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# Flourishing electronic textiles towards pervasive, personalized and intelligent healthcare

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## Abstract

In the face of pandemic infectious diseases and increasing aging trends, traditional public health systems lack the capacity for real-time monitoring, immediate clinical detection, continuous vital sign monitoring, and the implementation of long-cycle treatment protocols, among other deficiencies. On the basis of the rapid development of wearable electronic devices, the Internet of Things, and artificial intelligence, the future healthcare model will transform from a therapeutic, centralized, passive, and even one-size-fits-all treatment to a new paradigm of proactive, preventive, personalized, customized, and intelligent way. The development of wearable electronics has facilitated the evolution of healthcare from healthcare to biological monitoring, enabling continuous monitoring of critical biomarkers for diagnostic treatment, physiological health monitoring, and assessment. Electronic textiles (e-textiles) are among the rapidly developing wearable electronics in recent years. They have revolutionized the functionality of traditional textiles by incorporating smart attributes, enabling unique and multifunctional applications. Significantly, e-textiles have made notable advancements in the field of personalized healthcare. The article introduces several common e-textiles and their applications in personalized medicines, which also gives a forward-looking outlook on their future growth in infectious diseases, real-time health preventive monitoring, auxiliary therapy, and rehabilitation training.

**Keywords:** E-textiles, wearable sensors, personalized healthcare, preventive diagnosis, auxiliary therapy

## INTRODUCTION

Traditional public health systems face a range of problems in terms of limited, delayed, and inefficient healthcare delivery in the face of pandemics and aging populations[1-3]. At the same time, diagnosis of various chronic and acute diseases is becoming increasingly important, and the healthcare industry is changing dramatically due to the need for diagnostic and real-time monitoring of care for long-term health conditions[4-6]. Although there have been significant technological and scientific breakthroughs in disease treatment methods, disease diagnosis and classification based on clinical observations and self-reported questionnaires remain the primary means of monitoring an individual's health[7]. Medical help is typically sought by patients during routine follow-up visits or when symptoms associated with health conditions appear or change[8]. The impossible challenge for medicine is to correctly detect and effectively treat health conditions before they become symptomatic. Affordable, valid, and reliable real-time monitoring tools are also necessary. The urgency of this challenge has been heightened by the increasing elderly population, sudden rise in healthcare costs, and prevalence of chronic diseases. To overcome these challenges and transform detection methods using reliable and timely health models, it will be necessary to rethink current approaches to managing individual healthcare.

The traditional medical model is based entirely on the experience and memory of the physician, yet symptoms or characteristics of each patient are different. Every person will experience misdiagnosis in their lifetime. However, in the last few decades, scientific researchers have made it possible to develop daily and lifelong health monitoring systems through advances in integrated circuits, sensor technology, wireless communications, and mobile networks[9,10]. The use of existing wearable electronic devices for remote diagnosis, treatment, and health monitoring by researchers is ushering in a paradigm shift in healthcare. This shift will bring about a new era of smart disease control and detection, virtual medicine, smart health management, and smart decision-making[11,12]. Device size, power limitations, ergonomic comfort restrictions, and variations in quality and durability pose limitations to the application of wearable devices in decentralized healthcare despite their potential to assist in such settings[13].

Textiles are fascinating materials used in various human wears, including clothes, jewelry, shoes, bandages, *etc.*[14]. Their multiple structures offer a wide range of functionalities, making them excellent carriers for preparing smart wearables[15,16]. Many specific functions can be achieved by making them durable, lightweight, and porous while also offering the advantages of robustness, strength, and low manufacturing costs by adjusting the parameters of the textile preparation process[17]. The next generation of wearable devices and smart technology textiles will rely on active fabrics made from conductors, insulators, semiconductor fibers, and functionalized fibers by weaving them into textile yarns or braiding them[18]. Fabrics woven from such yarns will seamlessly integrate electronic functionality into everyday wearable, comfortable, lightweight garments[19]. The potential of wearable electronic textiles (e-textiles) for non-invasive health monitoring has gained tremendous attention from scientific researchers[20-23]. Integrating functions such as sensing, monitoring, and therapy into e-textiles of various situations (which can sense external physical stimuli or environmental changes) allows for patient diagnosis, treatment, care, and rehabilitation[24,25] [Figure 1]. By integrating wearable devices with wireless communication devices, a wearable medical textile system can be created, which can provide individuals with medical care in a fast, accurate, and convenient way[26]. A wearable care textile system that utilizes the integration of 5G technology and the Internet of Things could potentially revolutionize the healthcare sector in the future. This system could prevent disease, provide treatment, and promote human health more effectively than ever before[27]. Wearable care textile systems will eventually become an integral part of our daily attire[28].

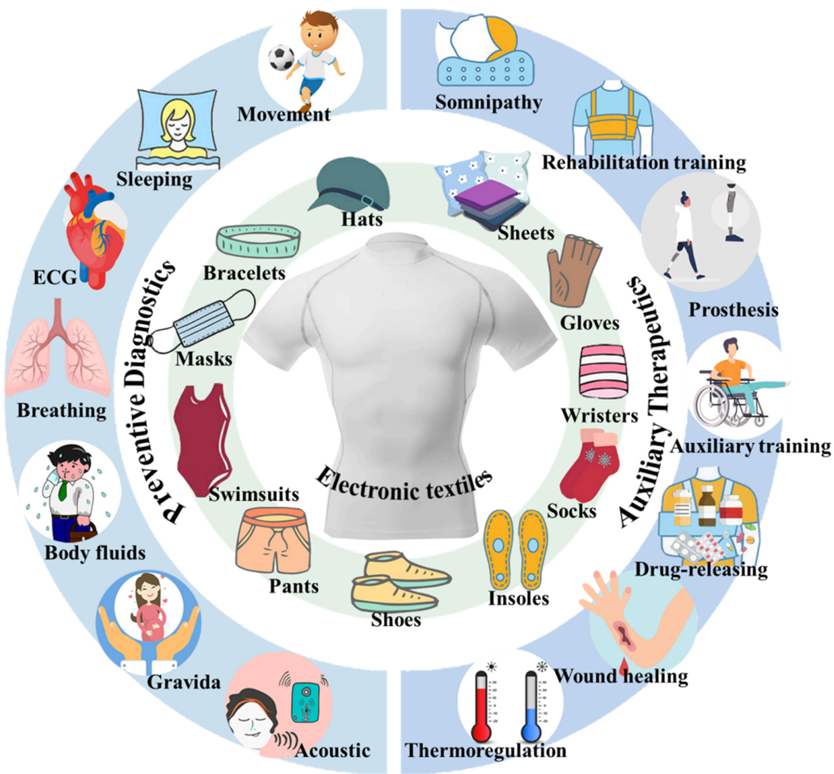


**Figure 1.** E-textiles for personalized healthcare, including preventive diagnostics and auxiliary therapeutics. The inner ring depicts various fabric accessories prepared as e-textiles with functional wearability. The outer ring shows the role of functionalized textiles in diagnosing and treating human diseases. ECG: Electrocardiogram.

This review describes the sensing principles, preparation materials and methods of several common e-textiles and outlines their typical applications in personalized medicine. Their future development in infectious diseases, real-time monitoring, complementary therapies, and rehabilitation training will have some informative implications for technological innovations in producing e-textiles in personalized medicine.

## SENSING MECHANISMS OF E-TEXTILES

In the realm of physical sensing technology for textiles, biomechanical sensors are the most advanced and come in various forms, such as piezoelectric[29], triboelectric[30], electrochemical[31], and capacitive or resistive strain or pressure sensors[32,33]. Figure 2 summarizes the mechanisms that make these types of sensors suitable for personalized healthcare.

### Piezoelectric effect

E-textiles can integrate piezoelectric nanogenerators (PENGs), which utilize the piezoelectric effect to both generate electricity and detect biomechanical motion through mechanical deformation. This property enables PENGs to produce various sensing signals, making them suitable for integration into e-textiles[38]. Figure 2A illustrates the piezoelectric effect, which occurs when mechanical stresses in the lattice of a piezoelectric material cause a change in the distance between the positive and negative charge centers[34]. This alteration modifies the original dipole moment, leading to the generation of polarized charges on the surface of the piezoelectric material.

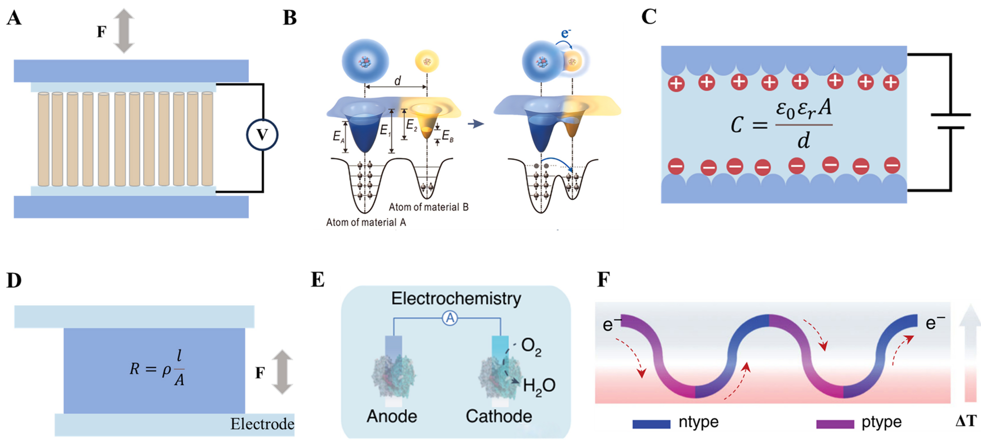


**Figure 2.** The mechanisms of (A) Piezoelectric[34], Copyright 2023 MDPI; (B) Triboelectric[35], Copyright 2018 WILEY-VCH; (C) Capacitive[33], Copyright 2022 MDPI; (D) Resistive[36], Copyright 2019 MDPI; (E) Electrochemical[13], Copyright 2022 Springer Nature; (F) Thermoelectric[37] sensors, Copyright 2020 Springer Nature.

### Triboelectric effect

Triboelectric nanogenerators (TENGs) use contact electrification and electrostatic inductive coupling to convert mechanical motion into electrical energy, a property that yields a number of sensing signals, following which TENGs can be integrated into e-textiles[35]. Figure 2B illustrates the electron cloud potential well model[39]. In this model, $E_A$ represents the energy level occupied by electrons in the atoms of material A, while $E_B$ represents the energy level occupied by electrons in the atoms of material B. Additionally, $E_1$ represents the energy level required for electrons to escape from the surface of material A, and $E_2$ represents the energy level required for electrons to escape from the surface of material B. Upon contact between materials A and B, their electron clouds overlap, resulting in the formation of an asymmetric double-potential well. This configuration enables the transfer of electrons from atoms in material A to atoms in material B. The energy levels of the electrons in materials A and B are represented by their respective electron clouds. By leveraging electrostatic induction, a change in the electric field strength occurs as the two materials are separated, leading to the generation of an electron flow and the production of electricity.

### Capacitive effect

Textile capacitive technology harnesses the changes in capacitance resulting from biomechanical pressure[33]. Figure 2C illustrates the typical construction of capacitive pressure sensors, which involves a “sandwich” structure consisting of an upper electrode, a dielectric layer, and a lower electrode. The capacitance value (C) can be calculated using the following formula:

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

In this equation, $\varepsilon_0$ represents the vacuum dielectric constant, $\varepsilon_r$ denotes the relative dielectric constant of the dielectric layer, A represents the effective area of the upper and lower electrodes, and d represents the distance between the two electrode plates. When pressure is applied, the elastic deformation of the soft material in the flexible capacitive pressure sensor causes changes in $\varepsilon_r$, A, d, and the capacitance of the sensor.

