin, F. Noor, Development of NFC and IoT-enabled measurement devices for improving health care delivery of indonesian children. J. Phys. **1450**, 012072 (2020). https://doi.org/10.1088/1742-6596/1450/1/012072
67. R. Lin, H.-J. Kim, S. Achavananthadith, Z. Xiong, J.K.W. Lee, Y.L. Kong, J.S. Ho, Digitally-embroidered liquid metal electronic textiles for wearable wireless systems. Nat. Commun. **13**, 2190 (2022). https://doi.org/10.1038/s41467-022-29859-4
68. M. Catrysse, R. Puers, C. Hertleer, L. Van Langenhove, H. Van Egmond, D. Matthys, Towards the integration of textile sensors in a wireless monitoring suit. Sens. Actuators A **114**, 302–311 (2004). https://doi.org/10.1016/j.sna.2003.10.071
69. L. Xu, X. Chen, S. Tan, Z. Hu, B. Ying, T.T. Ye, Y. Li, Characterization and modeling of embroidered NFC coil antennas for wearable applications. IEEE Sens. J. **20**, 14501–14513 (2020). https://doi.org/10.1109/JSEN.2020.3008594
70. L. Xu, Z. Liu, X. Chen, R. Sun, Z. Hu, Z. Zheng, T.T. Ye, Y. Li, Deformation-resilient embroidered near field communication antenna and energy harvesters for wearable applications. Adv. Intell. Syst. **1**, 1900056 (2019). https://doi.org/10.1002/aisy.201900056
71. W. Lee, S.Y. Baek, S.H. Kim, Deep-learning-aided RF fingerprinting for NFC security. IEEE Commun. Mag. **59**, 96–101 (2021). https://doi.org/10.1109/MCOM.001.2000912
72. Z.G. Prodanoff, E.L. Jones, H. Chi, S. Elfayoumy, C. Cummings, Survey of security challenges in NFC and RFID for E-health applications. Int. J. E-Health Med. Commun. **7**, 1–13 (2016). https://doi.org/10.4018/IJEHMC.2016040101
73. V. Karthik, T.R. Rao, SAR investigations on the exposure compliance of wearable wireless devices using infrared thermography. Bioelectromagnetics **39**, 451–459 (2018). https://doi.org/10.1002/bem.22133
74. K. Guido, A. Kiourti, Wireless wearables and implants: a dosimetry review. Bioelectromagnetics **41**, 3–20 (2020). https://doi.org/10.1002/bem.22240
75. J.R. Corea, A.M. Flynn, B. Lechêne, G. Scott, G.D. Reed, P.J. Shin, M. Lustig, A.C. Arias, Screen-printed flexible MRI receive coils. Nat. Commun. **7**, 10839 (2016). https://doi.org/10.1038/ncomms10839
76. D. Darnell, T. Truong, A.W. Song, Recent advances in radio-frequency coil technologies: flexible, wireless, and integrated coil arrays. Magn. Reson. Imaging **55**, 1026–1042 (2022). https://doi.org/10.1002/jmri.27865
77. M.A. Zahed, D.K. Kim, S.H. Jeong, M. Selim Reza, M. Sharifuzzaman, G.B. Pradhan, H. Song, M. Asaduzzaman, J.Y. Park, Microfluidic-integrated multimodal wearable hybrid patch for wireless and continuous physiological monitoring. ACS Sens. **8**, 2960–2974 (2023). https://doi.org/10.1021/acssensors.3c00148
78. A. Qayyum, I. Razzak, M. Tanveer, M. Mazher, B. Alhaqbani, High-density electroencephalography and speech signal based deep framework for clinical depression diagnosis. IEEE/ACM Trans. Comput. Biol. Bioinf. **20**, 2587–2597 (2023). https://doi.org/10.1109/TCBB.2023.3257175
