Chapter 10
The Flexible and Wearable Pressure Sensing Microsystems for Medical Diagnostics

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10.1 Introduction

In recent years, with the advancement in science and technology, a great number of new applications have appeared in many domains. For instance, artificial intelligence (Shi et al. 2020a, b; Dong et al. 2020; Wang 2020) and smart electronics (Kaichen et al. 2019; Ding et al. 2019; Liang et al. 2020; Tao et al. 2017) have changed the world a lot and have improved the living conditions of human beings in many ways. Particularly in the healthcare monitoring field, it provides equipment foundation for cardiovascular disease and diabetes (Chung et al. 2019; Meng et al. 2019; Park et al. 2017; Yang et al. 2017; Schüssler-Fiorenza Rose et al. 2019). The life expectancy will increase since people's living conditions have improved. In the future, wearable electronic equipment will have a great market prospect. As one of the core components, sensor will affect the functional design and the development of wearable devices in the future. Flexible wearable electronics are often used in human-machine interaction interface (Tang et al. 2021), electronic skin (e-skin) (Zhang et al. 2019), wearable healthcare monitoring devices, etc. The flexible electronics can withstand compression, pulling, twisting, and distortion, compared with traditional rigid silicon-based electronics. In recent years, with the rapid development of new material synthesis and processing technology, it also provides the foundation for flexible pressure sensors. The flexible pressure sensors have become one of the most concerned electronic sensors because of their certain characteristics such as high sensitivity, low cost, low weight, portability, outstanding flexibility, high tensile strength, and high integration (Wan et al. 2017).

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Wearable sensors which are used in medical detection can play an important role in people's daily life. It is well-known that the surface of the human skin is irregular and complex. With the advantages of fast response, portability, and wearability, the flexible pressure sensor has a great potential in continuous vital sign monitoring. Traditional centralized healthcare services require patients to travel to hospitals, which means that the patients' needs may not be addressed in time, especially for individuals who require emergency treatment. Flexible sensing electronics will transform traditional diagnostic methods, by giving a portable, wearable, real-time characteristic for medical diagnosis. Moreover, flexible sensors can measure physiological abnormalities in real time for early detection, which could provide a safer and more comfortable way to protect human health. Flexible pressure sensors can be attached to the human body to capture different physiological parameters such as blood pressure (Wang et al. 2017), heart rate (Shin et al. 2016), breath detection (Ghosh et al. 2021), and pulse rate (Kim et al. 2019a). Various internal pressures such as intracranial pressure (Wang et al. 2019a) and intraocular pressure (Zou et al. 2019) are important health indicators and can also be measured by flexible pressure sensors (Shin et al. 2019). In addition, some new wearable devices, for instance, gait analysis (Song et al. 2018), tactile perception (Xiong et al. 2020), and voice recognition (Wang et al. 2019b), are widely used in medical diagnostics. Figure 10.1 shows some flexible pressure sensors with the above applications.

In the last few years, by attaching sensors to a patient's arm, leg, or other organs for continuous monitoring, wearable pressure sensors have become a popular medical aid. Especially for elderly patients with low physical strength and immunity, the pressure sensor can respond quickly in emergency situations. Based on the feedback of pressure sensor, we can know our body's state in real time and make adjustments to let our lives become healthier. Therefore, research on flexible pressure sensors used in medical diagnostic is meaningful for the development of sensor technology. We summarize in this review the latest development of flexible pressure sensors for medical healthcare applications. In Sect. 10.2, we introduce the commonly used materials in fabrication. In Sect. 10.3, we review the transduction mechanisms of sensor and analyzed the property of the pressure sensor, for instance, sensitivity, power consumption, and linearity. In Sect. 10.4, we mainly focus on the recent progress in medical diagnostics applications. Conclusion and future perspectives are described in the final section.

10.2 Materials

The difference between a flexible sensor and a traditional sensor is that it has a certain degree of plasticity on the basis of realizing the function of the traditional sensor to adapt to irregular surfaces and can withstand deformations, such as contraction, extrusion, bending, and torsion. The materials commonly used in traditional sensors are silicon semiconductor materials (Jayathilaka et al. 2019; Jeon et al. 2019; Li et al. 2020a), metal oxides, and other rigid materials (Jayathilaka et al. 2019; Yang

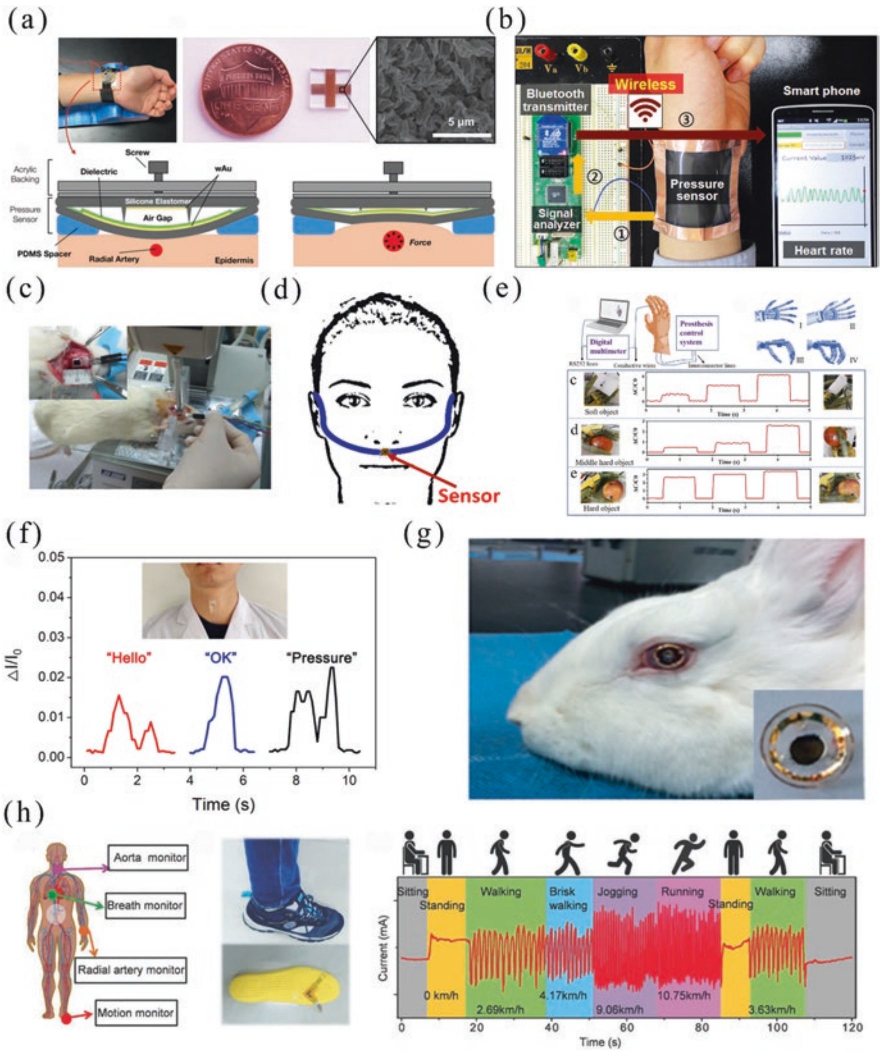

Fig. 10.1 (**a**) Image of how the pressure sensor is attached to the wrist. Photograph image of the parallel wAu electrodes (Kim et al. 2019a). (**b**) Photograph of wearable and wireless pressure sensor for heart rate monitoring (Shin et al. 2016). (**c**) Real-time photograph of intracranial surgery of a rat with the fabricated PEDOT:PSS/GO pressure sensor. R−P curve of the fabricated pressure sensor on the rat's brain surface without creating any major damage (Wang et al. 2019a). (**d**) Schematic of breath detection, indicating the sensor's placement on the philtrum (Ghosh et al. 2021). (**e**) Real-time monitoring of robotic hand grabbing objects (Xiong et al. 2020). (**f**) Relative current change of Ti3C2/NMC flexible sensor in terms of various sound stimuli, such as "hello," "Ok," and "pressure" (Wang et al. 2019b). (**g**) Intraocular biosensor made from GC−COOH worn on a rabbit's cornea. The inset shows the working side of the intraocular biosensor (Zou et al. 2019). (**h**) Schematic illustration of the pressure sensor for monitoring human vital signs, and real-time recording of the whole motion process, including sitting, standing, walking, brisk walking, jogging, and running (Song et al. 2018)

et al. 2019). These materials have poor plasticity, which is likely to cause irreversible damage during the application process if used in large deformation scene or irregular object surface. For the sensor, to endow deformable properties, flexible materials are required. After years of research, people have made outstanding achievements in the field of flexible sensors and have a relatively complete understanding of flexible sensors. In order to create a flexible wearable sensor with good sensing capabilities, the option of appropriate material is very vital. Here, we summarized some of the most commonly used functional materials, for instance, substrate materials and active materials.

10.2.1 Substrate Materials

The substrate material constitutes the base part of the flexible sensor, and the deformability of the flexible sensor is mainly determined by it. To meet the deformability requirements of a flexible sensor, the substrate material needs to have the characteristics of high flexibility and high ductility. In some special cases, the substrate material is also required to have other characteristics, such as water resistance, heat resistance, and biocompatibility, to allow the sensor to work normally under severe conditions. Many commercially available polymers and elastomers including polydimethylsiloxane (PDMS), polyimide (PI), polyethylene (PEN), polyethylene terephthalate (PET), and polyurethane (PU) can serve as substrates for flexible and stretchable electronics (Li et al. 2020a; Tan et al. 2022). PDMS, a product widely used in the market, is a silicon rubber with a low Young's modulus that can be prepared with readily accessible laboratory techniques (YuHao and JunPing 2022; Kang et al. 2021). The intrinsic flexibility and extensibility of PDMS make corresponding devices respond readily to torsion and compressive and tensile strain (Li et al. 2017a, 2019a; Wang et al. 2019c; Gong et al. 2021; Shi et al. 2018). Furthermore, the extensibility of PDMS can be improved by geometric structuring such as the formation of nets and bucking structures to meet the requirements of applications for coplanar devices (Mao et al. 2019). It should also be noted that PDMS possesses many other advantages such as high transparency and excellent stability over a large temperature range. These advantages broaden its applicability as a large-area substrate for transparent electronics and thermally stable devices (Rajitha and Dash 2018; Hwang et al. 2021; Mengdi et al. 2018).

