Study on Flexible Wearable Sensors for Motion Detection and Health Monitoring

Zehong Jiang

School of Mechanical Engineering, Northeast Electric Power University, Jilin City, Jilin Province

1164504962@qq.com

Abstract. Traditional rigid sensors are increasingly inadequate for effective human motion detection and health monitoring as awareness of personal health continues to rise. Flexible wearable sensors, celebrated for their exceptional biocompatibility and sensing performance, have become a focus of research in these domains. This paper examines four types of flexible wearable sensors: resistive, capacitive, piezoelectric, and triboelectric. In Chapter 2, the paper outlines their fundamental principles of operation. Chapters 3 and 4 discuss recent innovations by various research teams on active and passive sensors, encompassing advancements in material development, structural design, fabrication methods, and application contexts. Finally, Chapter 5 provides a summary of the challenges facing the evolution of flexible wearable sensors and offers insights into future research directions.

Keywords: Motion detection, health monitoring, wearable sensors.

1. Introduction

There is a growing emphasis on personal health now. However, traditional rigid medical devices are often bulky or invasive, making them ill-suited for everyday use. With advancements in Internet of Things (IoT) and artificial intelligence technologies, flexible sensors that are compact, high-performing, and exhibit exceptional flexibility and biocompatibility have emerged. These sensors show significant potential and broad applications in fields such as electronic skin, human-computer interaction, human motion detection, and health monitoring, attracting substantial interest from researchers[1-3]. This paper focuses on flexible wearable sensors designed specifically for motion detection and health monitoring.

Flexible wearable sensors can closely adhere to the skin, accurately capturing physiological parameters and monitoring motion states in real-time, thereby offering innovative methods for smart healthcare and health oversight. The continuous development of new materials and manufacturing processes enhances sensor performance and broadens their application scenarios[4]. Currently, these sensors can not only detect significant bodily movements but also capture subtle physiological signals, providing real-time, accurate health indicators. Based on their sensing mechanisms, flexible wearable sensors for motion detection and health monitoring can be classified into four categories, which are resistive, capacitive, piezoelectric, and triboelectric sensors. Resistive and capacitive sensors, as early technologies, are widely utilized due to their simple operating principles and established manufacturing processes[5-6]. However, their dependence on external power sources restricts their portability and practical use. In contrast, piezoelectric and triboelectric sensors have emerged, capable of converting mechanical energy into electrical energy, thereby enabling self-powering and continuous monitoring. Their adaptability and stability render them notable as a significant avenue for future development[7-8].

This paper begins by detailing the four types of flexible wearable sensors for motion detection and health monitoring in Chapter 2, alongside their respective sensing mechanisms. The advantages and disadvantages of active flexible wearable sensors are analyzed in Chapter 3, such as resistive and capacitive types, while presenting recent innovations from various research teams in material development, structural design, and manufacturing processes. Compared to their active counterparts, Chapter 4 explores the advantages of passive, self-powered flexible wearable sensors (such as piezoelectric and triboelectric sensors), as well as their application scenarios in human motion detection and health monitoring. Finally, Chapter 5 summarizes the current challenges faced by flexible wearable sensors in motion detection and health monitoring and offers insights into future development prospects.

2. Sensing Mechanisms of Four Types of Flexible Wearable Sensors

2.1 Sensing Mechanism of Resistive Flexible Wearable Sensors

The sensing mechanisms of resistive flexible wearable sensors can be divided into two categories of pressure-sensitive and resistive strain-sensitive. In pressure-sensitive sensors, the sensitive materials change the movement of electrons and holes when subjected to force, thereby converting pressure into resistance variations. In resistive strain sensors, the application of force causes the internal structure of the sensitive element to either contract or expand, resulting in alterations in the density of conductive materials and the configuration of conductive pathways. This, in turn, manifests as changes in resistance, as depicted in Figure 1(a). The change in the resistance value of the sensitive element can be calculated using the following equation (1):

$$R = \frac{\rho L}{A} \tag{1}$$

In the equation, R denotes the resistance value of the sensitive element, ρ represents the material’s resistivity, L is the length, and A is the contact area.

The sensitivity of resistive flexible wearable sensors is a critical parameter for assessing their performance. Enhancing sensitivity requires an increase in the rate of resistance change under a given pressure. This process can be expressed by the following equations (2) and (3):

$$\frac{\Delta R}{R_0} = \frac{R - R_0}{R_0} \times 100\% \tag{2}$$

$$GF = \frac{\Delta R}{R_0 \Delta P} \text{ or } GF = \frac{\Delta R}{R_0 \Delta \varepsilon} \tag{3}$$

In the equation, $\frac{\Delta R}{R_0}$ denotes the rate of resistance change, while R_0 and R represent the resistance values before and after the application of external force or strain, respectively. *GF* is the sensitivity factor of the sensor, whereas ΔP and $\Delta \varepsilon$ correspond to the variations in pressure and strain, respectively.