79. J. Martinot, V. Cuthbert, N.N. Le-Dong, N. Coumans, D. De Marneffe, C. Letesson, J.L. Pépin, D. Gozal, Clinical validation of a mandibular movement signal based system for the diagnosis of pediatric sleep apnea. Pediatr. Pulmonol. **57**, 1904–1913 (2022). https://doi.org/10.1002/ppul.25320
80. M. Zhao, Y. Yang, Z. Guo, C. Shao, H. Sun, Y. Zhang, Y. Sun, Y. Liu, Y. Song, L. Zhang et al., A comparative proteomics analysis

of five body fluids: plasma, urine, cerebrospinal fluid, amniotic fluid, and saliva. Prot. Clin. Appl. **12**, 1800008 (2018). https://doi.org/10.1002/prca.201800008

81. B. Hu, X. Kang, S. Xu, J. Zhu, L. Yang, C. Jiang, Multiplex Chroma response wearable hydrogel patch: visual monitoring of urea in body fluids for health prognosis. Anal. Chem. **95**, 3587–3595 (2023). https://doi.org/10.1021/acs.analchem.2c03806
82. W. Ji, J. Zhu, W. Wu, N. Wang, J. Wang, J. Wu, Q. Wu, X. Wang, C. Yu, G. Wei et al., Wearable sweat biosensors refresh personalized health/medical diagnostics. Research (2021). https://doi.org/10.34133/2021/9757126
83. J.M. Tiffany, Tears in health and disease. Eye **17**, 923–926 (2003). https://doi.org/10.1038/sj.eye.6700566
84. M. Echavarria, N.S. Reyes, P.E. Rodriguez, C. Ricarte, M. Ypas, A. Seoane, M. Querci, M. Brizio, M.E. Stryjewski, G. Carballal, Saliva screening of health care workers for SARS-CoV-2 detection. Rev. Argent. Microbiol. **54**, 309–313 (2022). https://doi.org/10.1016/j.ram.2022.05.001
85. T. Yokota, P. Zalar, M. Kaltenbrunner, H. Jinno, N. Matsuhisa, H. Kitanosako, Y. Tachibana, W. Yukita, M. Koizumi, T. Someya, Ultraflexible organic photonic skin. Sci. Adv. **2**, e1501856 (2016). https://doi.org/10.1126/sciadv.1501856
86. J.E. Sinex, Pulse oximetry: principles and limitations. Am. J. Emerg. Med. **17**, 59–66 (1999). https://doi.org/10.1016/S0735-6757(99)90019-0
87. R.K. Pathinarupothi, P. Durga, E.S. Rangan, IoT-based smart edge for global health: remote monitoring with severity detection and alerts transmission. IEEE Internet Things J. **6**, 2449–2462 (2019). https://doi.org/10.1109/JIOT.2018.2870068
88. U. Gogate, J. Bakal, Healthcare monitoring system based on wireless sensor network for cardiac patients. Biomed. Pharmacol. J. **11**, 1681–1688 (2018). https://doi.org/10.13005/bpj/1537
89. M. Clarke, J. De Folter, V. Verma, H. Gokalp, Interoperable end-to-end remote patient monitoring platform based on IEEE 11073 PHD and ZigBee health care profile. IEEE Trans. Biomed. Eng. (2017). https://doi.org/10.1109/TBME.2017.2732501
90. The International Consortium for Blood Pressure Genome-Wide Association Studies, Genetic variants in novel pathways influence blood pressure and cardiovascular disease risk. Nature **478**, 103–109 (2011). https://doi.org/10.1038/nature10405.