PI has excellent stability, insulating property, and mechanical performance. This material can sustain a large temperature range, from −100 to 300 °C, without obvious property changes (Xiaohe et al. 2020; Xiaoyu Chen et al. 2019). It is also invulnerable to corrosion by commonly used chemical solvents, which is vital in the subsequent device process steps. Furthermore, even ultrathin PI films are not damaged by high mechanical forces, and its excellent bending stability makes it a suitable candidate for compliant devices (Kwak et al. 2017; Liu et al. 2020). A very thin catheter was thus prepared for measuring the spatial distribution of pressure, demonstrating its potential application in medical diagnosis (Cui et al. 2019; Fan et al. 2019; Bi et al. 2019).

PET has a good mechanical property, excellent tensile strength and creep resistance, good electrical insulation performance, and little influence by temperature. PEN's excellent performance is mainly reflected in its relatively high heat resistance, with a glass transition temperature of 113 °C, higher than PET which is 65 °C. The physical and mechanical properties of PEN are also better than PET, and it can be widely used in fabrication of sensors. For instance, an ultralightweight plastic electronic device (3 g cm^{-2}) has been produced with an ultrathin PEN foil 1 um thick that can withstand repeated bending to a 5 mm radius and paperlike crumpling (Rui et al. 2019; Zhao et al. 2017; Lin et al. 2019; Yuan et al. 2017; Lamanna et al. 2019; Lee et al. 2019; Wang et al. 2018a). By combining pressure-sensitive rubbers with organic field-effect transistors (OFETs) on a PEN substrate, pressure-sensing matrices have been produced and demonstrated their encouraging potentials in e-skin (Shuaidi Zhang et al. 2019; Gao et al. 2019a, 2020; Cai et al. 2017; Seyedin et al. 2020; Ma et al. 2018).

10.2.2 Active Materials

The active material is the core part of the flexible sensor. Its physical properties change under the action of pressure, usually involving changes in the resistance, piezoelectricity and capacitance. It achieves the function of converting pressure signals into electrical signals on this basis. Commonly used active materials for making flexible sensors include carbon nanotubes (CNTs), which have well-charge carrier mobility, steady chemical property, and excellent elasticity. For example, benefiting from these material properties, as shown in Fig. 10.2a, Qin et al. presented a pressure sensor by integrating hydrophobic CNTs into hydrophobically associated polyacrylamide hydrogel and exhibited high linear sensitivity (0.127 kPa^{-1}) in a large-pressure region within 0–50 kPa (Qin et al. 2020). Graphene (GR) has lots of carrier mobility, good mechanical performance, great light transmittance, chemical stability, thermal conductivity, and low-cost mass-production potential (Xiaoyu Chen et al. 2019; He et al. 2019a; Cai et al. 2018; Li et al. 2018, 2021). Based on its good electrical conductivity, intrinsic and structural flexibility, high chemical and thermal stability, etc., He et al. presented and developed a novel material design strategy to fabricate a self-assembled graphene sensing film, in which the conductivity and thickness can be well balanced (Fig. 10.2c). The sensor showed high sensitivity (1875.53 kPa^{-1}) and wide linear detection range (0–40 kPa) (He et al. 2019b). Metal materials and their nanowires, such as silver nanowires (AgNWs) and gold films, have excellent conductivity, light transmittance, flexibility, and stability. Chu et al. reported a sensing system based on a fluorinated ethylene propylene (FEP)/Ecoflex/FEP/Au sandwich-structured piezoelectret for piezoelectric-like detections and showed high precision and stability (Fig. 10.2b) (Chu et al. 2018). As shown in Fig. 10.2e, the pressure sensor was based on Au/

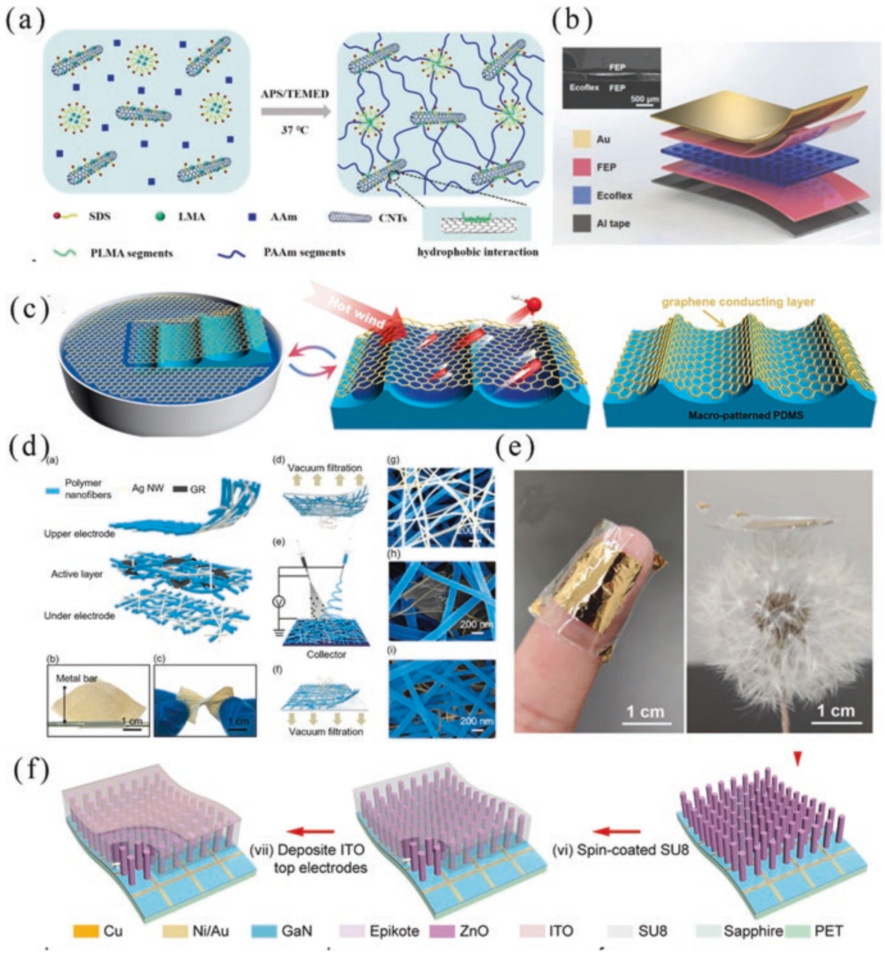

Fig. 10.2 (**a**) Schematic illustration of the preparation process for the CNTs/HAPAAm hydrogel (Qin et al. 2020). (**b**) Schematic diagram of the pulse sensing device using the FEP/Ecoflex/FEP sandwich-structured piezoelectret film (Chu et al. 2018). (**c**) Schematic of the fabrication process of PDMS-Gr (He et al. 2019b). (**d**) Structure and fabrication process of the AgNWs/GR/PANF pressure sensor (Li et al. 2020b). (**e**) Photo of a sensor surrounding a finger depicting its super flexibility, and photo illustrating the super lightness of the sensor (Zhong et al. 2022). (**f**) Schematic diagram of the device fabrication consisting of GaN LLO process and the synthesis of ZnO nanowire array (Peng et al. 2019)

parylene/Teflon AF films, and a sensor surrounding a finger depicting its super flexibility (Zhong et al. 2022). Li et al. presented a piezoresistive sensor based on hierarchical nanonetwork structured pressure sensitive material, including AgNWs, GR, and polyamide nanofibers (PANFs), and showed the sensitivity of 134 kPa^{-1} (0–1.5 kPa) (Fig. 10.2d) (Li et al. 2020b). And common piezoelectric materials such as ZnO have excellent optical properties, good reliability, and excellent stability and are environment friendly. Based on its properties, Peng et al. presented a pressure sensor, composed of a GaN/ZnO nanowire heterostructure light-emitting diode (LED), which can be enhanced by the local compressive strain based on piezo-phototronic effect (Fig. 10.2f) (Peng et al. 2019). Active materials with excellent performance are the most important component for the stable and accurate operation of sensors. Developing better materials and optimizing the performance of active materials is the key to our research on flexible sensors.

10.3 Fundamentals of Pressure Sensors

Firstly, in order to better understand the overall sensing equipment, we first outlined the basic principles of pressure sensors here. Next, we will discuss the conduction mechanism and key parameters of the pressure sensor in detail.

10.3.1 Sensing Mechanisms

When a force is applied to a sensor, the physical properties of the sensor can change. Changes in different physical properties correspond to different working principles of the sensor. According to the sensing principle, sensors can be classified into the following categories: piezoresistive, capacitive, piezoelectric, and triboelectric. Different working principles also have different working characteristics and structural characteristics. Here, a brief introduction and schematic illustrations of four typical transduction mechanisms are provided.

10.3.1.1 Piezoresistivity

A piezoresistive sensor exhibits resistance changes under pressure. A piezoresistive sensor has the characteristics of high sensitivity, big measurement range, long lifetime, simple construction, and easy manufacturing and realization of subminiaturization and integration, but the resistance is easily affected by the environment, especially temperature, and this nonlinear error under large strain is obvious. It is not suitable for working in temperature-unstable environment. The resistance of a piezoresistive pressure sensor is usually determined by its material, shape, temperature, and other elements. The resistivity is usually determined by the material of the resistor. It is also affected by temperature. We can change the resistance by changing the resistance length or the cross-sectional area. As shown in Fig. 10.3a, Yang et al. designed a hierarchically microstructure-bioinspired flexible piezoresistive sensor consisting of a hierarchical polyaniline/polyvinylidene fluoride nanofiber (HPPNF) film sandwiched between two interlocking electrodes with microdome structure. The sensor exhibited an ultrahigh sensitivity of 53 kPa^{-1}, a pressure detection range from 58.4 to 960 Pa, and excellent cycle stability over 50,000 cycles (Yang et al. 2021).