### Resistive effect

Textile resistive sensors utilize changes in electrical resistance caused by the magnitude and direction of biomechanical stress and, thus, can also be integrated into e-textiles as sensor devices[40]. The equivalent circuit in Figure 2D illustrates that the variation in the output of the sensor concerning the applied pressure on the sensing surface is influenced by the alteration in relative resistance[36].

### Electrochemical effect

Figure 2E illustrates how electrochemical sensors convert chemical energy signals from redox reactions into electrical signals[31]. Textiles, with their abundant elastic properties that enable conformal sensor-body contact, are appealing components for wearable sensing devices. The integration of chemical sensors directly into fabrics provides significant advantages for future healthcare monitoring systems.

### Thermoelectric effect

Figure 2F demonstrates how thermoelectric generators leverage the thermoelectric effect to convert changes in heat into electrical energy[37]. Within each thermoelectric cell, carriers flow in the same direction along the fiber, facilitating voltage multiplication. By connecting the fibers in series or parallel, the voltage or current can be increased accordingly. The thermoelectric conversion efficiency of a thermoelectric device is determined by the dimensionless figure of merit (zT), calculated as $zT = \sigma S^2 T/\kappa$, where $\sigma$ represents electrical conductivity, S represents the Seebeck coefficient, $\kappa$ represents thermal conductivity, T represents absolute temperature, and $S^2\sigma$ corresponds to the power factor[41]. These textile-based thermoelectric generators have been investigated for harnessing human body heat and generating electricity for healthcare applications.

## MATERIALS AND FABRICATION OF E-TEXTILES

### Nanofibers for e-textiles

Nanofibers possess several advantages over traditional textile materials, including their ultra-high specific surface area, surface activity, and responsiveness to stimuli. These unique characteristics make them highly promising for applications in diverse fields such as filtration, energy production and storage, biomedicine, tissue engineering scaffolds, chemistry, sensors, and smart textiles[42]. As a novel type of smart textile material, nanofiber membranes exhibit remarkable protective properties against various environmental threats, ensuring the well-being of individuals. There are multiple techniques available for manufacturing nanofibers, including composite (conjugate) spinning, chemical vapor deposition (CVD), drawing, template synthesis, self-assembly, melt blowing, and electrospinning[43]. Unlike conventional fiber spinning methods such as melt spinning, dry spinning, or wet spinning, which rely on mechanical force to extrude a polymer melt or solution through a spinneret and subsequently tow the resulting filaments during solidification and coagulation to produce fibers, electrospinning utilizes electrostatic force to stretch a polymer solution/melt jet into commercially viable ultrafine fibers. The electrospinning process involves the application of a high-voltage electrostatic force to the tip of a capillary tube, generating an electric field between the tube's tip and a grounded collector. As the polymer solution/melt flows through the capillary tube, it forms a droplet that sags, transforms into a hemispherical shape, and eventually assumes a conical shape under the influence of the electric field. The resulting fibers can be randomly oriented or aligned in a specific direction. However, the industrialization of electrospun nanofibers has encountered limitations due to their relatively weak mechanical properties. Furthermore, the low productivity of electrospinning equipment presents a significant challenge that hinders its commercialization.

### Nanomaterials for e-textiles

The realization of e-textiles heavily relies on the incorporation of conductive materials, which bestow electrical conductivity to textiles[44]. These materials serve as indispensable components for signal transmission, particularly in health monitoring sensors. Depending on their specific properties, conductive materials can also find application in resistive fiber sensors, electromagnetic interference shielding, and wearable antennas. Striking a balance between conductivity and stretchability is of paramount importance when it comes to the development of conductive textiles. Conventional textiles, such as cotton, nylon, and polyester, are considered electrical insulators. To introduce conductivity to textiles, commercially available conductive textiles often rely on solid metal wires such as copper and stainless steel or non-conductive yarns coated with a metallic film as found in silver. However, these conductive textiles tend to be rigid and brittle, making them prone to breakage during weaving and practical applications. The emergence of composites has paved the way for the utilization of various conductive materials as conductive layers. These materials include conductive polymers, such as polypyrrole and poly(3,4-ethylenedioxythiophene):poly(styrenesulfonic acid), graphene flakes, and carbon-nitrides[45,46]. Techniques such as solution impregnation, in-situ polymerization, and CVD can be employed to coat conductive polymers onto commercial polymer fibers, forming a conductive layer. However, polymers exhibit lower conductivity, are susceptible to damage from stretching, and lack stability, which limits their widespread usage.

To address the limitations of conventional conductive textiles, researchers have focused on fabricating conductive materials with one-dimensional nanostructures on fiber substrates. These nanostructures include nanorods, nanowires (NWs), nanosheets, nanopins, nanoballs, nanoflowers, and nanotubes, among others[47,48]. Among these, metal NW networks have gained significant popularity as conductors in e-textiles due to their notable advantages, especially improved stretchability of the conductive layer. Unlike continuous films, NW coatings form a network structure, allowing for the assembly of films with comparable optical and electrical properties using less material. This not only reduces material cost but also contributes to reduced weight and increased mechanical flexibility. Moreover, NW coatings can be easily deposited without the need for vacuum or complex processes. Currently, various metals, including gold, silver, and copper, are widely employed as conductive wires in the form of NWs.

The utilization of nanomaterials in smart textiles is already widespread, and there remain significant opportunities for advancements in numerous areas. By synthesizing novel nanomaterials or modifying existing materials, it is possible to further enhance the electronic properties and overall performance of smart devices. To achieve this, it is crucial to focus on developing and expanding the synthesis methods of nanomaterials and clarifying the synthesis parameters. This would enable precise control over the morphology and properties of the resulting materials, facilitating the efficient and reliable fabrication of high-performance smart devices. Additionally, simplifying the fabrication process and reducing manufacturing costs are important objectives in order to streamline production and enhance the affordability of smart textiles. The current synthesis methods for nanomaterials primarily rely on techniques such as CVD, solution treatment, hydrothermal methods, or anodic oxidation, often necessitating strict conditions or specialized equipment. However, considering the practical applications of smart devices, it becomes imperative to simplify the fabrication process of nanomaterials and reduce their manufacturing costs. This requires conducting extensive research and exploration in the future. Nanomaterials already possess a one-dimensional structure, rendering them highly flexible and electronic, thereby playing a pivotal role in achieving high performance and stability. It is crucial to intensify our efforts in promoting the development of e-textiles.

### Nanocomposites for e-textiles

Nanocomposites offer a solution to overcome the limitations of traditional materials, providing advanced functionalities that are crucial for e-textiles. By integrating functionality, nanocomposites can seamlessly become an integral part of e-textiles without compromising on comfort and aesthetics. This emphasizes the significance of nanocomposites in the realm of e-textiles. Flexibility holds great importance in e-textiles as it ensures comfort and enhances the longevity of the product. The advantage of incorporating multifunctional sensors lies in their ability to reduce material and energy consumption while simultaneously enhancing comfort. Achieving multifunctionality often requires a composite structure that combines various functional elements. Lightweight, flexibility, comfort, and multifunctionality can be achieved through the use of nanocomposites. In fact, nanocomposites find applications in a wide range of e-textiles, including sensors, defense protection, self-cleaning, antimicrobial properties, moisture management, fire protection, actuators, and energy harvesting[49-51].

Various methods are available for the production of composites[52,53]. For thermoset polymers, these methods encompass hand gluing, spraying, compression, resin transfer molding, injection molding, pultrusion, and foam molding. On the other hand, for thermoplastic matrix polymers, production methods include extrusion, injection molding, thermoforming, compression, foam molding, and coextrusion. When it comes to nanofibers with nanocomposite structures, production methods can be categorized into coaxial core-shell electrospinning, conjugate electrospinning, and island-in-the-sea methods. Polymer-based nanocomposites can be manufactured through a variety of processes, such as melt homogenization, in situ polymerization, sol-gel methods, electrodeposition, solution dispersion, template synthesis, and advanced processes seen in self-assembly and atomic layer deposition.

### Nanocoatings for e-textiles

In the realm of e-textiles, a diverse range of materials and methods are employed to coat fabrics and imbue them with new functionalities[54]. Typically, the coating process entails the application of a dense polymer solution, slurry, or similar substance onto a textile substrate[55]. This results in the formation of a continuous, durable, and homogeneous coating formulation on the substrate. Alternatively, the lamination process involves applying a pre-prepared polymer film onto the fabric's surface, utilizing techniques such as heat, mechanical bonding, pressure, adhesives, and binders[56]. In the textile industry, two common types of coatings are widely utilized: fluid coatings and dry laminates. The method and equipment employed for coating depend on factors such as the end application, substrate characteristics, polymer type, and coating slurry or solution viscosity. In industrial settings, the textile coating process involves several key steps, including the application of the coating formulation onto the fabric surface, stabilization of the coating through a curing step, cooling, and finally, rolling the coated product into rolls. The initial stage of the coating process entails applying a thick slurry or solution onto the textile, allowing the solvent to evaporate, thereby leaving behind a polymer network on the fabric. In a coated product, the textile substrate imparts strength and mechanical properties, while the coating introduces new functionalities to the surface. It is important to note that coatings are not limited to woven or knitted fabrics; they can be applied to various forms of fibrous materials such as fibers, yarns, and nonwovens. Polyvinyl chloride, polyvinyl acetate, acrylic, polyurethane, and polyvinylidene chloride are among the most commonly used polymers in the textile coating industry. Functionalized e-textiles should offer several advantages to end-users, including ease of care, comfort, and enhanced health and hygiene, while still possessing the inherent characteristics of regular textiles. E-textiles are generally considered a new generation of products that possess the ability to actively detect and sense various external stimuli, including changes in the environment, mechanical forces, chemical reactions, temperature fluctuations, and electrical signals. However, a major challenge in the production of such e-textiles lies in achieving acceptable wash fastness of the coatings. Various materials are utilized in the manufacturing of e-textiles, including conductive materials, phase change materials, shape memory materials, polymers, mechanically responsive materials, and metals, among others. Additionally, a wide range of textile coating methods is employed, such as sol-gel, plasma treatment, impregnation, spraying, chemical and physical methods, and acoustic wave treatment[57].

Nanosol technology serves as a versatile and multi-functional tool for functionalizing textile substrates, opening up new possibilities for materials and applications that go beyond the capabilities of conventional textiles. Through the use of nanosol technology, textiles can attain a range of functional properties, including biological attributes such as antimicrobial and biocompatible properties, chemical characteristics such as flame retardancy and catalytic activity, surface functionalities such as water repellency and abrasion resistance, and optical features such as UV and ray protection[58]. The application of nanosols to textile substrates can be achieved through various methods, including coating, impregnation, or spraying. Upon application onto the substrate, the nanosol undergoes a process where the solvent evaporates, causing the remaining nanoparticles to aggregate and form a three-dimensional (3D) network. The functionalization of the nanosol involves the addition of agents containing the desired functionality to the nanosol or precursor prior to the initiation of hydrolysis. These agents become embedded in the sol-gel coating through physical or chemical modifications during the coating and drying process. This embedding process is also known as the physical modification of the sol-gel coating. Typically, nanosols are prepared using organic solvents to ensure stability, but the use of organic solvents can present drawbacks in terms of flammability, safety, and cost considerations.

## APPLICATIONS OF E-TEXTILES IN PERSONALIZED HEALTHCARE

E-textiles have a wide range of potential applications in the wearable field of human monitoring and self-adaptation by installing smart components in clothes with sensing, driving, adapting, and healing functions to monitor parameters such as human health, position, localization, primary posture, walking speed, *etc.*[59-61]. There is potential for e-textiles to be widely used in wearable human monitoring and self-adaptation. E-textiles can convert physical stimulus inputs from human physiological activities into informative electrical signals to infer physiological information, and one meaningful application may be for disease preventive diagnosis[62]. In addition to the preventive diagnostic function, a simultaneous auxiliary therapeutic effect can be attached. The applications of these sensors are wide-ranging and include monitoring various life signals related to biomechanics, such as human motion, heart rate, tactile sensations, respiratory function, and pressure measurement, among others[63-66]. E-textiles can track human movement while collecting information about the human body. By combining these sensing capabilities with machine learning-based motion analysis, it may be possible to aid in early disease diagnosis and auxiliary rehabilitation efforts[67-69]. E-textiles can also be given some functionality, such as wound dressings that can be used for slow-release medication for rehabilitation purposes[70,71].