2.2 Sensing Mechanism of Capacitive Flexible Wearable Sensors

The sensing components of capacitive flexible wearable sensors are structured as a parallel plate capacitor, consisting of two conductive electrodes and a dielectric layer. The capacitance value can be calculated using the following equation (4):

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d} \tag{4}$$

In this equation, C represents the capacitance, ε_r is the vacuum permittivity, ε_0 is the dielectric constant, A denotes the contact area of the two electrode plates, and d is the separation between the plates.

When subjected to external forces, both the distance between the electrodes and the effective contact area change, resulting in a variation in capacitance. This phenomenon facilitates the conversion of changes in strain or force into alterations in capacitance, as illustrated in Figure 1(b). The sensitivity of the capacitive sensor is expressed by the following equation (5):

$$K_P = \frac{\Delta C}{C_0 \Delta P} = \frac{1}{\Delta P} \frac{d_0}{\Delta d} \frac{\Delta A}{A_0} \text{ or } K_\varepsilon = \frac{\Delta C}{C_0 \Delta \varepsilon} = \frac{1}{\Delta \varepsilon} \frac{d_0}{\Delta d} \frac{\Delta A}{A_0} \tag{5}$$

In this equation, K_P indicates the stress sensitivity, while K_ε refers to the strain sensitivity. Additionally, C_0, d_0 and A_0 correspond to the initial capacitance value, the distance between the plates, and the contact area, respectively. Conversely, ΔC, ΔP, $\Delta\varepsilon$, Δd and ΔA represent the changes in capacitance, stress, strain, plate separation, and contact area, respectively.

2.3 Sensing Mechanism of Piezoelectric Flexible Wearable Sensors

The operating principle of piezoelectric flexible wearable sensors is based on the conversion of external forces or strain into electric charges through the direct piezoelectric effect. These charges are subsequently processed by an amplifier to output electrical signals such as voltage and current. The constitutive equations governing the direct piezoelectric effect and the accumulation of surface charge in piezoelectric materials can be determined using the following equations (6):

$$\begin{gathered} D = dT + \varepsilon E \\ Q = d_{mn} \times F_x \end{gathered} \tag{6}$$

In these equations, D represents charge density displacement, d is the piezoelectric coefficient, T denotes stress, ε signifies the material's permittivity, E indicates the electric field strength, Q stands for charge, d_{mn} is the piezoelectric coefficient, and F_x reflects the force applied in various directions.

Based on the spatial relationship between the direction of the applied force and the polarization direction, piezoelectric materials can be categorized into Mode d_{31} and Mode d_{33}. In Mode d_{31}, the applied force is perpendicular to the polarization direction, while in Mode d_{33}, it is aligned with the polarization direction, as depicted in Figure 1(c). Typically, Mode d_{33} generates a greater amount of charge, while Mode d_{31} is effective for detecting lateral stress or strain. These two modes have distinct applications in human motion detection and health monitoring.

2.4 Sensing Mechanism of Triboelectric Flexible Wearable Sensors

Triboelectric flexible wearable sensors function through the coupling of the triboelectric effect and electrostatic induction. Materials with different electron affinities are utilized to create triboelectric electrodes, which generate a potential difference by facilitating electron transfer through friction. When the charged materials are separated, the resulting electrostatic induction in the electrodes causes a realignment and transfer of charge within the external circuit. As a result, triboelectric sensors can convert external forces into electrical signals, including short-circuit voltage V_{OC}, short-circuit charge Q_{SC}, and short-circuit current I_{SC}.

Based on their operational mechanisms, triboelectric flexible wearable sensors can be categorized into contact separation mode, single electrode mode, lateral slip mode and independent mode. In the contact separation mode, two dielectric films generate oppositely charged polarities upon contact. When external force separates the dielectric interface, an induced potential difference arises between the metal electrodes deposited on their respective backs. By connecting an external circuit, charge carriers migrate through the load, creating a reverse potential that balances the electrostatic field. When the gap is closed, the potential difference dissipates, allowing the charges to reset. This cyclic process results in alternating current (AC) output. The single electrode mode operates similarly to the contact separation mode, requiring only one electrode in contact with the triboelectric layer. When a charged object approaches or withdraws, electron flow occurs between the electrode and the ground, producing AC output. This mode eliminates the need for wired connections to the electrode, facilitating the collection of ambient mechanical energy with minimal operational constraints. In the lateral slip mode, frictional sliding between two triboelectric layers generates charge and potential differences. Changes in the effective contact area during sliding lead to periodic variations in the potential difference, thus generating AC output. The independent mode features a freely movable dielectric film situated between two fixed electrodes. When an external force acts on the film, a potential difference and current develop between the electrodes without direct contact between the charged object and the upper surface of the dielectric layer, thereby reducing wear and enhancing the sensor's durability.