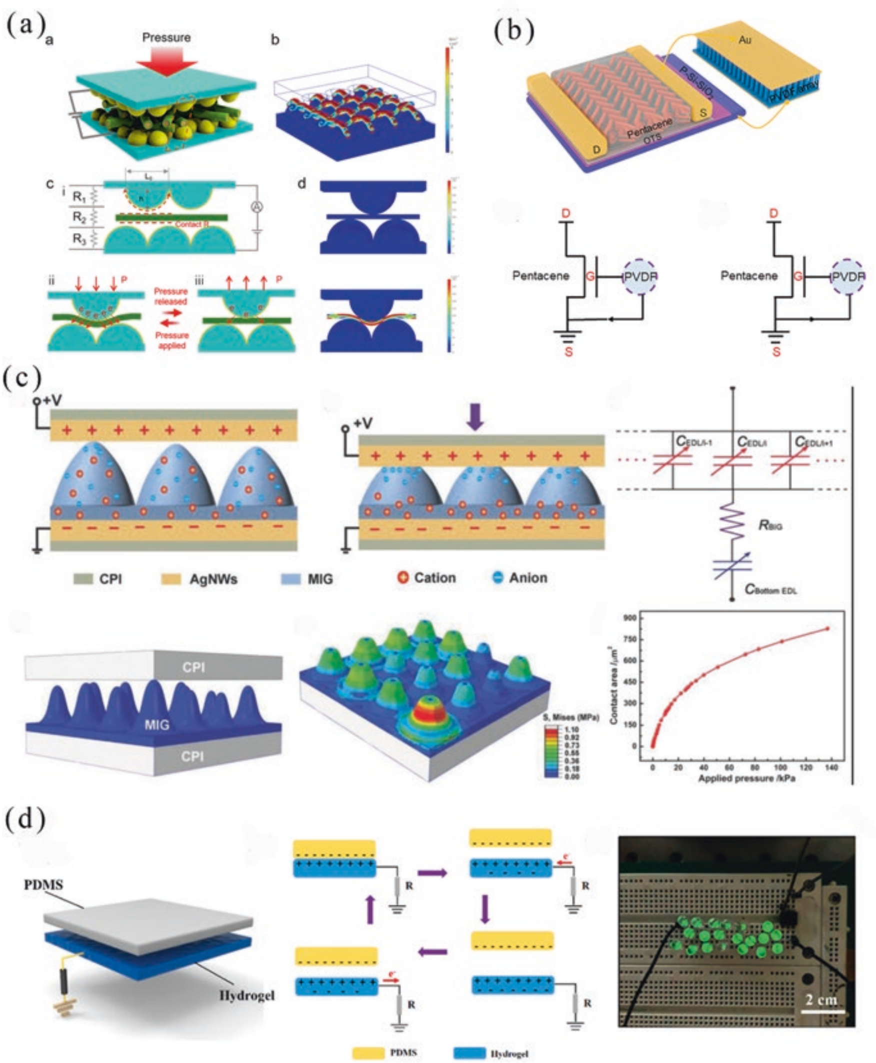

Fig. 10.3 (**a**) Schematic of flexible piezoresistive sensor under the normal pressure. And simulation results of the stress distribution of the flexible sensor under an applied pressure using the COMSOL software (Yang et al. 2021). (**b**) Working mechanism of the pentacene piezoelectric transistor (Wang et al. 2020). (**c**) Graphical explanation of the sandwiched structure and charge distribution in the capacitive sensor (Qiu et al. 2018). (**d**) Working principle of the triboelectric nanogenerators (He et al. 2020)

10.3.1.2 Capacitance

Capacitive sensors can convert perceived pressure changes into changes in capacitance, and changes in capacitance can also directly cause changes in electrical signals. A capacitive sensor has the performance of a simple structure, high sensitivity, less temperature effect, low power dissipation, and short dynamic response time. It can work under high-frequency conditions and is especially suitable for dynamic measurement. However, the capacitive sensor is highly susceptible to parasitic influence and electromagnetic interference. Therefore, it is not suitable for working in strong electric and magnetic fields. The definition formula of the capacitance is $= \varepsilon S/4\pi kd$, where ε is the relative permittivity, k is the electrostatic force constant, S is the overlapping area of the two panels, and d is the distance between the two panels. The capacitance is mainly affected by the area of the plates, the distance between the plates, and the insulating medium between the two plates. The change of the distance between the plates and the material composition will lead to the increase or decrease of capacitance value. We can also detect shear stress by changing the overlap area of the capacitor plates. As shown in Fig. 10.3c, Qiu et al. presented a low-cost microstructured ionic gel (MIG) with uniform cone-like surface microstructures for high-performance capacitive e-skins. The device exhibited a low limit of detection down to 0.1 Pa, a ultrahigh sensitivity of 54.31 kPa^{-1} in the low-pressure regime (<0.5 kPa), and a sensitivity that is kept larger than 1 kPa^{-1} over a broad-range pressure from 0.1 Pa to 115 kPa (Qiu et al. 2018).

10.3.1.3 Piezoelectricity

The physical basis of a piezoelectric sensor is the piezoelectric effect. The piezoelectric effect refers to some dielectric being deformed by the action of an external force along a certain direction, and a polarization phenomenon will occur inside it. Opposite positive and negative charges appear on its opposite surfaces at the same time. As the outer force is removed, the dielectric will return to an uncharged state. The commonly used piezoelectric materials include the following: ZnS, ZnO, and CaS with semiconductive and piezoelectric properties, as well as polyvinyl fluoride, nylon, polyvinylidene fluoride (PVDF), etc. The advantage of a piezoelectric pressure sensor is that it has a self-generated signal, large output signal, high-frequency response, and small size. The disadvantage is that it can only be used for dynamic measurement, and because the amount of charge of the piezoelectric material is fixed, special attention should be given to avoiding leakage when connecting it. In addition, when it is subjected to sudden vibrations or excessive pressure, self-recovery is slower. As shown in Fig. 10.3b, Wang et al. constructed a high-performance, energy-efficient, and fully flexible piezoelectric tactile sensor based on piezoelectric effect. The sensor exhibited excellent pressure sensitivity, detection limit, and response time of 5.17 kPa^{-1}, 175 Pa, and 150 ms, respectively (Wang et al. 2020).

10.3.1.4 Triboelectricity

The operating principle of a TES (triboelectric sensor) is the triboelectric effect. After two different objects are rubbed together, electrons are transferred from one object to the other such that the two different objects are charged. The polarity and strength of the charge generated in the process vary depending on the material, surface roughness, temperature, and other elements. Triboelectric sensors are usually made of two different materials. Selecting suitable materials and increasing the contact area between the two films are effective methods for enhancing the performance of flexible TES. Piezoelectric sensors and TES have self-powered characteristics, which provide a basis for the development of self-powered sensor system. But the output of the TES usually contains noncontinuous pulses with irregular magnitude. On the other hand, the relatively high voltage output and low current output greatly hinder the TES for practical applications. So, it is targeted to harvest "random" and possibly low-frequency mechanical signals. He et al. presented a pressure sensor, designed by proportionally mixing silk fibroin, polyacrylamide, graphene oxide, and poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate). The assembled sensor exhibited a wide sensing range (strain, 2–600%; pressure, 0.5–119.4 kPa) and reliable stability (Fig. 10.3d) (He et al. 2020).

10.3.2 Key Parameters of Pressure Sensor

Pressure sensors can convert the applied force into an electrical signal or other signal output. To estimate the property of pressure sensors, we need to evaluate key parameters such as the sensitivity, detection limit, response time, and durability.

10.3.2.1 Sensitivity

Sensitivity, which is commonly defined as the magnitude of electrical response upon pressure stimuli, is the most important parameter that can determine the measuring effect and accuracy of the pressure sensor. In general, the pressure sensor sensitivity is defined as $S = dX/dP$, where S represents the sensitivity, X represents the quantitative output signals, and P is the imposed external pressure. Various strategies have been reported to enhance the sensitivity of pressure sensors. Herein, we presented two typical optimization ways, which may be useful for the design and production of highly sensitive pressure sensors.

We may improve the sensitivity of sensors by choosing better active materials. In the above, we briefly introduced some common active materials used for fabrication of sensors; herein, we will further introduce the effect of these active materials for sensor's sensitivity. For example, as for the piezoresistive pressure sensors, Gao et al. used silver nanowires (AgNWs) as active material and a nanocellulose paper (NCP) as a bottom substrate, which showed a high sensitivity of 1.5 kPa^{-1} in the range of 0.03–30.2 kPa and retained excellent performance in the bending state (Gao et al. 2019b). As for the capacitive pressure sensors, Li et al. reported a novel capacitive flexible pressure sensor by using silver nanowire (AgNWs)-paper substrates as electrodes and polydimethylsiloxane (PDMS) as dielectrics, which showed dynamic ranges of the as-prepared sensor of 1.05 kPa^{-1} and 1 Pa to 2 kPa, respectively (Li et al. 2019a). As for the piezoelectric pressure sensor, Chen et al. reported a pressure sensor for static measurements and nanowires/graphene as active materials, based on the synergistic mechanisms between strain-induced polarization charges in piezoelectric nanowires and the caused change of carrier scattering in graphene. Compared to the conventional piezoelectric nanowire or graphene pressure sensors, this sensor is capable of measuring static pressures with a sensitivity up to 9.4×10^{-3} kPa^{-1} (Chen et al. 2017). As for the triboelectric pressure sensor, Ning et al. reported a pressure sensor by using AgNWs/CNT as active materials and PDMS as the substrate materials, which can reach 3.627 kPa^{-1} in the pressure range of 0–8 kPa and still keep 1.264 kPa^{-1} in the range of 8–80 kPa (Ning et al. 2020).