### Applications of e-textiles for preventive diagnostics

#### *Body movement monitoring*

Human movement can be monitored using a variety of e-textiles and wearable sensors[72]. The specific type of movement and intended application determines their construction. Body movement monitoring may help monitor an individual's health or encourage people who are obese or have cardiovascular disease to become more active to maintain their daily activity levels[73]. Measuring specific movements can also be valuable in rehabilitation. Assessing diseases that affect motor skills, such as Parkinson's disease[68], can benefit from monitoring body movement characteristics.

Currently, the commonly used methods for human motion detection can be classified into two categories: fixed monitoring and mobile monitoring, based on their placement location and working mechanism. Fixed monitoring involves the use of depth cameras mounted on walls or brackets and far-infrared cameras equipped with motion capture systems. These methods rely on optical principles to capture the joints of the human body and analyze their movement parameters. However, this approach has limitations that prevent its widespread adoption by the public. These limitations include high costs, large amounts of data, restricted monitoring space, and potential safety concerns. Furthermore, wearable accelerometers and dynamic joint goniometers offer a direct measurement of limb acceleration and bending angles, making them widely utilized in medical and sports monitoring. Textiles, with their numerous advantages, serve as an ideal platform for integrating sensors used in human motion monitoring. The application of e-textiles, which merge conventional textile techniques with state-of-the-art flexible sensor technology, enables the retention of the inherent benefits of textiles while facilitating real-time and continuous monitoring of human motion.

Body movements can be recorded using fabric sensors that detect stretch or pressure[74]. Smart textile sensors are capable of detecting movement in limbs or other body parts by being placed at a joint, such as the knee or elbow[75]. Furthermore, the placement of sensors on the back can enable the detection of spinal posture, upper body position, and hand gestures[76].

Smart textile sensors play a crucial role in clinical monitoring applications. Combining this sensing capability with machine learning-based motion analysis can aid in diagnosing neurological disorders such as Parkinson's disease, dystonia, and epilepsy [Figure 3A and B][68]. Since patient symptoms vary with medication dosage and medications can influence patients' perceptions of their motor state, clinical visits do not provide a real-time sampling of symptom severity across different disorders. Consequently, collecting data on the severity of a patient's symptoms over a period of time can effectively evaluate the effect of medication adjustments.

For the purpose of biological gait recognition and assisted rehabilitation training, a self-powered multipoint body motion sensing network (SMN) has been developed. This network utilizes an all-textile structure and consists of multiple sensing nodes placed at various body parts, allowing for effective monitoring of whole-body gait information. Consisting of vertically stacked layers, the sensing nodes are composed of a cotton fabric top layer, a 3D double-ribbed knitted fabric layer, a conductive fabric layer, and a cotton fabric bottom layer [Figure 3A] Cotton fabric is an encapsulation layer due to its lightweight, softness, breathability, and ease of integration. To ensure excellent electrical conductivity, flexibility, and stretchability, conductive silver fibers are employed as the core of the composite yarn. Furthermore, a sheath layer comprising multiple polyethylene fibers is incorporated. The composite yarn is woven into a 3D double-ribbed structure, which enhances its sensitivity to pressure and extends its response range beyond that of conventional flat fabrics. The increase in 3D structures leads to a larger contact area, resulting in a more effective contact friction effect. Spacers were created on the surface of the conductive fabric to support the textile sensors using a digital embroidery process. Cotton and polyethylene fibers are widely used in garments, while silver fibers have antimicrobial properties. Smart Motion Sensors (SMNs) can be integrated directly into garments that come into contact with the skin to monitor human movement. By utilizing the principle of TENGs, SMNs are integrated into everyday garments to generate multichannel dynamic signals during walking. By feeding these multichannel electrical signals into a machine learning algorithm, five common abnormal gaits can be recognized. A real-time human-computer interaction platform was developed for the purpose of biological gait recognition. The SMN generates multichannel electrical signals as the human body walks and the limbs bend and swing, which are then utilized for machine learning data analysis. Achieving the detection and differentiation of five abnormal pathological gaits, namely Parkinson's disease gait (PG), scissor gait (SG), mopping gait (MG), gluteus maximus gait (GG), and cross-threshold gait (CG), is possible. Neurologic delays, muscle atrophy, or external injuries

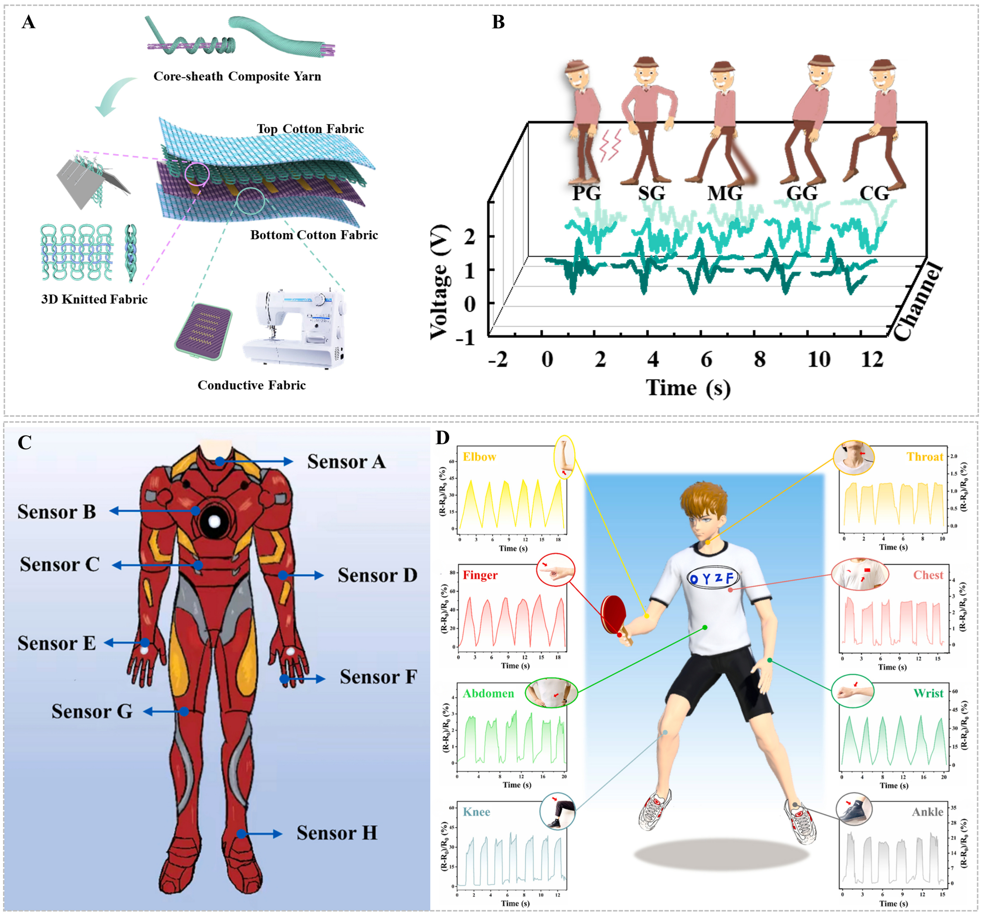


**Figure 3.** Applications in human movement monitoring. (A) Textile-based SMNs, a schematic design for recognizing gait; (B) For five gaits, confusion matrix for support vector machine algorithm[68]. Copyright 2023 Wiley-VCH; (C) Integrated smart clothing; (D) Responsive curves of SPC20 sensors in human motion monitoring[64]. Copyright 2022 Elsevier. CG: Cross-threshold gait; GG: gluteus maximus gait; MG: mopping gait; PG: Parkinson's disease gait; SG: scissor gait; SMNs: Smart Motion Sensors.

typically cause these five common pathological gaits. Each abnormal gait is characterized by a specific posture and limb orientation, resulting in a distinct electrical signal waveform for each [Figure 3B].

A bottom-up, scalable strategy is proposed to construct smart fabrics using conductive yarn units. Specifically, silk yarns are functionalized by customized conductive coatings composed of polyaniline (PANI) and carbon nanotubes (CNTs), which selectively etch the interfaces of silk yarns without destroying their internal structures. The prepared sensing units have robust mechanical properties and high conductivity and can also effectively monitor a range of key signals such as strain, temperature, and harmful gases. The sensing units can be sewn into fabrics with signal-sensing capabilities and integrated at multiple points in smart garments for human motion monitoring [Figure 3C][64]. When integrated into a one-piece integrated smart garment, a range of human motion and physiological signals can be accurately detected in real time [Figure 3D]. The smart fabric is connected as sensors to the elbow, throat, fingers, chest, abdomen, wrist, knee, and ankle joint parts of the human body for real-time monitoring of human motion with high sensitivity.

Potential assistance to physical therapists and their patients can be provided by these sensor garments. Physical therapists currently supervise and regulate the exercises that patients perform during treatment while also motivating them to continue with their self-exercise program. Successful treatment requires maintaining motivation to complete the prescribed exercises, yet adherence to the regimen is often hindered by a common problem that can impede recovery. When exercising at home, patients frequently experience a lack of motivation and become easily distracted. In certain cases, the condition can result in depression and a lack of self-motivation, which can impede healing. By providing therapists with information regarding the exercises that were performed and whether they were executed correctly, e-textiles have the potential to address these challenges. Furthermore, the patients can receive guidance and feedback through a user interface when connected to them.

*Sleep states diagnosing*

Sleep-related problems influence approximately 20% of the population[77]. Among the most prevalent issues are daytime sleepiness, sleep apnea syndrome, insomnia, and obstructive sleep apnea-hypopnea syndrome (OSAHS)[65,78]. These problems become more frequent with age, and 50% of people are affected by sleep problems after age 65[79,80]. Specialized testing equipment is accessible in hospitals, but these options are costly, necessitating patient hospitalization, occasionally resulting in fewer available beds and increased expenses. Numerous researchers have dedicated their efforts to achieving noninvasive sleep monitoring using various operating mechanisms such as piezoelectric, capacitive, infrared, ultrasonic, and fiber-optic systems. These technologies are often implemented in the form of wrist actigraphy, strips, or bedside devices. However, the widespread adoption of these technologies may face limitations due to factors such as low sensitivity, limited flexibility, chemical instability, and the challenge of maintaining cleanliness. With the need for clinical research increasing day by day, a number of mobile systems and data analytics may be reasonable solutions that can reduce the overall cost of research while shortening the time to commercialization. Devices that integrate parameters, such as electrocardiogram (ECG), respiration rates, and sleep position, into e-textiles are effective practices for diagnosing these issues, as many hospital devices do not allow for prolonged recordings and record only a limited number of digits[81]. The development of wearable smart textile-based sleep testing devices facilitates diagnosis and personalized case management[82]. Electroencephalogram (EEG), electromyogram (EMG), ECG, oxygen saturation, motion, posture, and respiration are among the components that need to be recorded[83].

An ultra-comfortable, ultra-soft smart textile was developed to measure physiological parameters, monitor sleep health, and detect sleep-related diseases at an early stage [Figure 4A][84]. With the advantages of high sensitivity, wide operating frequency range, and washability, this smart textile is readily available. Without disrupting normal sleep patterns, this smart textile can detect changes in body movement during sleep and various physiological signals, such as respiratory and ECG signals, simultaneously. E-textiles have the potential to replace traditional polysomnography systems and prevent sudden sleep death by monitoring patients with OSAHS. Figure 4A shows an enlarged view of the smart textile sensing device. This fiber is equipped with waterproof functionality, offers economic feasibility, and is favorable for industrial production because it adopts a sheath-core structure, which consists of a conductive inner core wrapped in silicon.