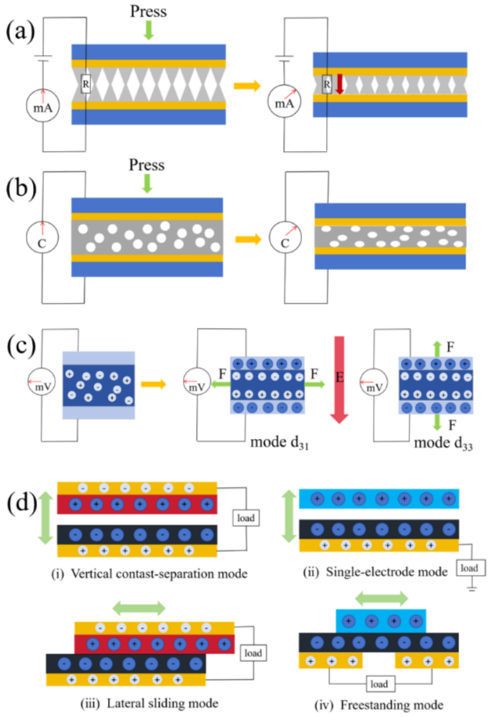

Figure 1. Schematic Diagram of Four Types of Flexible Wearable Sensors Principles

3. Advances in Active Flexible Wearable Sensors for Motion Detection and Health Monitoring

3.1 Research Progress of Resistive Flexible Wearable Sensors

The exploration of resistive flexible wearable sensors dates back to 1954, when Smith discovered the piezoresistive effect in silicon and germanium. Since that time, numerous research teams have focused on designing specialized sensor structures to enhance performance. For instance, Kim et al.[9] filled vertically aligned carbon nanotubes (VA-CNT) with polydimethylsiloxane (PDMS) to create a sensor composed of a dual-layer PDMS/VA-CNT composite conductor. This design effectively addresses the issue of reduced pressure sensitivity due to deformation of the composite conductor under external forces, enabling the sensor to accurately detect elbow flexion and blood pulse signals. Long et al.[10] proposed the integration of two PDMS foam plates with differing porosities to form a gradient stiffness foam plate (PGSF). The foam plates deform sequentially with increasing pressure, effectively broadening the detection range of the porous foam and allowing for precise monitoring of carotid artery signals. Zhang et al.[11] introduced a concave hexagonal negative Poisson's ratio structure into graphene-based stretchable fabrics (GMAF), enabling the materials to exhibit consistent resistance change trends across different directions, thereby amplifying the electrical signal response. The modified fabric sensor demonstrated an eightfold increase in sensitivity and excelled in detecting limb bending movements. Inspired by crossed honeycombs, Wang et al.[12] developed an asymmetric concave honeycomb crossed conductive network (ACHCN), which revealed significant differences in strain sensitivity between vertical and horizontal orientations. This innovative approach provides new perspectives for the study of complex multidimensional human movements.

In addition to structural innovations, the development of new materials has also been a focal point of research for many teams. Lu et al.[13] developed a flexible resistive strain sensor (MCT/FRS) by processing a composite film made of MXene (two-dimensional transition metal carbide), carbon nanotubes (CNTs), and thermoplastic polyurethane (TPU) through twisting, followed by the application of a PDMS layer on the surface. This composite material exhibits improved flexibility and stability, allowing the sensor to achieve a maximum elongation rate of 700% at a twist level of 200. Furthermore, several teams have enhanced the sensor fabrication processes. For example, a laser-induced carbonization technique introduced by Xu et al.[14] significantly reduces the incubation effect typically observed during traditional laser direct writing processes, thereby improving material laser absorption. This technique, utilizing a laser power of 9.6 watts and a repetition frequency of 50 kHz, produces electronic lines without excessive burning, providing a novel approach for fabricating resistive flexible sensors through laser processing. In summary, improving the structure of resistive flexible wearable sensors and developing new materials are crucial for enhancing sensor performance, as illustrated in Figure 2. The broader adoption of such sensors will require the exploration of additional application scenarios and the development of cost-effective fabrication processes, which represent the next research direction for many teams in this field.