91. M. Wetterholm, S.E. Bonn, C. Alexandrou, M. Löf, Y. Trolle Lagerros, Validation of two automatic blood pressure monitors with the ability to transfer data via bluetooth. J. Med. Internet Res. **21**, e12772 (2019). https://doi.org/10.2196/12772
92. Y.-S. Yan, Y.-T. Zhang, An efficient motion-resistant method for wearable pulse oximeter. IEEE Trans. Inform. Technol. Biomed. **12**, 399–405 (2008). https://doi.org/10.1109/TITB.2007.902173
93. J. Kim, P. Gutruf, A.M. Chiarelli, S.Y. Heo, K. Cho, Z. Xie, A. Banks, S. Han, K. Jang, J.W. Lee et al., Miniaturized battery-free wireless systems for wearable pulse oximetry. Adv. Funct. Mater. **27**, 1604373 (2017). https://doi.org/10.1002/adfm.201604373
94. A. Fanti, S. Casu, G. Mazzarella, A numerical estimation of a RFID reader field and SAR inside a blood bag at UHF. Electronics **5**, 77 (2016). https://doi.org/10.3390/electronics5040077
95. R. Davis, J. Gottschall, A. Gutierrez, C. Hohberger, D. Veeramani, J. Holcombe, Absence of acute adverse in-vitro effects on AS-1 RBCs and whole blood-derived platelets following prolonged exposure to 13.56 MHz radio energy: RF IMPACT ON RBCs and platelets. Transfusion **50**, 1596–1603 (2010). https://doi.org/10.1111/j.1537-2995.2010.02733.x
96. Y. Gai, E. Wang, M. Liu, L. Xie, Y. Bai, Y. Yang, J. Xue, X. Qu, Y. Xi, L. Li et al., A self-powered wearable sensor for continuous wireless sweat monitoring. Small Methods **6**, 2200653 (2022). https://doi.org/10.1002/smtd.202200653
97. Y. Song, J. Min, Y. Yu, H. Wang, Y. Yang, H. Zhang, W. Gao, Wireless battery-free wearable sweat sensor powered by human motion. Sci. Adv. **6**, eaay9842 (2020). https://doi.org/10.1126/sciadv.aay9842
98. D.P. Rose, M.E. Ratterman, D.K. Griffin, L. Hou, N. Kelley-Loughnane, R.R. Naik, J.A. Hagen, I. Papautsky, J.C. Heikenfeld, Adhesive RFID sensor patch for monitoring of sweat electrolytes. IEEE Trans. Biomed. Eng. **62**, 1457–1465 (2015). https://doi.org/10.1109/TBME.2014.2369991
99. M.-C. Desax, R.A. Ammann, J. Hammer, M.H. Schoeni, J. Barben, On behalf of the Swiss Paediatric Respiratory Research Group Nanoduct® sweat testing for rapid diagnosis in newborns, infants and children with cystic fibrosis. Eur. J. Pediatr. **167**, 299–304 (2008). https://doi.org/10.1007/s00431-007-0485-0
100. M. Bariya, H.Y.Y. Nyein, A. Javey, Wearable sweat sensors. Nat. Electron **1**, 160–171 (2018). https://doi.org/10.1038/s41928-018-0043-y
101. D.-H. Choi, A. Thaxton, I.C. Jeong, K. Kim, P.R. Sosnay, G.R. Cutting, P.C. Searson, Sweat test for cystic fibrosis: wearable sweat sensor vs. standard laboratory test. J. Cyst. Fibros. **17**, e35–e38 (2018). https://doi.org/10.1016/j.jcf.2018.03.005
102. W. Dang, L. Manjakkal, W.T. Navaraj, L. Lorenzelli, V. Vinciguerra, R. Dahiya, Stretchable wireless system for sweat pH monitoring. Biosens. Bioelectron. **107**, 192–202 (2018). https://doi.org/10.1016/j.bios.2018.02.025
103. G.M. Bianco, C. Occhiuzzi, N. Panunzio, G. Marrocco, A survey on radio frequency identification as a scalable technology to face pandemics. IEEE J. Radio Freq. Identif. **6**, 77–96 (2022). https://doi.org/10.1109/JRFID.2021.3117764
104. A.B. Barba, G.M. Bianco, L. Fiore, F. Arduini, G. Marrocco, C. Occhiuzzi, Design and manufacture of flexible epidermal NFC device for electrochemical sensing of sweat (2022).