The smart textile can be applied in sleeping posture detection, where each sensing unit generates an independent voltage signal when pressure is applied. A mobile terminal equipped with integrated algorithms scans all the sensing units in turn, creating a binary image of the entire smart textile. This process not only clearly shows the pressure distribution of the human body but also recognizes and records body movements. As depicted in Figure 4B, the subject initially lies in a supine position on the smart textile.

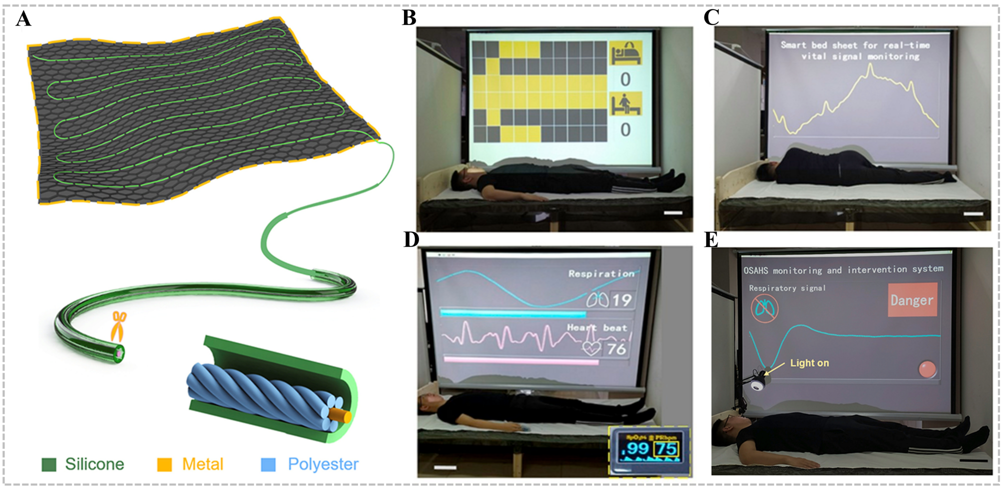


**Figure 4.** Applications in human sleep states. (A) Sensing unit constructed from woven functional fibers on serpentine textile substrates; (B) Image showing the detection of body movement and sleeping posture in real-time (Scale bar: 10 cm); (C) Real-time monitoring of subtle physiological signals during the supine sleep position can be achieved (Scale bar: 10 cm); (D) Real-time monitoring of respiratory rates and heart rates. Comparative test results from a commercial oximeter are shown in the inset (Scale bar: 10 cm); (E) The photograph shows a patient being woken up by an alarm and illuminated lamp (Scale bar: 20 cm)[84]. Copyright 2020 Elsevier.

After changing their sleep position, the display interface can record the movements and the number of times the subject gets up. Figure 4C shows the application of this smart textile in monitoring physiological signals, with real-time monitoring data of subtle physiological signals while the subject is sleeping in the supine position. Furthermore, the smart textile exhibits high accuracy for heart rate measurement, with an error rate of only 1.33% when compared to a commercially available handheld pulse-finger oximeter used for simultaneously testing the heart rate of the subject. This finding suggests that the smart textile provides the same level of accuracy as commercially available heart rate measurement devices [Figure 4D].

To validate the reliability of the e-textiles in practical applications, the experimenter simulated apnea symptoms by holding their breath while lying on the e-textiles. When the apnea duration exceeded the set threshold, as illustrated in Figure 4E, the monitoring screen would emit an alarm, and the light would turn on immediately. The alarm and light would continue until the participant woke up and resumed normal breathing. According to the results, e-textiles have the potential to effectively awaken OSAHS patients and decrease the occurrence of apnea during sleep.

Therefore, the advantages of using a networked smart textile approach to address real-time and prolonged tracking of trialists include several key aspects. Firstly, it enables continuous and highly accurate collection of patient data by allowing individuals to wear physiological data and side effect monitoring systems. Secondly, it offers remote patient monitoring through applications that can personalize the collection of patient data to achieve personalized and assisted diagnosis and treatment. Lastly, it facilitates real-time research for researchers and healthcare professionals. This involves the study of instruments, cloud solutions for monitoring and storage, and some degree of data visualization[85].

*Sweat or body fluids sensing*

Due to its convenience and effectiveness in real-time monitoring of physiological signals, wearable sensing technology has garnered significant attention in the biomedical field. However, the development of wearable sensors has been hindered to a large extent by the limitations of conventional thin-film non-textile wearable electronic devices. These devices lack breathability and comfort, which restricts their further advancement and limits their application in various fields beyond biomedical facilities. In order for wearable sensing devices designed for health monitoring to achieve success, there is a need for enhancements in their mechanical resilience and the resolution of large-scale manufacturing challenges. One of the primary obstacles encountered in the development of wearable biosensors is the requirement for physical contact and continuous analytical sampling. Continuous monitoring necessitates the management of a steady stream of sweat, which becomes particularly important in dynamic environments such as exercise and training, where a sweating response is elicited.

Blood is the most reliable diagnostic medium for clinical and sensing tests. Still, it increases patient burden due to its need for invasive sampling techniques, increasing patient pain and the need for sampling at defined time intervals[86]. Other body fluids, which are more easily accessible through noninvasive or minimally invasive methods, may be regarded as viable options for continuous analysis or monitoring sensing purposes[87]. Achievable body fluid samples include urine, sweat, saliva, wound exudate, and interstitial fluid[88]. Sweat is the most readily available in textiles of the above body fluids. Incorporating wearable chemical sensors into clothing can give users smart textile sensors that collect body fluids and monitor their health[89]. Sweat contains a variety of substances associated with blood, such as sodium, potassium, calcium, and various salts[90]. Sweat analysis provides useful physiological information about the body[31]. In addition, the composition of sweat varies considerably from one individual to another and is also influenced by activity levels and environmental conditions. Therefore, analyzing information about the different components of sweat can provide physiological information about the human body. Similarly, analyzing the diurnal and nocturnal sweating patterns of the human body can help to monitor the conditions of diabetes mellitus and hyperhidrosis, which are important references for our health monitoring.

Figure 5A illustrates the development of an electrochemical smart textile that integrates sensing fibers with distinct properties to enable real-time monitoring of sweat[91]. Smart textile sensors can detect substances such as glucose, sodium ions, potassium ions ($K^+$), calcium ions, and pH values. Despite being subjected to repeated bending and twisting deformations, the electrochemical fibers remain highly flexible and retain their structural integrity and sensing properties. The smart textile demonstrates the ability to monitor human health efficiently in real time.

Figure 5A illustrates the structure of the electrochemical sensing fibers and the resulting textile, as presented in a schematic form. CNT fiber electrodes are utilized as a substrate for depositing active materials to fabricate various sensing fibers. By electrodepositing Prussian blue (PB) as a dielectric, glucose-sensing fibers are fabricated to enhance sensitivity. On the other hand, the active layer is coated with glucose oxidase immobilized in a chitosan permeable membrane. By utilizing ion-selective membranes and poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) as an ion-to-electron converter, ion sensing fibers were produced. This was achieved due to the significant change in the impedance of PEDOT:PSS with ion concentration. By electrodepositing PANI on CNT fibers, pH-sensing fibers were fabricated. This was achieved by leveraging the ion-to-electron conversion property of PANI, which is affected by its surface protonation at various pH levels. The change in protonation of PANI on the fiber surface across different pH values results in a variation of zeta potential. These sensing fibers are used as working electrodes for each sensing function, and the Ag/AgCl fibers are used as reference electrodes. After a certain period of human movement, sweat can penetrate the fabric, enabling real-time analysis to obtain a stable signal [Figure 5B].

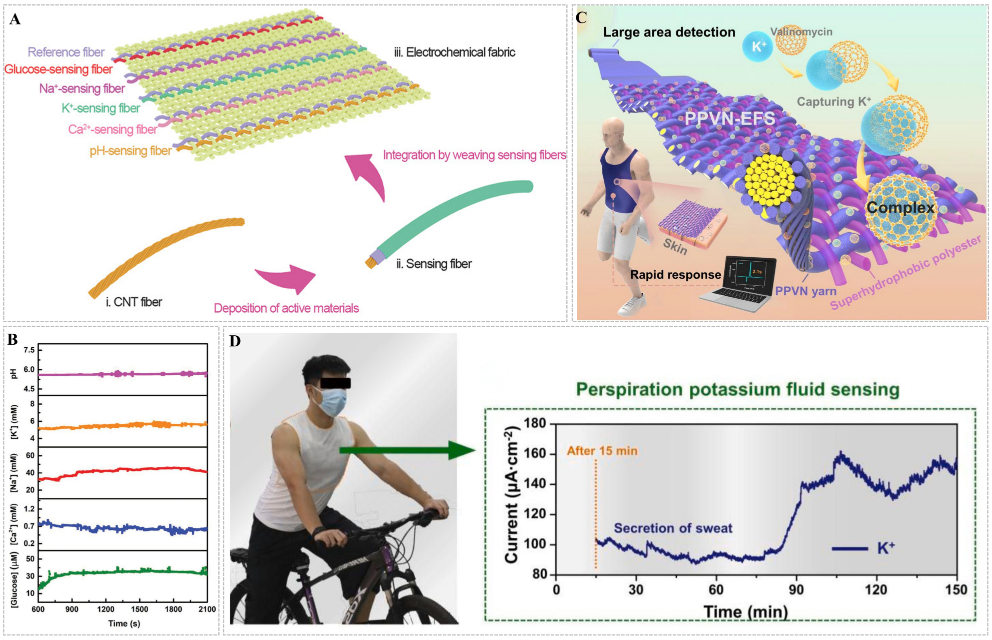


**Figure 5.** Applications in human fluid sensing. (A) The electrochemical fabric is constructed by weaving sensors deposited on carbon nanotube fiber substrates; (B) Wearable device for real-time sweat analysis[91]. Copyright 2018 Wiley-VCH; (C) The electrochemical fabric sensor integrated into the clothing can detect $K^+$ in sweat; (D) The sensor allows for real-time collection of $K^+$ signals from sweat[92]. Copyright 2023 Elsevier. CNT: Carbon nanotube.

Developed for real-time monitoring of $K^+$ concentration in human sweat, an electrochemical fabric sensor utilizing skin-core structured sensing yarns was created [Figure 5C][92]. By leveraging the contrasting hydrophilicity and hydrophobicity of the fabric's warp and weft yarns, the electrochemical fabric sensor achieves rapid response within a short time frame (2.1 s) and maintains stable sensing over an extended duration (over 6,000 s) within the localized sweat-absorbing region of the skin. This versatile sensor can be seamlessly incorporated into clothing and integrated into the human body, facilitating real-time in situ monitoring of $K^+$ signals in human sweat. In order to verify the feasibility and reliability of utilizing smart fabrics as comfortable textile garments for $K^+$ detection, a healthy volunteer was chosen as a test subject. Using warp and weft weaving techniques, a sensor measuring 55 cm × 35 cm was woven into a garment. The fabric was then cut into an undershirt and attached to the chest of a volunteer [Figure 5D]. Following 15 minutes of cycling, a substantial amount of sweat generated by the volunteer permeated the sensing area, enabling the capture of a stable electrochemical signal via the connected electrochemical workstation. The findings demonstrated that a peak current signal of $K^+$ was successfully detected after the 15-minute cycling session. The variation in the peak value effectively reflected the real-time monitoring of $K^+$ concentration by the smart textile. Additionally, due to its capacity to utilize electrical signals as sensing inputs, the smart textile holds promise as an integrated detection textile for sweat analysis, enabling the tracking and assessment of physiological indicators within the human body.

