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REVIEW

Fiber/Yarn and Textile-Based Piezoresistive Pressure Sensors

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Abstract

The rapid growth of wearable technology has significantly enhanced the capabilities of wearable sensors, transitioning from simple attachments of rigid electronics to the more comfortable and adaptable integration with soft substrates. Among these, flexible piezoresistive pressure sensors are particularly notable for their straightforward and reliable signal readout. Fiber, yarn, and textile-based sensors, which allow for multiscale material and structural engineering, present ideal solutions for achieving sensors with excellent wearability, sensitivity, and scalability potential. Innovations in materials and the advancement of artificial intelligence (AI) have further enhanced sensor performance, adding multifunctional capabilities and broadening their applications. This review systematically examines fiber, yarn, and textile-based piezoresistive pressure sensors, covering fundamental mechanisms, key performance metrics, conductive and substrate materials, structural designs, fabrication techniques, multifunctional integrations, and advanced applications in healthcare, fitness, and human–machine interaction, augmented by machine learning (ML). Finally, the review discusses sensor design and technical considerations, material–structure–property engineering, scalable production, performance evaluation, and offers recommendations and prospects for future sensor research and development. This comprehensive overview aims to provide a deeper understanding of current innovations and challenges, facilitating the advancement of flexible and intelligent wearable sensing technologies.

Keywords Wearable sensors · Smart textiles · Structural design · Fabrication strategies · Multifunctionality · Machine learning

1 Introduction

In recent decades, the field of wearable technology has experienced remarkable growth and innovation, transforming the way we interact with and perceive our surroundings. With the rise of information technology and the Internet of Things (IoT), wearable electronics have become essential parts of daily life, enhancing our capabilities in various domains, from healthcare and fitness to entertainment and beyond. Driven by the demand for unobtrusive and comfortable integration, wearable devices have evolved from the traditional attachment of rigid electronics to more flexible and conformable forms such as polymeric films and textiles with reduced bulkiness [1]. Electronic textiles (e-textiles) have garnered significant attention due to their material and structural engineering potential, as well as their unique mechanical properties, scalability, and breathability [2–5].

The convergence of material science, textile, and electrical engineering has accelerated the development of diverse e-textile devices with a wide range of functionalities, extending across scales from one-dimensional (1D) fiber to two-dimensional (2D) fabric and three-dimensional (3D) structures. These devices include sensors, actuators, light-emitting/color-changing devices, nanogenerators, supercapacitors/batteries, and antennas [6–16]. Sensors are central to the functionality of integrated wearable electronic systems, playing a crucial role in capturing physiological, biochemical, and biomechanical data [17, 18]. With an increasing focus on personalized health care due to the aging population, the demand for wearable sensors has been booming, reaching a market value of over USD 1.5 billion in 2023 and expected to grow significantly in the next decade [19]. Pressure sensors are a key category that measure electrical, electromagnetic, or light signals in response to compressive stress based on various physical mechanisms, such as piezoresistive, capacitive, triboelectric, piezoelectric, ionic, electromagnetic, and optical mechanisms

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[20–22]. Among these, piezoresistive sensors stand out due to their easy signal readout, resistance to interference, scalability, low power consumption, and low fabrication cost [23–25]. With the rapid advancement of nanotechnologies and e-textiles, several reviews have focused on piezoresistive pressure sensors, exploring their fundamentals, materials, microstructures, and performance enhancements from a material science perspective [20, 24, 26]. In addition, there are reviews on resistive strain sensors based on fiber and textile architectures [27, 28]. Advanced data analysis approaches, especially those utilizing ML algorithms, are increasingly employed to extract valuable insights from the complex data collected by piezoresistive pressure sensors. These approaches enable classification, identification, and prediction tasks, fostering the development of intelligent wearable sensing systems beyond traditional methods [22, 29]. Several recent reviews have discussed the integration of AI/ML with flexible sensing technologies for comprehensive processing and interpretation of multi-dimensional sensor data in fields such as human–machine interaction, health monitoring, and robotics [22, 29, 30]. However, a review addressing piezoresistive pressure sensors based on fiber/yarn/textile structures, encompassing advances in sensor design, fabrication, and ML-enhanced applications, is not available.

Therefore, this review aims to (1) provide a comprehensive overview of piezoresistive pressure sensors from a textile perspective, emphasizing materials, structures, fabrication strategies, and multifunctional applications (Fig. 1), and (2) summarize current innovations and challenges in sensor design and technology to facilitate the development of flexible and intelligent wearable sensing systems. The first section offers a brief understanding of the fundamentals of piezoresistivity and key performance metrics in sensor evaluation. The second section summarizes the vast variety of available conductive and substrate materials commonly employed. The third section elaborates on the structural principles and fabrication techniques of piezoresistive pressure sensors based on 1D fiber/yarn shapes and 2D/3D composites. The fourth section highlights advancements towards the integration of multifunctionalities. In the fifth section, applications enhanced by AI-assisted data analysis are reviewed in two major categories: healthcare and fitness, and human–machine interactions. In addition, we discuss design and technical considerations, key challenges of fiber/yarn/textile-based piezoresistive pressure sensors, and perspectives on potential solutions for future research and development.

2 Mechanism and Performance Parameters

2.1 Fundamentals and Working Principles

The variation in conductivity due to strain was initially discovered in iron and copper by Thomas in 1856 [42]. The term "piezoresistive effect" (also known as piezoresistance or piezoresistivity) was first introduced by Cookson in 1935 [43], following the discovery of piezoelectricity (the generation of charge when stress is applied) [44]. The piezoresistive effect is defined as the phenomenon where a material's resistance changes when subjected to mechanical loads.

Existing fiber or textile-based piezoresistive sensors primarily leverage two principles: alteration of the conductive network within heterogenous conductive composites and changes in interfacial contact resistance under pressure. To begin, we provide a fundamental understanding of the piezoresistive effect in homogeneous materials such as metals and semiconductors, which is explained by intrinsic geometric or resistivity (ρ) variance [45]. Assuming a metal conductor has a cylindrical shape, its resistance (R) can be expressed as

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

When the material is subjected to mechanical deformation under a longitudinal tensile force, the GF can be expressed as the relative resistance change ($\Delta R / R_0$) divided by the strain:

$$GF = \frac{\Delta R}{R_0 \varepsilon} = (1 + 2\nu) + \frac{\Delta \rho}{\rho_0 \varepsilon} \tag{2}$$

where L is the longitudinal length, A is its cross-sectional area, ν is the Poisson's ratio, $\Delta\rho / \rho_0$ is the relative resistivity change, and ε is the longitudinal strain of the material.

For crystalline materials, the relative resistivity change can be expressed with stress (σ) and the piezoresistive coefficient (π), and the GF or piezoresistive effect can correlate to the Young's modulus (E) as follows [46]:

$$GF = (1 + 2\nu) + \frac{\Delta \rho}{\rho_0 \varepsilon} = (1 + 2\nu) + \frac{\pi \sigma}{\varepsilon} = 1 + 2\nu + \pi E \tag{3}$$

The piezoresistive effect in intrinsic metals is mainly determined by geometry changes since their piezoresistive coefficient is negligible, resulting in a GF of around 1.5–2, which gives a resistance change of the magnitude 10^{-3} due to limited strain [46]. In contrast, for semiconductors, the piezoresistive effect occurs at the microscale depending on their crystallographic structure and is usually stronger than in metals [24, 47]. For example, the resistivity of slightly doped silicon and germanium has been measured to be around 1.5–22.7 Ω • cm

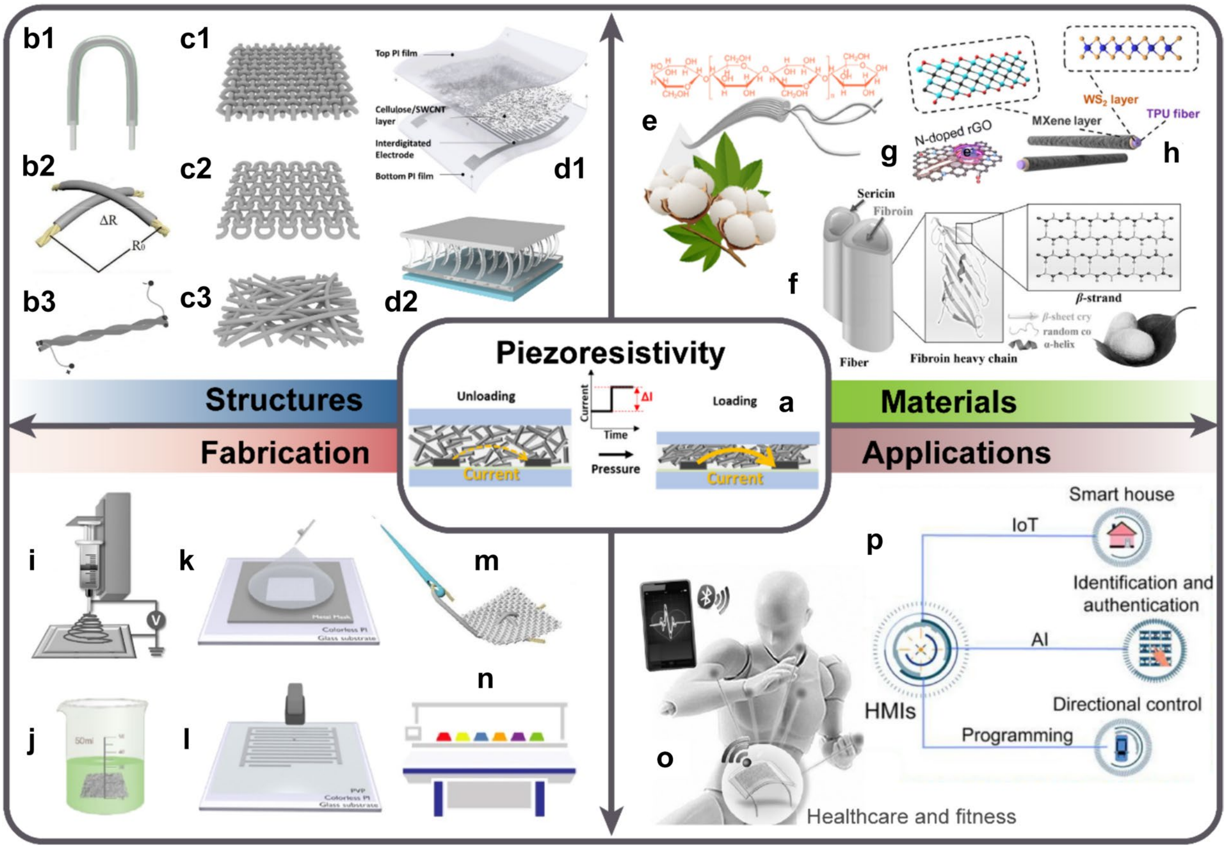

Fig. 1 An overview of materials, structures, fabrication approaches and applications for fiber/yarn and textile-based piezoresistive pressure sensors. **a** Schematic illustration of piezoresistivity; reproduced with permission from Ref. [31], Copyright 2021, American Chemical Society. One- to three-dimensional forms of sensor structures: **b1** a single yarn; reproduced under the terms of the CC-BY license from Ref. [32], Copyright 2023, The Authors; **b2** cross-arranged yarns; reproduced with permission from Ref. [33], Copyright 2022, Elsevier; **b3** a double-twisted yarn; reproduced with permission from Ref. [34], Copyright 2016, WILEY-VCH; **c1** wovens, **c2** knits, and **c3** nonwovens; **d1** a typical sandwiched configuration with film encapsulation; reproduced with permission from Ref. [31], Copyright 2021, American Chemical Society; **d2** a functional stacked configuration; reproduced with permission from Ref. [35], Copyright 2022, Elsevier. Various constituent substrate and conductive materials: **e** cotton; reproduced with permission from Ref. [36], Copyright 2022, Elsevier; **f** silk; reproduced with permission from Ref. [37], Copyright 2017, WILEY-VCH; **g** N-doped reduced graphene oxide (rGO); reproduced under the terms of the CC-BY license from Ref. [32], Copyright 2023, The Authors; **h** thermoplastic polyurethane (TPU) and $Ti_3C_2T_x$-MXene and tungsten disulfide (WS_2); reproduced with permission from Ref. [38], Copyright 2023, American Chemical Society. Fabrication methods for the formation and integration of functional elements: **i** electrospinning; reproduced with permission from Ref. [37], Copyright 2017, WILEY-VCH; **j** dip coating; reproduced with permission from Ref. [39], Copyright 2022, American Chemical Society; **k**, **l** spray coating and inject printing; reproduced with permission from Ref. [31], Copyright 2021, American Chemical Society; **m** embroidery; reproduced with permission from Ref. [33], Copyright 2022, Elsevier; **n** digital knitting; reproduced with permission from Ref. [40], Copyright 2021, The Authors, Springer Nature Limited. Applications span from **o** healthcare and fitness tracking; reproduced with permission from Ref. [37], Copyright 2017, WILEY-VCH, to **p** human–machine interaction; reproduced with permission from Ref. [41], Copyright 2023, Donghua University, Shanghai, China

[48]. In semiconductors, resistivity is a function of electron charge, concentration, and mobility, defined as

$$\rho = \frac{1}{ne\mu} \tag{4}$$

According to Eq. (2) the GF is derived as

$$GF = (1 + 2\nu) + \frac{\Delta(n\mu)}{n\mu\varepsilon} \tag{5}$$

where n, e, and μ are the concentration, charge, and mobility of an electron, respectively. Variance in resistivity in a semiconductor material is caused by alterations in the energy band and charge carrier mobility related to crystal distortion, resulting in significant changes in resistance. The degree of this charge is affected by dopants and lattice directions [24, 29].

For heterogeneous materials widely used in the development of flexible piezoresistive pressure sensors, the above equations cannot be applied due to their volumetric non-uniformity. Resistance change can occur at macro-, micro- or nanoscale levels in specific positions of heterogeneous textile materials. Different working principles and models can be introduced based on the material and structure design. Generally, the total resistance of a piezoresistive pressure sensor can be expressed as

$$R = R_s + R_c + R_e \cong R_s + R_c \tag{6}$$

where R_s is the resistance of the sensitive layer, R_c is the contact resistance between the functional layer and the electrodes and/or between multiple functional layers, and R_e is the resistance of the electrodes (which can be omitted due to the relatively high conductivity of metal conductors compared to other components).

Attributed to the unique hierarchical architecture of textiles, the piezoresistive effect can be derived from contact resistance changes between conductive components caused by the tightening of loose conductive fiber networks and/or enhanced contact points between the sensing layer and electrodes (decreased R_c). In conductive fiber networks, fiber contact transforms from separation or "point" contact to "plane" contact under pressure, increasing the contact area and conductive pathways (Fig. 2a) [49]. The relative resistance change for a textile piezoresistive pressure sensor can be described as follows, considering proportional resistivity to fiber length and Hook's Law [50]:

$$\frac{\Delta R}{R_0} = \frac{\Delta P}{E_p} = \frac{\Delta P}{\eta E_f V_f^3} \tag{7}$$

where E_p is the compression modulus of the textile structure, η is a coefficient correlated to fabric type, fiber size, and orientation, E_f is the fiber modulus (assuming equal values for compression and tension), and V_f is the fiber volume fraction.

Since $\eta<1$ and $V_f<1$ ($E_p<E_f$) for textile materials, inconsistency exists between bulk and fiber deformation as fiber bending dominants instead of compression at the microscale, resulting in a non-linear buffering effect in the textile structure [50]. Equation (7) indicates the structural dependency and importance of fiber size, volume, and distribution—i.e., the compressibility and porosity of fiber assemblies—in the piezoresistive effect of the material. This provides potential pathways for tuning sensor sensitivity by adjusting parameters such as fiber size, orientation, stiffness, and amount.

It is worth mentioning that material dimension is another crucial factor affecting piezoresistive performance. The coating of conductive nanomaterials synergistically enhances the effect of contact areas on resistance reduction. Reducing the

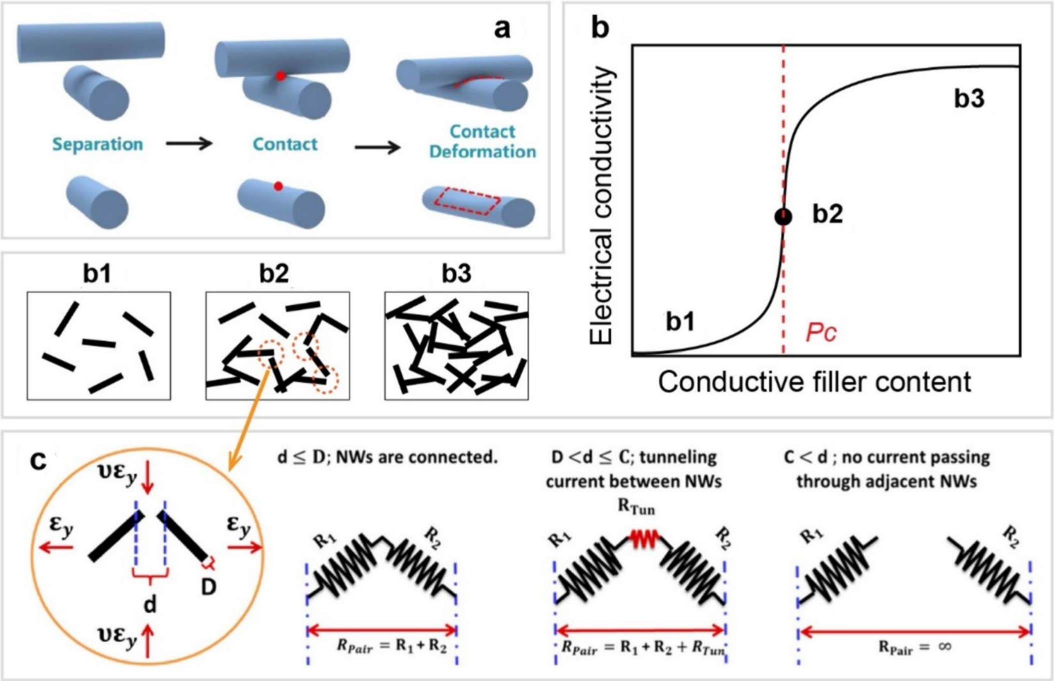

Fig. 2 Models and theories for piezoresistive pressure sensors. **a** A model of fiber contact within a conductive fiber network under pressure; reproduced with permission from Ref. [49], Copyright 2021, Elsevier. **b** Percolation theory for polymer composites with conductive fillers and three representative doping states: **b1** insulation, **b2** percolation, and **b3** conductive state. **c** Tunneling effect of adjacent conductive nanofillers and electrical interconnections depending on their distances; adapted with permission from Ref. [55], Copyright 2014, American Chemical Society

sizes of conductive elements from the 3D bulk to 0D–2D nanoscale leads to a significant increase in surface areas and the generation of discrete energy levels for electrons [24]. Surface electromechanical properties can, therefore, dominate the piezoresistive effect due to the substantial variation in charge carrier content and concentration caused by the confined movement of electrons [51]. In view of this, various microstructures and nanomaterials have been explored to improve piezoresistive performance, which will be discussed in later sections.