105. P. Escobedo, C.E. Ramos-Lorente, A. Martínez-Olmos, M.A. Carvajal, M. Ortega-Muñoz, I.D. Orbe-Payá, F. Hernández-Mateo, F. Santoyo-González, L.F. Capitán-Vallvey, A.J. Palma et al., Wireless wearable wristband for continuous sweat pH monitoring. Sens. Actuators B **327**, 128948 (2021). https://doi.org/10.1016/j.snb.2020.128948
106. Y. Jiang, K. Pan, T. Leng, Z. Hu, Smart textile integrated wireless powered near field communication body temperature and sweat sensing system. IEEE J. Electromagn. RF Microw. Med. Biol. **4**, 164–170 (2020)
107. J.D. Lane, D.M. Krumholz, R.A. Sack, C. Morris, Tear glucose dynamics in diabetes mellitus. Curr. Eye Res. **31**, 895–901 (2006). https://doi.org/10.1080/02713680600976552
108. H. Yao, Y. Liao, A.R. Lingley, A. Afanasiev, I. Lähdesmäki, B.P. Otis, B.A. Parviz, A contact lens with integrated telecommunication circuit and sensors for wireless and continuous tear glucose monitoring. J. Micromech. Microeng. **22**, 075007 (2012). https://doi.org/10.1088/0960-1317/22/7/075007
109. H. Song, H. Shin, H. Seo, W. Park, B.J. Joo, J. Kim, J. Kim, H.K. Kim, J. Kim, J. Park, Wireless non-invasive monitoring of cholesterol using a smart contact lens. Adv. Sci. **9**, 2203597 (2022). https://doi.org/10.1002/advs.202203597
110. M. Aihara, N. Kubota, T. Minami, R. Shirakawa, Y. Sakurai, T. Hayashi, M. Iwamoto, I. Takamoto, T. Kubota, R. Suzuki et al., Association between tear and blood glucose concentrations: random intercept model adjusted with confounders in tear samples negative for occult blood. J. Diabetes Investig. **12**, 266–276 (2021). https://doi.org/10.1111/jdi.13344
111. Y.-R. Wang, H.-C. Chuang, A. Tripathi, Y.-L. Wang, M.-L. Ko, C.-C. Chuang, J.-C. Chen, High-sensitivity and trace-amount specimen electrochemical sensors for exploring the levels of β-amyloid in human blood and tears. Anal. Chem. **93**, 8099–8106 (2021). https://doi.org/10.1021/acs.analchem.0c04980

112. J.H. Han, Y.C. Cho, W.-G. Koh, Y.B. Choy, Preocular sensor system for concurrent monitoring of glucose levels and dry eye syndrome using tear fluids. PLoS ONE **15**, e0239317 (2020). https://doi.org/10.1371/journal.pone.0239317
113. K. Ogasawara, T. Tsuru, K. Mitsubayashi, I. Karube, Electrical conductivity of tear fluid in healthy persons and keratoconjunctivitis sicca patients measured by a flexible conductimetric sensor. Graefe's Arch. Clin. Exp. Ophthalmol. **234**, 542–546 (1996). https://doi.org/10.1007/BF00448797
114. L.R. Azevedo, A.A.S. De Lima, M.Â.N. Machado, A.M.T. Grégio, P.D.V. De Almeida, Saliva composition and functions: a comprehensive review. J. Contemp. Dent. Pract. **9**, 72–80 (2008). https://doi.org/10.5005/jcdp-9-3-72
115. I.T. Gug, M. Tertis, O. Hosu, C. Cristea, Salivary biomarkers detection: analytical and immunological methods overview. Trends Anal. Chem. **113**, 301–316 (2019). https://doi.org/10.1016/j.trac.2019.02.020
116. Z. Yan, Z. Shi, Y. Wu, J. Lv, P. Deng, G. Liu, Z. An, Z. Che, Y. Lu, J. Shan et al., Wireless, noninvasive therapeutic drug monitoring system for saliva measurement toward medication management of schizophrenia. Biosens. Bioelectron. **234**, 115363 (2023). https://doi.org/10.1016/j.bios.2023.115363