*Pregnancy monitoring*

Complications can also arise during pregnancy and jeopardize the lives of the fetus and mother. Assessing fetal health during pregnancy and delivery is crucial for promptly detecting any complications and reducing the incidence of stillbirths[93]. Medical tools that can monitor fetal movement, heart rates, and development can provide physiological information about the fetus, effectively identify whether the fetus is in distress, and provide timely alerts for intervention[94]. The actions taken following the results of the monitoring are as important as the monitoring itself. It is important that the monitoring results are accurate enough.

Continuous monitoring allows for the timely detection of signs of fetal distress and for data-driven research for the accurate detection of fetal distress. To achieve continuous real-time monitoring of pregnant women, other factors need to be considered in addition to monitoring accuracy. These factors include being wireless, low-power, noise-proof, and suitable and comfortable to wear for long periods. E-textiles are an ideal solution for developing comfortable garments for continuous pregnancy monitoring[95]. These sensors will help manage pregnancy risks better and prevent stillbirths and miscarriages.

Implementing tight-fitting solutions to avoid skin-electrode contact artifacts for pregnancy monitoring is particularly challenging[96]. First, the shape of the abdomen varies from pregnancy to pregnancy. Second, the size and shape of the belly constantly change as the pregnancy grows. Finally, the surface of a pregnant woman's abdomen is in constant motion with both mother and fetus movements. Due to their flexibility, lightness, comfort, and breathability, wearable e-textile devices present a favorable opportunity for the continuous and real-time monitoring of human physiology. Therefore, fetal movement within the mother's body can also cause abdominal deformation, resulting in the creation of artifacts. The stretchability of e-textiles and their ability to conform to the pregnant woman's abdomen affects the comfort and sensitivity of the sensor in pregnancy monitoring. To avoid artifacts, it is preferred to use techniques that can maintain these textile properties.

To be considered ideal, a pregnancy monitoring system should have the following attributes: safety and portability for continuous use in the home environment, real-time data acquisition and analysis capability, timely alerts for any abnormalities, and compatibility with other monitoring devices. On the other hand, medical studies have shown that 24-hour real-time monitoring is more beneficial to the fetus. Yet moms-to-be are reluctant to wear such systems. If they have not been monitored before or when they experience physical symptoms of fetal distress, they may need to know if they should use a monitoring system. Therefore, it is crucial to design good e-textiles based on the user's preferences and needs.

Combining metal-organic frameworks with fabric substrates for electromagnetic interference shielding expands smart textile applications. Co@C@ carbon fabrics (Co-CCF) derived from ZIF-67@ cotton fabrics were fabricated by a simple method[97]. Using polydimethylsiloxane (PDMS), Co-CCF was encapsulated to prepare Co-PCCF [Figure 6A]. Due to electrostatic interactions and coordination between metal ions and -OH functional groups in ZIF-67 nanoparticles and cellulose molecules on cotton fibers, the metal ions can stably exist on the cotton fibers. After annealing, the reduced carbon obtained from ZIF-67 reduces $Co^{2+}$ to metallic Co. The introduction of magnetic metal Co leads to magnetic loss of the material. The metal Co, on the other hand, can graphitize the amorphous carbon and enhance the conductivity of the material. The waterproofing effect of PDMS ensures the mechanical properties of the material and further improves the corrosion resistance and stability of the fabric. Co-PCCF can resist damage by pregnant women during use, thanks to its good performance in blocking over 99% of electromagnetic waves, even after undergoing repeated bending, ultrasonic treatment, and acid/alkali/salt corrosion. The smart textile can produce a thermo-therapeutic effect by controlling the voltage and light intensity. At the same time, the Co-PCCF monitors various body movements such as pulse, respiration, and joint activity in real time. Figure 6B illustrates that multi-functional Co-PCCF e-textiles for pregnant women show promising applications in protecting against electromagnetic pollution, providing thermal physiotherapy, and detecting body movement.

Some pregnant women may experience swelling of the lower extremities during pregnancy, which can lead to decreased blood supply and lower body temperature in the lower extremities. At the same time, prolonged exposure to weather extremes during pregnancy may increase the risk of miscarriage or preterm

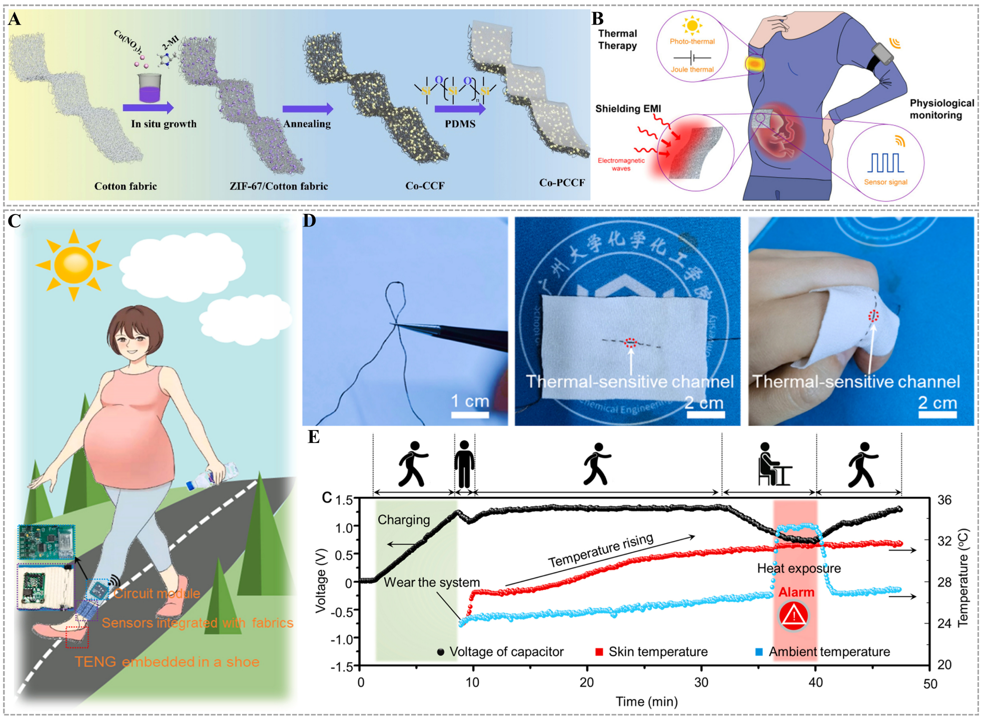


**Figure 6.** Applications in pregnancy monitoring. (A) Co-PCCF composite formation process; (B) Pregnant women can benefit from this multifunctional Co-PCCF[97]. Copyright 2022 American Chemical Society; (C) Schematic diagram of a smart fabric sensing platform for tracking skin temperature and ambient temperature of pregnant women; (D) Optical images of a temperature yarn sensor in a bent state and woven into a fabric; (E) Skin temperature and ambient temperature during exercise in pregnant women[98]. Copyright 2022 Elsevier. Co-CCF: Co@C@ carbon fabrics.

labor. With the proposal of a temperature monitoring platform, pregnant women can benefit from real-time monitoring of temperature changes in their lower limbs and surrounding areas during exercise, along with receiving specific recommendations. These recommendations include encouraging increased physical activity to raise body temperature or cautioning against exposure to hot environments [Figure 6C][98]. The fabric sensor, as depicted in Figure 6D, exhibits excellent flexibility and can be seamlessly woven into fabric without compromising its flexibility. Figure 6E showcases the real-time recording of both the skin temperature and ambient temperature of a pregnant volunteer during exercise and rest. Over a duration of continuous walking ranging from ten to 32 minutes, the skin temperature exhibited a gradual increase from 28 °C to 31 °C, suggesting that moderate exercise can effectively alleviate the discomfort of cold lower extremities in pregnant women. Furthermore, to simulate heat exposure, an environment with an approximate temperature of 33 °C was created. The sensor employed for monitoring the ambient temperature demonstrated swift responsiveness to heat exposure and returned to its initial state once the volunteer left the heated environment.

*Acoustic sensing*

Researchers have started investigating whether textiles can serve as efficient sound collectors to detect and process weak sound signals, owing to the growing use of e-textiles and the wearability of textiles that enable them to be in close proximity to the human body[99]. On the one hand, they can be applied for sound collection and processing, and on the other hand, they can be used for human sound-sensing acquisition (e.g., heart rates or fetal heart). The shift towards the use of textiles in mediating acoustic communication and sound collection from the human body holds great significance, as conventional medical devices are not portable and lack the necessary comfort for long-term continuous monitoring. This transition allows textiles to address these limitations and enables them to serve as a more comfortable and portable solution for continuous monitoring.

The researchers utilized flat fabrics to efficiently convert pressure waves into electrical signals, drawing inspiration from the significance of fibers in the auditory system [Figure 7A][100]. The fabric can be a tympanic membrane, converting the pressure wave into a mechanical vibration of the membrane. Fiber converters woven into the fabric can provide electrical output, playing a similar role to the cochlea. The fibers have certain conformal properties, while fiber-to-fiber coupling can be effective, resulting in acoustic textiles. First, the researchers designed and constructed a piezoelectric fiber, which can effectively convert the mechanical vibration of the membrane into an electrical output signal. By conducting simultaneous electrical measurements and laser vibrometry, the displacement patterns of films and fibers can be studied, thereby aiding in the design of smart acoustic textiles that can detect audible sound waves and produce corresponding electrical output signals.

A wide range of applications is possible due to the properties and shape of smart acoustic fibers. For example, the output of each fiber can be recorded when clapping at different angles. By analyzing the time delay between the peaks, the direction of the sound can be inferred. This application is of great interest to people who need to wear hearing aids, not only to eliminate background noise but also to determine the direction of the sound. Moreover, by supplying the fabric with a modulated AC voltage, audible sounds can be produced. Figure 7B demonstrates that bidirectional acoustic communication with matching time-domain waveforms and frequency-domain spectrograms is possible between two shirts for transmitted and received speech. The smart textile enables acoustic communication between individuals and has potential applications in deaf or covert communication and underwater communication. The high sensitivity of textiles to vibrations and matching impedance to the skin make them suitable for physiological sensing as well. The acoustic textile can effectively capture heart signals by touching a person's chest, making it a useful tool for diagnosing cardiovascular diseases and abnormalities through cardiac auscultation. It detects information about the cardiovascular system of the wearer. Wearable e-textiles can detect physiological information about the human heart and breathe in real time and continuously.