For fiber/yarns containing intrinsic piezoresistive material made of a stretchable matrix and conductive fillers, piezoresistive sensing is based on percolation theory and tunneling effect (decreased R_s). At a critical value (known as the percolation threshold, P_c) of filler concentration, the conductivity of the composite (σ) exhibits a drastic increase due to the formation of conductive paths (Fig. 2b). The relationship between material conductivity and filler properties is expressed as follows [29, 52]:

$$\sigma \propto \sigma_0 \left(P - P_c\right)^t \tag{8}$$

where σ_0 is the conductivity of the conductive filler, P is the filler concentration, and t is the power of conductivity increase after reaching the threshold, as discussed by Stauffer and Aharony [53]. They have explored the percolation theory by examining cluster number, size, and geometry for a more in-depth understanding from statistical and material science perspectives.

Mechanical deformation of the composite material reduces the spaces between adjacent non-contacting filler particles. When adjacent conductive fillers come within a certain cutoff distance, a quantum tunneling junction is formed, allowing electrons to pass through the polymer matrix and thereby decreasing the macroscopic resistance of the composite (Fig. 2c). The tunneling resistance (R_{tun}) can be estimated based on Simmons's theory as a function of the electrical potential difference (V), cross-sectional area (A), and current density (J) at the tunneling junction as follows [54, 55]:

$$R_{tun} = \frac{V}{AJ} = \frac{h^2 d}{Ae^2\sqrt{2m\lambda}} \exp\left(\frac{4\pi d}{h}\sqrt{2m\lambda}\right) \tag{9}$$

where h is Plank's constant, d is the distance between fillers, e is the charge of a single electron, m is the electron mass, and λ is the height of the energy barrier for the polymer matrix.

2.2 Performance Evaluation Metrics

As mentioned above, the GF, also known as sensitivity, is universally used to quantitatively characterize the piezoresistive response of a pressure sensor under an external compressive force. Sensitivity is crucial for determining the sensor's responsiveness to subtle changes in stimuli and the accuracy of signal measurement [56]. According to the literature, sensitivity as a function of the relative change in resistance can also be expressed in current (I) according to Ohm's Law when the sensor is subjected to a pressure (P):

$$GF = \frac{\Delta R}{R_0 P} = \frac{\Delta I}{I_0 P} \tag{10}$$

where $\Delta I / I_0$ is the relative current change. Often, force in Newton is characterized instead of pressure for piezoresistive sensors in the form factor of a fiber/yarn due to the small contact area of a single sensing unit, which changes as the fiber cross-sectional area deforms under compression.

The sensing range of pressure and signal linearity are also significant performance metrics to consider in practical sensor applications. The trade-off between high sensitivity and a large linear sensing range has been one of the most studied topics for flexible sensors due to the non-linear elasticity of soft materials. Equations (7, 8, 9) also indicate non-linear relationships between resistance and pressure for heterogenous textile materials. Typically, fiber/yarn or textile-based piezoresistive sensors exhibit high initial sensitivity, which decays as pressure increases due to saturation. Maintaining high sensitivity across a wide linear sensing range remains challenging. Improvements in sensitivity or sensing range are widely studied through careful design schemes exploiting various microstructures and nanomaterials, which will be discussed in more detail in later sections. It is worth noting that the optimization of these metrics should be based on a comprehensive evaluation of application requirements, considering the placement position of the sensor on the human body, preload range, and signal characteristics such as range and frequency. Specially, physiological pressure signals span from hundreds of pascals to megapascal. For instance, tactile sensing of hands requires a sensitivity range of 0.01–10 N [57]. Target pressures are several to over a hundred kilopascals for respiration and knee flexion, and more than one megapascal for treading [58]. Artery pulse generates pressure around 200 Pa [58], and precise measurement needs sensitive linear response under specific preload (20–100 kPa) [59] and bandwidth (0.1–20 Hz) [60].

Moreover, the performance of a piezoresistive pressure sensor is often evaluated by its durability and stability. Durability testing involves measuring the maximum cycles of deformation (compression, bending, stretch, abrasion, etc.) the sensor can endure without significant deterioration in its electromechanical performance. Stability, on the other hand, refers to the sensor's ability to maintain material and performance integrity against external factors, such as time, mechanical loads, temperature, moisture, and chemicals. Stability is influenced by aspects such as signal drift, the frequency and intensity of loads, and the material's susceptibility to environmental stresses. Strategies to enhance the stability and accuracy of flexible sensors include material engineering, physical protection, and effective calibration [56]. For textile-based pressure sensors, additional factors such as air/moisture permeability and washability are considered, given the intrinsic porous structure of textiles. These factors validate the breathability and reliability of functional coatings for wearability.

In addition to durability and stability, hysteresis, response time, and recovery time are key performance characteristics of pressure sensors. Hysteresis refers to the variation in resistance response curves during loading and unloading and is calculated by the ratio of the area difference under the two curves to the area under the loading curve [61]. Response and recovery time are defined as the time taken for 90% of the signal change upon application or removal of pressure, sometimes described within 10%-90% signal levels [62–65]. Short response and recovery times generally result in low hysteresis and high sensitivity [27]. In textile-based pressure sensors, hysteresis often stems from the viscoelastic behavior of the polymer used and depends on the tightness and constraint of the materials and fiber/yarn networks [56, 66]. Strategies to reduce response/recovery time and hysteresis include integrating wrinkled microstructures on the fiber surface, enhancing interfacial adhesion of materials, and employing helical yarn structures [27, 34, 66].

The above chapters addressed essential concepts related to the piezoresistive effect and the critical metrics used to assess piezoresistive pressure sensors. We first introduced the example of homogeneous metals and semiconductors for a basic understanding and then elaborated on the piezoresistive effect of heterogeneous materials in practical scenarios. These scenarios considered two working principles: the change in interfacial contact resistance and the alteration of the conductive network within a piezoresistive composite (percolation theory and tunneling effect) under pressure. Factors such as volumetric compressibility, porosity (including fiber attributes, content, and distribution), and the dimension and concentration of conductive materials are crucial in determining piezoresistive performance. We then discussed key metrics for performance characterization, evaluation, and optimization, including sensitivity, sensing range, linearity, durability, stability, hysteresis, and response and recovery time.

3 Conductive and Substrate Materials

3.1 Conductive Materials

The diverse range of existing materials offers numerous options for flexible sensor design and performance optimization. Conductive networks formed between or within electrodes and sensing layers are essential components of flexible pressure sensors. The choice of conductive materials significantly determines the electrochemical properties of the sensor. Common conductive materials used for fiber/yarn or textile-based pressure sensors can be categorized into inorganic metallic materials and organic conductive materials, including carbonaceous materials and conductive polymers.

3.1.1 Inorganic Metallic Materials

Traditionally, metallic wires such as silver/copper and stainless steel can be used as intrinsic conductive cores [40, 67–69] or wrapped around non-conductive fibers to create electrical connections for specially constructed conductive yarns [70]. While the rigid bulk of a metal core provides excellent electrical conductivity, it limits deformability and flexibility for wearable applications due to its intrinsic stiffness. A commonly adopted strategy to address this problem is to coat the substrate surface physically or chemically with zero- to two-dimensional metallic materials/compounds in the form of nanoparticles/nanocrystals (0D), nanowires (1D), nanosheets (2D), etc. As previously mentioned, the size effect plays an important role in the piezoresistive effect. Reducing material dimensions to the nanoscale not only ensures the intrinsic lightweight and flexibility of yarns and fabrics but also greatly improves performance, such as sensitivity. Metallic nanoparticles (NPs) like silver are among the most common materials in soft electronics due to their high conductivity. Incorporating nanomaterials with different dimensions can further enhance sensing performance [26, 71–73]. However, these materials can suffer from oxidation and adhesion problems when exposed to air and mechanical stress in practical applications, and the preparation involving chemical reduction and deposition complicates the fabrication process. On the other hand, MXenes, which are transition metal carbides, nitrides, or carbonitrides, have attracted increasing attention in the development of wearable pressure sensors due to their hydrophilic surface properties, easily modifiable functional groups, and outstanding electrical and mechanical properties [25]. MXene nanosheets, such as $Ti_3C_2T_x$, are typically produced by chemically etching their parent ternary phase selectively in an acid environment and exfoliated by sonication. They have been applied to fiber/textile-based pressure sensors using simple methods such as impregnation, dip/spray coating, and screen printing as electrodes or to improve sensitivity and sensing range [39, 74–77]. For instance, ultrathin 2D MXene nanosheets offer excellent transparency for optoelectronics and flexible electrodes. They can patch the voids between 1D silver nanowires (AgNWs) to form an interconnected, highly conductive network due to interfacial interactions between the abundant functional groups [77–79]. In addition, gallium-based liquid metals have emerged as a new option for flexible electronics due to their low density, excellent conductivity, fluidic properties, and non-toxicity [80]. For example, pure or copper particle-mixed gallium liquid metal has been introduced into channels in elastomeric poly[styrene-b-(ethylene-co-butylene)-b-styrene] (SEBS) fibers, which are thermally drawn to form pressure-sensing fibers [80, 81]. However, poor adhesive properties, air oxidation, and sealing requirements could potentially limit the practical applications of liquid metals.

3.1.2 Organic Conductive Materials

3.1.2.1 Carbonaceous Materials Carbonaceous materials are among the most extensively used conductive materials in fiber/yarn and textile-based piezoresistive sensors, alongside metallics, due to their excellent conductivity, lightweight nature, and mechanical robustness. Various forms of carbon with high surface areas, including carbon nanotubes (CNTs), graphene, and carbon black (CB), have been incorporated into textile structures as conductive fillers or coatings to enhance their piezoresistive properties. CNTs, categorized into single-walled (SWCNTs) and multi-walled carbon nanotubes (MWCNTs), are 1D nanomaterials typically made through chemical vapor deposition (CVD) with a high aspect ratio (>1000) and excellent electrical conductivity (up to 10^7 S/m) [27]. The intrinsic flexibility and robustness of CNTs make them ideal candidates for integrating into flexible textile structures without compromising their mechanical integrity. In addition, their straightforward deposition through wet/dry processes such as dip/drip coating [41, 82, 83] and wet/dry spinning [84–86] make them advantageous for practical applications in smart textiles. Graphene, known for its honeycomb-like single atomic layer structure and high surface area, enables efficient strain transfer and exhibits superior electrical conductivity ($\sim 10^{-6}$ $\Omega\bullet$cm) [27] and outstanding mechanical robustness. Chemical exfoliation is a commonly used method of mass-producing graphene for textile pressure sensors, involving the reduction of oxidized graphene in an aqueous environment at elevated temperatures to obtain stable reduced graphene oxide (rGO). However, it remains challenging to generate high-quality graphene with no defects during chemical treatment [26]. High-temperature reduction is an alternative approach to fabricating environmentally friendly rGO [87, 88]. CB nanoparticles, produced from the pyrolysis and combustion of hydrocarbons, offer low fabrication cost, flexibility, and stability, apart from high conductivity and low density. CB is cost-effective and easily integrated into textile structures due to its powder form, and it is commonly employed as a conductive filler for active materials [72, 89]. In addition, carbon fibers and fabrics in bulk form are common types of carbon materials used as conductive fillers and electrodes in the fabrication of textile composite piezoresistive pressure sensors due to their high purity and abundant hierarchical surface areas [90–93].

Carbonaceous materials derived from carbonized cotton, silk, and polyimide (PI) are also employed due to the high conductivity of the resulting graphitic structure and facile processing. In this process, insulative precursor materials decompose under high thermal energy produced by a furnace or laser beam to form conductive graphitic rings [35, 37, 94–96]. As heteroatoms are removed by volatilization, the material skeleton becomes hierarchically porous with mass loss while retaining its original macrostructure (yarn, weave, knit, or film). These carbonized materials are favored for their abundant contact points and conductive networks but are limited by their intrinsic brittleness. It should be noted that nitrogen-containing polymers (e.g., PI) are prone to defects generated from impurities during the carbonization process [97]. Overall, it remains challenging to realize the full applicational potential of carbon materials due to energy-intensive synthesis and limited performance reproducibility [97].

3.1.2.2 Conductive Polymers Inherently conductive polymers, considered excellent candidates for biomaterials, are characterized by conjugated carbon–carbon double bonds along their backbone chain, which contain π-electrons that can be polarized to provide electrical conductivity [98]. Typically, insulators or semiconductors in their pure form, these polymers generate delocalized carriers in their doped state, which move directionally upon the application of an electric field. Polypyrrole (PPy), poly(3,4-ethylenedioxythiophene) (PEDOT), and polyaniline (PANI), are common conductive polymers used in fiber/yarn or textile-based piezoresistive sensors due to their ease of processing, good electrical conductivity, flexibility, and biocompatibility. PPy benefits from easy synthesis, good mechanical flexibility, biocompatibility and low cost, making it suitable for sensor applications. Fabrication methods for PPy-based sensors include in-situ chemical oxidation polymerization [33, 99–105] and vapor-phase polymerization (VPP) [106, 107], allowing precise control over the sensor morphology and properties. PANI is known for its biocompatibility, low cost, and facile synthesis routes, including acidic solution-based in-situ chemical polymerization, and has shown compatibility with cellulose for wet spinning [108–114]. Both PPy and PANi possess electrochromic properties under redox reactions, which have been utilized in color-shifting functional devices such as color-warning battery [115] and visualization of non-pixelated pressure mapping [116]. PEDOT and its derivatives, such as PEDOT:PSS (poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate)), a blend of conducting polymer and polyelectrolyte, offer high transparency and compatibility with various substrates. PEDOT is typically fabricated by VPP [62, 117–119], while PEDOT:PSS deposition commonly involves solution-based processes such as inject printing [119], die coating [120], and dip coating [121, 122]. However, the conjugated backbones of conductive polymers limit their extendibility and mechanical stability, making them prone to failure under large deformations when used as functional coatings [28, 123]. They are redox-active and have tunable conductivity in response to environmental stimuli such as humidity, temperature and pH, providing opportunities for developing multifunctional sensors but also posing challenges for long-term performance stability and signal discrimination.

3.2 Substrate Materials

Substrate materials are a vital component in the hierarchical structural design and assembly of fiber/yarn and textile-based pressure sensors. Researchers often utilize natural or synthetic materials that are not intrinsically conductive, subjecting them to special treatments and functionalization to impart electrical properties while maintaining their intrinsic characteristics, such as stretchability and breathability. In addition, synthetic polymers are widely used as matrix materials to create conductive composite layers or yarns that are inherently piezoresistive. These polymers can also serve as substrates for the deposition of conductive materials or protective layers.

3.2.1 Synthetic Polymers

Commercially available synthetic yarns and fabrics, such as polyester, nylon, polyethylene terephthalate (PET), and polyamide (PA), provide a wide variety of substrate choices for functional modifications. As conventional textile materials, they offer reliable mechanical strength, stability, and deformability for wearable sensors. Often, combining these materials with spandex and conductive coatings achieves the desired stretchability and conductivity. In addition, elastomeric polymers such as PU [34, 70, 72, 124–126], polydimethylsiloxane (PDMS) [40, 69, 127], and SEBS [81, 128] are commonly compounded with conductive fillers or designed as fiber base. These materials are favored for their low cost, straightforward preparation, good stability, flexibility, and extendibility, making them ideal for various sensor configurations and applications. PU is especially valued for its excellent stability, remarkable extendibility, and flexibility, making it suitable for applications requiring dynamic movement. PDMS is renowned for its biocompatibility, optical transparency, and flexibility, making it ideal for wearable sensors and biomedical applications. SEBS, which contains both soft and hard phases, offers tunable mechanical properties with high elasticity and softness, beneficial for applications involving repeated deformations. Furthermore, polymers such as PI [66, 75, 87, 129, 130], PDMS [37, 39, 75, 89, 95, 121, 131–134], and PET [39, 130], are commonly used as flexible encapsulation layers or films for active materials in hierarchical fiber/yarn/textile-based pressure sensors. These materials are chosen for their robust mechanical properties, chemical and thermal stability, and compatibility with various fabrication techniques. The versatility and complementary properties of these elastomeric and flexible polymers contribute to the advancement and diversification of fiber/yarn and textile-based piezoresistive sensor technologies.