117. H. Park, W. Park, C.H. Lee, Electrochemically active materials and wearable biosensors for the in situ analysis of body fluids for human healthcare. NPG Asia Mater. **13**, 23 (2021). https://doi.org/10.1038/s41427-020-00280-x
118. P.R. Miller, R.M. Taylor, B.Q. Tran, G. Boyd, T. Glaros, V.H. Chavez, R. Krishnakumar, A. Sinha, K. Poorey, K.P. Williams et al., Extraction and biomolecular analysis of dermal interstitial fluid collected with hollow microneedles. Commun. Biol. **1**, 173 (2018). https://doi.org/10.1038/s42003-018-0170-z
119. C.-I. Kim, J.-H. Lee, The non-contact biometric identified bio signal measurement sensor and algorithms. THC **26**, 215–228 (2018). https://doi.org/10.3233/THC-174569
120. M. Scarsella, G. Barile, V. Stornelli, L. Safari, G. Ferri, A survey on current-mode interfaces for bio signals and sensors. Sensors **23**, 3194 (2023). https://doi.org/10.3390/s23063194
121. C. He, C.-R. Phang, T.-P. Jung, L.-W. Ko, Diversity and suitability of the state-of-the-art wearable and wireless EEG systems review. IEEE J. Biomed. Health Inform. 27 (2023).
122. W. He, Y. Zhao, H. Tang, C. Sun, W. Fu, A wireless BCI and BMI system for wearable robots. IEEE Trans. Syst. Man Cybern. Syst. **46**, 936–946 (2016). https://doi.org/10.1109/TSMC.2015.2506618
123. G. Niso, E. Romero, J.T. Moreau, A. Araujo, L.R. Krol, Wireless EEG: a survey of systems and studies. Neuroimage **269**, 119774 (2023). https://doi.org/10.1016/j.neuroimage.2022.119774
124. S.L. Eagleman, C.M. Drover, X. Li, M.B. MacIver, D.R. Drover, Offline comparison of processed electroencephalogram monitors for anaesthetic-induced electroencephalogram changes in older adults. Br. J. Anaesth. **126**, 975–984 (2021). https://doi.org/10.1016/j.bja.2020.12.042
125. K.K. MacKenzie, A.M. Britt-Spells, L.P. Sands, J.M. Leung, Processed electroencephalogram monitoring and postoperative delirium. Anesthesiology **129**, 417–427 (2018). https://doi.org/10.1097/ALN.0000000000002323
126. M. Chochoi, L. Tyvaert, P. Derambure, W. Szurhaj, Is long-term electroencephalogram more appropriate than standard electroencephalogram in the elderly? Clin. Neurophysiol. **128**, 270–274 (2017). https://doi.org/10.1016/j.clinph.2016.10.006
127. J. Wu, R. Srinivasan, E. Burke Quinlan, A. Solodkin, S.L. Small, S.C. Cramer, Utility of EEG measures of brain function in patients with acute stroke. J. Neurophysiol. **115**, 2399–2405 (2016). https://doi.org/10.1152/jn.00978.2015
128. A. Searle, L. Kirkup, A direct comparison of wet, dry and insulating bioelectric recording electrodes. Physiol. Meas. **21**, 271–283 (2000). https://doi.org/10.1088/0967-3334/21/2/307
129. R. Kaveh, J. Doong, A. Zhou, C. Schwendeman, K. Gopalan, F.L. Burghardt, A.C. Arias, M.M. Maharbiz, R. Muller, Wireless user-generic ear EEG. IEEE Trans. Biomed. Circuits Syst. **14**, 727–737 (2020). https://doi.org/10.1109/TBCAS.2020.3001265
