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Mini Review

Recent Advances in Textile-Based Sensors for Smart Textiles

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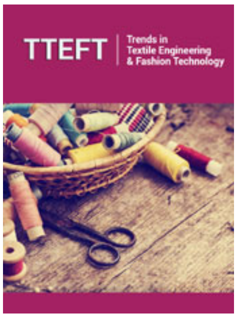

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Abstract

Textile-based sensors are a class of textile electronic devices that enable electrical responses to external stimuli through the integration of conductive or functional materials into fibers, yarns, or fabric structures, and serve as fundamental functional units in smart textiles. Compared with conventional rigid sensors, textile-based sensors exhibit distinct advantages, including high flexibility, large-area conformability, stretchability, lightweight, breathability, and wearing comfort, allowing them to detect physiological and environmental signals while preserving the intrinsic properties of textiles. In recent years, with the rapid development of advanced materials and fabrication technologies, the performance and functionality of textile-based sensors have been significantly expanded, demonstrating great potential in applications such as human motion monitoring, physiological signal detection, and human-machine interaction. This review systematically summarizes the material systems, structural designs, and sensing mechanisms of textile-based sensors, highlights the key challenges in current research, and further discusses their future development directions in health monitoring, smart garments, and interactive wearable systems in light of emerging technological trends.

Keywords: Textile-based sensors; Smart textiles; Sensing materials; Sensing mechanisms; Wearable electronics

Introduction

With the rapid development of wearable electronics, the demand for smart textiles in health monitoring, motion tracking, and human-machine interaction has increased significantly [1,2]. Current wearable systems are predominantly based on rigid sensors for signal acquisition and processing [3-5], which suffer from poor breathability, limited conformability, and compromised long-term comfort. In contrast, textile-based sensors can achieve signal detection while preserving the intrinsic properties of fabrics, providing a promising route toward imperceptible wearability.

However, the key challenge of textile-based sensors lies not merely in material flexibility, but in constructing stable and reproducible signal transmission pathways within highly deformable, porous, and structurally random textile architectures. Fiber contact, interfacial sliding, and structural evolution directly affect the formation and stability of conductive networks, thereby determining sensing performance. Consequently, improving material properties alone is insufficient to address issues of stability and reproducibility. This paper systematically reviews the materials, structures, and sensing mechanisms of textile-based sensors, with particular emphasis on recent advances in applications. Furthermore, the key challenges in current research are analyzed. On this basis, future development directions are discussed.

Materials for textile-based sensors

Carbon-based nanomaterials: Carbon nanotubes (CNTs) and graphene are widely used to construct conductive networks due to their excellent electrical conductivity and mechanical flexibility. These materials are typically integrated into fibers or fabrics via coating, impregnation, or composite spinning, forming flexible conductive pathways. Their sensing mechanism mainly arises from deformation-induced reconstruction of conductive networks, where variations in inter-filler contact and tunneling distance lead to resistance changes [6,7]. Although multiscale conductive networks can enhance sensing performance, the interfacial adhesion between carbon nanomaterials and textile substrates remains a critical challenge. Under repeated deformation or washing, conductive materials may detach, resulting in performance degradation.

Metal nanomaterials: Metal nanomaterials, such as silver nanowires (AgNWs), gold nanoparticles, and copper nanowires, can form highly conductive networks on textile surfaces via spraying, dip-coating, or printing techniques. Their sensing performance is governed by changes in the connectivity of the nanowire network under mechanical stimuli, leading to pronounced resistance variation. By tailoring nanowire density and distribution, sensor sensitivity and detection range can be optimized [8]. However, metal nanomaterials are prone to oxidation and mechanical failure during long-term use, necessitating encapsulation or composite strategies to improve durability.