3.2.2 Natural Biopolymers

As plastic waste becomes an increasing environmental concern, natural biopolymers such as cellulose, silk, and chitosan, are gaining attention for their use in fiber/yarn/textile-based piezoresistive pressure sensors. These biopolymers are valued for their biodegradability, biocompatibility, renewability, and natural abundance. Derived from various bioresources such as plants, pulps, and bacteria, cellulose consists of highly linear polymer chains with abundant hydroxyl groups and is renowned for its hydrophilicity, surface functionality, mechanical strength, and thermal stability [135]. Constructed with naturally fibrous nanostructures, the shape and morphology of cellulose can be easily controlled or functionalized to develop flexible, porous, and sensitive hierarchical composites in the form of fibers, nonwoven membranes, sponges, and aerogels. These structures can be created using facile methods such as wet/electrospinning, soak/spray coating, and freeze-drying [31, 36, 91, 134, 136–142]. Cotton fibers and fabrics are among the most widely used cellulosic supporting materials, offering easy obtainability, excellent softness, breathability, and moisture absorption capabilities, making them suitable for long-lasting wearable sensors and healthcare applications. Due to their inherent properties, high solubility, and modifiability at the molecular level, silk fibroin is considered as an ideal medium for constructing conductive composites, enabling the creation of diverse multifunctional flexible devices [143–147]. The utilization of natural biopolymers in fiber/yarn/textile-based piezoresistive pressure sensors not only contributes to the development of sustainable sensor technologies but also offers unique advantages such as biocompatibility, mechanical robustness, and environmental friendliness. This expands the scope of wearable and biomedical sensing applications.

This section discussed the variety of constituent materials used for fiber/yarn/textile piezoresistive pressure sensors, including their fabrication and characteristics. Table 1 summarizes and compares the performance, cost, and application suitability of different conductive and substrate materials.

4 Structural Design and Fabrication Strategies

The structural and material design of fiber/yarn/fabric-based sensors plays a pivotal role in determining their sensitivity, durability, and compatibility with various applications. Diverse design strategies and manufacturing techniques have been employed to integrate piezoresistive elements into textile matrices, ranging from functionalizing fibers with conductive coatings to incorporating nanomaterials within yarns. This section delves into the crucial aspects of how these sensors are engineered and fabricated to achieve optimal pressure-sensing performances. By understanding the intricacies of structure design and fabrication strategies, researchers and engineers can advance the development of fiber/yarn/textile-based piezoresistive pressure sensors to meet the growing demands for wearable applications.

4.1 Fiber/Yarn-Shaped Piezoresistive Pressure Sensors

Fiber/yarn-shaped sensors provide distributed sensing capability, allowing for the measurement of pressure across desired areas with unobtrusive and seamless integration. Their 1D form factors enable a higher sensing pixel density compared to fabric or film formats. In addition, they are favored for their customizable breathability and pattern design, which can be achieved through various scalable integration techniques such as weaving, knitting, braiding, sewing, and embroidery [112, 148]. By leveraging existing fiber fabrication technologies such as fiber spinning and extrusion, these sensors offer intriguing opportunities for functional design and material incorporation, promoting fundamental transformations in wearable electronics [89].

4.1.1 Fiber/Yarn Structures

Fiber/yarn level sensor design is characterized by the integration of sensing elements directly into the structure of a fiber or yarn (consisting of multiple fibers) before higher level integration, providing inherent flexibility, lightweight, and conformability to irregular surfaces. Fiber/yarn-shaped piezoresistive pressure sensors are mainly constructed with core-sheath compositions in three primary manners: 1) single fibers, 2) cross-arranged (or interlaced) yarns, and 3) twisted (or plied) yarns.

Single fiber piezoresistive pressure sensors require careful material and structure design to ensure adequate inherent compressibility and sensitive resistance variation. They are commonly made by incorporating conductive materials into elastomer matrices or tubes (Fig. 3a). For example, Deng et al. [70] developed a specially constructed piezoresistive fiber by inserting a copper-wire-wrapped pre-stretched shape memory polymer (SMP) fiber core into a premade CNT/PU composite sheath. When heated, the SMP fiber swells in the cross-sectional area and shrinks in length, resulting in a helically bulged structure due to the constraint of copper wires. This creates space between the sensing layer and electrode for contact, producing a prominent sensitivity of 1500 N^{-1} and allowing for bending-insensitive measurement of pressure intensity and position along fiber length according to the contact point (Fig. 3a1) [70]. Leber and colleagues [128] designed a hollow rectangular elastomeric fiber with an inclined ground electrode and multiple upper electrodes inside its structure formed by thermal drawing. Due to consecutive electrode contact, the fiber experienced a sharp increase in conductance at certain pressure thresholds (250 kPa being the highest) [128]. Tan et al. [32] demonstrated the importance of design schemes on the piezoresistive behavior of a single fiber pressure sensor by comparing two different incorporation method of N-doped rGO and polydopamine (PDA)-coated CNT (N-doped rGO/PDA@CNT) hybrid conductive powder with elastomeric polymers: one involves filling into a silicone rubber tube (CSRT), and the other involves compounding with Ecoflex (CEF) by wet spinning (Fig. 3a2). Electromechanical results showed opposite correlations between resistance and applied pressure for the two fibers: CSRT exhibited a resistance decrease due to enhanced powder contact with maintained bulk structure, while the resistance of CEF increased due to the flattened cross-section and filler separation attributable to intrinsic softness and possible material breakage [32]. Leveraging the low viscosity of liquid metals, highly deformable and sensitive piezoresistive fibers have been made by drawing an elastomeric tube (e.g., PDMS and SEBS) and filling it with liquid metals [80, 149]. In a low-cost and scalable way, Tang et al. [150] fabricated a piezoresistive pressure/strain fiber sensor with MWCNT-silicone core and silicone sheath by coaxial wet spinning. The use of elastomers benefits from mechanical strength and stretchability for fabric integration and wearing, but it also introduces interference issues caused by strain-coupled pressure sensitivity. This can potentially be addressed by employing a non-ductile material as the core (e.g., AgNWs-coated flax fibers [151]) in an elastomer sheath. Single pressure-sensing piezoresistive fibers have been integrated into textiles by sewing [70], weaving [70, 80], knitting [150], and embroidery [32] for applications in pressure detection, human–machine interaction, and healthcare.

For cross-arranged yarns in a weaving pattern, the piezoresistive sensing unit is formed at the interlacing point between two core electrodes. This architecture has emerged as a preferred design that enables a variety of functional devices with well-defined contact interactions and stimuli

Table 1 Performance, cost and application suitability of common conductive and substrate materials for fiber/yarn/textile piezoresistive pressure sensors

Category	Material	Performance		Cost	Application suitability
		Pros	Cons		
Inorganic metallic materials	Metal wires	Excellent conductivity	Poor flexibility; heavy	Low	Low demand on sensitivity and conformability; high scalability
	Metallic nanoparticles	Excellent conductivity and flexibility	Susceptive to environmental corrosions like oxidation	High	High demand on sensitivity and conformability; flexible transparent electrodes/e-skin
	MXenes	High surface functionality and conductivity; good transparency	Susceptive to environmental corrosions like humidity	High	
	Liquid metals	Fluidic properties; high conductivity; self-healing	Material leakage; poor adhesion	High	Demand on deformability or phase transition (liquid near/above room temperature)
Carbonaceous materials	CNTs Graphene	Excellent conductivity; low density; high surface area and functionality; good mechanical strength and chemical stability	Easy agglomeration (limited filler concentration); low transparency	High	High demand on sensitivity, conformability, mechanical strength and thermal properties
	CB	Excellent conductivity; low density; high surface area		Low	
	Carbonized materials	Excellent conductivity; high surface area; easy processing	Poor mechanical strength and stability; high brittleness	Low	High demand on sensitivity and conformability but low on mechanical strength
Conductive polymers	PPy PANI	Tunable conductivity; color-shifting by redox reaction; biocompatibility; high substrate compatibility	Relatively lower conductivity; poor mechanical strength and adhesion; environmental sensitivity (humidity, temperature, pH, etc.)	Low	Demand on multifunctionality and processability; low demand on conductivity and stretchability
	PEDOT:PSS	Good optical transparency; tunable conductivity; high substrate compatibility			
Synthetic polymers	Polyester, nylon, PDMS, etc	Good mechanical and chemical stability; good processability and deformability	Poor biodegradability and breathability	Low	Versatile applications; device encapsulation
Natural polymers	Cellulose, silk fibroin, etc	Biocompatibility and biodegradability; good breathability, hydrophilicity, and modifiability	Material source variation	Low	Versatile (especially wearable) applications

responses [152]. The yarns are typically made of stretchable/conductive cores (elastomer wires or insulative threads coated with metallic materials) and piezoresistive sensing layers. This single crossing unit enables high sensing spatial resolution over customizable surface areas, utilizing various existing integration technologies such as weaving [67, 100, 153, 154], knitting [40], and embroidery [33, 112]. Inserting piezoresistive material between crossing yarn electrodes is a commonly adopted strategy for array design, making use of commercially available conductive yarns, fabrics, and sheets [131, 155, 156]. Due to the limited contact area and confined space at the single overlaying point, material dimensions and microstructure play crucial roles in sensing performances. Inspired by bridge-binder cell structure in cytoskeleton networks, Ke et al. [33] developed a piezoresistive pressure-sensing yarn consisting of a silver-plated nylon core electrode and a shell consisting of PPy/Ethylene–vinyl alcohol copolymer (PPy@EVOH) nanofiber bridges and waterborne PU cells (Fig. 3b). The sensor yarn achieved both high sensitivity (~ 5.15 N^{-1}) and a large working range (up to ~ 25 N or ~ 148.017 MPa) with good stability by optimizing bridge and binder parameters to control conductive network density and deformation reversibility [33].

Twisting is another widely adopted strategy to ensure effective fiber packing and electronic transmission within a yarn. Twisted/plied sensing yarns, consisting of two or more filaments, commonly have a core-sheath structure and are compatible with sewing [34], machine weaving [157, 158], and knitting [158]. It has been reported that a twisted double helix yarn structure facilitates fast recovery from pressure deformation and electrical signal recovery compared to untwisted yarns due to the stored twisting force and friction, demonstrating extraordinary response and recovery times of only 2 ms and a low hysteresis of 5.3% [66]. For

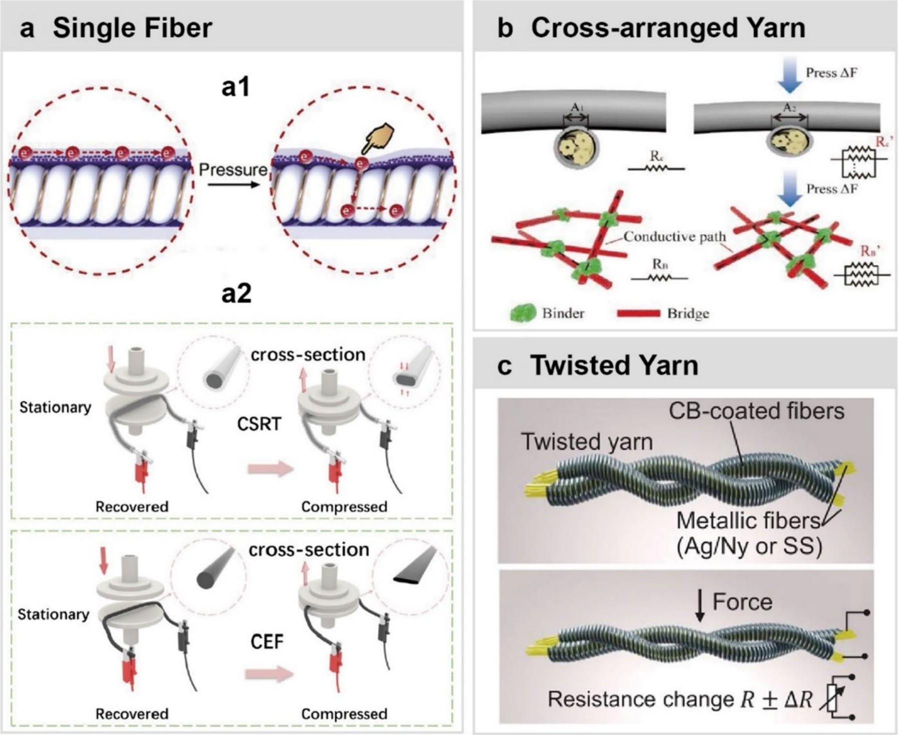

Fig. 3 Structures of fiber/yarn-shaped piezoresistive sensors. **a** Single fiber with **a1** multilayered architecture that enables position detection capability; reproduced with permission from Ref. [70], Copyright 2019, Elsevier; **a2** different incorporation methods of conductive particles: simple core-sheath structure or loading as conductive fillers; reproduced under the terms of the CC-BY license from Ref. [32], Copyright 2023, The Authors. **b** Cross-arranged/interlaced yarn with bridge-binder microstructure; reproduced with permission from Ref. [33], Copyright 2022, Elsevier. **c** Twisted/plied yarn with conductive core and piezoresistive fiber sheath; reproduced with permission from Ref. [158], Copyright 2023, Wiley-VCH

twisted yarns, the piezoresistive effect ideally occurs at any pressing position along the longitudinal axis of the yarn, and resistance can be measured either through a single fiber channel or across the yarn diameter. In this case, the sheath of the constituent fiber is expected to offer sufficient resistance change with pressure loading while preventing electrical shorting between fibers due to close fiber contact. This is often achieved by embedding dielectric fiber, matrix, or coating in the pressure-sensing sheath, such as CB-coated PET multifilament (Fig. 3c) [158], PU/AgNW composites [34, 72], tubular textile cloth attached with carbon fibers (CFs) [90], and poly(vinyl alcohol) (PVA) coating [121]. Interestingly, double-twisted conductive yarn with a sheath entirely made of intrinsically electrically insulating PET, polylactic acid (PLA), or nylon multifilament has been reported to exhibit a piezoresistive effect under pressure or strain between two core electrodes. This is attributed to the impact of microfiber structure on resistivity reduction and manufacturing impurities that provide charge carriers for electrical conduction [157].

Table 2 lists several representative reports on fiber/yarn-shaped piezoresistive pressure sensors with enhanced sensing performance based on different configurations, materials, fabrication and integration methods and applications.

4.1.2 Fiber/Yarn Fabrication and Modification Techniques

The formation of reversible conductive pathways is key to developing a piezoresistive sensor. For fiber/yarn shape piezoresistive pressure sensors, electronic properties are imparted either through intrinsically conductive fibers/yarns or by modifying non-conductive polymers via various physical and chemical methods. Common fabrication and modification techniques used for fiber formation and functionalization include spinning, drawing, extrusion, coating, and in-situ deposition.

4.1.2.1 Spinning As nanomaterials become the forefront of material engineering and wearable technologies, electrospinning has received substantial attention as a straightforward and economical approach to fabricate continuous nanofibers and their assemblies. These nanofibers offer sufficient surface area and tunable porous structures, ideal for wearable and healthcare applications [159–161]. The basic setup for electrospinning includes a high voltage supply, a metal collector, and a spinneret consisting of a solution container, syringe, and an injection pump. The high electric voltage between the syringe needle and the collector creates a liquid jet of the polymer solution, which is further elongated under the effect of multiple forces, including coulombic repulsive force, viscoelastic force, air drag, and surface tension [159]. Incorporating nanomaterials such as CNTs [124, 125, 154], GO [101], and AgNWs [153] into the electrospinning solution or process has proven effective in forming hierarchical yarns with uniformly wound nanofibers, abundant contact points, and high sensitivity. Figure 4a illustrates the setup of double conjugate electrospinning with two pairs of symmetrically placed, oppositely charged needles for the fabrication of GO-doped polyacrylonitrile (PAN) nanofiber yarns which are further coated and wrapped around an elastic core. However, electrospun nanofiber composite yarns suffer from problems of narrow sensing range and easy saturation due to their ordered and delicate surface structures [33].

Wet spinning is another common solution spinning method used to continuously produce conductive fibers. In this process, the fiber is formed out of a spinneret through the gelation process in a coagulation bath containing solvent and non-solvent, and is finally wound onto a fiber collector. By controlling the mass transfer during gelation and material relative sizes, different microstructures can be achieved. For example, similar particle diameters and lengths of AgNW and cellulose nanofibers generated a porous fiber structure [134], while size differences resulted in a hollow fiber [162]. By wet spinning an aramid nanofiber solution and subsequent freeze-drying, Zuo et al. [163] fabricated a porous aerogel fiber that acted as a skeleton for constructing conductive network by absorbing solutions containing AgNWs and MXene through capillary force. Zhong et al. [154] applied a CNTs/TPU layer onto a silver-plated nylon core by wet spinning, with exposure to water vapor as the non-solvent, which induced phase separation at different TPU concentrations and formed a microporous surface on the yarn (Fig. 4b).

Other industrial yarn spinning techniques have also been applied as scalable solutions for conductive yarn manufacturing, such as friction spinning MXene impregnated cotton roving onto a spandex core (Fig. 4c) [76], and wrapping functional fibers around a core yarn by twisting/core spinning [82, 157, 158]. Furthermore, direct/dry spinning is used to produce CNT yarn by directly drawing a CNT sheet from a CNT forest and twisting it to form a pressure-sensing yarn [164] or wrapping it around a supporting core yarn [85, 86].