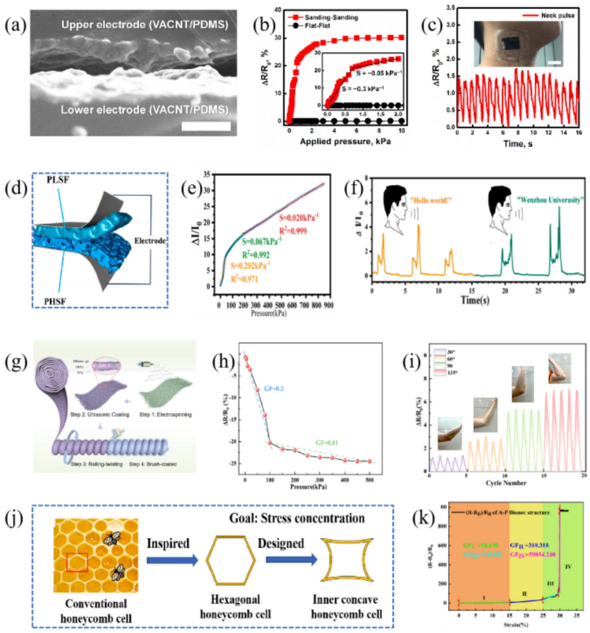

Figure 2. Research Outcomes of Resistive Flexible Wearable Sensors

3.2 Research Progress of Capacitive Flexible Wearable Sensors

Capacitive flexible wearable sensors have a sandwich structure comprising two electrode layers surrounding a dielectric layer. This design provides greater simplicity and stability compared to resistive configurations, resulting in enhanced resistance to interference during human motion detection and health monitoring. Many research teams have focused on developing innovative electrode and dielectric materials to improve sensor performance. For instance, Xiao et al.[15] introduced NaCl powder and a stearic acid curing agent into a mixed solution of multi-walled carbon nanotubes (MWCNTs), carbon black (CB), barium titanate ($BaTiO_3$, BT), and isopropanol (IPA) to fabricate a porous four-phase composite material for the dielectric layer. This sensor demonstrated a sensitivity of 2.28 kPa^{-1} within a pressure range of 0 to 50 kPa, showing promising results for monitoring human respiration and recognizing facial expressions. To mitigate the release of ammonia gas during the preparation of micropores, Simin et al.[16] utilized nitric acid (HNO_3) and sodium bicarbonate ($NaHCO_3$) to neutralize the carbon dioxide (CO_2) produced, resulting in a non-toxic, uniformly porous PDMS dielectric layer. This sensor achieved an impressive sensitivity of 3.2 MPa^{-1} in a high-pressure range of 0.2 MPa to 1 MPa, making it suitable for integration into an athlete's helmet to assess fit.

In addition to developing new materials, the incorporation of microscale structures such as pyramids, domes, hemispheres, micro-columns, and wrinkles can significantly reduce the elastic modulus of the dielectric layer. This reduction facilitates greater deformation under applied forces, thereby enhancing the sensor's sensitivity and detection range. Wang et al.[17] used electrostatic spinning to make a solution of polyvinyl alcohol (PVA) and phosphoric acid at a 1:0.3 ratio and subsequently fabricated micro-cone structures on the surface of the PVA/phosphoric acid electrospun membrane. This configuration enabled the sensor to achieve a detection range of 1 MPa, exhibiting a sensitivity of 0.54 kPa^{-1} within a pressure range of 0 to 70 kPa. To mitigate the pronounced non-linearity of ionic conductors at high pressures, Allen et al.[18] solidified a PVA/H_3PO_4 solution in specially designed micro-dome molds, creating an electrolyte layer with a gradient-height micro-dome structure. This gradient design allows the sensor to undergo sequential deformation in response to applied pressures, yielding a high sensitivity of 423.42 kPa^{-1} across a detection range of 0 to 400 kPa, with a linearity coefficient of R=0.99. This sensor has proven effective for monitoring pulse signals.

Particularly notable are efforts by various teams to design composite dielectric layers and electrodes that harness the complementary strengths of different materials to enhance performance. For instance, Li et al.[19] introduced a composite dielectric layer composed of a thermoplastic polyurethane/silver nanoparticle electrospun network (TPU/AgNP) in combination with a micro-column array of PDMS. Complementing this is a composite electrode made from carbon nanotubes (CNTs), two-dimensional titanium carbide ($Ti_3C_2T_x$, MXene), and PDMS. The inclusion of silver nanoparticles in the composite material not only improves the sensor's sensing performance but also imparts antibacterial properties, making it highly applicable in the wearable healthcare sector. Furthermore, Feng et al.[20] developed a layered gradient hybrid foam dielectric layer by integrating two types of MWCNT/PDMS foam with differing pore densities and dielectric constants between two conductive fabrics. This innovative design enables the sensor to achieve a detection range of 50 Pa to 500 kPa, along with a sensitivity of 2.155 kPa^{-1}, facilitating precise detection of finger bending motions. This work presents a viable avenue for the development of non-invasive medical assistive devices. Figure 3 showcases some of the research achievements from these teams.

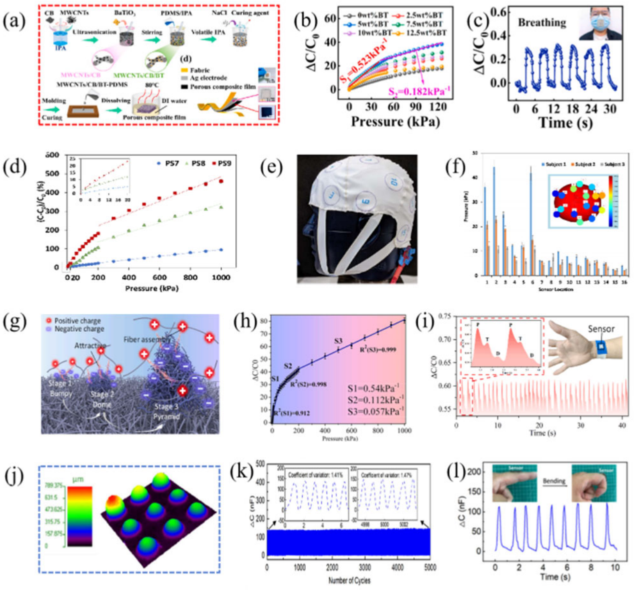

Figure 3. Research Achievements in Capacitive Flexible Wearable Sensors

4. Advancements in Passive Flexible Wearable Sensors for Motion Detection and Health Monitoring

The two traditional flexible wearable sensors discussed in Chapter 3 rely on external power sources, which can impede continuous monitoring and restrict their potential applications. This chapter introduces two innovative types of passive flexible wearable sensors, the piezoelectric and triboelectric sensors, which are capable of self-generating power during operation. By eliminating dependence on external power sources, these self-powered sensors offer significant prospects for future development.