In the early diagnosis of cardiovascular disease, continuous monitoring of cardiac acoustic signals plays a vital role. These signals, characterized by low intensity and frequency, necessitate the use of ultra-sensitive, lightweight, and breathable acoustic sensors capable of measuring them over extended periods. In this study, we present an all-nanofiber acoustic sensor that exhibits exceptional sensitivity, reaching up to 10,050.6 $mV \cdot Pa^{-1}$, specifically in the low-frequency region (< 500 Hz). By incorporating a durable and ultrathin (2.5 μm) nanofiber electrode layer, the acoustic sensor attains its remarkable sensitivity, enabling it to experience substantial vibrations in the presence of sound waves. The structure of this all-nanofiber mechanical acoustic sensor is illustrated in Figure 7C[101]. Comprising three layers, namely the bottom nanofiber electrode layer, PVDF nanofiber layer, and top nanofiber electrode layer, the sensor incorporates a porous structure that naturally establishes air gaps between the layers. These air gaps, with an average spacing of 5-15 μm, are clearly visible in the cross-sectional image of the all-nanofiber acoustic sensor obtained using a scanning electron microscope. In Figure 7C, an optical photograph of the sensor and a magnified 3D microscopic image of its surface are displayed. An important aspect to highlight is that the sensor has the unique ability to generate a voltage signal in the presence of acoustic waves without requiring an external power supply. These advantageous characteristics render the sensor well-suited for long-term continuous monitoring of mechanical acoustic signals. To assess the sensitivity of the sensor, the output voltage produced by the sensor was monitored while acoustic waves were present. Upon application of a

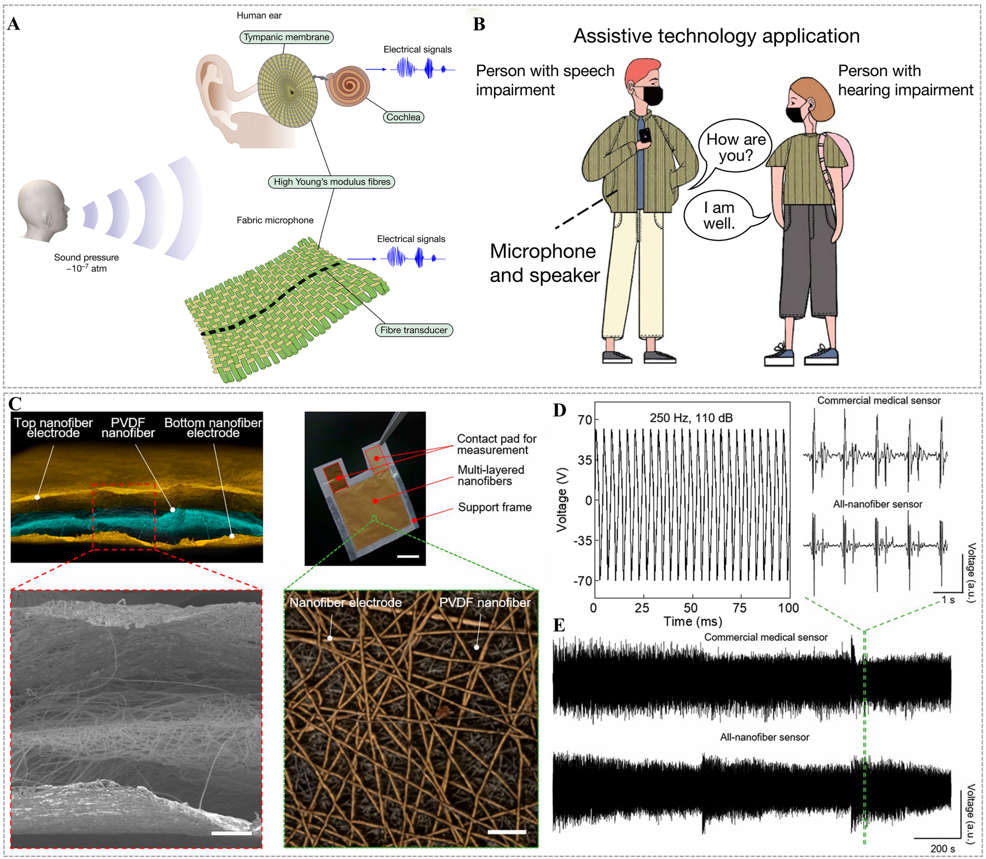


**Figure 7.** Applications in acoustic sensing. (A) Principles and design of fabric microphones; (B) The application of acoustic fabrics for communication[100]. Copyright 2022 Springer Nature; (C) Schematic and image of the ultrasensitive all-nanofiber acoustic sensor; (D) Voltage waveform generated when a sound wave of constant frequency (250 Hz) and sound pressure level of 110-dB is applied to the sensor; (E) Comparison of cardiac signals measured by a commercial cardiac microphone and an all-nanofiber sensor, as well as a magnified view of the signals[101]. Copyright 2020 PNAS.

250 Hz, 110 dB sound wave, the sensor produces a peak output voltage of 64 V, as depicted in Figure 7D. Additionally, Figure 7E presents a comparison between the data obtained from our all-nanofiber sensor and a commercial cardiac microphone over a 30-minute duration, along with a magnified view of the comparison. The results indicate that our sensor is capable of measuring minute acoustic cardiac signals with a level of quality comparable to that of commercially available medical-grade cardiac microphones.

## Applications of e-textiles for auxiliary therapeutics

### *Thermal management and therapy*

In addition to diagnostic functions, e-textiles can be utilized in personalized medicine to develop specific treatment plans by accessing physiological information and personal lifestyle factors of patients[1,13]. E-textiles with therapeutic functionality can provide continuous or one-time treatment programs that can be adapted to an individual's changing health status[102]. E-textiles have emerged as a potential alternative to traditional therapies, offering personalized treatment options[103]. Researchers have shown great interest in exploring physical and chemical therapies in e-textiles[104].

Temperature control plays a crucial role in maintaining a stable body temperature and can even aid in treating certain medical conditions through controlled physiotherapy[105]. However, current indoor heating and cooling methods are energy-intensive, inefficient, and unable to adapt to changing environments.

Moreover, much energy is wasted in heating the surrounding space, exacerbating the energy crisis and global warming. It is equally important to consider outdoor temperature control, which poses additional challenges due to higher radiation losses. Therefore, research is needed to develop e-textiles that are environmentally independent, energy efficient, and capable of accurately heating or cooling the human body. Figure 8A shows that the deposition of MXene flakes on the surface of cellulose fibers was accomplished through dip-coating[106]. E-textiles synthesized by this method exhibit exceptional thermal and antimicrobial properties. The properties of the fabric dictate that it can be used in personal care and medical applications, particularly respiratory monitoring, smart heat therapy, and wound healing.

In order to validate the Joule heating capability of the MXene-based smart fabrics (M-fabric), temperature variations were measured over time. Figure 8B illustrates that the M-fabric textile achieved a temperature of approximately 100 °C in the shortest duration when a 6 V input voltage was applied. The swift heating performance renders M-fabric textiles suitable for personal thermal management devices. This is exemplified by the wearable neck pad featuring thermal therapy functionality, as depicted in Figure 8C. The heat generated by the M-fabric can diffuse throughout the cervical pad, radiating toward the epidermis and even subcutaneous tissues, thereby alleviating neck stiffness, enhancing blood circulation, and mitigating pain. The demonstration in Figure 8C corroborates the consistent heat generation of the M-fabric, regardless of the position of the head, underscoring its potential in wearable thermal therapy applications.

A multi-scale porous sensing fiber, consisting of a bilayer structure, was designed. The substrate is made of multi-scale disordered porous elastic polyurethane (MPPU) fiber using microfluidic technology, and its structure ensures the excellent heat dissipation performance of the fiber, which is very important for smart fabrics. The conventional columnar chemical fibers are poor in air permeability and thermal conductivity, thereby affecting the long-term wear comfort of clothes. This new fiber solves this problem [Figure 8D and E][107]. In personal thermal management, the garment offers inherent autonomous self-sensing capabilities, including strain and temperature sensing, alongside self-cooling features. By employing a multiscale disordered porous structure, the fiber attains a high level of transparency to mid-infrared radiation and visible light backscattering emitted by the human body. This unique characteristic contributes to a noteworthy reduction of at least 2.5 °C in the microenvironmental temperature between the skin and the garment, surpassing the performance of cotton fabrics. A graphene nanoflake solution coated on the surface of the porous fiber acts as a conductive layer for strain and temperature sensing, but the graphene conductive layer can be affected by both strain and temperature simultaneously. It is difficult to separate body temperature alterations from strain changes in the read signal. Monitoring body temperature, limb movement, and human physiological signals, the integrated smart sportswear also possesses a certain degree of self-cooling capability.

Figure 8D presents the mechanism of preparing MPPU fibers using a microfluidic spinning method based on phase separation. The MPPU preparation process involves three channels at the inlet and a coaxial flow channel in the middle to facilitate fiber formation. The core flow channel is used for injecting the polyurethane/dimethylsulfoxide spinning solution, while the symmetric outer sheath flow channel receives the non-solvent (deionized water/dimethylsulfoxide). Through the principle of non-solvent-induced phase separation, the fiber gel solidifies within the coaxial flow channel. When the dispersed polyurethane molecular chains encounter the non-solvent in the coaxial flow channel, rapid diffusion occurs between the deionized water and dimethyl sulfoxide solvents. This leads to the aggregation of polyurethane chains and phase separation of dimethyl sulfoxide, resulting in the formation of macroscopic fibers. Furthermore, the self-cooling properties of fibers with multiscale disordered porous structures were evaluated by subjecting five types of fibers and their braids to the same heating stage. The corresponding infrared thermal images

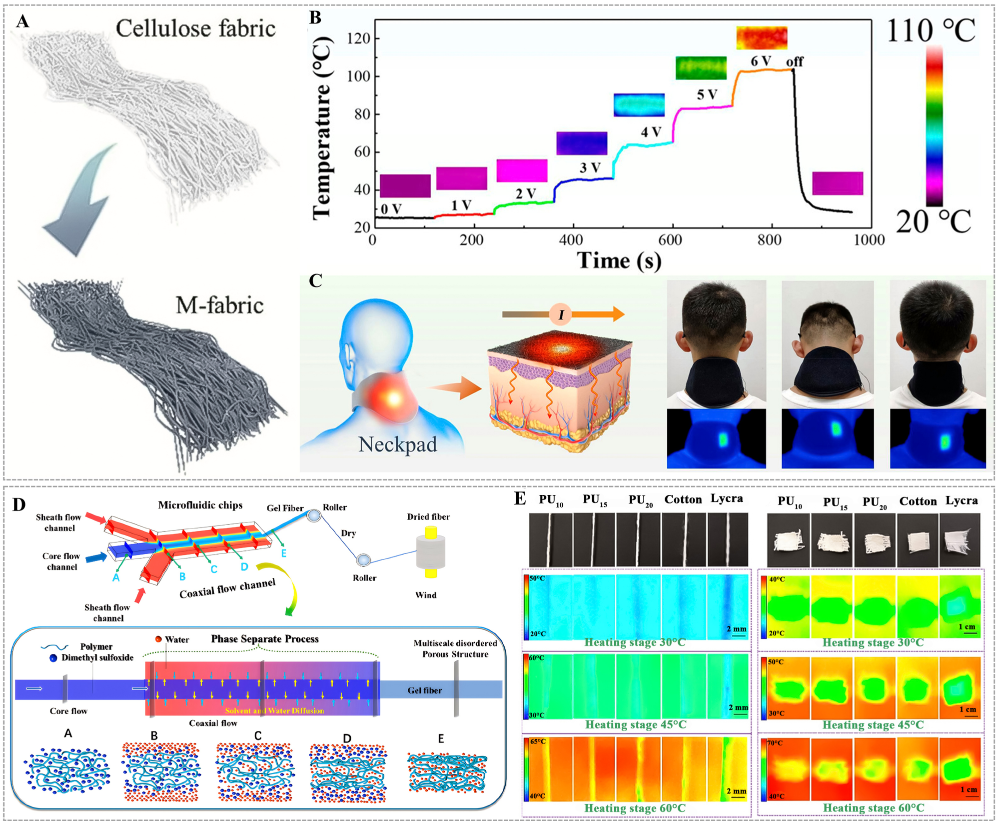


**Figure 8.** Applications in thermal management. (A) Schematic illustration of the M-fabric; (B) Temperature profiles of M-fabric at 0, 1, 2, 3, 4, 5, and 6 V and their infrared thermal images (inset); (C) M-fabric can be used for neck thermotherapy[106]. Copyright 2020 American Chemical Society; (D) The mechanism of fiber formation; (E) Self-cooling properties of MPPU fibers[107]. Copyright 2019 American Chemical Society. MPPU: Multi-scale disordered porous elastic polyurethane.

were captured in Figure 8E. The results indicate that MPPU10 exhibits the smallest chromatic aberration and demonstrates a temperature closest to the stage temperature. This suggests that MPPU10 possesses superior heat dissipation properties compared to the other four samples. Consequently, this multifunctional polyurethane fiber can be utilized in the production of smart sportswear for efficient temperature regulation.