Conductive polymers: Conductive polymers, including Poly(3,4-ethylenedioxythiophene)/ poly (styrenesulfonate) (PEDOT: PSS), polyaniline (PANI), and polypyrrole (PPy), are attractive due to their flexibility, processability, and relatively high conductivity. These materials can be directly coated onto fibers or fabrics via solution-based methods, forming porous conductive layers that respond to mechanical deformation [9]. Despite their advantages, conductive polymers often suffer from environmental instability, particularly under exposure to air and humidity, leading to performance degradation.

Structural design and sensing mechanisms of textile-based sensors

The core function of textile-based sensors is to transduce external mechanical or physiological stimuli into electrical signals. Unlike conventional rigid devices, textile sensors must achieve high sensing performance while maintaining softness, breathability, and mechanical compliance. Therefore, constructing stable and functional conductive pathways within fibers, yarns, or fabric structures is central to their design. According to signal transduction mechanisms, textile-based sensors can be broadly classified into resistive, capacitive, piezoelectric, and triboelectric types.

Resistive textile-based sensors: Resistive textile-based sensors operate by inducing changes in resistance through deformation of the textile, which alters the structure of the conductive network. Their structure is typically realized by constructing conductive networks on the surface of fibers or fabrics, including conductive coating, yarn compositing, and formation of conductive pathways through textile structures [10]. When the textile is stretched or bent, the contact area between fibers and the spacing between conductive materials change, leading to the reconstruction of conductive pathways. Essentially, this process can be attributed to the dynamic evolution of conductive percolation networks under external stress.

Resistive textile-based sensors have the advantages of simple structure and easy fabrication; however, there exists a certain trade-off between sensitivity and linear detection range [11]. Therefore, developing resistive textile sensors with high sensitivity over a wide pressure range remains a significant challenge. Yu et al. [12] prepared textile sensors with different fabric structures, including plain weave, twill weave, weft plain weave, and rib structures, by attaching MXene nanosheets onto textile surfaces via hydrogen bonding. These sensors exhibit high sensitivity, wide sensing range, fast response/recovery time, and excellent durability. Nevertheless, resistive textile-based sensors still suffer from poor recovery performance and insufficient stability, mainly due to the irreversible evolution of conductive networks during deformation (such as interfacial sliding and local fracture). Therefore, the performance of resistive textile-based sensors is essentially limited by the controllability and reversibility of contact states within textile structures.

Structure and principle of capacitive textile-based sensors: Capacitive textile-based sensors usually adopt a structure similar to that of a parallel-plate capacitor, consisting of two conductive textile electrodes and a flexible dielectric layer in between. This “sandwich” structure can be realized through lamination, weaving, or knitting, where conductive yarns serve as electrodes and porous textiles or elastic polymers act as dielectric layers [13]. When the textile is subjected to pressure or deformation, the distance between electrodes or the effective contact area changes, resulting in a variation in capacitance.

In recent years, significant progress has been made in the structural design of capacitive textile-based sensors. You et al. [14] fabricated a stretchable capacitive textile sensor via electrospinning, which exhibits high sensitivity, a wide sensing range, and a low detection limit. Ma et al. [15] developed a multifunctional capacitive textile sensor by designing a composite textile structure consisting of core-sheath yarns and spacer fabrics, enabling both tactile sensing and tensile response. The performance of capacitive textile sensors depends on the compressibility of the dielectric structure and the controllability of the electric field distribution. By tailoring the pore structure of dielectric materials or increasing the dielectric constant, the electric field modulation capability can be enhanced, thereby improving sensitivity. However, the porosity and hygroscopicity of textile dielectric layers may also introduce signal fluctuations and affect stability.

Structure and principle of piezoelectric textile-based sensors: Piezoelectric textile-based sensors utilize the property of piezoelectric materials to generate electrical charges under mechanical stress for signal conversion. Common piezoelectric materials include poly (vinylidene fluoride) (PVDF) and its copolymers, which are suitable for wearable applications due to their good flexibility and piezoelectric properties [16]. In terms of structure, these sensors are typically realized by embedding piezoelectric fibers into textile structures or integrating piezoelectric films with textile substrates.