4.1 Advancements in Piezoelectric Flexible Wearable Sensors

Piezoelectric materials generate electrical charges in response to external forces. The commonly used piezoelectric materials can be broadly categorized into two groups: piezoelectric ceramics represented by various inorganic salt compounds, and polymer piezoelectric materials, with polyvinylidene fluoride (PVDF) serving as a notable example. Additionally, the design of microstructures and the development of novel piezoelectric materials are important strategies employed to enhance sensor performance.

To mitigate the brittleness of piezoelectric ceramics, Xu et al.[21] drew inspiration from the arched structure of the hinge in scallops and designed a droplet-shaped barium zirconate titanate (BCZT) ferroelectric ceramic piezoelectric sensor. This innovative structure converts vertical loads into internal compressive stresses distributed along the arch, resulting in a more uniform stress distribution and significantly improving performance in detecting knee joint bending. In contrast to piezoelectric ceramics, polymer piezoelectric materials offer greater flexibility but generally exhibit lower piezoelectric performance. To address this issue, Zhang et al.[22] used electrostatic spinning to make a mixture of polyvinylpyrrolidone (PVP) and PVDF, followed by the removal of the PVP core to obtain PVDF nanofibers featuring a microporous structure. This hollow design increases both the friction area and compressibility of the PVDF material when subjected to pressure, resulting in a sensitivity of 2.7 V/N (1.08 V/kPa) and a maximum output voltage of 10.1 V, making it suitable for detecting finger movements.

Beyond structural design, the creation of composite materials that integrate complementary properties has become an important research focus. For instance, Xiong et al.[23] introduced dopamine (DA) into PVDF materials. The hydrogen bonding and dipole interactions within DA promote the formation of additional β-phase crystals in PVDF and enable the uniform adhesion of ultrafine nanofibers to the surfaces of coarser fibers, thereby alleviating stress concentration. This enhancement allows the sensor to withstand 10,000 cycles of stress and demonstrates a sensitivity of 7.29 V/N within a pressure range of 0-4 N, making it effective for monitoring vocalization. Huang et al.[24] discovered that polydopamine (PDA) can enhance the adhesion and interfacial compatibility of zinc oxide (ZnO) with a polyacrylonitrile (PAN) matrix, thereby improving the bonding strength between the piezoelectric nanoparticles and the matrix. This improvement results in enhanced piezoelectric performance and stability, showing a high sensitivity of 28.56 V/N and stability during 3,000 cycles of loading and unloading. These sensors demonstrate excellent performance in gait recognition and motion posture correction. A selection of the research data and findings is illustrated in Figure 4.

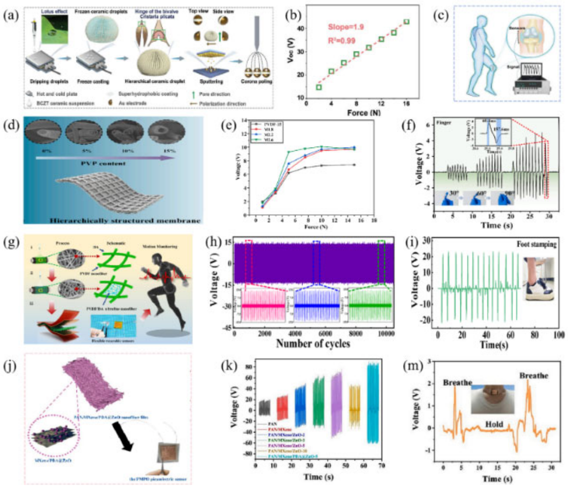

Figure 4. Research Achievements in Piezoelectric Flexible Wearable Sensors

4.2 Advancements in Triboelectric Flexible Wearable Sensors

Triboelectric flexible wearable sensors provide broader energy generation conditions and a wider range of material options compared to piezoelectric sensors. These sensors can convert external forces into electrical signals through the triboelectric effect and electrostatic coupling when two materials with differing electrostatic properties contact and rub against each other. As a result, triboelectric sensors are a promising choice for future passive, self-powered applications, garnering significant interest from researchers.