*Drug-releasing and wound healing*

Providing controlled, convenient, and non-invasive drug delivery solutions, textiles are widely employed in healthcare for protective clothing and wound dressings to enhance drug delivery and promote wound healing[103]. Textile materials for drug delivery can replace or complement traditional drug delivery methods. Due to their ability to be applied directly to the skin without causing pain or irritation, e-textiles offer a viable option for personalized medication slow release or administration[71]. Numerous drug delivery systems based on textiles have been developed to release a wide range of drugs through the skin and are referred to as transdermal drug delivery systems, which are suitable for the delivery of drugs for a wide range of conditions such as skin injuries, microbial infections, cardiovascular disease, skin cancer, and pain control[108-110]. These textiles can safely and effectively deliver drugs to specific body parts through the skin, thus avoiding the traditional systemic route. Transdermal drug delivery can also bypass the liver, which may metabolize large amounts of the drug, thereby reducing its effectiveness. In addition, oral administration may not be practical in many cases, such as in children or patients with swallowing difficulties, so the transdermal route of administration may be preferred. Drug-releasing textiles may be a more effective and safer option than traditional routes of administration, as the dose can be controlled and the duration of administration can be extended. Efforts to develop and improve new delivery methods continue, as there is no single ideal route of administration that meets all of the requirements for administering various types of drugs under different conditions and for a variety of delivery mechanisms.

For wound sensing and healing, an intelligent artificial spider silk protein composite programmable textile (i-SPT) has been introduced, incorporating photonic crystal (PC) structures, micropillar arrays, and microelectronic circuits [Figure 9A][111]. Spider silk, renowned for its exceptional mechanical properties, can be transformed into transparent films with microstructures or cut into thin strips and woven into i-SPTs capable of sensing, monitoring motion, and facilitating wound healing.

A cost-effective, simple, and rapid fabrication process involved the preparation of artificial spider/polyurethane composite (SP) microfluidics with patterned features, utilizing PDMS molds created through direct replication of silicon micropillar templates. When the i-SPT was applied to the wound surface, the wound secretions flowed into the microchannels of the i-SPT, establishing complete contact with the PC structures. Consequently, the fluorescence signal emitted by the PC structures allowed for the analysis of the biosignature of the wound secretion. Moreover, the stretchable nature of the i-SPT prevented further damage to the wound during human movement. The i-SPT has been extensively investigated for motion sensing, such as finger, wrist, and elbow flexion, wound secretion monitoring, and promotion of wound healing. This multifunctional composite i-SPT exhibits vast potential in the realm of wound management and various clinical applications.

Gauze is frequently employed in wound care, particularly in areas with compromised mechanical properties such as joints. The repetitive stretching experienced by gauze during exercise can potentially contribute to the deterioration of wounds. Therefore, for effective wound management, it is imperative to utilize novel biomaterials that exhibit high permeability, stretchability, and biocompatibility. To validate its efficacy in promoting wound healing, i-SPT was woven through thin strips of SP, as depicted in Figure 9B. In addition, to study the wound healing ability of i-SPT, researchers made a diameter of 1 cm incision on the back of diabetic mice. The progression of healing was documented by capturing photographs of the wound area at specific time intervals. The results clearly demonstrated that the group treated with drug-loaded i-SPT maintained a biologically safe environment in the wound throughout the healing process and exhibited a faster recovery compared to the control group.

Utilizing the technique of electrospinning, a novel fiber called Janus membrane was designed and manufactured to exhibit asymmetric wettability (hydrophobic/superhydrophilic) along its thickness direction. The fabrication process of the hydrophobic/superhydrophilic Janus membrane is depicted in Figure 9C. Initially, titanium dioxide ($TiO_2$) nanoparticles were immobilized on the surface of cotton gauze, which served as a superhydrophilic substrate, using the sol-gel method. Subsequently, a thin hydrophobic layer was formed by electrospinning polycaprolactone (PCL) micro/nanofibers onto the $TiO_2$@Cotton substrate. This unique combination of hydrophobic PCL and superhydrophilic $TiO_2$@Cotton facilitated the diversion of wound exudate and excess water away from the wound site, thereby accelerating the wound healing process. Furthermore, the PCL/$TiO_2$@Cotton Janus membrane demonstrated excellent antimicrobial properties due to the presence of $TiO_2$ nanoparticles, along with biocompatibility attributed to PCL itself. To explore the impact of Janus Membranes, which possess the ability to deliver fluids in a targeted manner, on wound healing, researchers employed these membranes as wound dressings. Each film was individually applied to incisions on the backs of mice, with an average diameter of approximately 1 cm [Figure 9D]. Notably, dressings with the hydrophobic side in close proximity to the wound effectively

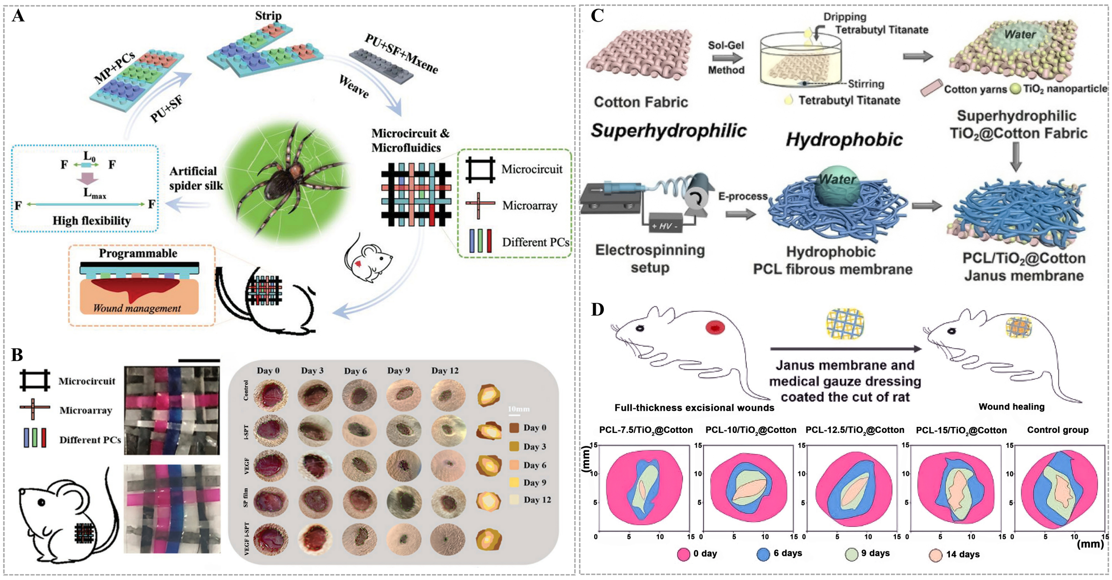


**Figure 9.** Applications in wound healing. (A) Schematic diagram of the i-SPT; (B) Images of woven i-SPT and the diabetic mice treated with i-SPT[111]. Copyright 2022 Wiley-VCH; (C) Fabrication and structure of the PCL/$TiO_2$@Cotton Janus membrane; (D) A schematic diagram illustrates the prepared membranes utilized as wound dressing in a rat full-thickness cutaneous defect model[71]. Copyright 2023 Elsevier. i-SPT: Intelligent artificial spider silk protein composite programmable textile; PC: photonic crystal; PCL: polycaprolactone.

drained wound exudate, preventing backflow into the hydrophobic layer and maintaining a moist wound environment. Conversely, samples lacking targeted fluid delivery allowed wound exudates to accumulate around the wound, leading to excessive hydration and increased vulnerability to infections. This study provides a novel perspective on the design and manufacture of multifunctional wound dressings, showcasing their immense potential in facilitating effective wound healing within the medical field.

*Auxiliary rehabilitation training*

The rising prevalence of infectious diseases and the aging population underscore the significance of developing continuous vital signs monitoring, real-time health management, and long-term therapeutic programs in personal healthcare[72]. In addition to the diagnosis of diseases, e-textiles also have the application of assisting clinical therapeutics, rehabilitation training, and the assessment of the implementation of the efficacy of treatment[68]. Enabling data-driven, precise, and scientific medical diagnosis and treatment, artificial intelligence (AI) technology and smart textile sensors offer valuable data support for the design and development of smart textile-based rehabilitation aids[112].

Due to the prevalence of poor postures among individuals, which often result in pain, discomfort, and a range of physical and psychological problems, the utilization of e-textiles for long-term posture monitoring proves advantageous. E-textiles, known for their stretchability, durability, breathability, and washability, can be comfortably worn for extended durations. Specifically designed garments incorporating e-textiles enable real-time observation of sitting postures, triggering appropriate alerts to prompt posture changes and ultimately alleviate these ailments. Researchers have introduced a self-powered sitting posture monitoring undershirt (SPMV), as depicted in Figure 10A, which employs machine learning algorithms for sitting posture recognition[76]. The SPMV, composed of a knitted double-layer textile interwoven with conductive fibers and nylon yarns, incorporates sensor arrays sewn into different sections of the garment. These sensors facilitate the recognition of various sitting postures, provide feedback, and alert the wearer while ensuring long-term comfort during use.

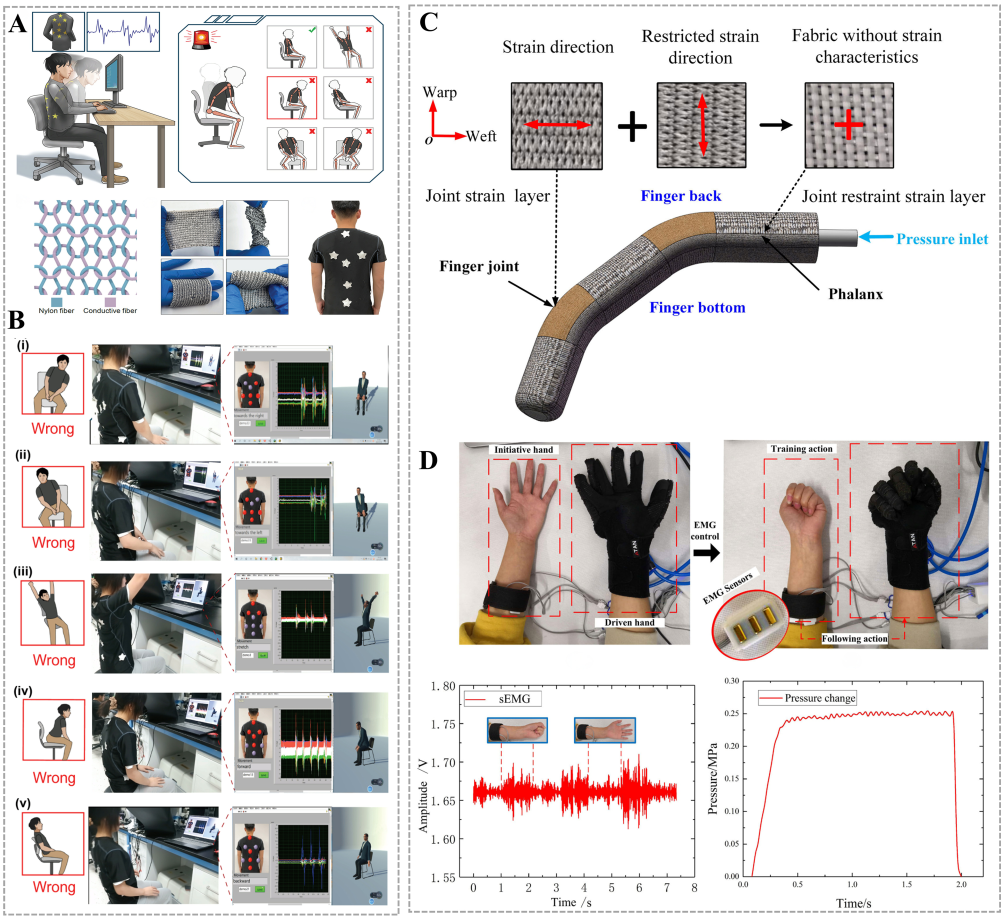


**Figure 10.** Applications in auxiliary rehabilitation training. (A) Fabrication and structure of SPWV; (B) Photographs at different sitting postures[76]. Copyright 2022 Springer; (C) A schematic diagram illustrates the composition of the joint fabric-reinforced soft body rehabilitation finger; (D) Passive training of hand stretching[113]. Copyright 2020 IEEE. EMG: Electromyogram.