4.1.2.2 Thermal Drawing and Melt Extrusion

The process of thermal drawing and melt extrusion is also utilized in the large-scale fabrication of piezoresistive pressure-sensing yarn, offering unique advantages in terms of versatility and efficiency. In thermal drawing, a polymer preform embedded with conductive additives or other functional materials/microdevices is heated until softened. It is then stretched into a fine filament while its properties are monitored [2]. Originally developed for fiber optics, this process enables the direct incorporation of multiple materials and complex fiber architecture in one step, resulting in a continuous and flexible sensing fiber with versatile physical or chemical functionalities along its length [2, 81, 165]. For example, Leber et al. [128] thermally drew a hollow fiber with a rectangular cross-section consisting of SEBS cladding and carbon black-loaded polyethylene (cPE) electrodes inside, which establish electrical contact under pressure (Fig. 4d1-d3). Melt extrusion, on the other hand, involves forcing a molten polymer blend through a die to create filaments with controlled dimensions and compositions. This technique has been used to produce EVOH nanofibers for conductive composite coating of a piezoresistive yarn [33] and to fabricate polypropylene (PP)/PE core-sheath filaments to create thermally bonded piezoresistive nonwovens (Fig. 4e) [166]. Both techniques allow for the production of piezoresistive sensing yarns with aligned microstructures, tailored properties, and sensing capabilities by selecting materials with matching rheological and thermal properties and adjusting the drawing and extrusion parameters. However, the requirement for specialized equipment such as drawing towers and screw extruders, along with high-temperature operation, may pose challenges in terms of cost-effectiveness [21]. To address these challenges, direct printing techniques have demonstrated potential in fiber-based pressure sensor fabrication [167–169]. For instance, Gao et al. [169] created elastomer fibers containing PDMS microspheres by extrusion printing and further coated them with CNTs to form cross-arranged piezoresistive and capacitive pressure sensors.

4.1.2.3 Coating

Physical coating is one of the simplest and most cost-effective methods for depositing conductive materials onto fiber/textile substrates on a large scale. This process involves uniformly dispersing functional materials in solvents, then either impregnating the fiber/textile substrates into the coating solution or applying the coating solution directly onto the substrate material, followed by a drying step for solvent evaporation (Fig. 4f). This dip-and-dry procedure is typically repeated multiple times to achieve the desired conductivity, which largely depends on the thickness and evenness of the conductive layers. Researchers have demonstrated the effectiveness of adding a scraper after the fiber passes through the coating solution to precisely control coating thickness and ensure uniformity for large-scale production [33, 67, 170–172]. Various methods such as dip coating, die coating, drop coating, spray coating, and brush coating have been adopted to effectively apply active nanomaterials or composites to the curved fiber surface. In addition, modifying fiber morphologies with wrinkles and pores is possible by combining prestretching before coating or solvent evaporation after coating. Multiscale micro/

Table 2 Representation on fiber/yarn-shaped piezoresistive pressure sensors

Structure	Material	Fabrication and integration	Highest sensitivity	Sensing range	Application	References
Single fiber	CNTs/PU sheath, copper wire-wrapped SMP core	Dip coating, template and temperature assisted fiber shaping, winding, machine sewing and weaving	1500 N^{-1}	1–5 N	Smart glove for bending-independent tactile sensing and mobile control	[70]
	N-doped rGO/PDA@CNT hybrid powder inside a silicon rubber tube (CSRT) or mixed with ecoflex matrix (CEF)	Hydrothermal reaction, chemical reduction, vacuum filtration, vacuum filling (CSRT), wet spinning (CEF), tailored fiber placement embroidery technique	0.09 N^{-1} (0–5 N, CSRT)	0–40 N	Cardiorespiratory and pulse monitoring	[32]
	Copper particle-mixed liquid metal, SEBS	Thermal drawing	15.29 MPa^{-1} (0–2 MPa)	0–7.2 MPa	Human motion monitoring, joule heating	[80]
Cross-arranged yarns	Stainless-steel thread core, graphite/CuNPs filled PDMS elastomer sheath	Customized coaxial yarn coating system, digital machine knitting	1.75 kPa^{-1} (< 0.5 N/2.5 kPa, without fabric)	Up to 87.5 kPa (integrated into fabric)	Machine learning enhanced motion pattern and object classification and full-body pose prediction	[40]
	Silver-plated nylon core yarn, PPy@EVOH nanofibers-waterborne PU sheath	Melt extrusion, high-speed shearing, in-situ polymerization, immerse-and-dry coating, embroidery	5.15 N^{-1} (~ 0.8698 Mpa^{-1})	0–25 N (~ 148.017 MPa)	Pulse and movement monitoring, pressure mapping	[33]
	Latex-polyester core-spun elastic yarn, PPy coating	Prestretching, in-situ polymerization, weaving	187.33 MPa^{-1} (< 15 kPa)	< 0.3 MPa	Tension insensitive pressure-sensing, monitoring massage intensity	[100]
Twisted yarn	PU-AgNP fiber core, PU-CB-AgNW sheath	Dip coating; pressure-assisted imprinting technique	32 N^{-1} (0–10 kPa)	0–100 kPa	Waterproof multimodal sensor; gaming interface control	[72]
	Double-plied yarn made of silver-plated nylon-6,6 (Ag/Ny) or stainless-steel (SS) core and CB-coated PET multifiber sheath	Twisting, heat treatment, weaving, knitting	0.016 (SS) and 0.014 (Ag/Ny) kPa^{-1} (5–7 kPa)	0.1–800 kPa	Finger motion and respiration monitoring	[158]
	Double helix yarn of silicone rubber core loaded with Al plated Ag particles and CFs-coated tubular cloth sheath, polyethylene heat shrinkable tube encapsulation	Polymer crosslinking reaction and radiation processing technology, heat treatment	0.178 N^{-1} (3–330 N)	3–480 N	Human movement monitoring	[90]

nanostructures can be formed by adding subsequent twists to enhance effective contact areas [34, 172].

4.1.2.4 In Situ Growth In-situ growth refers to the process of directly depositing conductive materials onto fibers or yarns, providing a versatile means of enhancing their electrical conductivity and functionality. One commonly utilized method is in-situ polymerization, where conductive polymers are synthesized directly onto the surface of fibers or yarns through a chemical reaction. This leads to the formation of a uniform and adherent coating without compromising the intrinsic mechanical properties and breathability of the original fiber materials [152]. Monomers are usually in either a liquid or vapor phase, with the latter eliminating the need for binders. This technique offers excellent adhesion and uniform coverage, resulting in enhanced electrical properties and mechanical stability. However, controlling the polymerization process to achieve desired properties can be challenging, requiring careful determination of parameters such as oxidant selection and weight fraction [173].

Electroless plating and electron-beam (e-beam) evaporation are effective methods for depositing metallic electrodes such as nickel [124] and gold [112] onto fibers/textiles. In electroless plating, metal ions are reduced onto the substrate surface in a chemical bath without the need for an external power source. The deposition occurs through autocatalytic reactions, resulting in the formation of a continuous metal layer with uniform thickness [174]. Electroless plating offers advantages such as high conductivity and the ability to coat non-conductive substrates. However, challenges such as bath impurity, weak bonding, and waste disposal require careful optimization of process parameters for reliable and sustainable production [174]. E-beam evaporation is a physical vapor deposition (PVD) technique wherein a high-energy electron beam is directed at a target material, causing it to vaporize and condense onto the substrate surface to form a thin film. This method offers advantages such as precise control over film thickness, high coating purity and efficiency, and compatibility with various substrates. However, the process can be costly due to the need for vacuum conditions, and the deposition rate and coverage may be limited, particularly for large-scale production.

Hydro/solvothermal processing involves the synthesis of conductive materials for fibers or yarns in an aqueous or solvent environment under high temperature and pressure. This method enables the controlled growth of nanostructures directly onto the fiber surface, leading to enhanced conductivity and sensitivity. Lu et al. [95] grew molybdenum disulfide (MoS_2) nanosheets on carbonized silk fabric through solvothermal treatment, creating a multiscale fiber surface that resembles the faceplate of sunflowers, producing a high-performance multifunctional piezoresistive pressure sensor. Hydro/solvothermal processing offers scalability and versatility in producing tailored material contents and architectures. Nonetheless, optimizing reaction conditions and controlling particle size distribution can be challenging, and a fiber substrate with a high melting point is desired to withstand the thermal treatment over time.

4.2 Piezoresistive Pressure Sensors Based on Fiber Assemblies and Textile Composites

The design of piezoresistive sensors at the hierarchical textile level has become a significant research focus in wearable technology and smart textiles. This approach involves integrating active materials with textile substrates to create conductive composites, thereby expanding their capabilities beyond those of traditional textiles. Notably, textile-based piezoresistive sensors can be fabricated using readily available materials, eliminating the need for specialized fiber/yarn processing equipment, which makes device innovation more accessible [21]. Various configuration schemes have been developed with tailored combinations of materials and structures, ranging from 2 to 3D fiber/yarn assemblies with single-layer or multilayer working modes. Performance enhancement often necessitates layer stacking to increase fiber contents or bonding with electrodes and additional non-textile materials, such as adhesives and encapsulation/supporting films, for device assembly and protection.

4.2.1 Structural Principles and Assembly

Textile piezoresistive pressure sensors are typically composed of three main elements: electrodes, a sensing layer, and encapsulation/supporting layers. Resistance change is induced by the deformation of the porous sensing layer, increasing contact points among fibers and conductive materials, and sometimes between the sensing layer and electrodes. To ensure reliable electrical contact and effective measurement under pressure, electrodes are usually paired on two sides of functional textile materials (vertical) or applied, often in an interdigitated pattern, to a bottom substrate (horizontal) (Fig. 5a). The vertical/horizontal approach of electrode assembly impacts the piezoresistive performance of the pressure sensor, which can be tailored for applications involving different pressure ranges. According to Zhang et al. [117], the horizontal electrode design resulted in higher sensitivity within a small pressure region (0–5 kPa), while vertical placement was more suitable for sensing larger pressure (5–40 kPa).

As discussed in the previous section, the porosity and compressional resilience of the sensing layer are crucial factors affecting sensing performance. Conventional fabrics are limited in terms of deformability across the bulk due to their confined structures. Therefore, extensive research has focused on improving sensor porosity

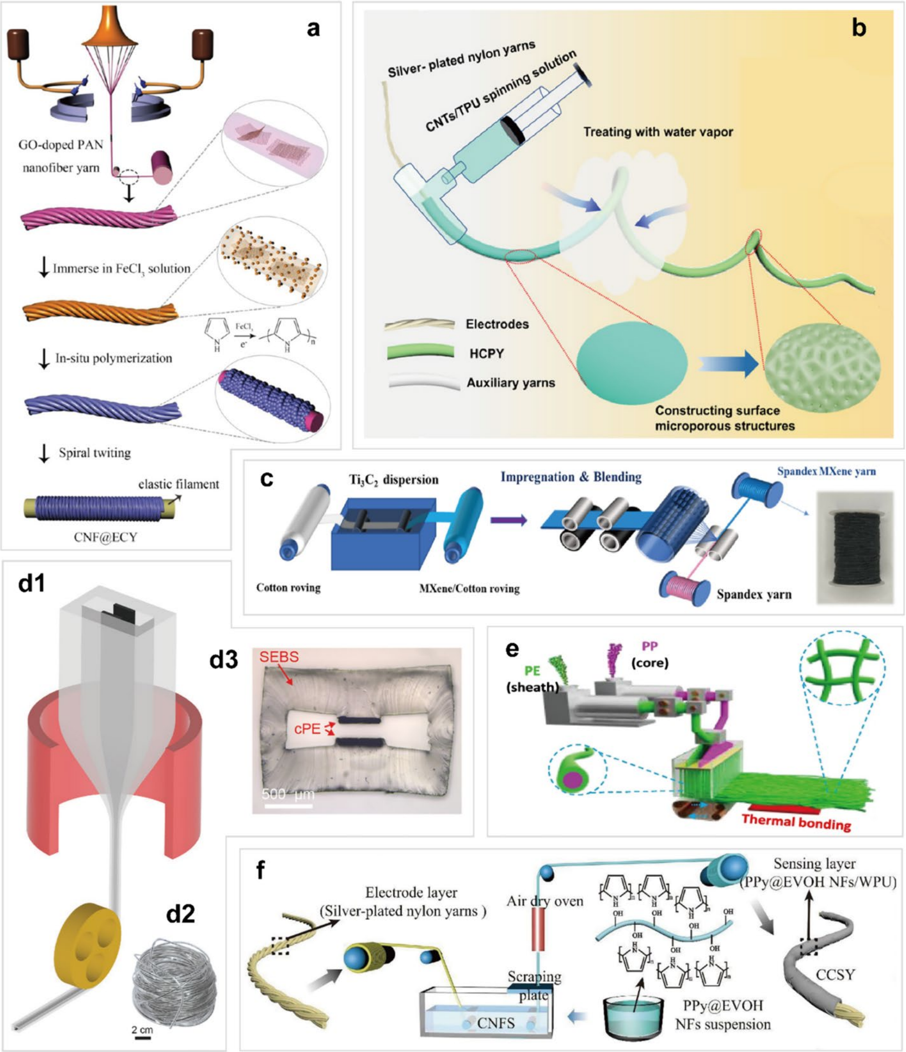

Fig. 4 Fiber/yarn fabrication and modification techniques. **a** Double conjugate electrospinning process, coating an elastic filament core with GO-doped PAN nanofibers, followed by in-situ polymerization of PPy; reproduced with permission from Ref. [101], Copyright 2018, WILEY-VCH. **b** Wet spinning of CNTs/TPU sheath with microporous surface morphology formed by water vapor induced phase separation; reproduced with permission from Ref. [154], Copyright 2021, American Chemical Society. **c** Manufacturing of MXene-coated core-spun piezoresistive composite yarn by impregnation and industrial friction spinning; reproduced with permission from Ref. [76], Copyright 2023, American Chemical Society. Thermal drawing: **d1** schematic illustration of thermally drawing a hollow fiber with rectangular cross-section consisting of SEBS substrate and CB-loaded PE electrodes; **d2** optical image and **d3** cross-sectional view of the thermally drawn fiber; reproduced with permission from Ref. [128], Copyright 2019, WILEY-VCH. **e** Fabrication of PP/PE core-sheath fibers and nonwovens by melt extrusion and thermal bonding; reproduced with permission from Ref. [166], Copyright 2023, Donghua University, Shanghai, China. **f** A standard continuous yarn dip-coating setup with a scraping plate and drying process; reproduced with permission from Ref. [33], Copyright 2022, Elsevier

and compressibility to maximize contact area and thus conductivity variation in response to pressure, aiming for enhanced sensitivity over a large detection range. For instance, Xia et al. [130] utilized pore-abundant filter papers made of nanoscale plant fibers and functionalized them with 1D indium tin oxide (ITO) nanocrystals via a hydrothermal process. The resulting piezoresistive pressure sensor exhibited high sensitivity and a wide working range (464.88 kPa^{-1} in 0–50 kPa and 251.96 kPa^{-1} in 50–100 kPa), providing eco-economical solutions for sustainable wearable applications [130]. Moreover, the combination with 3D substrates has enabled enhanced compressibility and sensor performance. For instance, Choi et al. [35] introduced a 3D spacer knitted textile with prestretched monofilaments in the middle. Placing this on a carbonized cellulosic nonwoven fabric contributed to local strain and enhanced contact of the carbonized fibers, leading to improved sensitivity and sensing range (Fig. 5b1).

Tian et al. [175] utilized a random PP fiber assembly thermally encapsulated by TPU between conductive silver-coated and spandex knit fabrics to form a pillow-shaped highly compressible piezoresistive pressure sensor. The resistance decrease depended on the deformation of loop structures and enhanced contact within the top conductive knit fabric (Fig. 5b2). Larger PP fiber diameters improved sensitivity, which can be explained by the decreased fiber modulus. Substrate/conductive fibers act as structural/electrical binders in these 2D and 3D porous composites, providing connections for continuous and effective stress/charge transfer. The integration of protective layers such as elastomeric PDMS can enhance the mechanical integrity and working range of the sensor but may sacrifice its sensitivity and breathability.

In other design schemes, signal variation is caused by the closing of gaps under external pressure between initially separated conductive layers, which function as both electrodes and sensing elements. Textile pressure sensors in a multilayer construction experience drastic changes in conductivity with a switch-like behavior due to the formation of contact between conductive materials, leading to prominently high sensitivity and small working ranges. Chen et al. [41] designed programmable textile touch sensors by arranging CNTs-coated cotton fabric strips in parallel, which are connected by touch with conductive copper foils to form a circuit and location-dependent resistance value (Fig. 5b3). Similarly, Lai et al. [176] stitched conductive yarns on a substrate fabric as two parallel electrodes bridged under pressure by a bulged AgNW-coated PDMS film placed over the threads. In addition, sensing capability is largely determined by the separation distance and contact areas of the conductive layers. Ju et al. [177] fabricated textile pressure sensors consisting of two inject printed nonwoven fabrics separated by a TPU spacer. Tuning the thickness and hole diameters of the spacer simultaneously changed the sensing threshold (Fig. 5b4). Chen et al. [178] used cotton mesh as the spacer layer, with larger hole sizes allowing more multi-scale contact between AgNW-coated fabrics, thus enhancing the sensing performance of the textile piezoresistive pressure sensor, achieving the highest sensitivity of 3.24×10^5 kPa^{-1}.

Table 3 compares several representative reports on piezoresistive pressure sensors made from fiber assemblies or textiles, highlighting enhanced sensing performance based on different device assembly configurations, materials, fabrication methods, and applications.