Piezoelectric textile-based sensors exhibit fast response and high sensitivity, making them suitable for dynamic pressure detection. Jiang et al. [17] improved piezoelectric performance and mechanical strength by incorporating $BaTiO_3$ inorganic fillers or constructing composite nanostructures. Guo et al. [18] fabricated electrospun PVDF fiber-based sensors, and further enhanced piezoelectric response by regulating the β-phase content of PVDF. Piezoelectric textile-based sensors have clear advantages in dynamic signal detection; however, their response depends on changes in applied stress, which fundamentally limits their ability to achieve stable static pressure detection.

Structure and principle of triboelectric textile-based sensors: Triboelectric textile-based sensors operate based on the triboelectric effect and electrostatic induction. When two different materials come into contact and separate, charge transfer occurs at the interface, generating a potential difference [19]. In textile-based systems, triboelectric structures are typically composed of two layers of different textile materials, and alternating electrical signals are generated through periodic contact and separation. These sensors usually exhibit high output voltage and can operate without an external power supply, showing advantages in dynamic motion detection and energy harvesting. Guan et al. [20] utilized polystyrene as an interfacial material to provide high electron trapping capability, and further enhanced charge density by doping polystyrene with conductive carbon black, achieving a peak output power of 52.3μW. However, due to the high output impedance of triboelectric signals and their sensitivity to environmental factors such as humidity, further optimization in structural design and material selection is required for practical applications.

By correlating textile structural design with sensing mechanisms, it can be found that the performance of different types of textile-based sensors is not only determined by the materials themselves, but is also strongly influenced by textile structures. Factors such as fiber arrangement, fabric density, and interfacial contact states can directly affect conductive pathways or electric field distribution, thereby determining sensing performance. Therefore, future research should focus on the synergistic optimization of structural design and material engineering to achieve improved sensitivity, stability, and mechanical reliability.

Applications of textile-based sensors

The applications of textile-based sensors in smart textiles are evolving from single-signal acquisition toward multimodal sensing, system integration, and intelligent development. By enabling real-time acquisition and analysis of physiological signals, motion states, and tactile information, textile-based sensors can realize long-term continuous monitoring and provide important data support for medical diagnosis, sports training, and human-machine interaction. Current research mainly focuses on physiological monitoring, motion and rehabilitation assessment, and human-machine interaction.

Physiological monitoring in smart garments: In physiological monitoring, textile-based sensors can achieve continuous acquisition of multiple signals such as electrocardiogram (ECG), respiration, and sweat analysis [21]. Textile electrodes can replace traditional Ag/AgCl gel electrodes, enabling long-term and non-irritating ECG monitoring, while also offering washability and sewability, thus realizing the integration of sensing and signal transmission [22].

Respiration monitoring is typically achieved by detecting changes in the chest and abdominal regions. Textile-based strain or triboelectric sensors have been used to monitor respiration frequency and identify abnormal breathing patterns [23]. In addition, fiber-based electrochemical sensors can detect ions (Na^+, K^+), metabolites (glucose, lactate), and hormones in sweat, enabling dynamic evaluation of physiological states [24].

Motion monitoring and rehabilitation assessment: In motion monitoring, textile-based sensors can be used to obtain real-time information on joint angles, motion frequency, and muscle activation. Guo et al. [25] demonstrated that textile strain sensors can achieve quantitative analysis of joint motion and have the potential to be integrated with exoskeleton systems. In rehabilitation medicine, sensor-integrated garments can be used to record gait patterns, joint mobility, and muscle activation, providing data support for personalized rehabilitation [26].

Human-machine interaction interfaces: Textile-based sensors, as flexible tactile interfaces, show great potential in human-machine interaction. Luo et al. [27] demonstrated that by integrating sensors and actuators into textile structures, tactile perception and feedback can be achieved. In addition, textile-based touch interfaces based on ionic conductive materials provide new approaches for biodegradable and multifunctional interaction systems, enabling responses to various external stimuli [28].