Another approach to realize high sensitivity relies on the utilization of micro- and nanostructures such as multilevel structure (Tang et al. 2019), pyramid structure (Li et al. 2020c), patterned structure (Shi et al. 2018), porous structures (Mahanty et al. 2017), and microdome structure (Park et al. 2018a). For example, Tang et al. reported a pressure sensor by combining a sandpaper-molded multilevel microstructured PDMS and a reduced oxide graphene film, which showed an ultrahigh sensitivity (2.5–1051 kPa^{-1}) (Tang et al. 2019). Li et al. reported a sensor by adding elastic pyramidal microstructures on one side of the electrode, and the sensitivity of the proposed device has been improved from 3.1 to 70.6 kPa^{-1} compared to no microstructure of sensor (Li et al. 2020c). Shi et al. fabricated a flexible transparent capacitive pressure sensor based on patterned microstructured silver nanowires (AgNWs)/polydimethylsiloxane (PDMS) composite dielectrics. Compared with the pure PDMS dielectric layer with planar structures, the patterned microstructured sensor exhibits a higher sensitivity (0.831 kPa^{-1}, <0.5 kPa) (Shi et al. 2018). Hwang et al. reported a capacitive pressure sensor using hierarchically porous structured PDMS composites, which exhibited a sensitivity 22.5 times higher (0.18 kPa^{-1}) than the sensors using bulk PDMS (Hwang et al. 2021). Park et al. reported a pressure sensor using microdome structure in fabricating sensor, which exhibited extremely high pressure sensitivities over broad pressure ranges (47,062 kPa^{-1} in the range of <1 kPa, 90,657 kPa^{-1} in the range of 1–10 kPa, and 30,214 kPa^{-1} in the range of 10–26 kPa) (Park et al. 2018a).

10.3.2.2 Power Consumption

The power consumption of flexible pressure sensors is a significant obstacle for practical integrated sensing systems. Various strategies have been demonstrated to reduce the power consumption of flexible sensors.

The first approach relies on the reduction of both operating voltage and operating current of the sensor (Jiang et al. 2019a). For example, Ai et al. demonstrated a flexible resistive pressure sensor based on polystyrene ball@reduced graphene-oxide (PS ball@rGO) core-shell microball composite materials (Ai et al. 2018). The PS ball@rGO-based wearable pressure sensors exhibit a high sensitivity of 50.9 kPa^{-1} at 3–1000 Pa with a low power consumption of 1 mW at an operating voltage of 1 V. Zhu and co-workers designed a novel flexible resistive pressure sensor by conformal coating of vertically aligned gold nanowires (v-AuNWs) on pyramid microarrays on PDMS elastomer (Zhu et al. 2019). The hierarchical structured pressure sensor can achieve a high sensitivity of 23 kPa^{-1} in a low regime (<600 Pa) and a rapid response time (<10 ms). Furthermore, owing to the high conductivity of v-AuNWs, the operation voltage of the pressure sensor was only 0.1 V, and the current during operation was less than 2 mA, resulting in a low power consumption below 0.2 mW.

Another approach to resolve the power consumption issues for the sensing unit is the fabrication of self-powered pressure sensors. Therefore, piezoelectric and triboelectric pressure sensors have attracted increasing attention in recent years (Yang et al. 2020; Li et al. 2017b). Hosseini et al. fabricated a flexible piezoelectric pressure sensor based on biodegradable glycine and chitosan piezoelectric films (Hosseini et al. 2020). The β-glycine/chitosan (β-Gly/CS)-based pressure sensor could produce an output voltage of 190 mV under 60 kPa pressure with a sensitivity of 2.82 ± 0.2 mV kPa^{-1}. Wang's group reported a self-powered thin-film-based triboelectric tactile sensor. They produced a highly triboelectric-negative fluorinated ethylene propylene (FEP) film with nanowire-structured surface applied as the contact electrification layer, which can generate triboelectric charges upon contact with a foreign object. Ouyang and co-workers reported a novel flexible and self-powered triboelectric nanogenerator (TENG)-based pulse sensor, which can directly acquire voltage signal that is consistent with second derivative of conventional pulse signal without complex mathematical operations and circuit design (Ouyang et al. 2017). The flexible self-powered ultrasensitive pulse sensor (SUPS) is composed of two friction layers, electrode layers, a spacer, and an encapsulating PDMS layer. The pulse wave velocity can be measured by using two SUPS simultaneously, which can be used to indicate the degree of arteriosclerosis.

10.3.2.3 Other Key Parameters

The sensing range of flexible pressure sensors is an important parameter, which refers to the minimum and maximum pressure that can be detected. Jiang et al. constructed by introducing a knoll-like microstructured surface into a percolative thermoplastic polyurethane/carbon black sensitive film, which exhibited an ultrawide sensing range of 0–1500 kPa (Jiang et al. 2019b). Response time, another key parameter, is defined as the time consumption of the flexible wearable pressure sensor from applying stimuli to applying a steady signal output. It is related to the contact conditions between the active material and the electrode as well as the viscoelastic property of the elastomeric materials (Lee et al. 2017). Some practical applications of pressure sensors such as real-time pulse monitoring device and instant-response displays have the requirement of short response time. Chen et al. presented a microfluidic flexible strain sensor by introducing liquid metal eutectic gallium-indium (EGaIn) embedded into a wave-shaped microchannel elastomeric matrix (300 μm width × 70 μm height), which showed quick response time ($t = 116$ ms) and exhibited a good response in pulse monitoring (Chen et al. 2020a).

Linearity is typically defined as the degree of deviation between the calibration curve and the selected fitting line and is represented as a percentage (Chen et al. 2018). In the linear range, the output signals of pressure sensors are more precise and credible. Furthermore, high linearity is beneficial to the calibration process and data processing. Therefore, developing pressure sensors with good linearity is highly desired. For example, Pang et al. proposed a special surface morphology with spinosum microstructure of random distribution via the combination of an abrasive paper template and reduced graphene oxide, which exhibited a wide linearity range of 0–2.6 kPa (Pang et al. 2018). Hysteresis of a pressure sensor refers to the phenomenon that the sensing performance is inconsistent between loading and unloading. The performance of hysteresis is mostly affected by the viscoelasticity of the active materials. Hysteresis is usually defined as the maximum difference between the output signals under the same pressure in a loading-unloading cycle by the full-scale output (Ray et al. 2019). Chen et al. presented a pressure sensor by the wave-patterned structure, which improved the hysteresis performance from 6.79 to 1.02% and achieved the accurate measurement (Chen et al. 2020a). Durability represents the ability to maintain stable electrical functionality during reciprocating deformation. Flexible sensors with high durability can sustain various applied pressures and strains (Park et al. 2018a). Fan et al. reported a wearable liquid-capsule sensor platform, which exhibited high durability over 30,000 loading cycles (Fan et al. 2018). Herein, some typical flexible pressure sensors are compared and summarized in Table 10.1 "Summary of materials/structure, sensing mechanism, sensitivity/linearity range, power consumption, detection range, and duration of recently reported pressure sensors."

10.4 Applications for Flexible Pressure Sensors

The wearable flexible sensors can be widely used in various areas of society. They can be used to detect various force signals and behavioral signals of the human body, such as blood pressure, heart rate, and pulse rate, intracranial pressure, intraocular pressure, tactile perception, and gait monitoring. Based on the feedback of wearable sensor, we can know our body's state in real time and make adjustments to let our lives become healthier.

Table 10.1 Summary of recently reported pressure sensors and their performance parameters

Materials/structure	Sensing mechanism	Sensitivity(kPa^{-1})/linearity range	Power consumption	Detection range	Duration (cycles)
Au/PDMS (Wang et al. 2018b)	Piezoresistivity	196/0–10 kPa	–	0–100 kPa	>10,000
Ecoflex/graphene (Qi et al. 2020)	Piezoresistivity	12.3/–	–	0–200 kPa	5000
SF/PAN I (Mengting et al. 2021)	Piezoresistivity	2.54/0–100 kPa	–	–	>2000
ZnOEP/CNTs/PDMS (Xia et al. 2017)	Piezoresistivity	39.4/0–10 kPa	<30 μW	–	5000
PDMS/PEDOT:PSS (Wang et al. 2016)	Piezoresistivity	851/0–3 kPa	100 nW	34 Pa–20 kPa	–
PEN/@rGO (Ai et al. 2018)	Piezoresistivity	4.2/–	35 nW	0–50 kPa	>30,000
PANI@silica (Kim et al. 2019b)	Piezoresistivity	17.5/–	–	0.008–120 kPa	>6000
GO/KGM (Xianzhang et al. 2018)	Capacitance	0.28/–	–	0–10 kPa	>1000
Ag/PVDF/micro-arrayed (Xiong et al. 2020)	Capacitance	30.2/0–130 Pa	–	–	>100,000
MXene (Ti3C2Tx)/PVA (Zhang et al. 2019)	Capacitance	0.4/–	–	–	10,000
AgNWs/PDMS	Capacitance	20.08/0–0.8 kPa	–	–	>5000
Ag/PET/FEP (Chen et al. 2020b)	Capacitance	7.989/–	–	0.1–60 kPa	10,000
PDA@BTO/PVDF (Yang et al. 2020)	Piezoelectricity	–	0.122 μW	–	>5000
$PbTiO_3$ nanowires/PI (Chen et al. 2017)	Piezoelectricity	9.4×10^{-3}/–	–	–	10,000

(continued)

Table 10.1 (continued)

Materials/ structure	Sensing mechanism	Sensitivity(kPa^{-1})/ linearity range	Power consumption	Detection range	Duration (cycles)
Ag/PVDF/ PDMS (Lin et al. 2021)	Piezoelectricity	7.7 mV/–	–	–	80,000
Au/PET (Park et al. 2017)	Piezoelectricity	0.018/–	–	–	5000
PDMS/ bamboo structures (Lei et al. 2022)	Triboelectricity	3.627/0–8 kPa	–	0–80 kPa	–
AgNWs/CTT/ PDMS (Ning et al. 2020)	Triboelectricity	–	–	–	15,000
rGO/PI (Xia et al. 2022)	Triboelectricity	30.3/–	–	–	>4000

10.4.1 Detecting Heart Rate or Pulse

Heart rate is defined as the frequency of the cardiac cycle, and long-term heart rate monitoring during daily life can provide important information about human health status for noninvasive medical diagnosis. The heart rate or pulse can be commonly measured from radial artery at the wrist or carotid artery at the neck (Kaisti et al. 2019).