To address the challenges of low output power and energy conversion efficiency in PVDF films, Liu et al.[25] developed a nanostructured antimony-doped tin oxide (ATO). The addition of ATO increases the interfacial area and creates charge trap sites, thereby enhancing the interfacial polarization effect and mitigating the decay of triboelectric charges. Furthermore, ATO promotes the formation of a more favorable β-phase in PVDF, resulting in an open-circuit voltage and short-circuit current of 548.0 V and 11.25 μA for the ATO/PVDF composite material, representing improvements of 4.45 times and 4.12 times, respectively, compared to pure PVDF. This substantial increase in output power—by 11.5 times—demonstrates its excellent suitability for gesture recognition systems. In another approach, Meena et al.[26] created a positive triboelectric layer by electrospinning a highly adhesive polybutadiene polyurethane (PBU) material onto a conductive silver-coated fabric. PBU, which contains maleimide, furfural, and hydrogen bonds, can undergo a Diels-Alder reaction to reconnect broken polymer chains when exposed to heat, thereby enabling self-repair. This feature allows the sensor to effectively recognize different breathing patterns.

Enhancing the surface roughness of triboelectric materials is a well-established method for improving sensing performance, often achieved by incorporating inorganic particles or utilizing sandpaper as a mold. Hema et al.[27] embedded cobalt ferrite (CF, $CoFe_2O_4$) with a spinel structure into polyvinylidene fluoride (PVDF), which increased the surface roughness of the PVDF fibers and expanded the contact area when subjected to force. The presence of CF particles also improved the hydrophobicity of the sensor, allowing it to effectively monitor pulse signals from various parts of the body. Designing microstructures on the contact surfaces of triboelectric materials can yield comparable benefits. For example, Luo et al.[28] developed a NaCl/PVA hydrogel triboelectric sensor featuring a gradient microporous structure by sacrificing salt grains of varying sizes within a polyvinyl alcohol (PVA) hydrogel. This innovative structure enhanced the sensor's output performance and charge transfer rate, achieving a sensitivity of 1.95 V/kPa within a pressure range of 0–11.28 kPa. The team employed this sensor to monitor drivers' health status and fatigue levels, showcasing its potential applications in health monitoring.

Interdigitated electrode structures can similarly enhance the performance of triboelectric flexible wearable sensors. For instance, Yang et al.[29] designed an interdigitated electrode structure using manganese dioxide/carbon/polyvinyl alcohol (PVA) as the cathode and conductive silver paste as the anode, leveraging the electrochemical reaction between manganese and silver. The interdigitated design increases the contact area between the electrodes and the electrolyte under applied force, resulting in an open-circuit voltage of 0.927 V, a short-circuit current of 6 μA, and a sensitivity of 14 mV/kPa. This sensor can effectively detect bending movements at various joints, highlighting its promising applications in motion rehabilitation. Inspired by the structure of neural synapses, Zhang et al.[30] developed an interdigitated electrode structure designed to maximize contact area. They also incorporated fluorescent isothiocyanate particles into a fluorescent acrylic layer to enhance surface microroughness, facilitating charge separation between the polyvinyl alcohol film and the acrylic fluorescent layer through interfacial effects. These sensors were integrated into insoles for human gait recognition and detection. A selection of research data and findings is illustrated in Figure 5.

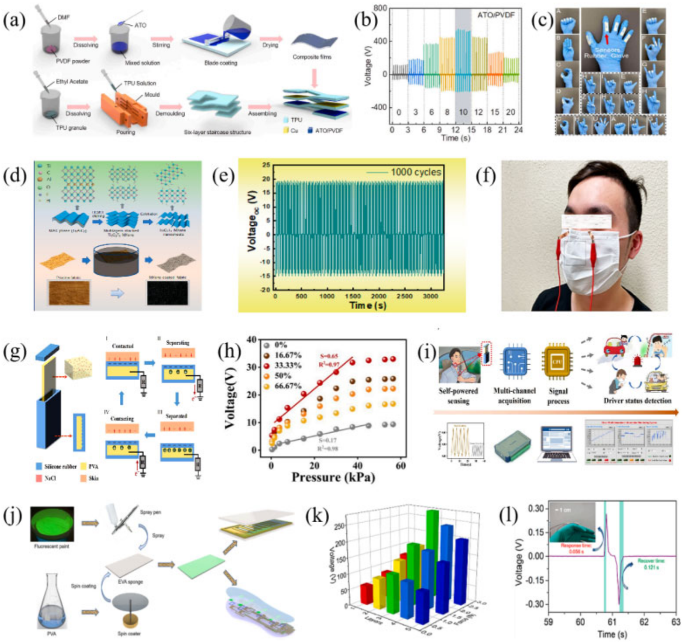

Figure 5. Research Achievements in Triboelectric Flexible Wearable Sensors

5. Summary and Outlook

This thesis presents a comprehensive overview of the fundamental principles behind four types of flexible wearable sensors designed for motion detection and health monitoring. It highlights innovations in material development, structural design, fabrication processes, and application scenarios. Biocompatible flexible polymers and inorganic materials with superior electromechanical properties are extensively utilized, and their combination in composite materials allows for complementary advantages. Structural design plays a critical role in enhancing sensor performance; macroscopic structures, such as grid-like configurations and interdigitated electrode structures, significantly increase the contact area of the sensors. However, the incorporation of microscopic structures, such as micropores and microspheres, is more prevalent, as these features enhance the deformation of the sensing elements during operation, thereby improving both detection range and sensitivity. Moreover, advancements in fabrication techniques, including electrospinning and laser-induced processes, have lowered manufacturing costs, enabling large-scale production and distribution of these sensors. The integration of cutting-edge technologies, such as convolutional neural networks and the Internet of Things (IoT), has expanded the application scenarios for these four types of sensors in motion detection and health monitoring, providing more accurate and reliable data for fields such as rehabilitation medicine and real-time patient monitoring.