130. K.S. Gangadharan, A.P. Vinod, Drowsiness detection using portable wireless EEG. Comput. Methods Programs Biomed. **214**, 106535 (2022)
131. H.-C. Seo, G.-W. Yoon, S. Joo, G.-B. Nam, Multiple electrocardiogram generator with single-lead electrocardiogram. Comput. Methods Programs Biomed. **221**, 106858 (2022). https://doi.org/10.1016/j.cmpb.2022.106858
132. Y. Xuan, H. Hara, S. Honda, Y. Li, Y. Fujita, T. Arie, S. Akita, K. Takei, Wireless, minimized, stretchable, and breathable electrocardiogram sensor system. Appl. Phys. Rev. **9**, 011425 (2022). https://doi.org/10.1063/5.0082863
133. A.J. Boe, L.L. McGee Koch, M.K. O'Brien, N. Shawen, J.A. Rogers, R.L. Lieber, K.J. Reid, P.C. Zee, A. Jayaraman, Automating sleep stage classification using wireless, wearable sensors. NPJ Digit. Med. **2**, 131 (2019). https://doi.org/10.1038/s41746-019-0210-1
134. L. Xie, Z. Li, Y. Zhou, Y. He, J. Zhu, Computational diagnostic techniques for electrocardiogram signal analysis. Sensors **20**, 6318 (2020). https://doi.org/10.3390/s20216318
135. J.-C. Heo, J. Park, S. Kim, J. Ku, J.-H. Lee, Development and application of wireless power transmission systems for wireless ECG sensors. Journal of Sensors **2018**, 1–7 (2018). https://doi.org/10.1155/2018/5831056
136. N. Rodeheaver, H. Kim, R. Herbert, H. Seo, W.-H. Yeo, Breathable, wireless, thin-film wearable biopatch using noise-reduction mechanisms. ACS Appl. Electron. Mater. **4**, 503–512 (2022). https://doi.org/10.1021/acsaelm.1c01107
137. J.-H. Lee, D.-W. Seo, Development of ECG monitoring system and implantable device with wireless charging. Micromachines **10**, 38 (2019). https://doi.org/10.3390/mi10010038
138. J. Wannenburg, R. Malekian, G.P. Hancke, Wireless capacitive-based ECG sensing for feature extraction and mobile health monitoring. IEEE Sens. J. **18**, 6023–6032 (2018). https://doi.org/10.1109/JSEN.2018.2844122
139. N. Dey, A.S. Ashour, F. Shi, S.J. Fong, R.S. Sherratt, Developing residential wireless sensor networks for ECG healthcare monitoring. IEEE Trans. Consum. Electron. **63**, 442–449 (2017). https://doi.org/10.1109/TCE.2017.015063
140. H. Kim, Y. Kwon, C. Zhu, F. Wu, S. Kwon, W. Yeo, H.J. Choo, Real-time functional assay of volumetric muscle loss injured mouse masseter muscles via nanomembrane electronics. Advanced Science **8**, 2101037 (2021). https://doi.org/10.1002/advs.202101037
141. Z.O. Khokhar, Z.G. Xiao, C. Menon, Surface EMG pattern recognition for real-time control of a wrist exoskeleton. BioMed Eng OnLine **9**, 41 (2010). https://doi.org/10.1186/1475-925X-9-41
142. C. Castellini, P. Van Der Smagt, Surface EMG in advanced hand prosthetics. Biol. Cybern. **100**, 35–47 (2009). https://doi.org/10.1007/s00422-008-0278-1
143. S. Lee, J. Yoon, D. Lee, D. Seong, S. Lee, M. Jang, J. Choi, K.J. Yu, J. Kim, S. Lee et al., Wireless epidermal electromyogram sensing system. Electronics **9**, 269 (2020). https://doi.org/10.3390/electronics9020269
144. Y. Fukuoka, K. Miyazawa, H. Mori, M. Miyagi, M. Nishida, Y. Horiuchi, A. Ichikawa, H. Hoshino, M. Noshiro, A. Ueno, Development of a compact wireless Laplacian electrode module for electromyograms and its human interface applications. Sensors **13**, 2368–2383 (2013). https://doi.org/10.3390/s130202368