Recently, various flexible pressure sensors have demonstrated the capability of accurate pulse or heart rate measurement in real time. He et al. presented a novel material design strategy developed to fabricate a self-assembled graphene sensing film (He et al. 2019b). Figure 10.4a shows the schematic illustration of artery pulse detection on the skin surface. The applied pressure forces the sensor close to the artery, which maximizes the signal from the artery pulse. Although there is a prominent progress in wearable health monitoring electronics, long-term monitoring weak pulse signal during daily activities remains a challenge owing to their sensitivity and vulnerability to body movement. The pulse wave is a significant physiological phenomenon detectable along the arterial system during blood circulation, containing numerous and reliable signals. Wu et al. demonstrated a flexible pressure sensor with a positive resistance-pressure response based on laser scribing graphene, and the sensor exhibited an ultrahigh sensitivity and a broad detection range (Qi et al. 2020). By collecting the pulse strength, frequency, and reflection, professional medical professionals can infer a variety of information, providing a diagnosis and prophylaxis of relevant diseases. In addition to detecting the weak signals such as pulse directly, the sensor with amplification ability is able to amplify the pulse signal by applying external pressure, making detection more accurate (Fig. 10.4b). Chen et al. presented a flexible hierarchical elastomer tuned self-powered pressure sensor, which achieves both high sensitivity (7.989 V kPa^{-1}) and

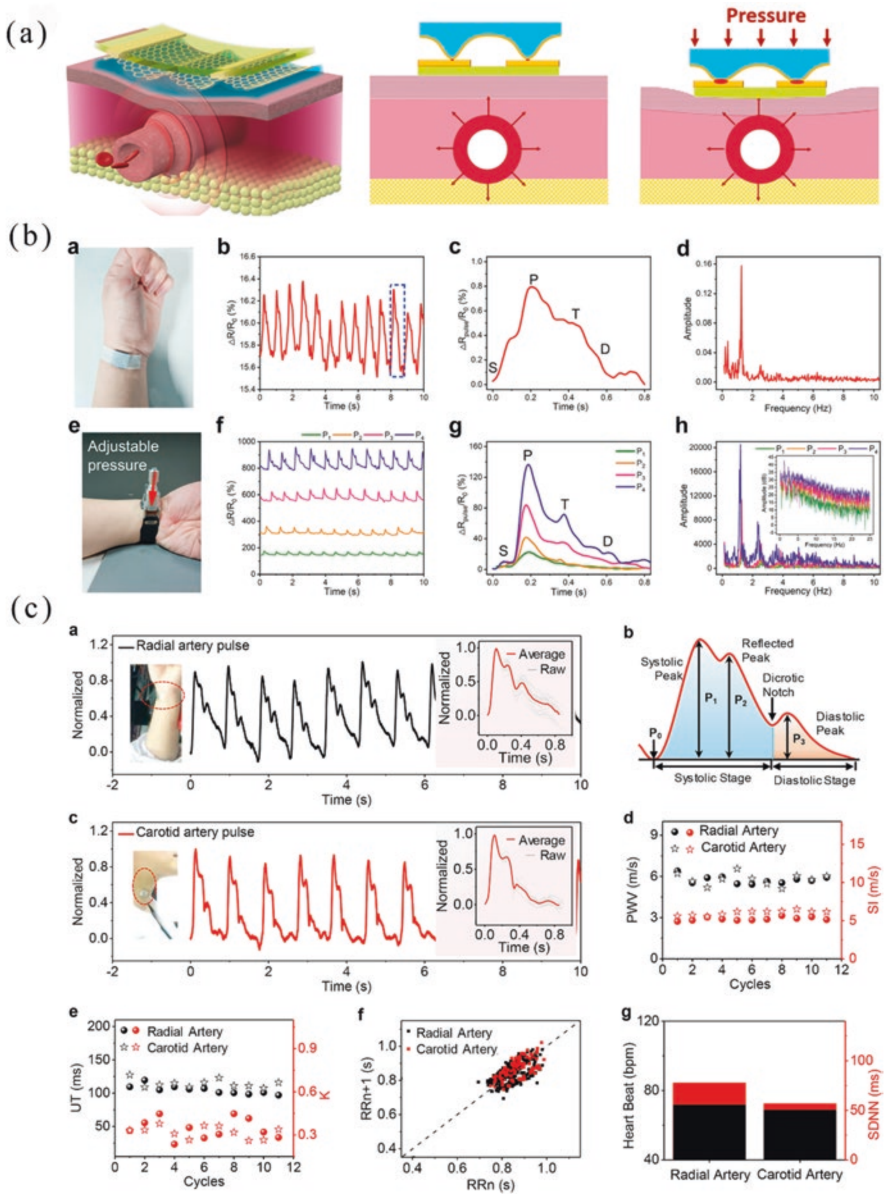

Fig. 10.4 (**a**) Schematic illustration of artery pulse detection on the skin surface. The applied pressure forces the sensor close to the artery, which maximizes the signal from the artery pulse (He et al. 2019b). (**b**) Photograph of the TMPGPS attached to the wrist by medical tape and the corresponding real-time, pulse signal detected, single pulse wave, and frequency spectrum (Qi et al. 2020). (**c**) HSPS for CVD monitoring. The radial and carotid arterial pulse waves of a 30-year-old healthy female. Inset is the enlarged view of each cycle (Chen et al. 2020b)

wide pressure range (Chen et al. 2020b). As shown in Fig. 10.4c, the sensor is used in monitoring radial artery pulse and carotid artery pulse. They studied the pulse wave and cardiovascular conditions of different adults, such as diastolic blood pressure (DBP), systolic blood pressure (SBP), pulse transit time (PTT), etc. By using an easier way to know about our body state such as heart rate and pulse signal information, it can make people live a healthier life. And the device could obtain accurate arterial pulse signal information from the sensor output even under the strong interference of body movement such as running and cycling.

10.4.2 Detecting Pressure In Vivo

Intracranial hypertension is an acute and chronic condition with a variety of causes that include traumatic brain injury, aneurysms, brain tumors, hydrocephalus, stroke, and meningitis. Accurate measurement of intracranial pressure can provide useful information for clinical diagnosis and management of such diseases. Karmakar et al. developed a pressure sensor that can be used to monitor the applied pressure during surgery for intraoperative care (Karmakar et al. 2020). As shown in Fig. 10.5a, it exhibits real-time photograph of pressure sensor placement along with the (intracranial pressure) ICP catheter on a live rodent model. In this study, it has been proven that real-time intraoperative pressure monitoring is important to save the complication and risks of patients (especially older patients), and our fabricated flexible pressure sensor can be an ideal candidate for this. Besides, Lee et al. presented a pressure sensor that is used for detecting the intracranial pressure of sheep (Fig. 10.5b) (Lee et al. 2020). The fixed sheep brain did not come with the skull or intact meninges; a sheep brain tends to be easily deformed, causing a technical challenge to implant the valve. Thus, they cast the entire brain in PDMS to form a watertight seal with the valve implanted. Pressure sensors measured the inlet and outlet pressure of fluidic ports. It also provides a method for better measurement of intracranial pressure.

As for intraocular pressure, Kim et al. developed a pressure sensor to monitor the intraocular pressure and applied this for noninvasive monitoring in association with the intraocular islet transplantation in diabetes (Fig. 10.5c) (Kim et al. 2019c). A strain sensor inside the lens can detect detailed changes in intraocular pressure by focusing the strain only in the desired, selective area of the contact lens. In addition, this smart sensor can transmit the real-time value of the intraocular pressure wirelessly using an antenna. This type of monitoring will provide important information on potential changes in the intraocular pressure associated with the transplantation procedure, and it enables appropriate clinical safety steps to be taken, if needed. Savariraj et al. presented a intraocular pressure sensor by using graphene-AgNWs hybrid electrodes (Fig. 10.5d) (Savariraj et al. 2021). In this work, only in vitro wireless monitoring of intraocular pressure was carried out on bovine eyeballs, and the sensor exhibited transparency adequately on the bovine or mannequin eye, ensuring clear vision. At lower pressure (>50 mmHg), the frequency response is