Challenges and future development of textile-based sensors

Challenges of textile-based sensors: Although textile-based sensors have achieved significant progress in terms of materials, structures, and applications, they still face multiple challenges in practical applications and industrialization.

First, structural stability and durability remain critical issues. Textiles are inherently porous, soft, and deformable, and under repeated stretching, bending, and friction, conductive materials are prone to cracking, detachment, or interfacial delamination, leading to failure of conductive networks. Meanwhile, washing, sweat, and environmental humidity can further weaken interfacial adhesion, thereby reducing the long-term reliability of devices.

Second, signal stability and environmental interference are major concerns. Due to the high porosity and hygroscopic nature of textiles, they are highly sensitive to temperature, humidity, and the human body environment, which can induce variations in electrical conductivity and interfacial contact states, resulting in signal drift and increased noise.

Third, device consistency and reproducibility remain challenging. Textile structures consist of randomly distributed fibers, and variations in fiber arrangement, pore structure, and conductive material distribution across different regions can lead to significant fluctuations in device performance.

Fourth, scalable manufacturing and system integration present considerable difficulties. Current fabrication methods are still not fully compatible with traditional textile processes. At the same time, achieving integration of sensors with power sources, signal processing circuits, and communication modules while maintaining softness and breathability remains challenging.

Finally, data processing and system reliability are critical issues. Long-term continuous monitoring generates large amounts of complex data, often accompanied by noise and environmental interference. Therefore, achieving stable data acquisition and reliable analysis is a key factor limiting practical applications.

Future development of textile-based sensors: In response to the above challenges, the future development of textile-based sensors will mainly focus on the following aspects.

First, the design of interfacially stable conductive materials. Compared with simply improving conductivity, more attention should be paid to the interfacial bonding between materials and fibers, as well as their stability under deformation, in order to construct conductive networks capable of long-term operation.

Second, the synergistic design of textile structures and device architectures. By regulating structures at multiple scales, including fibers, yarns, and fabrics, it is possible to achieve coordinated optimization of mechanical properties and sensing performance. In addition, introducing functional materials into fiber interiors or constructing functionalized fiber-based devices may further improve structural stability and integration.

Third, the development of scalable manufacturing technologies. It is necessary to establish fabrication methods compatible with conventional textile processes, thereby promoting the transition of textile-based sensors from laboratory research to industrial applications.

Fourth, system-level integration and intelligent development. Future textile-based sensors need to be integrated with power management, electronic circuits, and wireless communication modules to form complete sensing systems. Meanwhile, the introduction of machine learning and data-driven methods can enhance the recognition and analysis of multimodal signals.

Fifth, multifunctional integration and intelligent textile systems. Textile electronics are expected to evolve from single sensing units to multifunctional integrated systems, enabling the integration of sensing, processing, and feedback.

Conclusion

Textile-based sensors, as a technology that deeply integrates functional materials with textile structures, fundamentally rely on the variation of contact states and interfacial physical processes within multiscale textile architectures to achieve electrical responses to mechanical stimuli and physiological signals. Compared with conventional planar devices, textile-based sensors not only exhibit excellent flexibility and breathability, but also depend on the tunable contact interfaces and mechanical response characteristics arising from their three-dimensional porous structures, thereby forming structure-dominated sensing mechanisms. On this basis, textile-based sensors have demonstrated broad application potential in physiological monitoring, motion detection, and human-machine interaction.

However, the development of textile-based sensors is still constrained by structural randomness and interfacial instability. During long-term use, issues such as performance degradation, signal drift, and insufficient device consistency are likely to occur. In addition, challenges remain in scalable manufacturing, system integration, and data reliability. Therefore, future research should focus on the synergistic optimization of material design, structural engineering, and system integration, with particular emphasis on improving the stability and controllability of conductive networks, and promoting the transition of textile-based sensors from individual devices to highly reliable and scalable intelligent textile systems.

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