145. K. Lee, Y.Y. Choi, D.J. Kim, H.Y. Chae, K. Park, Y.M. Oh, S.H. Woo, J.J. Kim, A wireless ExG interface for patch-type ECG holter and EMG-controlled robot hand. Sensors **2017**, 17 (1888). https://doi.org/10.3390/s17081888
146. Y.-H. Yang, S.-J. Ruan, P.-C. Chen, Y.-T. Liu, Y.-H. Hsueh, A low-cost wireless multichannel surface EMG acquisition system. IEEE Consumer Electron. Mag. **9**, 14–19 (2020). https://doi.org/10.1109/MCE.2020.2986792
147. B. Shi, Wearable exercise monitoring equipment for physical exercise teaching process based on wireless sensor. Microprocess. Microsyst. **81**, 103791 (2021). https://doi.org/10.1016/j.micpro.2020.103791
148. V. Galli, S.K. Sailapu, T.J. Cuthbert, C. Ahmadizadeh, B.C. Hannigan, C. Menon, Passive and wireless all-textile wearable sensor system. Adv. Sci. (2023). https://doi.org/10.1002/advs.202206665
149. F.J. He, M. Tan, J. Song, G.A. MacGregor, Salt substitution to lower population blood pressure. Nat. Med. **26**, 313–314 (2020). https://doi.org/10.1038/s41591-020-0784-9
150. R. Aggarwal, V. Gunaseelan, D. Manual, M. Sanker, S. Prabaaker, Clinical evaluation of a wireless device for monitoring vitals in newborn babies. Indian J. Pediatr. (2023). https://doi.org/10.1007/s12098-022-04459-8
151. A. Chen, J. Zhang, L. Zhao, R.D. Rhoades, D.-Y. Kim, N. Wu, J. Liang, J. Chae, Machine-learning enabled wireless wearable sensors to study individuality of respiratory behaviors. Biosens. Bioelectron. **173**, 112799 (2021). https://doi.org/10.1016/j.bios.2020.112799
152. A. Chen, A.J. Halton, R.D. Rhoades, J.C. Booth, X. Shi, X. Bu, N. Wu, J. Chae, Wireless wearable ultrasound sensor on a paper substrate to characterize respiratory behavior. ACS Sens. **4**, 944–952 (2019). https://doi.org/10.1021/acssensors.9b00043
153. T. Elfaramawy, C.L. Fall, S. Arab, M. Morissette, F. Lellouche, B. Gosselin, A wireless respiratory monitoring system using a wearable patch sensor network. IEEE Sens. J. **19**, 650–657 (2019). https://doi.org/10.1109/JSEN.2018.2877617
154. H.-K. Wu, Y.-S. Ko, Y.-S. Lin, H.-T. Wu, T.-H. Tsai, H.-H. Chang, The correlation between pulse diagnosis and constitution identification in traditional Chinese medicine. Complement. Ther. Med. **30**, 107–112 (2017). https://doi.org/10.1016/j.ctim.2016.12.005
155. N.G.R. De Moura, I. Cordovil, A. De Sa Ferreira, Traditional Chinese medicine wrist pulse-taking is associated with pulse waveform analysis and hemodynamics in hypertension. J. Integr. Med. **14**, 100–113 (2016). https://doi.org/10.1016/S2095-4964(16)60233-9
156. J.-H. Zhang, Z. Li, J. Xu, J. Li, K. Yan, W. Cheng, M. Xin, T. Zhu, J. Du, S. Chen et al., Versatile self-assembled electrospun micropyramid arrays for high-performance on-skin devices with minimal sensory interference. Nat. Commun. **13**, 5839 (2022). https://doi.org/10.1038/s41467-022-33454-y