4.2.2 Fiber Assemblies/Textile Fabrication and Modification Techniques

4.2.2.1 Sensing Layer Formation The approaches to forming a sensing layer can be categorized into two main methods: 1) customizing 2D/3D fiber assemblies with desired properties and functionalities, and 2) modifying existing textile substrates, such as wovens, knits, and nonwovens.

Construction of Fiber Assemblies. Conventional textile manufacturing technologies offer diverse possibilities for integrating piezoresistive sensing functionality into textile structures, leveraging various conductive yarns. Weaving, knitting, nonwoven, and embroidery/stitching techniques are common approaches used to assemble fibers and yarns into or onto textile structures for functional integration.

Woven structures are beneficial in terms of mechanical and performance stability due to their ordered yarn arrangement, and they have been widely used in the formation of sensing materials. The abundant combinations of interlacing units made by weft and warp yarns allow for various weaving patterns and tunable sensor properties (Fig. 6a). Li et al. [180] investigated the effects of yarn types, weaving density, and patterns on the sensing performance of a multilayer piezoresistive sensor consisting of woven functional fabric, interdigitated bottom electrodes, and PDMS encapsulation films. They found that the insulation provided by non-conductive polyester yarns to the conductive silver-plated nylon yarns in the woven network increased resistance change and ensured an adequate sensitivity range. This made it a better candidate for a sensing layer than a woven fabric entirely made of conductive yarns. Higher weaving density and larger float length promoted more electrical contact under pressure. When integrating multiple sensing units based on the crossing of conductive yarns, the number of pairings and the positioning distance are important parameters to consider to prevent crosstalk/shorting between adjacent sensing yarns while ensuring easy data interpretation and desirable sensing resolution and distributions across the fabric. It is worth mentioning that inherent tensions caused by the weaving structure pose a potential issue of limited compressibility and sensitive range, which can be improved to some extent by increasing the float length [67, 180].

Knitting is one of the most widely employed approaches for constructing functional smart textiles, highly favored for the flexibility, stretchability, and conformability of the knitted structure. Existing knitting technologies allow for customizable and seamless integration of materials in a scalable manner, enabling diverse 2D and 3D architectures to cater to specific working modes and applicational requirements. Chen et al. [66] plain-knitted double-plied conductive yarns to create a piezoresistive pressure sensor with low hysteresis for pulse measurements, leveraging the highly elastic knitted structure. Lin and Seet [181] integrated a pair of textile electrodes made of conductive yarns using the intarsia knitting technique to sandwich two piezoresistive films within fabric. The resulting sensor exhibited good linearity of resistance change over a wide pressure span up to 1 MPa. While 2D knitting provides good flexibility, it demonstrates limited design and sensing capabilities. In contrast, 3D knitting materials offer more opportunities for hierarchical structuring and functionality integration. Jiang et al. [63] exploited the 3D spacer-knitting technique using two conductive yarns (one with smaller resistance for surface electrodes and the other with larger resistance as the sensing middle layer) to enable multidirectional sensing (vertical pressure and lateral strain) of small mechanical loads (below ~ 1 kPa/60%) (Fig. 6b). It should be noted that knitting presents challenges to signal quality and hysteresis when used for piezoresistive sensing layer due to the inherent loose structure and loop friction. This requires careful engineering optimization in terms of materials and knitting parameters [63, 66, 182].

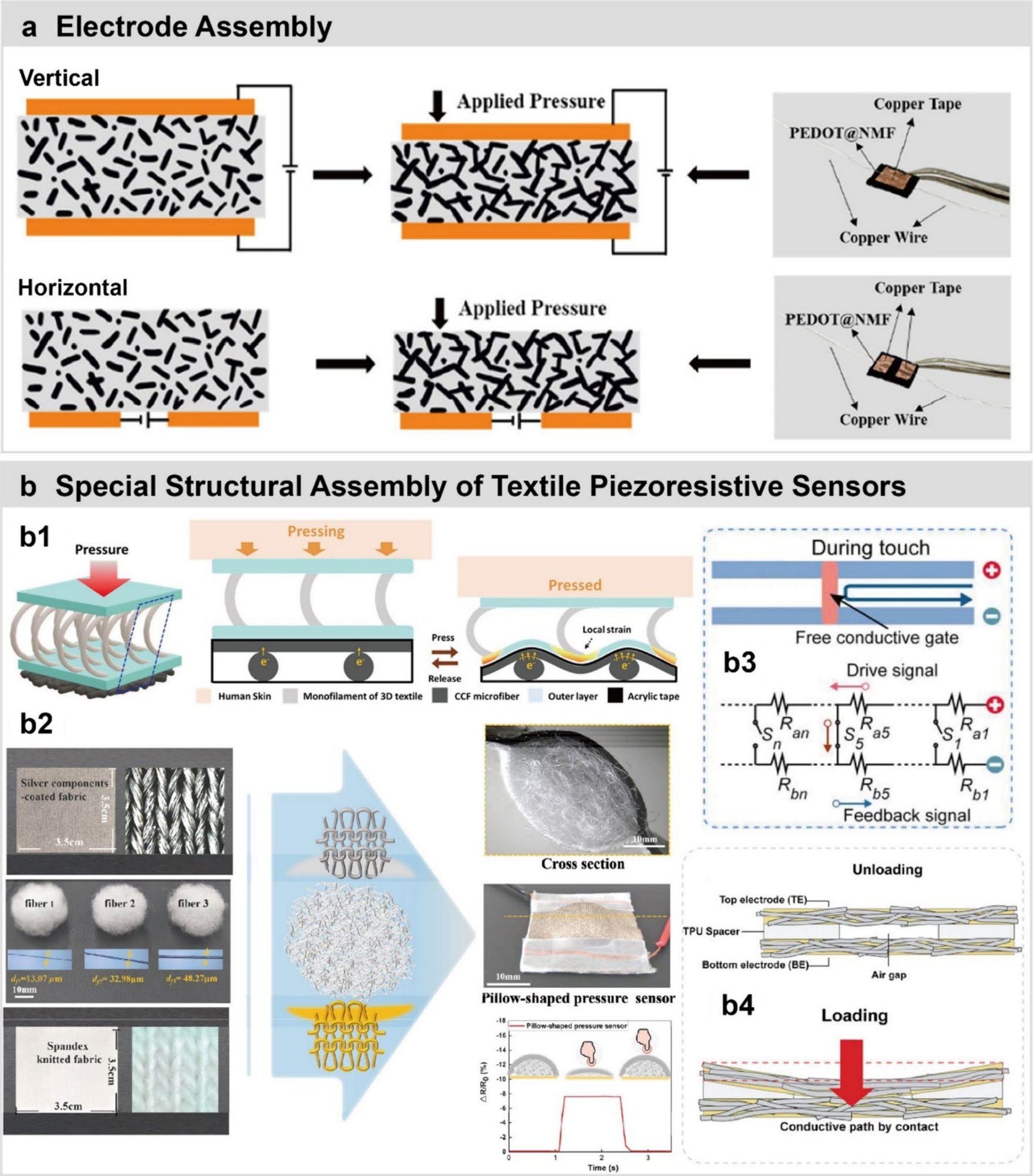

Fig. 5 Electrode assembly and special structures of piezoresistive pressure sensors based on textiles and fiber assemblies. **a** Vertical and horizontal electrode assembly for 3D piezoresistive pressure sensor; reproduced with permission from Ref. [117], Copyright 2021, American Chemical Society. **b** Special structural assembly of fiber and textiles: **b1** stacking of a 3D spacer fabric on top to enhance piezoresistivity; reproduced with permission from Ref. [35], Copyright 2022, Elsevier; **b2** enhancing sensor compressibility with a pillow-shaped construction by filling knit fabrics with random fiber; reproduced with permission from Ref. [175], Copyright 2019, American Chemical Society; **b3** a programmable

Embroidery, stitching, and sewing are common additive techniques traditionally used for decoration, splicing, and layering fabrics by inserting threads into the fabric at defined locations either manually or through various specialized machines (Fig. 6c). These methods provide easy access to functional design freedom, enhancing textile substrates with esthetically pleasing patterns for various applications. Parzer and colleagues [67] demonstrated e-textiles with different interactive sensing functions by leveraging additive sewing and embroidery techniques with the piezoresistive yarn they fabricated. Hand and machine sewing were utilized to integrate orthogonally crossed units and matrices on a couch or pants for light or smartphone control. They also manually embroidered the piezoresistive yarn intersections over decorative embroidery patterns made with non-conductive threads for better force sensing and esthetic effect, creating an interactive machine control panel. Since the first proposal by Post et al. [183], machine embroidery has been widely used to create e-textiles for user interfaces and functional devices, benefiting from highly automated operations for precise and reproducible pattern designs and layer assembly [156, 184, 185]. Leveraging this technology, Wang et al. [184] developed a toolkit for the prototyping and computing of functional textile interfaces by creating various sensing and feedback modules with carefully patterned and paired components made from commercial yarns and fabrics. Machine embroidery has also been used for anchoring or patterning cross-arranged arrays of yarns with tailored placement capabilities [32, 112, 155].

Due to their randomly arranged structure, nonwoven sensing layers exhibit favorable traits such as inherent high porosity and compressibility but are usually less stable and elastic compared to woven and knitted fabrics. Various 3D meso- and micro-structural porous nonwoven composites have been developed, such as silicone foams loaded with vapor-grown CFs formed using a low-boiling-point foaming agent [186], freeze-dried MXene/bamboo cellulose fiber composite foam [187], loofah sponge incorporated with CF/CNTs through dip coating [91], conductive ink-modified plant-fiber sponge fabricated by physical foaming and dip coated with PDMS [188, 189], intertwined CB@PU yarn network on a perforated ring frame [190], and 3D nonwovens consisting of crimped staple fibers coated with CNTs made by carding and thermal bonding [191, 192]. As material size significant impacts the piezoresistive effect and sensing performance, many researchers have also developed 2D/3D composite nanofiber networks, such as spray coated (Fig. 6d) or electrospun nanofiber membranes (Fig. 6e) [31, 37, 73, 74, 103, 193–195], and freeze-dried nanofiber aerogels (Fig. 6f) [137, 138, 142, 196, 197]. Benefiting from abundant fiber surfaces and contact points, nanofiber composite networks tend to exhibit high sensitivity and low detection limits but are relatively less mechanically robust due to their ultralight weight and low density. For example, aerogels with a 3D multiscale porous structure and interconnected fiber skeletons (combined with conductive fillers or polymer coating) can generate high sensitivity (over 100 kPa^{-1} within 10 kPa [137, 138]) and can detect a range of signals from subtle airflows and acoustic vibrations (human, geophysical, animal, and instrumental) to heavy loads like car movement [141, 197].

Textile Modification. One effective way to form a sensing fiber network is to directly modify a textile substrate with conductive elements using solution-based methods, including coating (e.g., dip and spray coating) and in-situ deposition (e.g., in-situ polymerization and laser/thermal treatment). In this context, the adhesion of the coating through physical or covalent bonding plays a critical role in determining the sensing performance and reliability of the device. The curvy surfaces of fibers and fabrics, along with their porous nature, pose challenges to the uniformity and fastness of coating deposition. To address these challenges, it is advantageous to use combinations of substrates and conductive nanomaterials with hydrophilic chemical properties. For instance, cellulosic fabrics impregnated with MXene [36, 39, 75] or CNTs [31, 83, 198, 199] leverage their intrinsic surface functionality, ensuring good interfacial adhesion, which has been widely adopted by researchers. Chen et al. [113] utilized a magnetic filtration cathodic vacuum arc deposition method with an ion beam, which is environmentally friendly, to ensure dense and uniform coating of metal particles and improve the conductivity of PANI-modified cotton fabric.

For hydrophobic textile substrates, the challenge is particularly prominent in these solution-based fabrication techniques due to the need for binders or surface modifications that may affect conductivity and intrinsic fabric properties, complicating the fabrication process. Plasma treatment is a common method used to improve hydrophilicity and surface wettability of yarns and fabrics by incorporating abundant hydroxyl groups onto the substrate, enhancing the anchoring of conductive coatings [71, 102, 125, 200]. In a more efficient and less intricate approach, Guo et al. [201] used a physically induced self-assembly technique with bovine serum albumin as a natural glue on the fabric substrate. This enhanced the attachment of GO/CNTs based on hydrogen bonds and electrostatic interaction. In addition, Clevenger et al. [62] exploited the oxidative CVD (oCVD) technique to polymerize vapor-phase EDOT monomers and deposit uniform conductive PEDOT coatings on various substrate materials in a single step, without adding binders or surface treatments beforehand. The use of a mask allowed for the patterning of conductive coatings, which withstood 200 abrasion cycles. However, device durability in terms of washability needs improvement for practical wearable applications, and the fabrication process may be challenging for large-scale production due to the confined chamber with

Table 3 Representation on piezoresistive pressure sensors made from fiber assemblies or textiles

Structure	Material	Fabrication	Highest sensitivity	Sensing range	Application	References
Parallel electrodes	ITO nanocrystalline–plant fiber composite paper, ITO-coated PET electrode film, PI encapsulation film	Solution casting, electrode etching	464.88 kPa^{-1} (0–50 kPa)	0–100 kPa	Pulse, respiration and human motion monitoring, voice recognition	[130]
	Cellulose nanofibers (CNFs)/MWCNTs papers, CNFs/PVA substrate with silver electrodes, TPU tape	Solution casting, screen printing	4.11 kPa^{-1} (0–1000 kPa)	0–3800 kPa	Pulse and finger bending detection, plantar pressure, gait analysis	[179]
	Cellulose/SWCNT nonwoven composite, PI films, silver ink	Spray and spin coating, inject printing	9.097 kPa^{-1}	0–400 kPa	Pressure mapping, 3D touch and 3D morphology scanning	[31]
	MXene/cotton fabric, PDMS film, PI electrode film	Chemical etching, dip coating	5.30 kPa^{-1} (0–1.3 kPa)	0–160 kPa	Finger/arm muscle movement, breath, pulse, e-skin (pressure mapping)	[75]
Vertical electrodes	AgNWs/cotton fabrics, cotton mesh spacer, copper electrodes	Dip coating	3.24×10^5 kPa^{-1} (0–10 kPa)	0–100 kPa	Pulse detection, wearable heater, PM2.5 particle filtering facial mask	[178]
	rGO/nylon cloths, carbonized PI electrode films	Laser carbonization, soak coating, thermal reduction	35.9 (< 2.5 kPa)	0–20 kPa	Weak body signals, voice recognition by machine learning, self-powered force measurement-control combined system	[87]
	AgNWs/graphene/polyamide nanofibers (PANFs) nonwoven, PANFs supported AgNWs network electrodes, PET substrate	Electrospinning, vacuum filtration	134 kPa^{-1} (< 1.5 kPa)	0–80 kPa	Voice and pulse monitoring, pressure mapping	[73]
	MXene/cotton fabric, PDMS film deposited with Ni/Au electrodes	Drip coating, spin coating, e-beam evaporation	17.73 kPa^{-1} (0.1 kPa-30 kPa)	0–50 kPa	Biomonitoring (cheek, neck, arm, finger, pulse), detection of imitated tremors of early-stage Parkinson's disease	[36]
	Bacteria cellulose nanofiber network, GO/graphene, chitosan powders, copper foil electrodes	Unidirectional freeze-casting and freeze-drying, thermal carbonization	150 kPa^{-1}	0–7 kPa	Human motion detection (Morse code, joint bending, mouth blowing), sound visualization (natural and music spectrum)	[138]

elevated temperatures. In a scalable manner, Tian et al. [166] introduced hydrophilic PP as a fiber core in the filament-forming process to improve the wettability of thermally bonded nonwoven fabric for further welding of CNT coatings. Furthermore, Doshi and Thostenson [202] introduced acid-protonated polyelectrolyte polyethyleneimine (PEI) to form positively charged CNTs. These were attached to an aramid/polyester nonwoven fiber veil on a cathode through electrophoretic deposition under an electric field (Fig. 6g). The resulting piezoresistive sensor showed stable and robust performance compared to carbon fiber and dip-coated samples.