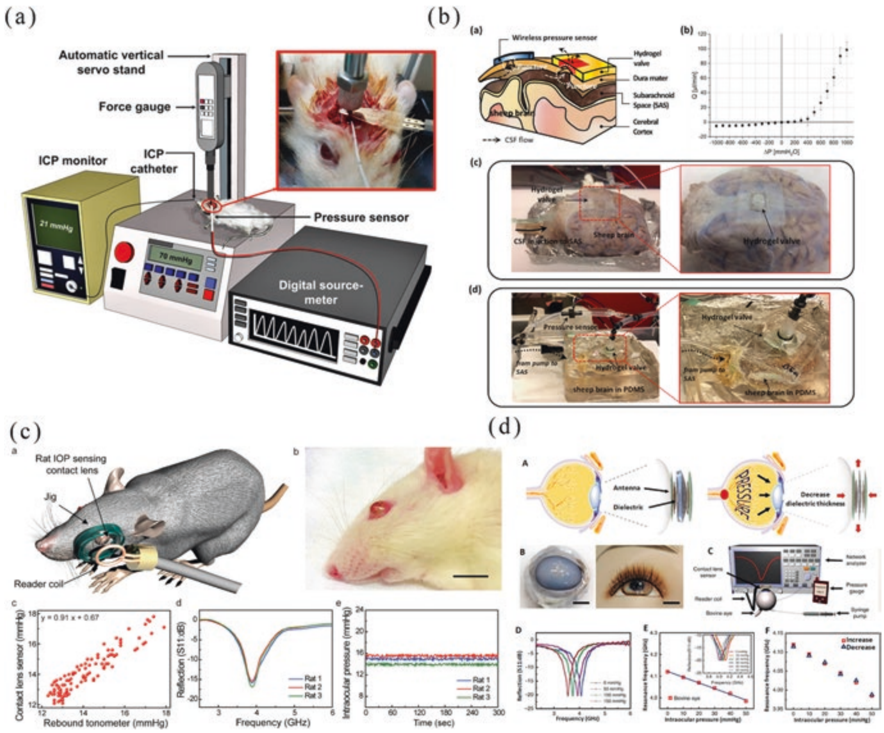

Fig. 10.5 (**a**) Schematic diagram of the measurement setup for in vivo pressure monitoring. Real-time photograph of pressure sensor placement along with the ICP catheter on a live rodent model is shown in the inset fig (Karmakar et al. 2020). (**b**) Actual configuration of the experimental setup. A syringe pump injects CSF to the cavity formed by SAS and the valve. The excess portion of manual cut was sealed by PDMS to prevent any leakage. The pressure sensor measures the differential pressure across the valve (Lee et al. 2020). (**c**) Correlation between the IOP measurements using the contact lens sensor and the rebound tonometer. Real-time continuous monitoring of the IOP in the rats (Kim et al. 2019c). (**d**) Graphene-AgNWs hybrid electrodes incorporated IOP sensor, fabrication, working principle, and results. Schematic showing the mechanism of AgNWs spiral coil-based intraocular pressure sensor. Photographs of the sensor transferred onto the contact lens worn by a bovine eyeball (left) and a mannequin eye (right). Scale bar, 1 cm (Savariraj et al. 2021)

linear, with a high sensitivity, and the sensor was noninvasive so that it can be well used in monitoring intraocular pressure.

10.4.3 Gait Monitoring

Accurate gait monitoring, which could be used in various health-related applications such as dynamic monitoring of Parkinson’s disease, early diagnosis, and rehabilitation assessment, has attracted more and more attention in recent years (Park et al. 2018b). Generally, the gait status could be monitored by measuring the force applied by the periodic foot stepping, and as a consequence, pressure sensors with suitable sensitivity in a wide pressure range are highly desired. Zhu et al. reported a highly flexible, compressible, and conductive PEDOT:PSS-@MS-based piezoresistive sensors for human motion detection. The conductive sponge was fabricated by dip-coating the melamine sponge (MS) in an aqueous dispersion of PEDOT:PSS. Owing to the highly porous and interconnected open-cell structure of MS, the PEDOT:PSS@MS exhibits excellent compressibility and flexibility. As a demonstration, three pressure sensors were fixed at three different positions (heel, arch, and forefoot) of an insole to collect different walking signals simultaneously. The fabricated pressure sensors can recognize gait and speed of walking, which may be useful in physical therapy such as helping stroke patients recover using gait training method.

Based on piezoelectric effect, Ahn et al. presented a new wearable multi-local strain sensor (MLS sensor) based on 3D textile structure with prestrained monofilament (Ahn et al. 2020). It detects signals from body movement based on pressure of the fingertip and gait, four movements of the neck, and joint movement (elbow and knee). Figure 10.6a presents the analysis result of the difference in gait pressure and stride length between the normal gait (5°) and toe-out angle gait (25°) using the output voltage. An MLS sensor was attached to the insole such that the output voltage (normal gait, 50 V; toe-out angle gait, 80 V) that varies based on the pressure on the heel and the one that varies based on the stride length (normal gait, 1.56 s; toe-out angle gait, 1.89 s) are analyzed to identify the difference between the toe-out angle and normal gaits. This enables the detection of pattern change in the gait due to dementia. In addition, the Bluetooth module is linked to a mobile phone in order to monitor the number of steps in real time. This suggests the possibility of its application in remote medical care.

Moreover, gait monitoring pressure sensors can be utilized in sports training to improve the performance of athletes (Zhu et al. 2019; Li et al. 2019b). Wu et al. demonstrated a low-cost flexible pressure sensor with a positive resistance-pressure response based on laser scribing graphene (Fig. 10.6b) (Qi et al. 2020). To perform human gait monitoring, they first attached a triode-mimicking graphene pressure sensor (TMPGPS) onto the heel to detect plantar pressure of various movements. And due to the good sensitivity of sensors under high pressure, different motion modes such as standing, walking, and jumping can be distinguished easily not only from the waveform but also from the intensity. Furthermore, several TMPGPSs were attached to a sponge insole with a flexible printed circuit board (PCB) to fabricate a pressure sensing array shoe pad. After processing, the data will be wirelessly transmitted to terminals such as mobile phones and laptops using Bluetooth modules and antennas. Finally, according to the feedback data, athletes can judge their own body state, so that they can achieve better protection in the following training.

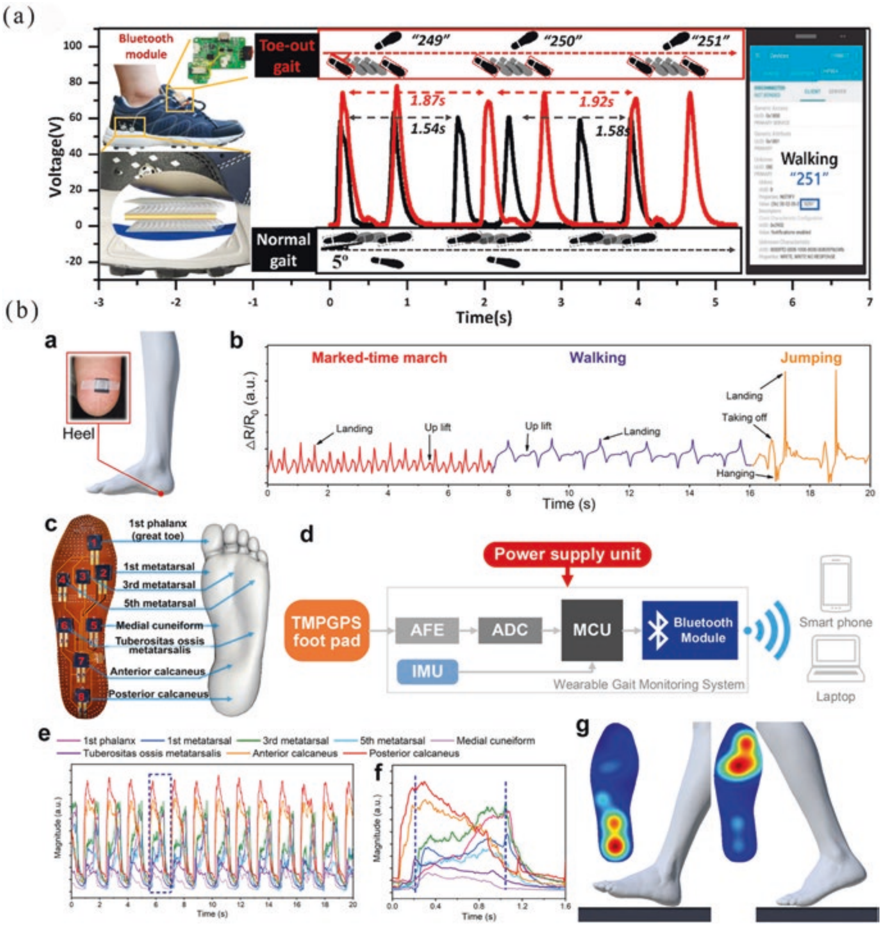

Fig. 10.6 (**a**) Output voltage change when on normal gait and toe-out gait. MLS sensor attached to the insole and illustration of smartphone application showing gait using Bluetooth (Ahn et al. 2020). (**b**) Schematic illustration and photograph of the sensor attached under the testing object's heel. Signal of foot pressure detected during various movements of marked-time march, walking, and jumping. Photograph of the shoe pad with TMPGPSs and corresponding anatomy in the schematic diagram of a human foot. Block diagram of the wearable gait monitoring system (Qi et al. 2020)

10.4.4 Recognition of Sound Signal

The sound signal, which is defined as the process of producing a certain sound through quasiperiodic vibration of vocal cords, is the most vital way of communication between people. In general, pressure changes across the larynx during the voicing process can induce oscillation of vocal folds. The characteristic signals of different throat motions can be used to record the word or speech. Recently, different kinds of flexible wearable pressure sensors have been used for word recognition. While the flexible pressure sensor is attached to the human neck, the subtle pressure changes induced by the muscle movements around the throat during speech will be captured by the device.