Despite the significant progress achieved in these studies, several challenges and unresolved issues persist. The primary challenge is balancing high sensitivity with a wide detection range; future efforts must focus on developing sensors that optimize overall performance. Another concern is that the repetitive stress generated by prolonged human motion can compromise the internal microstructures of the sensors, leading to irreversible damage or material degradation, which ultimately reduces sensitivity and may even result in sensor failure. For example, microcolumn structures can collapse, or piezoelectric hydrogels may experience dehydration and ion leakage under extreme strain. To address this issue, there is a need for advanced packaging techniques that enhance the stability of these sensors. Additionally, the output and processing of physiological signals by flexible wearable sensors face significant challenges. The electrical signals generated by the piezoelectric effect tend to be weak, necessitating complex amplification circuits. Moreover, the high voltage and low current produced by the triboelectric effect can complicate integration with conventional sensors. Environmental factors, such as humidity on the skin and external mechanical vibrations, can further impede the sensors’ ability to accurately capture motion and physiological signals. Enhancing the sensors' resistance to interference and their capability to effectively detect subtle physiological signals in complex environments remains an urgent challenge. Furthermore, much of the current research emphasizes simplifying laboratory-scale sensor fabrication techniques, which do not satisfy the requirements for large-scale production and commercialization. For instance, the widely used electrospinning method struggles to maintain uniformity in nanofiber structures during mass production, while template-based methods may suffer damage during material detachment, leading to inaccuracies. There is a pressing need to develop cost-effective processing technologies that facilitate the industrial-scale production of high-performance flexible wearable sensors. Lastly, concerns regarding potential skin irritation and environmental pollution from the materials used in flexible wearable sensors cannot be overlooked. For example, polydimethylsiloxane (PDMS) is commonly employed as a flexible substrate and sensing layer, but prolonged use can lead to discomfort and allergic reactions. Although polyvinylidene fluoride (PVDF), often used in self-powered sensors, is reusable, its recycling costs remain prohibitively high, and incinerating it with other waste may lead to environmental contamination. Therefore, the development of materials that are both biocompatible and environmentally friendly represents a crucial challenge for future research.

In the future, as technologies such as materials science, the IoT, and artificial intelligence continue to evolve, flexible wearable sensors for motion detection and health monitoring are poised to advance toward greater intelligence, multi-functionality, and portability. We can anticipate the development of materials with enhanced self-healing properties to ensure that these sensors can be comfortably worn for extended periods. Moreover, by utilizing big data and artificial intelligence, these sensors will be able to detect physiological signals in real-time with remarkable accuracy. The next generation of flexible wearable sensors will significantly enhance their capabilities for processing and analyzing bodily signals, further improving data accuracy and reliability.

References

[1] Luo Y, Abidian M R, Ahn J H, et al. Technology roadmap for flexible sensors[J]. ACS nano, 2023, 17(6): 5211-5295.

[2] Sun T, Feng B, Huo J, et al. Artificial intelligence meets flexible sensors: emerging smart flexible sensing systems driven by machine learning and artificial synapses[J]. Nano-Micro Letters, 2024, 16(1): 14.

[3] Niu H, Yin F, Kim E S, et al. Advances in flexible sensors for intelligent perception system enhanced by artificial intelligence[J]. InfoMat, 2023, 5(5): e12412.

[4] Zhou Y, Zhang Y, Zhou Y, et al. Waterproof breathable multifunctional flexible sensor for underwater tactile sensing and ammonia gas monitoring[J]. Nano Energy, 2023, 117: 108881.

[5] Li L, Wang X, Gao S, et al. High-toughness and high-strength solvent-free linear poly (ionic liquid) elastomers[J]. Advanced Materials, 2024, 36(7): 2308547.

[6] Roy A, Zenker S, Jain S, et al. A Highly Stretchable, Conductive, and Transparent Bioadhesive Hydrogel as a Flexible Sensor for Enhanced Real-Time Human Health Monitoring[J]. Advanced Materials, 2024, 36(35): 2404225.

[7] Li Y, Yang D, Wu Z, et al. Self-adhesive, self-healing, biocompatible and conductive polyacrylamide nanocomposite hydrogels for reliable strain and pressure sensors[J]. Nano Energy, 2023, 109: 108324.

[8] Roy A, Zenker S, Jain S, et al. A Highly Stretchable, Conductive, and Transparent Bioadhesive Hydrogel as a Flexible Sensor for Enhanced Real-Time Human Health Monitoring[J]. Advanced Materials, 2024, 36(35): 2404225.

[9] Kim K H, Hong S K, Jang N S, et al. Wearable resistive pressure sensor based on highly flexible carbon composite conductors with irregular surface morphology[J]. ACS Applied Materials & Interfaces, 2017, 9(20): 17499-17507.