Chemical residues produced from the solution-based synthesis of conductive materials raise environmental concerns

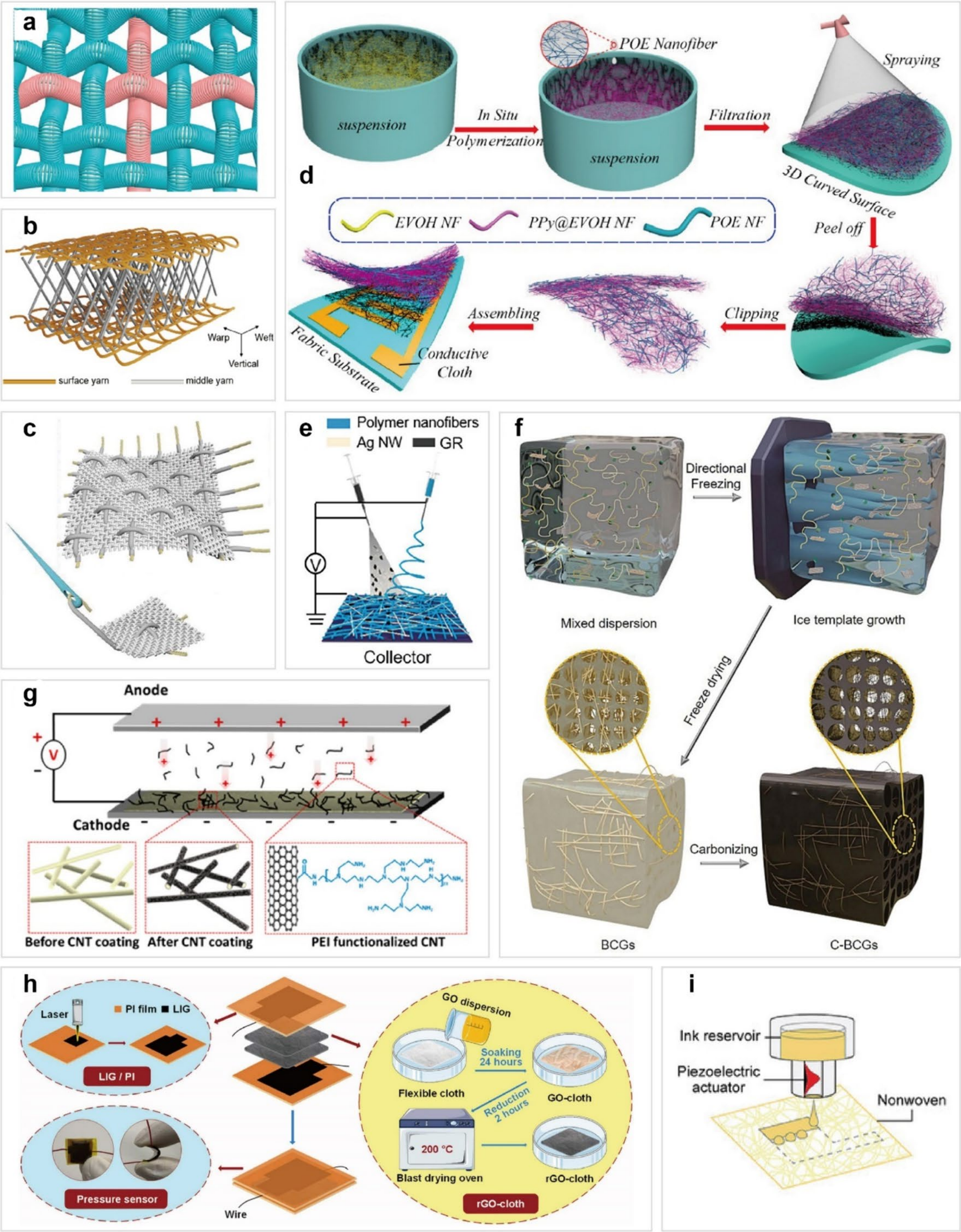

Fig. 6 Fabrication and modification techniques for piezoresistive sensors based on fiber assemblies and textile composites. Textile manufacturing methods: **a** weaving; reproduced with permission from Ref. [100], Copyright 2020, American Chemical Society; **b** 3D spacer-knitting; reproduced with permission from Ref. [63], Copyright 2023, American Chemical Society; **c** manual embroidery; reproduced with permission from Ref. [33], Copyright 2022, Elsevier. Composite nanofiber networks made by **d** spray coating; reproduced with permission from Ref. [103], Copyright 2020, American Chemical Society; **e** electrospinning; reproduced with permission from Ref. [73], Copyright 2020, American Chemical Society; **f** freeze-drying; reproduced with permission from Ref. [138], Copyright 2023, Elsevier. Textile modification methods: **g** electrophoretic deposition; reproduced with permission from Ref. [202], Copyright 2018, American Chemical Society; **h** laser-induced carbonization and thermal reduction of GO; reproduced with permission from Ref. [87], Copyright 2022, Elsevier. Electrode patterning by **i** inject printing; reproduced with permission from Ref. [177], Copyright 2021, Wiley-VCH

[189]. In a straightforward and eco-economical manner, the carbonization of biomaterials such as cellulose and silk is extensively adopted by researchers to obtain highly conductive and sensitive porous carbon materials by generating graphitic structures through pyrolysis treatment [35, 37, 94, 95, 203, 204]. However, conventional thermal carbonization requires high temperatures around 800–1000℃ or above, with low energy efficiency. Laser-induced graphitization (LIG) has attracted much interest as a facile method of directly patterning conductive graphene on organic substrates based on laser pyrolysis, which is considered a more sustainable and energy-efficient solution [97]. The LIG technique generates porous microstructures that are tunable by adjusting machine parameters such as wavelength and scanning speed. In-situ laser-induced graphene without binders holds potential for applications in various flexible electronics such as batteries, biomechanical sensors, and gas sensors [205]. It has been used in place of metal electrodes for textile-based piezoresistive pressure sensors and nanogenerators (Fig. 6h) [87], and has demonstrated applicability to aramid yarns for making piezoresistive bending sensors [96]. A major drawback of carbonized porous graphitic materials is their mechanical instability and fragility, which necessitates film encapsulation and limits their suitability for wearable applications.

4.2.2.2 Electrode Patterning Electrodes are usually made by either depositing conductive materials on fabrics/films through additive/subtractive methods or directly utilizing off-the-shelf conductive fabrics/tapes for assembly. Typical additive deposition approaches include printing, plating, and PVD (i.e., e-beam evaporation and sputtering). Screen printing is a common, facile method used to manually coat conductive ink (e.g., MXene [74] and carbon [126]) on textile substrates with specific interdigitated patterns using a mask for electrode deposition. Inkjet printing is a preferable technique for its automation and high resolution with low-viscosity ink (e.g., silver [31, 177]) and high resulting conductivity without the need for a mask (Fig. 6i). Electroless plating [83], e-beam evaporation [36] and sputtering [200] are common metallization techniques that impart electrical conductivity to textile materials. Patterning of electrodes using these techniques is often assisted by a mask. Both e-beam evaporation and sputtering involve vapor-phase deposition in a vacuum chamber; the primary difference is that e-beam evaporation uses an electron beam for bombardment, whereas sputtering uses ionized inert gas. These methods are considered more environmentally friendly than solution-based processes. Etching is a subtractive approach that involves the partial removal of conductive materials. This method has been utilized to pattern electrodes on a conductive composite film for textile-based piezoresistive pressure sensors [129, 130]. Vu and Kim [129] utilized hand-drawing with a marker pen to directly write electrodes on a pyralux film with conductive copper on one side and PI on the other, followed by chemical etching of the unwritten part for easy customization of flexible piezoresistive pressure sensors.

The above chapters elaborated on the various form factors of piezoresistive pressure sensors from a textile perspective. These include 1D single fiber structures, cross-arranged/interlaced yarns, twisted/plied yarns, and 2D/3D fiber assemblies or textile structures based on woven, knit, and nonwoven fabrics. In addition, various fiber and textile-based sensor fabrication methods were introduced, covering fiber formation (e.g., spinning, thermal drawing, and melt extrusion), textile manufacturing (e.g., weaving, knitting, and embroidery), and fiber/yarn/textile functional coating and modification (e.g., dip coating, in-situ deposition, hydro/solvothermal treatment, screen/inkjet printing). Table 4 summarizes the advantages and challenges/limitations of common fabrication techniques used in the development of fiber/yarn/textile-based piezoresistive pressure sensors.

fabric sensor responsive to electrical connection formed by the touch of a copper foil between two parallel conductive paths made by CNTs-coated woven fabric strips; reproduced with permission from Ref. [41], Copyright 2023, Donghua University, Shanghai, China; (**b4**) a textile force resistor with two conductive nonwovens separated by a spacer; reproduced with permission from Ref. [177], Copyright 2021, Wiley-VCH.

The integration of conductive materials is a key process in forming piezoresistive pressure sensors and is typically achieved in two ways: surface treatment and integrated fiber molding. Surface treatment (e.g., coating, in-situ deposition, printing, and sputtering) involves the physical or chemical modification of a substrate material to endow it with electrical properties. This method is often easy to conduct with high controllability of conductivity, but it can result in weak adhesion of conductive materials and unstable conductive networks. Integrated fiber molding methods (e.g., wet spinning, electrospinning, and thermal drawing) involve doping, direct fiber forming, and composite structure techniques. These methods have the advantage of stronger interfacial bonding with integrated conductive networks within a fiber or fiber assembly. However, they are currently limited to laboratory-scale preparation due to unresolved technical issues and high costs.

5 Multifunctional Integration

To push the boundaries of soft sensor technology beyond monomodal sensing, there is an increasing demand for flexible multimodal sensors and multifunctional sensing systems.

These aim to minimize device integration and replicate the diverse mechanical properties and sensory capabilities of human skin [206]. Achieving multimodal sensing involves utilizing structures and functional materials that are responsive to multiple mechanical and physical stimuli other than pressure (e.g., strain, bending, temperature, humidity, and gas) and/or integrating different mechanisms other than piezoresistivity (e.g., triboelectric, capacitive, and magnetic) into an ensemble through material matching and structural assembly. For instance, some conductive materials such as MXene and GO/rGO are intrinsically humidity-sensitive due to the presence of abundant hydrophilic functional groups (e.g., hydroxyl, oxygen, and carboxyl) which allow for the detection of multiple physical stimuli [76, 206]. Moreover, a 3D porous composite cellulose/aramid nanofiber aerogel combining conductive AgNWs and electromagnetic cobalt–nickel@carbon (CoNi@C) fillers functions as a good candidate for absorbing electromagnetic waves with an optimal minimum reflection loss of -51.6 dB, attributed to the synergistic balance between dielectric and magnetic losses of the conductive network [197]. The prepared composite aerogel also demonstrated excellent triboelectric performance as a nanogenerator, capable of charging a 1 μF capacitor within 60 s (Fig. 7a) [197]. Leveraging the unique optical and thermal properties of CNTs, He et al. [145] developed a multifunctional silk nonwoven sensor modified with CNTs by micro-dissolving sericin. The sensor is not only responsive to strain (up to ~ 40%) and pressure (0.01–13 kPa) but also capable of sensing light (Fig. 7b1) and temperature (Fig. 7b2). It showed varied response behavior depending on temperature due to the negative temperature coefficient of resistance: resistance increased below 0 °C while decreased at 40 °C and 80 °C (Fig. 7b2). Mechanical multimodal sensors have also been developed utilizing different signal patterns. Choi et al. [72] designed a double-twisted hairy conductive composite yarn that can discern different mechanical deformations (pressure, stretch, and bending) by varying signal patterns determined by contact resistance and internal percolation networks, measured through a single or mutual channel (Fig. 7c). Lai et al. [176] stitched two parallel conductive threads (electrodes) on a textile substrate with a bulged AgNW-coated PDMS film above that comes in contact with them to varying extents under different mechanical distortions (pressure, bending, twist, and stretch), leading to different piezoresistive response signals.

Integrating multiple mechanisms, Zhang et al. [207] extended the functionality of pressure sensing with proximity detection by depositing a composite of magnetic Iron(II,III)-oxide nanoparticles/PDMS and conductive MXene on a PDA-modified spandex substrate concentrically. The magneto-straining effect caused an increase in resistance as the magnet approached the functional fabric, while further pressing counteracted the magnetic force and initiated resistance reduction. By thermally co-drawing multiple materials from a micro-structured preform, Qu and colleagues [81] designed elastomeric SEBS fibers with channels filled with liquid metal, capable of resistive and capacitive pressure/strain sensing due to variations in channel distance. Leveraging stacked configurations, Pang et al. [198] enabled multifunctional tactile sensing mimicking human mechanoreceptors by incorporating triboelectric and piezoresistive layers separated by medical tape into a single textile sensor with two distinct signal types. This setup demonstrated promising potential in applications such as pulse and motion monitoring, texture recognition, and robotic control (Fig. 7d). Similarly, Wu et al. [185] developed an interactive multimodal textile sensor consisting of a piezoresistive sheet sandwiched between two conductive fabrics for both resistive and capacitive pressure sensing, and an inductive sensing layer with machine-embroidered antenna coils for near-field communication (NFC). This sensing system, integrated into a pants pocket, is able to recognize essential daily objects and motions for human–machine interactions.

Furthermore, researchers have also successfully endowed fiber/textile-based piezoresistive sensors with other functionalities such as energy supply, heating, and waterproof/self-cleaning capabilities by utilizing various functional materials and architectures. Lian et al. [178] added thermoregulation and particle filtration capabilities to a multilayer spacer-assisted piezoresistive pressure sensor by coating AgNWs on cotton fabrics. The abundant and dense silver conductive networks can reflect infrared radiation, provide electrical heating, and act as physical barriers to particulate matter, making them multipurpose wearable textile devices potentially beneficial for wellbeing in extreme weather conditions. Self-powering is a desirable feature for flexible sensors to achieve widespread and portable use, ensuring wear comfort without rigid energy devices. Huang et al. [93] fabricated a highly biocompatible pressure sensor based on piezoresistive hydrogels made from locust bean gum (LBG), PVA and CNTs, with conductive carbon fabric electrodes. This sensor can be self-powered through the integration of a flexible zinc-ion battery by directly depositing zinc on an existing carbon fabric electrode as anode and stacking another hydrogel electrolyte and cathode layer to allow continuous wireless transmission of signals for 1.2 h of pronunciation monitoring (Fig. 7e). Xia et al. [87] developed a self-powered measurement-control system capable of monitoring and responding to different forces for practical applications. This system combines a piezoresistive pressure sensor consisting of LIG/PI electrodes and rGO cloths with a triboelectric nanogenerator made with LIG/PI and nylon. Self-cleaning capability is also an important characteristic that enhances sensor durability and stability for long-term practical use. This has been achieved through hierarchical surface roughness and low surface energy by incorporating nanostructures on textile substrates [102, 132]. For instance, utilizing a graphene and silica mixture of different sizes and PDMS coating, Lu et al. [132] created a superhydrophobic piezoresistive pressure/strain fabric sensor. This sensor also enabled photo-thermal energy conversion and showed its feasibility for operation under water and in extreme cold conditions (Fig. 7f).

The exploration of novel materials, structures, and mechanisms has advanced efforts towards enabling multimodal sensing and other functionalities (e.g., energy/thermal/moisture management), but it has also introduced challenges in the systematic integration of multifunctionality. In multifunctional sensing platforms, specific sensor and hardware design, as well as data processing strategies, are required to reduce wiring, address signal discrimination, and enhance data quality and accuracy. Most existing fiber/textile piezoresistive pressure sensors exhibit cross-sensitivity to other mechanical deformations (e.g., stretch, bending, and torsion) that commonly occur during daily activities. This elasticity and unwanted straining of materials can be problematic for handling and interpreting user data in practical scenarios. Potential solutions include reducing the interference of tension by prestretching elastic substrate yarn before coating it with conductive material to maintain low sensitivity under tensile load [100]. In addition, developing sensors with structures that modulate fiber strain, such as using ultrathin nanofibers [179, 195], tailored fiber placement [208], or

Table 4 Advantages and challenges/limitations of common fabrication techniques for fiber/yarn/textile-based piezoresistive pressure sensors

Fabrication technique		Advantage	Challenge/limitation
Fiber/yarn and their assemblies	Electrospinning	High surface area of nanofibers; material versatility; straightforward process	High operating voltage; low production yield and speed; high cost
	Wet spinning	Tunable fiber shape and morphology	Specific solvent and coagulation bath needed; additional steps to remove impurities
	Thermal drawing/melt extrusion	Tailorable fiber configuration and material composition; simple one-step fiber formation	Intensive energy consumption; special equipment; matching material rheological and thermal properties
	Yarn spinning	Cost-effectiveness; scalability	Additional production steps to incorporate conductive materials
	Solution casting/spray coating	Controllable material thickness; low cost	Low product mechanical strength
	Freeze-drying	Highly compressible and porous 3D structure	High cost; low production speed; structure stability
Textile manufacturing	Weaving	Easy integration of crossed sensing yarns; mechanical stability	High yarn tension; low material compressibility and stretchability
	Knitting	Seamless integration; versatile pattern design; high stretchability	Easy yarn slippage; signal quality and hysteresis
	Embroidery/stitching/sewing	Easy accessibility; versatile esthetic pattern design; tailored sensor placement	Obtrusiveness; device thickness; firmness (abrasion/washing resistance)
Functional coating and modification	Dip coating	Facile process; low cost	Coating adhesion; surface treatment; multiple coating cycles
	In-situ polymerization	Uniform coating	Controlling polymerization process
	Electroless plating	Low cost; no power source; uniform metal deposition	Chemical waste
	E-beam evaporation/sputtering	Precise thickness control; high coating purity and efficiency; compatibility with various substrates	High cost; coating mask; limited deposition rate and coverage
	Hydro/solvothermal treatment	Scalable and tailored nanostructure formation	Intensive energy consumption; reaction control; substrate with high melting point
	Carbonization	Environmental friendliness; no need for binders	High cost; low material mechanical strength
	Inject printing	Automation and high resolution; no need for masks	Low viscosity ink

distinctive signal patterns for different deformations [72, 94, 206], can help. Multimodal sensors adopting novel materials may have conductivity that is responsive to environmental stimuli (e.g., light and temperature), exhibiting different resistance variation trends [145]. However, signal decoupling is difficult when different stimuli are applied simultaneously. Promisingly, with the rise of AI, machine learning (ML) is a powerful tool for addressing material or structure-related stimuli coupling effects in multimodal sensors. ML can use references that respond to only one of the stimuli to improve signal decoupling [209]. Instead of integrating different sensing units into one platform, single multimodal sensors that also work for other signal transducing mechanisms allow easy simultaneous signal discrimination by integrating additional functional materials in a stacked manner with shared electrodes and different measurement channels. For instance, voltage output based on triboelectricity [198] or thermoelectricity [163], and inductance shift based on NFC [185] are promising methods. The layered configuration also facilitates the incorporation of multifunctionalities such as particle filtering [178], thermal heating/cooling [79], powering [93], and gradient moisture transfer [210]. However, sensor thickness and complexity can pose potential issues in garment integration and signal acquisition. Fiber-shaped electronics offer potential solutions for unobtrusive and scalable multifunctional system integration.