Zhang et al. proposed a piezoresistive pressure sensor by forming a cobweb-like network made of a zinc octaethylporphyrin (ZnOEP)/carbon nanotube (CNT) hybrid on an array of polydimethylsiloxane (PDMS) microposts (Zhang et al. 2020). The sensor exhibited an ultrahigh sensitivity of 39.4 kPa^{-1}, a superfast response time of 3 ms, a low detection limit of 10 Pa, and a reproducible response without degradation after 5000 cycles of pressure loading/unloading. With the rapid response, the sensor could also recognize fast rhythms from light music, as shown in Fig. 10.7a. It can be noted that the response curve of the sensor at the bottom of the figure matches well with the acoustic spectrum of the music depicted in the

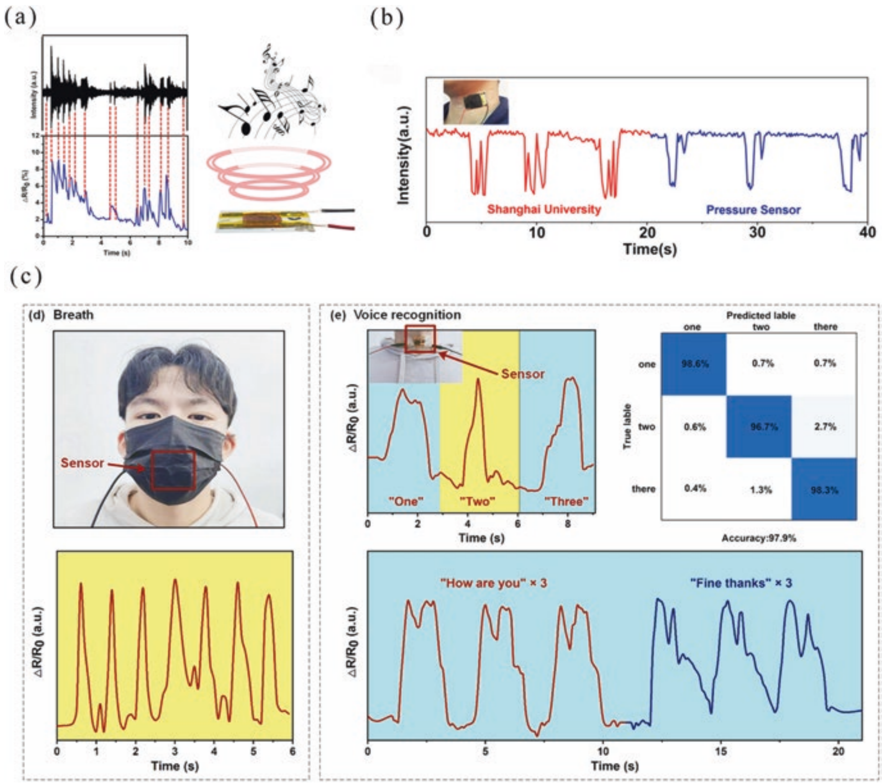

Fig. 10.7 (**a**) Acoustic spectrum of a light music and sensor response curve matches well, showing that the pressure sensor can also recognize the rhythm of music (Zhang et al. 2020). (**b**) Real-time recording of current changes for detecting the acoustic vibration (inset: photograph of the pressure sensor attached onto the neck of a speaker) (Zhao et al. 2019). (**c**) Applications of the rGO-cloth/LIG pressure sensor. Breath and response of rGO-cloth/LIG pressure sensor for voice recognition and confusion matrix of the deep learning outcome (Xia et al. 2022)

upper part of the figure, proving its great potential for use in electronic skin systems. Zhao et al. presented a highly sensitive flexible piezoresistive pressure sensor based on hybrid porous microstructures (HPM) (Zhao et al. 2019). The HPM combines the advantages of hybrid structures, which increase the contact area because of stress concentration and reduce Young's modulus, and the porous structure, which introduces an additional pore resistance. Consequently, the pressure sensor had a high sensitivity of 83.9 kPa^{-1} at an applied pressure < 140 Pa. As shown in Fig. 10.7b, a pressure sensor device was attached to the neck of a speaker directly. When the speaker spoke different words such as "Shanghai University" and "pressure sensor" repeatedly, the output current signal changed correspondingly, indicating that the device was able to discriminate the voice through the vibration patterns.

However, the high performance of pressure sensors mainly powered by external batteries cannot meet the needs of ultra-long standby and portability. Hence, the self-powered sensors are emerging. Herein, Xia et al. presented a reduced graphene oxide (rGO)-cloth-based pressure sensor with laser-induced graphene (LIG) prepared by a simple and low-cost preparation process (Xia et al. 2022). LIG not only contribute to the sensitivity of pressure sensors (from 20.6 to 30.3 kPa^{-1}) but also improve the transfer charge density of triboelectric nanogenerator (TENG) (from 160 to 270 $\mu C/m^2$). The resistance variation response for different words and sentences is displayed in Fig. 10.7c, which shows that this sensor has excellent repeatability and distinguishability in recognizing voices. Moreover, the BP neural networks are employed to further detecting the accuracy of voice recognition, and the results suggest the total recognition accuracy reaches 97.9%. Given these advantages, a high-performance self-powered measurement-control combined system consisting of the LIG-based pressure sensors and TENG is constructed, which bears huge potential to support the development of wearable devices, smart skin, and human-computer interaction. Based on these advantages, the application of our sensor could potentially be used to detect vocal fold vibration for mute and deaf people.

10.4.5 Breath Detection

Respiratory rate, as a physiological parameter, is a sensitive indicator of acute respiratory dysfunction. Both doctors and nursing staff take it as one of the vital signs. The respiratory rate sensor can reflect the respiratory status in real time, record the number of breaths per unit time, and display the current respiratory rate. It can help doctors and researchers to grasp the patient's condition in real time and make effective treatment in time to save patient's life. Zhong et al. presented a wireless smart face mask by integrating an ultrathin self-powered pressure sensor and a compact readout circuit with a normal face mask (Zhong et al. 2022). The wireless breath monitoring by a smart face mask was successfully developed by combining an ultrathin self-powered pressure sensor as a breathing sensor, a power supply unit with a lithium battery, a voltage boost circuit, and a measuring circuit based on an Arduino board, as shown in Fig. 10.8a. Based on the average breath rate and

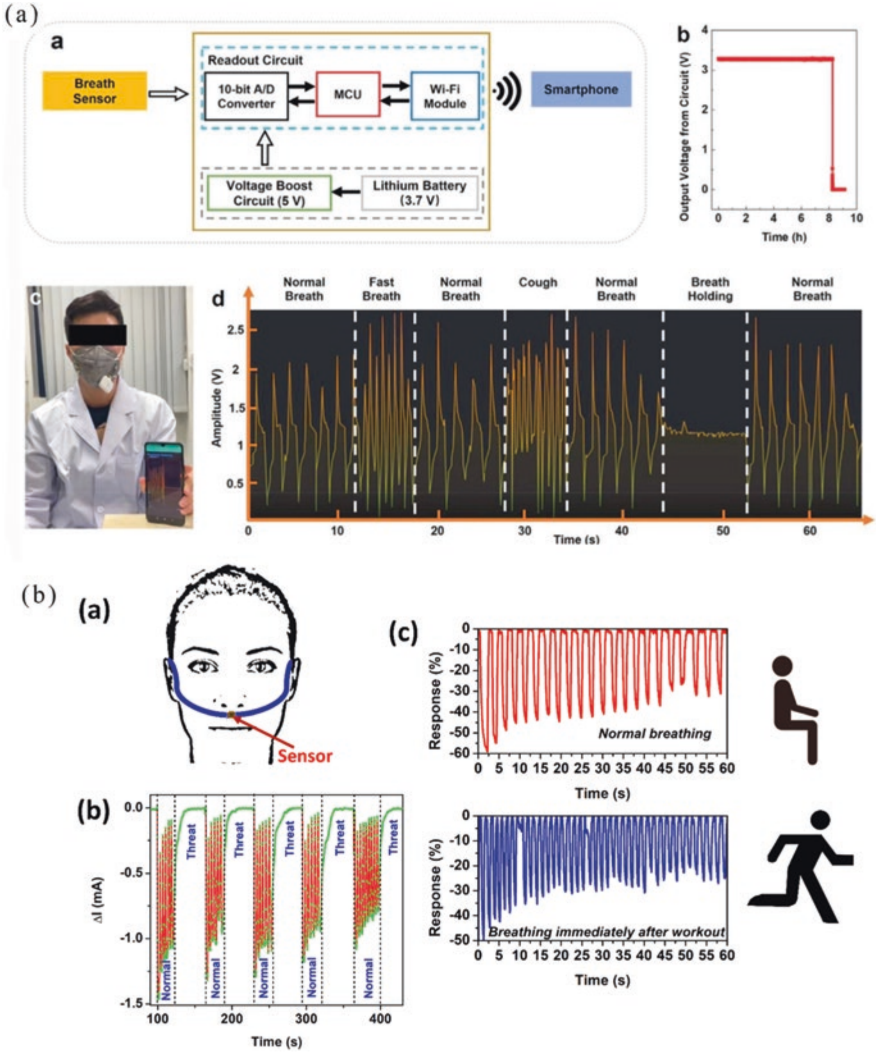

Fig. 10.8 (**a**) Photos showing the measured continuous and successive breath conditions of normal breath, fast breath, normal breath, cough, normal breath, breath-holding, and normal breath of tester 1 (Zhong et al. 2022). (**b**) Schematic of breath detection, indicating the sensor's placement on the philtrum. Pressure response for NB and intermittent breathing (threat) condition in a regular interval. Comparison of breathing pattern before (upper panel) and after (lower panel) a physical workout (Ghosh et al. 2021)

amplitude (peak-peak voltage) for normal breath, different breath conditions, including normal breath, fast breath, cough, and breath-holding, were recognized by the wireless breath-monitoring system. The sensor responds sensitively to breathing airflow owing to its ultrathin/light structure and high electrostatic induction efficiency; unlike breath measurement using a non-embedded device, it is completely portable and wearable, making it easy to use in daily life; and it can easily achieve an efficient breath information process including data measurement, transmission, storage, and analysis. Finally, the smart face mask has potential applications in maintaining personal health and preventing breath-related epidemic diseases.