157. S. Min, D.H. Kim, D.J. Joe, B.W. Kim, Y.H. Jung, J.H. Lee, B. Lee, I. Doh, J. An, Y. Youn et al., Clinical validation of wearable piezoelectric blood pressure sensor for continuous health monitoring. Adv. Mater. (2023). https://doi.org/10.1002/adma.202301627
158. W. Liao, J. Shi, J. Wang, Electromagnetic interference of wireless power transfer system on wearable electrocardiogram. IET Microw. Antennas Propag. **11**, 330–335 (2017). https://doi.org/10.1049/iet-map.2016.0119
159. T. Wang, X. Liu, N. Jin, H. Tang, X. Yang, M. Ali, Wireless power transfer for battery powering system. Electronics **7**, 178 (2018). https://doi.org/10.3390/electronics7090178
160. S.S. Hassan, S.D. Bibon, M.S. Hossain, M. Atiquzzaman, Security threats in bluetooth technology. Comput. Secur. **74**, 308–322 (2018). https://doi.org/10.1016/j.cose.2017.03.008
161. H. Nesser, H.A. Mahmoud, G. Lubineau, High-sensitivity RFID sensor for structural health monitoring. Adv. Sci. (2023). https://doi.org/10.1002/advs.202301807
162. A. Lazaro, M. Boada, R. Villarino, D. Girbau, Color measurement and analysis of fruit with a battery-less NFC sensor. Sensors **19**, 1741 (2019). https://doi.org/10.3390/s19071741
163. M. El Khamlichi, A. Alvarez Melcon, O. El Mrabet, M.A. Ennasar, J. Hinojosa, Flexible UHF RFID tag for blood tubes monitoring. Sensors **19**, 4903 (2019). https://doi.org/10.3390/s19224903
164. C. He, R.K. Chikara, C.-L. Yeh, L.-W. Ko, Neural dynamics of target detection via wireless EEG in embodied cognition. Sensors **21**, 5213 (2021). https://doi.org/10.3390/s21155213
165. R. Chai, G.R. Naik, S.H. Ling, H.T. Nguyen, Hybrid brain-computer interface for biomedical cyber-physical system application using wireless embedded EEG systems. BioMed. Eng. OnLine **16**, 5 (2017). https://doi.org/10.1186/s12938-016-0303-x
166. T. Vuorinen, K. Noponen, A. Vehkaoja, T. Onnia, E. Laakso, S. Leppänen, K. Mansikkamäki, T. Seppänen, M. Mäntysalo, Validation of printed, skin-mounted multilead electrode for ECG measurements. Adv Mater. Technol. **4**, 1900246 (2019). https://doi.org/10.1002/admt.201900246
167. L.-H. Wang, W. Zhang, M.-H. Guan, S.-Y. Jiang, M.-H. Fan, P.A.R. Abu, C.-A. Chen, S.-L. Chen, A low-power high-data-transmission multi-lead ECG acquisition sensor system. Sensors **19**, 4996 (2019). https://doi.org/10.3390/s19224996
168. M.-S. Song, S.-G. Kang, K.-T. Lee, J. Kim, Wireless, skin-mountable EMG sensor for human-machine interface application. Micromachines **10**, 879 (2019). https://doi.org/10.3390/mi10120879
169. X. Chen, Z.J. Wang, Pattern recognition of number gestures based on a wireless surface EMG system. Biomed. Signal Process. Control **8**, 184–192 (2013). https://doi.org/10.1016/j.bspc.2012.08.005
170. G. Biagetti, P. Crippa, L. Falaschetti, A. Mansour, C. Turchetti, Energy and performance analysis of lossless compression algorithms for wireless EMG sensors. Sensors **21**, 5160 (2021). https://doi.org/10.3390/s21155160
171. Y. Feng, E. Benassi, L. Zhang, X. Li, D. Wang, F. Zhou, W. Liu, Concealed wireless warning sensor based on triboelectrification and human-plant interactive induction. Research (2021). https://doi.org/10.34133/2021/9870936