6 Applications

Piezoresistive pressure sensors have found applications in various real-life scenarios, including healthcare, fitness, augmented reality, and human–machine interactions. The thriving of AI technologies such as machine learning (ML) has empowered the efficient analysis and interpretation of multifaceted and complex data collected from sensing systems, enhancing accuracy and user experiences. This opens up more opportunities for advanced applications such as motion and object recognition. There are a variety of ML models available for unsupervised (automatic grouping of datasets without predefined labels) or supervised (classification with discrete labels or regression for continuous quantities) learning. These include traditional algorithms such as support vector machines (SVM) and artificial neural networks (ANN), as well as deep-learning algorithms such as convolutional neural networks (CNN) and recurrent neural networks (RNN) [22, 29, 30]. The typical ML-assisted data analysis process includes the collection of time series/mapping data from analog signals (e.g., voltage/current), data preprocessing/transformation (e.g., noise filtering, outlier removal, data normalization, and feature extraction), and dataset division into training (usually 60–80%), validation (usually 0–20%), and test (usually 20%) sets for model parameter determination, hyperparameter tuning, and performance evaluation, respectively [22, 29]. Afterwards, the trained ML model can be used to make output inferences for new data inputs, achieving real-time health monitoring or multifunctional control.

6.1 Healthcare and Fitness

An important application of textile piezoresistive pressure sensors is the real-time detection of vital physiological signs (e.g., pulse and respiration), and various human motions (e.g., facial expression, voice, joint, and plantar movements). These sensors provide valuable information on health conditions for early prevention, fitness training, or rehabilitation. Zhang et al. [211] developed a piezoresistive pressure sensor with linear high sensitivity (35 kPa^{-1} in 0–40 kPa) using a MXene-coated PET 3D spacer fabric. This sensor can monitor various physiological and motion signals, including finger, wrist, elbow, head, facial, and ankle movements, as well as pulse waves. They further applied machine learning to analyze pulse wave signals from both diseased and healthy volunteers, comparing three different algorithms: random forest (RF) with the highest accuracy of 98.8%, support vector machine (SVM), and convolutional neural network (CNN) (Fig. 8a). Wang et al. [38] created a piezoresistive sensor by coating TPU nonwoven fabric with WS_2 and MXene through self-assembly. This sensor is suitable for monitoring small and medium physiological and joint motions. By combining this with deep-learning models, including Savitzky–Golay filters, bi-directional long short-term memory networks, and long short-term memory networks (SG-BiLSTM-LSTM), they were able to detect abnormal respiration patterns based on breathing rhythms and frequencies with an overall accuracy of 97.5% for identifying five patterns (Fig. 8b). By integrating piezoresistive yarns using in-lay technique on a digital knitting machine and double-layer assembly, Luo et al. [40] reported a fully textile array platform with high resolution (more than a million frames for a full-body ensemble) and accuracy for tactile learning of human interactions with the environment, using convolutional neural network (CNN) models. By integrating piezoresistive yarns using an in-lay technique on a digital knitting machine and double-layer assembly, the tactile sensing system can self-calibrate by training with reference and perform various classification tasks such as motion pattern or object discrimination and posture prediction (Fig. 8c1-c4). Building on this work, Wang et al. [172] fabricated twisted porous piezoresistive yarns and adopted a single-layer integration strategy through biaxial insertion to ensure robust and comfortable tactile sensing in a vest and insole. For gait analysis, the mapped plantar pressure data were transformed into color distribution and processed using a local binary pattern operator. They further carried

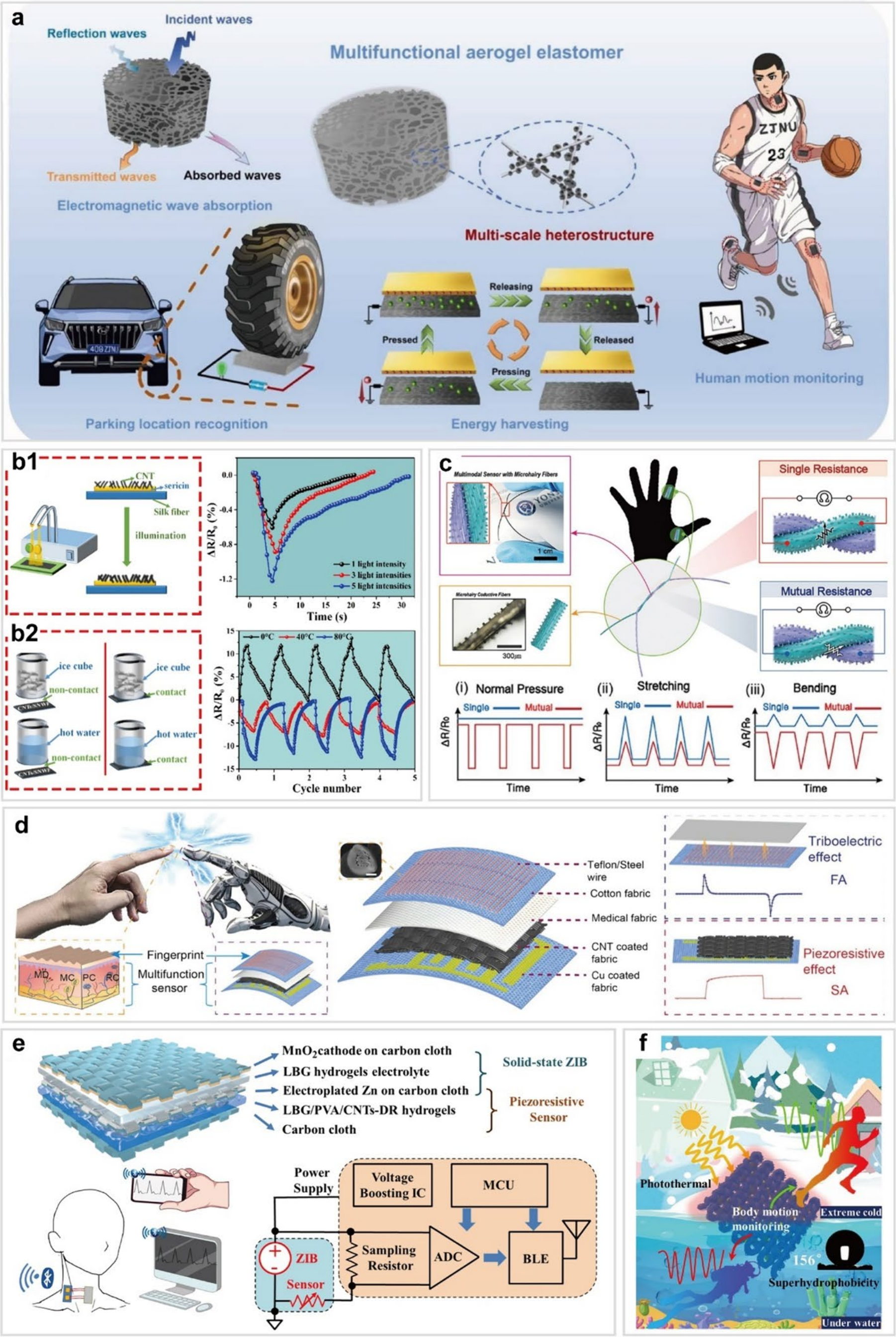

Fig. 7 Multifunctionalities of fiber, yarn and textile-based piezoresistive sensor. **a** A multifunctional composite aerogel piezoresistive sensor for pressure monitoring, electromagnetic wave absorption and triboelectric energy harvesting; reproduced with permission from Ref. [197], Copyright 2022, Elsevier. A silk nonwoven strain/pressure sensor modified with CNTs that is also responsive to **b1** light and **b2** temperature; reproduced with permission from Ref. [145], Copyright 2022, The Authors, under exclusive license to Springer Nature. **c** A double-twisted hairy multimodal mechanical sensor yarn that can discern pressure, stretch and bending by their distinct signal patterns; reproduced with permission from Ref. [72], Copyright 2019, WILEY-VCH. **d** A textile tactile sensor mimicking two human mechanoreceptors by incorporating triboelectric and piezoresistive layers to obtain two types of signals; reproduced with permission from Ref. [198], Copyright 2022, Elsevier. **e** A biocompatible piezoresistive sensor based on hydrogels consisting of LBG, PVA and CNTs, and conductive carbon fabric electrodes, capable of self-powering by integrating additional functional layers that form a flexible zinc-ion battery for wireless pronunciation monitoring; reproduced under the terms of the CC-BY license from Ref. [93], Copyright 2022, The Authors. **f** A superhydrophobic piezoresistive pressure/strain fabric sensor with photo-thermal property that enables operation under water and extreme cold conditions; reproduced with permission from Ref. [132], Copyright 2022, Donghua University, Shanghai, China

out body posture classification using SVM, achieving a high prediction accuracy of 97.5%.

On-body measurement often requires close body contact, conformability to the skin, and distributed sensor placement. In some cases, off-body interactive pressure mapping using pixelated arrays with ML can be an effective alternative for detecting motion patterns such as gait and posture. Sundholm et al. [212] fabricated a piezoresistive pressure-sensing mat capable of detecting and counting a series of different exercises, such as push-ups, abdominal crunches, and squats. This was achieved using a k-Nearest Neighbor (kNN) classifier based on the resistance changes in the middle conductive fabric layer under stress. Zhao et al. [155] developed a textile pressure-sensing array for gait analysis featuring a sandwiched structure with conductive threads embroidered in a perpendicular arrangement on the top and bottom fabric layers (Fig. 8d). Assisted by a LeNet CNN model, this array could accurately recognize different standing postures, making it potentially useful for extracting multi-dimensional information for medical care and user authentication.

6.2 Human–Machine Interactions

Flexible media like textiles are favorable user interfaces in integrated wearable sensing systems owing to their intrinsic flexibility and conformability, enhancing human–machine interaction (HMI) with improved user experiences [8]. Fiber or textile-based piezoresistive pressure sensors are integral parts of HMI systems, serving as input devices for various functions and enhancing everyday life. Deng et al. [70] designed fiber-shaped piezoresistive pressure sensors using SMP, copper wires, and a CNT/PU sheath, which can be woven into a glove to function as a control panel for wireless phone number input and dialing (Fig. 9a). Choi et al. [72] utilized different signal responses from pressing, stretching, and bending of a double helix yarn-shaped piezoresistive sensor to control a virtual shooting game (Fig. 9b). Zhang et al. [102] reported a self-cleanable piezoresistive sensor made of PET nonwoven with CNTs, PPy, PDA, and perfluorodecyltriethoxysilane (PFDS). This sensor can synchronically control a robotic hand for gesturing and can train a robot for handling fragile objects without damage. Vu and Kim [129] developed a waterproof piezoresistive sensor based on a CNT-coated wet tissue, a PU spacer, pyralux, and adhesive films, which was used for wireless music control on a cellphone. The system, trained with five commands by autoencoders (an unsupervised ML model), achieved a classification accuracy of 94% (Fig. 9c).

In addition to device and robotic manipulation, tactile sensation and feedback systems are important for perception training, therapy, and entertainment. Liao et al. [92] proposed a sensor based on contact resistance change within AgNW-coated PU scaffolds and between AgNWs and carbon fiber electrodes, which is applied to tactile sensing systems with visual and audio feedback in response to force amplitude (Fig. 9d1, d2). Using fully textile structures, Zhong et al. [213] integrated conductive yarns with an electrode core wrapped with polymeric multifilament onto fabric using a cross-stitch technique, enhancing sensitivity by increasing the number of crossing points. Five cross-stitched sensors with nine crossing points were employed as a multichannel HMI interface for tapping input, providing color and audio output through an Android device based on force intensity and position.

7 Discussions and Perspectives

The realm of soft wearable technologies has witnessed rapid iterative updates, performance improvement, and functionality extension since its emergence. Flexible wearable piezoresistive sensors based on textile structure (fiber assemblies) or polymeric films constitute an integral part of this field. Hierarchical textile structures offer a versatile platform with favorable attributes for fabricating wearable sensors, such as adjustable breathability at different scales, structural pattern designability, as well as comfortable, scalable integration with garments using existing manufacturing techniques [112]. The curved and multiscale rough surfaces of fiber assemblies provide substantial surface areas conducive to functionalization, especially for hydrophilic natural fibers like cellulose with abundant hydroxyl groups. However, they pose difficulties in forming intricate microstructures compared to flat film-based sensors, which can be easily achieved and controlled using microelectromechanical system (MEMS) fabrication technologies. For textile piezoresistive pressure sensors, compressibility, stretchability, and breathability can be tuned by adjusting fiber materials and the structure of fiber assemblies (wovens, knits, nonwovens, etc.); however, the intrinsic cushioning effect of fibers usually hinders the linearity of the piezoresistive response, with gradual sensitivity decay after a small pressure range (usually < 100 kPa). In contrast, for film-based sensors, sensitivity and sensing range are tunable by altering material orientation and stiffness, incorporating SMP micro-inclusions into ionogels [214], and using a stiffness regulator (rubber frame) with a micropatterned sensitive layer to achieve high linear sensitivity over a wide range [58]. In addition, textiles are highly conformable to the human body with curvy surfaces (particularly those made of knitted structure) due to fiber/yarn slippage, while films typically demonstrate a single bending curvature [172]. A comparison of wearable and sensing attributes between textile and film-based piezoresistive pressure sensors is summarized in Table 5.

To further advance fiber/yarn/textile-based piezoresistive pressure sensors, it is crucial to identify existing challenges and potential pathways for future research and development. From an engineering perspective, key trade-offs need to be carefully considered and balanced to cater to end uses. Firstly, breathability versus film encapsulation is one of the main aspects to consider, as coating functional materials still plays a major role in forming piezoresistive sensors. Film protection is often necessary to ensure material and structure integrity, as well as durable electromechanical performance which depends on the recoverable and repeatable contact resistance changes of conductive networks. This is especially important for delicate nonwoven conductive fiber networks and fabric level coatings, particularly when hierarchical textures are formed on the surface, which could potentially affect the intrinsic air and water permeability of the original textile substrate. When building sensors from a fiber form factor, coating thickness and fabric scale porosity can be more precisely controlled, offering more possibilities in later stages of integration yet at the same time requiring more expertise in fiber/textile manufacturing.

In terms of performance metrics, sensitivity and working range represent a significant trade-off for practical applications. It is highly desirable to have remarkable sensitivity over a wide range without performance decay for both subtle and large-scale motion, with minimal interference from

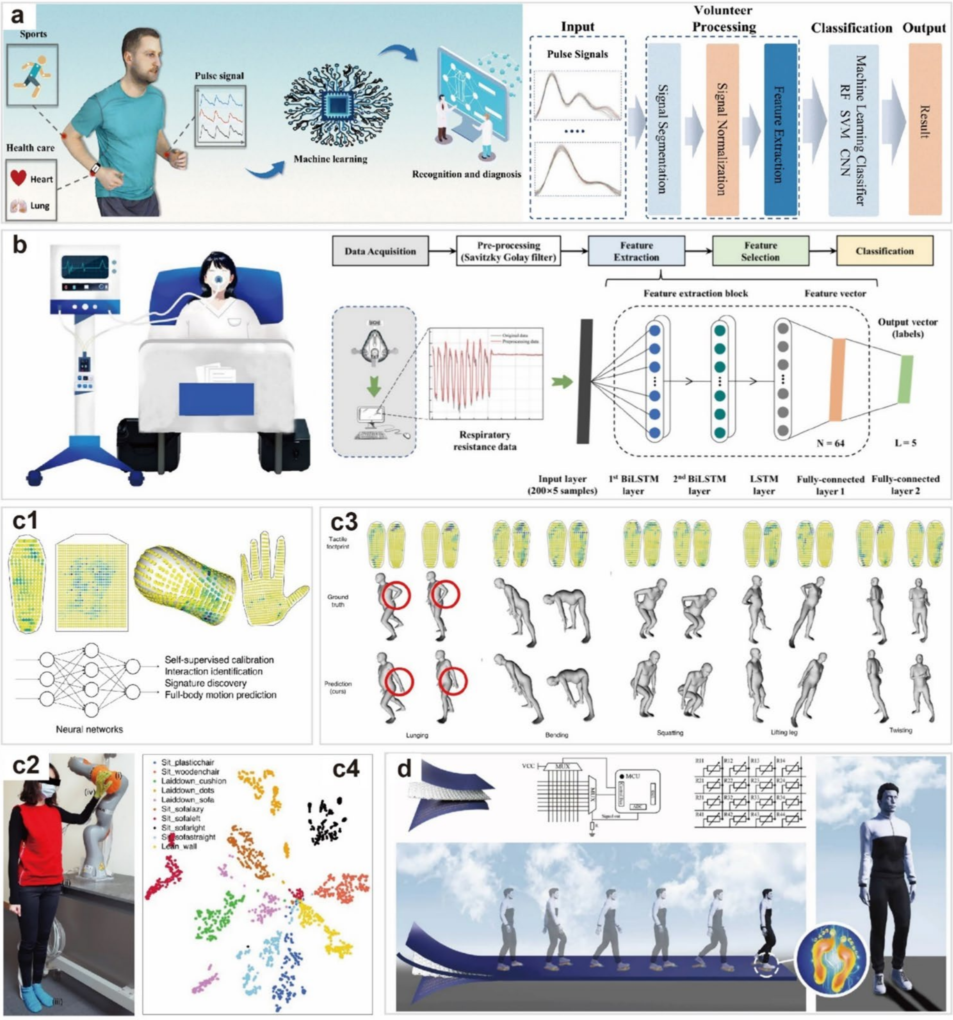

Fig. 8 ML-enhanced applications in healthcare and fitness. **a** Schematic application of $Ti_3C_2T_x$-MXene spacer fabric sensor for monitoring physiological and motion signals and cardiovascular disease diagnosis by analyzing pulse waves using ML models; reproduced with permission from Ref. [211], Copyright 2023, Royal Society of Chemistry. **b** Clinical respiratory-type diagnosis enabled by combining textile piezoresistive sensor with deep-learning algorithms and relative data acquisition and processing flow; reproduced with permission from Ref. [38], Copyright 2023, American Chemical Society. **c1-c2** A fully integrated textile array platform for tactile learning of human interactions with the environment based on CNN models, capable of **c3** discriminating motion patterns or objects and **c4** predicting postures by plantar pressure mapping; reproduced with permission from Ref. [40], Copyright 2021, The Authors, Springer Nature Limited. **d** A textile pressure-sensing array with embroidered perpendicular conductive threads on top and bottom fabric for ML-assisted gait analysis; reproduced with permission from Ref. [155], Copyright 2023, Elsevier