[10] Chen L, Ye H, Yu P. A breathable and sweat-absorbing pressure sensor based on PDMS gradient foam to achieve high sensitivity and wide detection range[J]. Composites Science and Technology, 2024, 253: 110628.

[11] Zhang M, Yang Y, Hu H, et al. High-Performance Stretchable Strain Sensors Based on Auxetic Fabrics for Human Motion Detection[J]. ACS Applied Materials & Interfaces, 2024, 16(37): 49845-49855.

[12] Liu L, Luo T, Kuang X, et al. Highly stretchable and multimodal MXene/CNTs/TPU flexible resistive sensor with hierarchical structure inspired by annual ring for hand rehabilitation[J]. ACS sensors, 2024, 9(5): 2476-2487.

[13] Xia X, Ding X, Zhang L, et al. Laser direct writing inkless flexible sensor[J]. IEEE Sensors Journal, 2023, 24(4): 4267-4273.

[14] Wang J, Li L, Liu H, et al. Screen-printed highly sensitive and anisotropic strain sensors with asymmetrical inner concave honeycomb cross-conducting structure for health monitoring of medical electrophysiological signals[J]. IEEE Sensors Journal, 2023, 23(21): 25732-25748.

[15] Xiao Y, Guo D, Yang L, et al. Fabric-based capacitive pressure sensors for porous four-phase composites with high sensitivity and wide linearity range[J]. Composites Science and Technology, 2024, 256: 110794.

[16] Masihi S, Panahi M, Maddipatla D, et al. Highly sensitive porous PDMS-based capacitive pressure sensors fabricated on fabric platform for wearable applications[J]. ACS sensors, 2021, 6(3): 938-949.

[17] Wang X, Li Y, Wang Y, et al. Fabrication method and various application scenarios of flexible capacitive pressure sensor based on direct formation of conical structure[J]. Chemical Engineering Journal, 2024, 496: 153957.

[18] Cheng A J, Chang W, Qiao Y, et al. High-performance supercapacitive pressure sensors via height-grading micro-domes of ionic conductive elastomer[J]. ACS Applied Materials & Interfaces, 2024, 16(43): 59614-59625.

[19] Li X, Liu Y, Ding Y, et al. Capacitive pressure sensor combining dual dielectric layers with integrated composite electrode for wearable healthcare monitoring[J]. ACS Applied Materials & Interfaces, 2024, 16(10): 12974-12985.

[20] Feng Z, He Q, Wang X, et al. Capacitive sensors with hybrid dielectric structures and high sensitivity over a wide pressure range for monitoring biosignals[J]. ACS Applied Materials & Interfaces, 2023, 15(4): 6217-6227.

[21] Xu Q, Tao Y, Wang Z, et al. Highly flexible, high-performance, and stretchable piezoelectric sensor based on a hierarchical droplet-shaped ceramics with enhanced damage tolerance[J]. Advanced Materials, 2024, 36(18): 2311624.

[22] Zhang Q, Li J, Li G, et al. Hierarchically structured hollow PVDF nanofibers for flexible piezoelectric sensor[J]. Chemical Engineering Journal, 2024, 498: 155661.

[23] Xiong J, Wang L, Liang F, et al. Flexible Piezoelectric Sensor Based on Two-Dimensional Topological Network of[J]. 2024.

[24] Huang Y, Chen S, Li Y, et al. Flexible piezoelectric sensor based on PAN/MXene/PDA@ ZnO composite film for human health and motion detection with fast response and highly sensitive[J]. Chemical Engineering Journal, 2024, 488: 150997.

[25] Liu S, Qing W, Zhang D, et al. Flexible staircase triboelectric nanogenerator for motion monitoring and gesture recognition[J]. Nano Energy, 2024, 128: 109849.

[26] Meena J S, Khanh T D, Jung S B, et al. Self-repairing and energy-harvesting triboelectric sensor for tracking limb motion and identifying breathing patterns[J]. ACS Applied Materials & Interfaces, 2023, 15(24): 29486-29498.

[27] Venkatesan H M, Mohammad S R, Ponnan S, et al. Cobalt ferrite-embedded polyvinylidene fluoride electrospun nanocomposites as flexible triboelectric sensors for healthcare and polysomnographic monitoring applications[J]. Nano Energy, 2024, 129: 110003.

[28] Luo F, Chen B, Ran X, et al. Wearable and self-powered triboelectric sensors based on NaCl/PVA hydrogel for driver multidimensional information monitoring[J]. Nano Energy, 2023, 118: 109035.

[29] Yang Z, Wang Q, Yu H, et al. Self-Powered Biomimetic Pressure Sensor Based on Mn–Ag Electrochemical Reaction for Monitoring Rehabilitation Training of Athletes[J]. Advanced Science, 2024, 11(25): 2401515.

[30] Zhang D, Xu Z, Wang Z, et al. Machine-learning-assisted wearable PVA/Acrylic fluorescent layer-based triboelectric sensor for motion, gait and individual recognition[J]. Chemical Engineering Journal, 2023, 4