Besides, Ghosh et al. presented a highly sensitive piezoresistive sensor by using Si nanorod (NR) arrays (Ghosh et al. 2021). The sensor exhibited an ultralow-pressure detection, and excellent ambient stability (>several months) for detecting breath signals. As shown in Fig. 10.8b, the sensor can efficiently detect the difference between the normal breathing (NB) and the states of hold breathing/stop breathing (SB) for some moments and provide an alarm in the case of risky events for an individual with breathing disorders such as sleep apnea. It is more convenient for those patients with respiratory diseases to know about real-time physical condition, which also provides guarantee for their safety. Wireless integration of the sensors, having the portable and smart platform, can enhance the utility of the breath sensor as a routine-life workout partner and can be considered to realize next-generation breath-sensing gadgets. We believe that this work provides guidance to develop next-generation breath-sensing gadgets and other leading-edge applications in electronic and healthcare devices.

10.4.6 Tactile Perception

Tactile sense plays a critical role in enabling human beings to interact with the surrounding environments. Humans can feel and manipulate diverse objects by applying precisely controlled forces, which is important for accomplishing fundamental activities of daily life. Moreover, tactile perception is extremely significant in various applications, containing the control of prosthetic limb, tactile reconstruction of patients with neurological diseases, clinical rehabilitation therapies after trauma (Boutry et al. 2018), robotic manipulation (Sundaram et al. 2019), and artificial intelligence (Wan et al. 2018).

With extensive investigation in recent years, various types of flexible tactile sensors that can mimic the tactile sensory features of the human skin have been developed. Inspired by the human skin as a highly sensitive biological sensor, Cheng et al. fabricated a highly sensitive MXene-based piezoresistive sensor with micro-spinous microstructures formed by a simple abrasive paper stencil printing process (Cheng et al. 2020). Importantly, the randomly distributed spinous microstructures can effectively promote increased contact area of the conductive channels with improved performance of the pressure sensor: high sensitivity (151.4 kPa^{-1}), fast response time (<130 ms), small pressure detection limit (4.4 Pa), and excellent stability over 10,000 cycles. As shown in Fig. 10.8a, flexible sensor could be attached onto the robot joint surface with the aid of a PI tape. The obvious changes of the peak shape indicate that the sensor can easily detect the robot movement. In practice, the sensor shows great performance in monitoring human physiological signals, tactile sensing, and remote monitoring of intelligent robot motion in real time.

Besides, Lin et al. presented a skin-inspired piezoelectric tactile sensor array with real-time differentiation ability of diverse external stimuli (Lin et al. 2021). As shown in Fig. 10.8b, the manipulator with tactile sensor array was used to grab tofu and observe whether the tofu was damaged. It turned out that the former was intact and the latter damaged. Integrated with a signal processor and a logical algorithm, the tactile sensor array achieves to sense and distinguish the magnitude, positions, and modes of diverse external stimuli, including gentle slipping, touching, and bending, in real time. Herein, the proposed tactile sensor array possesses the characteristics of high sensitivity (7.7 mV kPa^{-1}), long-term durability (80,000 cycles), and rapid response time (10 ms) (less than human skin). And this research provides a new strategy for tactile sensor design and would broadly benefit many fields, especially for electronic skins, health monitoring, animal movement detection, and robotics (Fig. 10.9).

10.5 Conclusions and Perspectives

In this article, we have provided a state-of-the-art review of the emerging flexible pressure sensors for biomedical applications. In the past few years, advances in new materials, power supplies, sensing modalities, and assembly techniques provide important foundations for the development of new classes of skin-like flexible sensors. Among these sensors, some basic parameters such as stretchability, spatial resolution, and sensitivity even exceed those of the biological skin. Herein, based on the rapid development of science and technology, we have summarized some applications of flexible pressure sensors in medical diagnostic in recent years. It is obvious that flexible wearable sensors have greatly improved our medical conditions and have provided safer social environment.

While numerous basic and applied research results have been translated from the laboratory to the real word, many important challenges still exist in practical applications. For instance, due to the viscoelastic performance of the polymers, response delay existed in all polymers based on pressure sensors, which limits the application of these sensors. The hysteresis of elastic materials will affect the accuracy of collected physiological signals and bring inconvenience to the doctor's analysis. Moreover, when measuring pulse signals, blood pressure, or other data by wearable sensors, in order to get accurate data, we usually need to improve the high sensitivity and linearity of sensor. It requires us to select appropriate substrates and active materials in the fabrication. Also, standard everlasting electronic implants used in modern clinical medicine usually acts as a nidus for infection, with the potential to provoke pathological tissue reactions. In the meantime, the associated surgical removal can cause patients' reoperating-related pain. Consequently, developing materials that can naturally resorb via metabolic and/or hydrolysis action might be an important trend for implantable devices. These are all we need to put forward higher requirements for material synthesis technology.

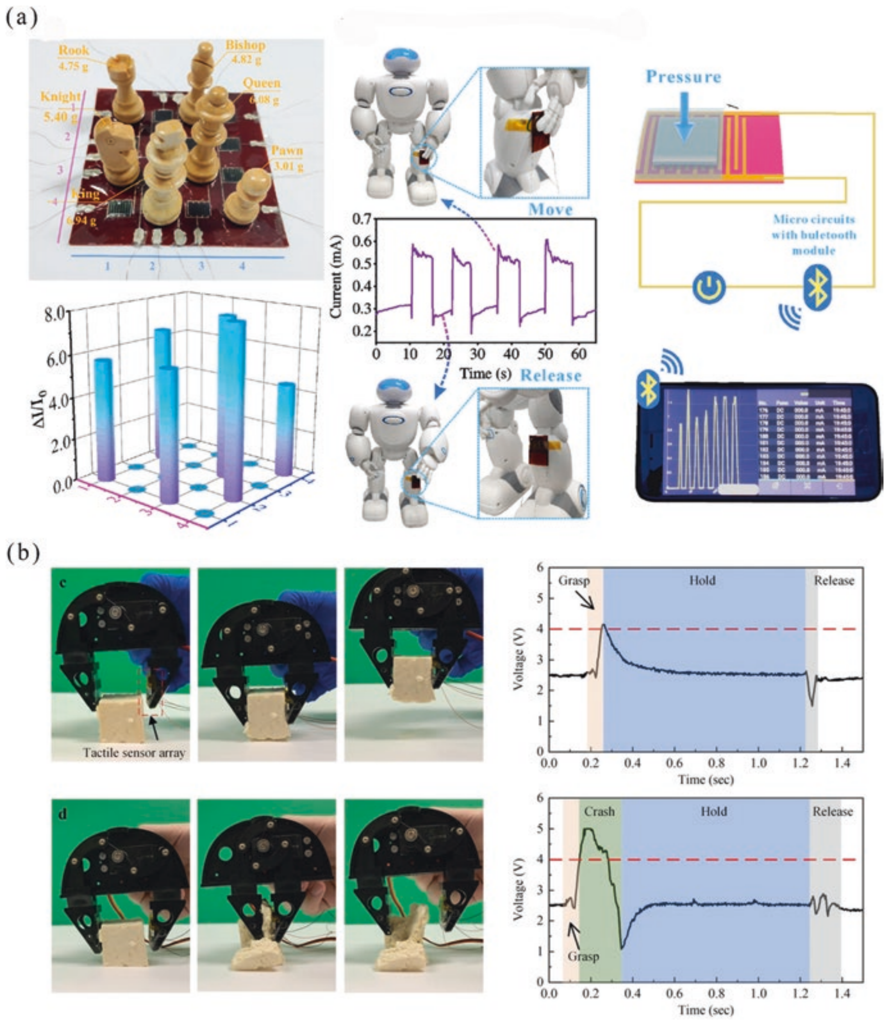

Fig. 10.9 (**a**) Photograph of the 4 × 4 array of MXene-based piezoresistive sensor and detection of the corresponding pressure distributions. Photograph of the pressure sensor assembled on a robot (inset: enlarged view of the sensing position) and detection of its response to the motion behavior. Piezoresistive sensor with a Bluetooth circuit module converts its current signal to a portable mobile device display (Cheng et al. 2020). (**b**) Demonstration of grasping objects using a robotic hand with a feedback module. The tactile sensor is mounted on the robotic hand and used as real-time feedback. A piece of soft and fragile tofu keeps integrity during the movement of the robotic hand. The sensor array detects the whole of the grasping process. And demonstration of grasping objects using a robotic hand without the proposed sensor array. A piece of soft and fragile tofu damaged during the movement of the robotic hand (Lin et al. 2021)

Another important challenge is the power supply of sensors, for instance, some physiological signals (pulse, blood pressure, etc.) require continuous monitoring, which is vital for long-term operations. Thus, continued progress in energy harvesting and energy storage technologies will be needed to support increasing requirements for communication bandwidth, operating distance, sampling frequencies, and operating lifetimes. Developing self-powered sensing devices represents a promising candidate to achieve sustainability in pressure sensors. By combining the sensing components with various energy harvest units (such as thermoelectric devices, organic solar cells, piezoelectric electronics, etc.), self-powered pressure sensor that can operate continuously without external power supply might be fabricated. In particular, triboelectric and piezoelectric phenomena could be applied to external pressure sensing in the self-powered flexible devices. However, uninterrupted supply of energy from sources including mechanical motions, ambient light, and others is typically not possible. Therefore, combinations of self-power devices together with some other energy storage components such as batteries and supercapacitors may provide an attractive solution.

In the future, a complete sensor system should have the following foundations. Firstly, the sensor tends to be integrated. The system contains batteries, circuits, and sensors so that users can wear it comfortably for a long time. The sensor can be multifunctional. When we put sensor in some extreme circumstances, it still can measure various body signals (blood pressure, pulse signal, etc.) accurately. Moreover, the sensor can achieve intelligence. It can achieve signal acquisition in real-time analysis and get health report and feedback to users. In addition, in terms of the recycle mechanism of wearable sensors, we should try to use degradable materials in fabrication for the in vivo sensors, so as to minimize the harm to human. As for the ex vivo sensors, we should choose greener materials to protect the environment.

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