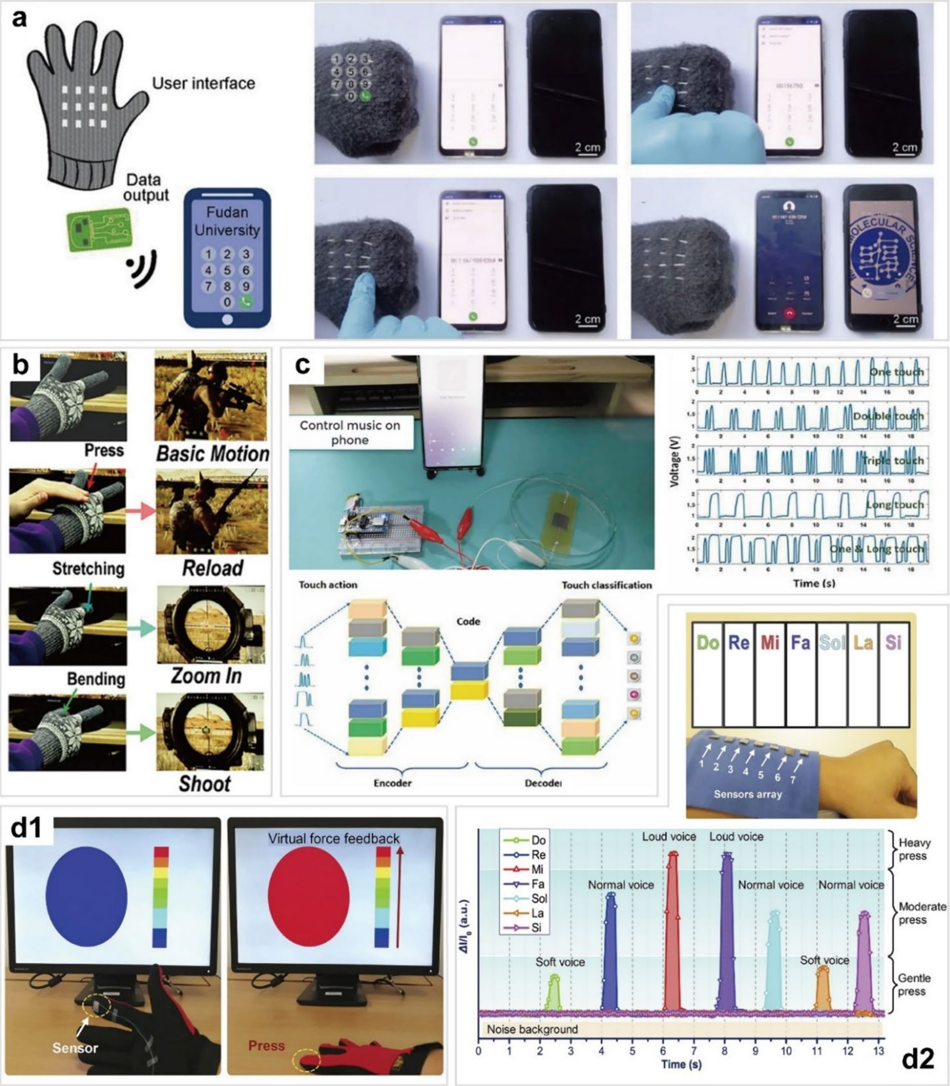

Fig. 9 Applications in human–machine interaction. **a** Fiber-shaped piezoresistive pressure sensors woven into a glove as a control panel for wireless phone number input and dialing; reproduced with permission from Ref. [70], Copyright 2019, Elsevier. **b** A glove integrated with a double helix yarn-shaped piezoresistive sensor to control a virtual shooting game; reproduced with permission from Ref. [72], Copyright 2019, WILEY-VCH. **c** A waterproof textile-based piezoresistive sensor for wireless music control on a cellphone with five commands trained by autoencoders; reproduced under the terms of the CC-BY license from Ref. [129], Copyright 2021, The Authors. A tactile sensing **d1** glove with force correlated visual color feedback and **d2** panel with seven sensors producing sounds according to the tonic solfa in response to force amplitude; reproduced with permission from Ref. [92], Copyright 2019, Elsevier

irrelevant movement. This is crucial for accurate measurements, as deformation range varies depending on the placement of the sensor. As a universal challenge for flexible sensors due to intrinsic viscoelastic properties, much literature has been devoted to seeking solutions to surpass the easy saturation of resistance decrease under pressure. Some solutions include developing sophisticated microstructures, such as bridge-cell micro-structured conductive coatings [33], or directly 3D printing cellular composites with crossing filaments that have tunable piezoresistivity (positive or negative) due to the joint effect of contact resistance and bulk resistance change [167]. Promisingly, recent work by Lin and colleagues leveraged a Janus conductive structure by stacking two sensitive layers of high and low resistance made of cellulose nanofibers/CNTs to construct a piezoresistive pressure sensor with high linear sensitivity of 4.11 kPa^{-1} up to 1 MPa and an ultrawide sensing range up to 3.8 MPa [179]. However, the sensor requires encapsulation to remain its structure integrity and protection against mechanical wear and water.

Third, the selection of materials and structures is crucial for sensor performance and accurate long-term

Table 5 Comparison between textile and film-based piezoresistive pressure sensors

Structure	Surface properties	Piezoresistivity	Wearability	Integration
Textile	Multiscale rough and irregular surface for building hierarchical morphology	Tunable deformability; inefficient compressive stress transfer; easy saturation	Excellent conformability to arbitrary surface; high flexibility; tunable permeability	Scalable and patternable garment integration; high pixel resolution possible
Film	High modifiability with easily patternable flat surface to build sophisticated microstructures	Tunable stiffness, sensitivity and working range; efficient compressive stress transfer	Low wearability; less conformable and flexible; poor permeability	High-cost MEMS fabrication; poor garment compatibility

measurement. For instance, the environmental instability of MXenes and the brittleness and mechanical weakness of conductive polymers pose potential longevity issues for practical applications [5]. Elastomers compounded with fillers or fibers can promote shape recovery by reducing hysteresis [32, 103]; however, this often sacrifices breathability and sensitivity by eliminating pores and voids [103, 153]. The intrinsic rigidity of solid metals or filler materials also needs to be considered, as it may affect flexibility and conformability. In addition, plied conductive yarns could potentially provide fast response due to their sensor configuration [66]. The design of the conductive network is an essential factor that affects the properties and performance of piezoresistive pressure sensors. Combining multiscale nanostructures can generate interlocked conductive networks that significantly enhance sensitivity and stability. For example, 2D MXene sheets with abundant surface functional groups have been employed for the dispersion of graphene sheets and the growth of ZnO nanowires. The incorporation of 1D nanowire arrays provides spaces for further embedding MXene, increasing contact areas for piezoresistive response [79, 215]. Conductive PANI can strongly bind with electrospun PLA-Poly(butyleneadipate-co-terephthalate) (PBAT) substrate nanofiber mats through hydrogen bonds. Piezoresistive sensitivity and structural stability can be enhanced by doping toroidal β-cyclodextrin, which forms inclusion complexes that confine the polymer chains of PANI through hydrogen bonding and nanostructure interlocking with copper-grafted polyamide-imide (PAI) fiber mat electrodes [216].

Furthermore, it is worth mentioning that the resistance response is closely correlated to the viscoelastic behavior of polymeric substrates or matrices and the rearrangement of the conductive network, which can result in abrupt signal variation (overshooting behavior) upon stress application and resistance relaxation over time [150, 217]. This phenomenon is more prominent in piezoresistive strain sensors because macroscopic structural deformation and microscopic movement of polymer chains and conductive filler materials under loads directly affect conductive pathways and thus device resistance [218]. Various parameters need to be considered, including polymer properties (e.g., strain rate and viscoelasticity), characteristics of conductive fillers (e.g., size, morphology, amount, and dispersion state), material interfacial interactions, and the level of stress/strain, which are all crucial aspects affecting sensor waveform output [150, 218]. For example, 2D graphene nanosheets have been reported to have less effect on the reconstruction of the conductive network compared to 1D CNTs with point contacts in a TPU matrix, leading to a much lower overshoot error (1.51% versus 8.69%) [219].

From a product development perspective, sensor form factor is a crucial aspect to consider when catering to specific applicational needs. Table 6 summarizes the advantages and disadvantages/challenges of different form factors for the design of piezoresistive pressure sensors. 1D fiber/yarn-shaped piezoresistive pressure sensors are favorable for unobtrusive pressure mapping with high spatial resolution and sensitivity over arbitrary areas from the palm to plantar/body pressure. Although large-scale integration methods, including textile structuring and additive techniques (e.g., weaving, knitting, and embroidery), provide opportunities for diverse constructional designs tailored to user requirements, the formation of fiber/yarn sensors often requires specialized processing and assembly setups (spinning, coating, twisting/winding, etc.) to ensure consistent properties and performance. Matching material properties, such as melting temperature, viscosity, and interfacial adhesion, is significant for fiber fabrication methods such as melt extrusion, thermal drawing, and coating deposition. Off-the-shelf fabrics offer easily accessible options for functional design and fast sensor prototyping through straightforward fabrication technologies such as in-situ growth, printing, and plasma/thermal treatment. Sensitive layers made of fabric structures benefit from intrinsic mechanical stability and wearability but are limited in terms of coating adhesion and manufacturing scalability. With the booming of nanomaterials, 3D porous composite nanofiber networks are another candidate with the merits of high compressibility and sensitivity, which is tunable through multiscale material mixture and various approaches such as electrospinning, solution casting, and freeze-drying. Nanofiber structures are usually pressure sensitive and well suited for detecting subtle signals such as acoustic vibration and pulse. However, the fabrication and assembly process often requires careful material handling, posing challenges to device reproducibility. In addition, they are less mechanically robust due to their intrinsic light weight and low density.

Furthermore, production cost and scalability are key factors for commercializing sensor products. During the design stage, it has become prevalent to validate structures or predict sensing behavior for fiber/textile-based piezoresistive pressure sensors by leveraging theoretical models or computational simulations like finite-element analysis. This approach is essential as a potential means of reducing design and production costs. It helps in understanding the fundamentals of the sensing mechanism considering material heterogeneity and the unique anisotropic mechanical properties of textile architectures. Many studies have analyzed equivalent circuits to explain sensing behavior, while others have applied theoretical and computational modeling to textile-based sensors to study pressure-dependent conductivity [220] and stress distribution under pressure/strain [33, 72, 128, 154] or bending [32, 195]. A recent study introduced a novel inverse design approach for flexible pressure sensors with a sandwiched configuration and surface microstructure. This approach used a reduced-order contact area model and efficient data screening by the "jump selection" method to optimize sensor parameters and achieve desired properties. It was validated for a series of materials aiming for wide-range linear capacitive sensing, holding great potential in facilitating cost reduction and productivity for diverse sensing schemes and applications. To achieve industrial-scale production, efforts are needed to develop highly automated platforms that can be universally used for sensor fabrication, ensuring property consistency. Fiber, yarn, or textile piezoresistive sensors that can be fabricated using established manufacturing processes (e.g., fiber drawing, yarn spinning, weaving, knitting, and embroidery machines) are favorable for ensuring product quality and economic efficiency. However, they face challenges in incorporating piezoresistive conductive networks, which involve special material or setup requirements. Most solution-based processing methods, such as electroplating, etching, and wet spinning, raise environmental concerns with chemical residues, while physical surface treatment approaches such as plasma treatment and e-beam evaporation are limited in mass production due to high costs. As surface properties are crucial for piezoresistive sensors, more efforts should be directed toward developing eco-economic functionalization methods that are both green and scalable. This will help address the environmental concerns associated with traditional processing methods while ensuring the scalability required for commercial production.

For product evaluation, a well-rounded assessment is desirable to encompass all kinds of human and environmental factors. In most reports, static and dynamic electromechanical properties are characterized, examining sensing response and reproducibility under varying frequency and pressure loads, as well as sensor durability over thousands of press-and-release cycles. However, these laboratory tests are limited in terms of comparability due to different testing conditions. In addition, because large biomechanical stresses are often exerted on sensors when they are embedded in garments through motions such as donning, doffing, and bending, more attention should be paid to the performance of fully integrated sensors to ensure electromechanical sensing stability and precision in practical situations, which is rarely examined [221]. Washability tests are becoming more common but are rarely conducted in accordance with existing protocols of test standards (e.g., ISO 6330 for domestic textile washing and drying procedures [222]). At times, conductivity or sensing behavior is compared before and after simple soak-and-stir washing or unspecified machine-washing cycles. Moreover, as conductive coatings are still the integral constitution of piezoresistive pressure sensors, coating fastness under mechanical abrasion is a key factor to consider in a practical context but is often not characterized through standardized testing. Other factors such as temperature, humidity, and chemical stability are rarely reported thoroughly, yet they are also important for ensuring the overall longevity of the sensor under conditions of sweating and environmental corrosion. In addition, test standardization is another significant aspect of product development considering the limited quantity of existing standards applicable to e-textiles [222]. This involves performance validation at both semi-finished state (e.g., conductive yarns or fabrics) and finished goods with fully integrated functionalities to enable product comparison and commercialization.

Table 6 Advantages and disadvantages/challenges of different sensor form factors

Form factor	Advantages	Disadvantages/challenges
Fiber/yarn	High spatial resolution, unobtrusive large-scale integration	Specialized processing and assembly setups required
Functionalized fabric	Material accessibility, easy prototyping, mechanical integrity	Scalability, coating adhesion and uniformity
Nanofiber network	High compressibility and sensitivity	Reproducibility, poor mechanical robustness

8 Conclusion and Outlook

As the era of wearable technology and smart textiles continues to unfold, the integration of flexible pressure sensors, particularly piezoresistive sensors based on fiber or textile structures, will play a pivotal role in shaping the future of wearable devices. These sensors have not only enhanced the diversity and performance of wearables but have also paved the way for innovative applications that prioritize user comfort, accessibility, and style, going beyond the capabilities of conventional rigid electronics. This paper reviews wearable pressure sensors based on the piezoresistive sensing principle and fiber, yarn, or textile structures. We first discussed the basics of the piezoresistive effect, sensor working principle, important performance evaluation metrics (e.g., sensitivity, stability, and hysteresis), and sensor constituent materials (e.g., conductive materials categorized into inorganic metallics, carbonaceous materials, and conductive polymers; substrate materials including natural and synthetic polymers). We then elaborate on various structural designs in the form factors of fiber/yarn and composites of their assemblies, as well as fabrication strategies for forming functional textile materials such as fiber spinning, and coating techniques. We also highlight the incorporation of multifunctionalities into a single sensor, such as responsiveness to multiple stimuli (e.g., strain, bending, temperature, and humidity) or mechanisms (e.g., triboelectric or capacitive sensing), energy supply, heating, and waterproof/self-cleaning. Associated challenges and potential solutions for system integration and signal processing are also discussed. Furthermore, we summarize various advanced applications, including healthcare, fitness, and human–machine interactions enhanced by the rising AI technology. We provide discussions on the comparison of sensor form factors, technical considerations, and challenges in terms of material-structure–property design, scalable production, and product evaluation. Recommendations for sensor development and engineering are also provided.

With the booming of modern technologies, wearable piezoresistive sensors have found their place in numerous domains, mimicking and even transcending human tactile sensations. They hold the promise of reshaping industries from medical care and prevention to robotics. However, to promote the maturation of these innovations and enable more widespread applications, various challenges remain, such as sensor reproducibility and the construction and costs of manufacturing lines for commercialization and scaled-up production. Moreover, wearable sensors, being directly in contact with human skin, are generally expected to be flexible, biocompatible, and biodegradable, without causing skin irritation or toxicity to our bodies and the environment. This exciting field still holds great potential for future exploration of new materials and structures toward more sustainable and robust smart textile-based electronic systems that are cost-effective and long-lasting. Due to the multidisciplinary nature of the field, comprehensive support from professionals with diverse backgrounds—ranging from material science, textile and electrical engineering, data analysis, to design and supply chain management—is crucial. As research and development in this field progress, we can anticipate further breakthroughs that will redefine the boundaries of wearable technology and its impact on our lives, empowering healthier, more productive, more connected, and versatile lifestyles.

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Data availability Data is available upon reasonable request.

Declarations

Conflict of Interest Rong Yin is an editorial board member/editor-in-chief for Advanced Fiber Materials and was not involved in the editorial review or the decision to publish this article. All the authors declare that there are no competing interests.

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