Figure 10B illustrates the recorded instances of incorrect sitting positions when the user leans to the right or sits idly, accompanied by an on-screen avatar. In Figure 10B i-v, the five postures of the user, including tilting to the right and left, stretching, hunching, and leaning back, are presented with their corresponding sensing responses and enlarged screen images displayed on the right side. It is worth noting that maintaining correct posture is crucial for good health, as incorrect sitting positions can lead to spinal pain and increase the risk of various diseases. This smart textile solution has the potential to assist students and individuals with sedentary jobs in avoiding pain, discomfort, and long-term health issues.

With the purpose of facilitating assisted rehabilitation exercise training, a wearable exoskeletal soft rehabilitation glove was designed[113]. Figure 10C illustrates the glove, which includes a soft finger comprising a combination of a phalanx and a soft joint. While the soft joints mimic human finger joints, the toughness of the glove is maintained by the phalanges. The fabric layer at the soft joint is composed of a single layer of knitted fabric that is axially arranged along the silicone liner. The knit fabric exhibits unidirectional stretch, enabling the joint to elongate in the transverse direction while maintaining stability in the longitudinal direction. Comprising two interlaced layers of knitted fabric, the fabric layer at the phalanx enables joint bending movements. Through the utilization of distinct shape variables in the fabric layers positioned at the finger's base and back, the soft finger attains the ability to flex at the joints. The joint region facilitates flexible bending movements while preserving the original shape of the metacarpal and phalangeal areas throughout the bending process. For patients undergoing rehabilitation therapy for hand dysfunction resulting from spinal cord injury or stroke, a soft rehabilitation glove was utilized. In the experiment, the subject's forearm was fitted with sEMG electrodes, while the soft rehabilitation glove was worn on the opposite hand. The subject executed slow and regular hand extension and contraction movements, as depicted in Figure 10D. Gathering sEMG signals from the electrodes positioned on the subject's arm, the control system of the soft rehabilitation glove accurately reflects the muscle movement status during finger joint motion. Based on this information, the control system drove the glove to produce a mirrored following movement in the subject's other hand. The subject had the ability to perceive the squeezing force applied by the actuators of the glove on each finger, leading to passive movements. Pressure variations within the rehabilitation glove were monitored throughout a cycle of continuous passive extension and contraction movement training. The bionic soft glove not only facilitates skillful grasping, aligning with the universal grasping characteristics of the human hand, but also serves as an assistive device for daily activities and fulfills rehabilitation needs.

Given the growth of the elderly population, the development of upgraded everyday clothing with diverse smart and assistive features, in addition to the aforementioned applications, becomes imperative. E-textiles can also be used in assistive technologies to enable disabled, ill, and elderly patients to regain the mobility they need to live independently. Some textile-based assistive features include mobility-assisted exoskeleton supports, hearing aids, assistive rehabilitation devices, and prosthetics[89,114]. For individuals facing language barriers, the utilization of e-textiles proves instrumental in facilitating communication, with the development of smart textile gloves specifically designed for sign language interpretation. Such assistive applications help translate sign language gestures into speech on mobile user interfaces. Alongside these complementary therapeutic solutions, commercially available smart socks and textile pressure sensors serve as valuable tools for motion detection and provide complementary therapeutic effects to patients. In the near future, the majority of individuals will require assistive technology, and e-textiles have the potential to fulfill this growing need.

## CHALLENGES IN MEDICAL APPLICATIONS

In the future, e-textiles as medical smart materials will have tremendous development prospects. However, there are significant challenges to overcome before they can be introduced to the market. Firstly, e-textiles need to possess wearability, user-friendliness, and easy maintenance. Secondly, they need to gain recognition and acceptance within the medical field while ensuring safety in terms of data and materials. Lastly, e-textiles should combine the traditional properties of wearable textiles with special functionalities, such as stretchability, wrinkle resistance, windproofing, UV protection, breathability, and static resistance, among others. Ultimately, as shown in Figure 11, e-textiles for the healthcare industry can be produced on a large scale and widely used in both home and hospital settings.

### Wearability

For e-textiles to achieve optimal functionality, it is crucial that they possess the characteristics of flexibility, breathability, washability, and comfort akin to regular clothing, *etc*. The ability to be washed is particularly vital for ensuring the long-term effectiveness of the product[115]. As functional materials continue to advance and electronic devices become increasingly miniaturized, wearable technologies can be seamlessly integrated into textile structures, resulting in the creation of e-textiles with a myriad of functions. E-textiles can maintain their normal haptic properties by increasing the functionality of fabrics and creating fabric sensors. The integration of sensors and the design of smart clothing are dependent on the specific application and user requirements. For instance, when designing smart garments for newborn babies, the primary consideration is reducing stress during wear. Fabric sensors need to be seamlessly integrated into

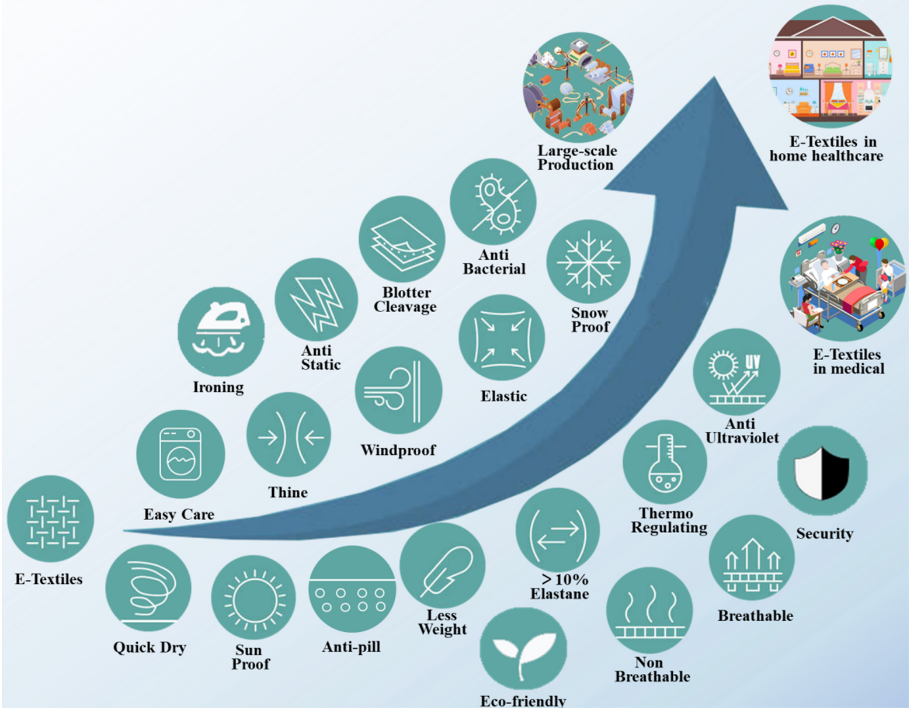


**Figure 11.** Challenges in medical applications of e-textiles.

the garment, and conductive threads can be connected to the sensors using techniques such as embroidery or braiding. Despite notable advancements in flexible wearable electronics, certain wireless electronic devices still retain conventional rigid components. Hence, careful packaging is essential for ensuring user safety and comfort in these areas. Furthermore, it is imperative to emphasize the development of fully flexible wearable e-textiles in future endeavors. Current research initiatives should also focus on standardizing various existing smart textile products, encompassing parameters such as preparation, usage methods, product specifications, and performance evaluation within healthcare settings.

### Ease of use and maintenance

E-textiles have sensors built in at appropriate locations for monitoring vital signs. To enable the monitoring of vital signs and enhance human healthcare, e-textiles incorporate built-in sensors strategically positioned at relevant locations. It is essential for e-textiles to be scalable and equipped with a suitable display interface for presenting the final health data. This display interface plays a crucial role in providing healthcare information to the user. Consequently, designing user feedback tailored to the specific purpose serves as a significant challenge in this domain.

When electronics are integrated directly into threads or fabrics, rather than being based on/using appropriately sized removable batteries, the issue of maintenance (washing, drying, ironing, *etc.*) becomes critical, as this will limit the lifespan of the textile (e.g., number of washes, *etc.*), which, in turn, will affect its use, price, and replacement value. In the realm of clothing and household bedding maintenance, are there any discrepancies between the practices of washing, ironing, storage, folding, and other related activities carried out by individuals in their homes compared to those performed by companies, hotels, laundries, catering services, and similar establishments? To prevent this from becoming a hindrance to the marketing of their products, manufacturers must furnish their professional suppliers and customers with comprehensive information concerning the shelf life, durability, material properties, intelligent textile systems employed, operational modes, and storage requirements (including folding, unfolding, laying flat, hanging on hangers, *etc.*). Furthermore, details regarding usage methods, maximum wash cycles, material quality, fiber blends, drying procedures (including drying mode and duration), ironing guidelines (such as maximum temperature), maintenance instructions, repair guidelines, and sterilization information should be provided. In summary, it is imperative to provide thorough and detailed information on usage and maintenance aspects.

### Security aspects

One aspect is the safety of wearable e-textiles, i.e., their impact on the environment and human health. For textiles containing electronic components or functional materials, aspects to be considered include the risk of connection breaks related to the hardness and thickness of the components, the risk of chemical changes and oxidization if these components contain metals or the threat of toxicity of the functional materials. Therefore, research should be conducted to detect the adverse effects of this new class of materials, especially those in close contact with the skin. In addition, corrosion or chemical changes are at risk if the integrated devices within the fabric are damaged during washing and ironing. On the other hand, is the confidentiality and security of personalized health data of human sensing data. Encrypted data is often required to ensure the security of information transmitted by wearable e-textiles.

### Approval from the medical community

If patients or clinicians are unwilling to utilize them, smart textile systems with integrated sensors become obsolete. The primary user preference for wearable sensor systems is that they should be compact, seamlessly integrated, and user-friendly in terms of operation and maintenance. Moreover, these systems should not disrupt daily activities or attempt to directly replace healthcare professionals. The integration of personal health monitoring systems into healthcare necessitates connecting with existing healthcare information systems and electronic health records, thereby requiring interoperability with current and future communication infrastructure (including broadband, fixed, and wireless networks). Research is crucial to persuade the healthcare community about the advantages of this technology. These studies should investigate the impact on users' quality of life and demonstrate how this technology helps reduce hospitalization rates and improve the quality of care.

## PROSPECTS

The future of e-textiles involves integration with 5G networks, big data, and AI cloud network platforms. Ultimately, the aim is to create products with integrated, intelligent, miniaturized, networked, and functional characteristics [Figure 12A][116]. When it comes to researchers, the development of e-textiles should encompass various aspects such as material innovation, ensuring reliability and stability, optimizing device structure, facilitating functional integration, and establishing performance standardization. Industrial companies venturing into e-textiles should prioritize product standardization, value chain creation, manufacturing processes, and clinical integration[117]. Additionally, the utilization of new raw materials and composites should address concerns regarding cleanliness and safety. Among them, the application of hybrid composites is more promising and should be further explored. In addition, for product performance, e-textiles should be breathable, washable, robust, thermally stable, and air/moisture absorbent, which are the current weak points[118]. Hence, the primary emphasis should be on safeguarding against oxidation, moisture, and mechanical deformation. This concern can be effectively addressed by employing well-sealed textile sensors that utilize polymer encapsulation, enabling coverage of curved surfaces[26].

From a materials science perspective, the selected materials need to be safe, corrosion-resistant, biocompatible, comfortable, and cost-effective for full integration and mass production[119]. Therefore, novel

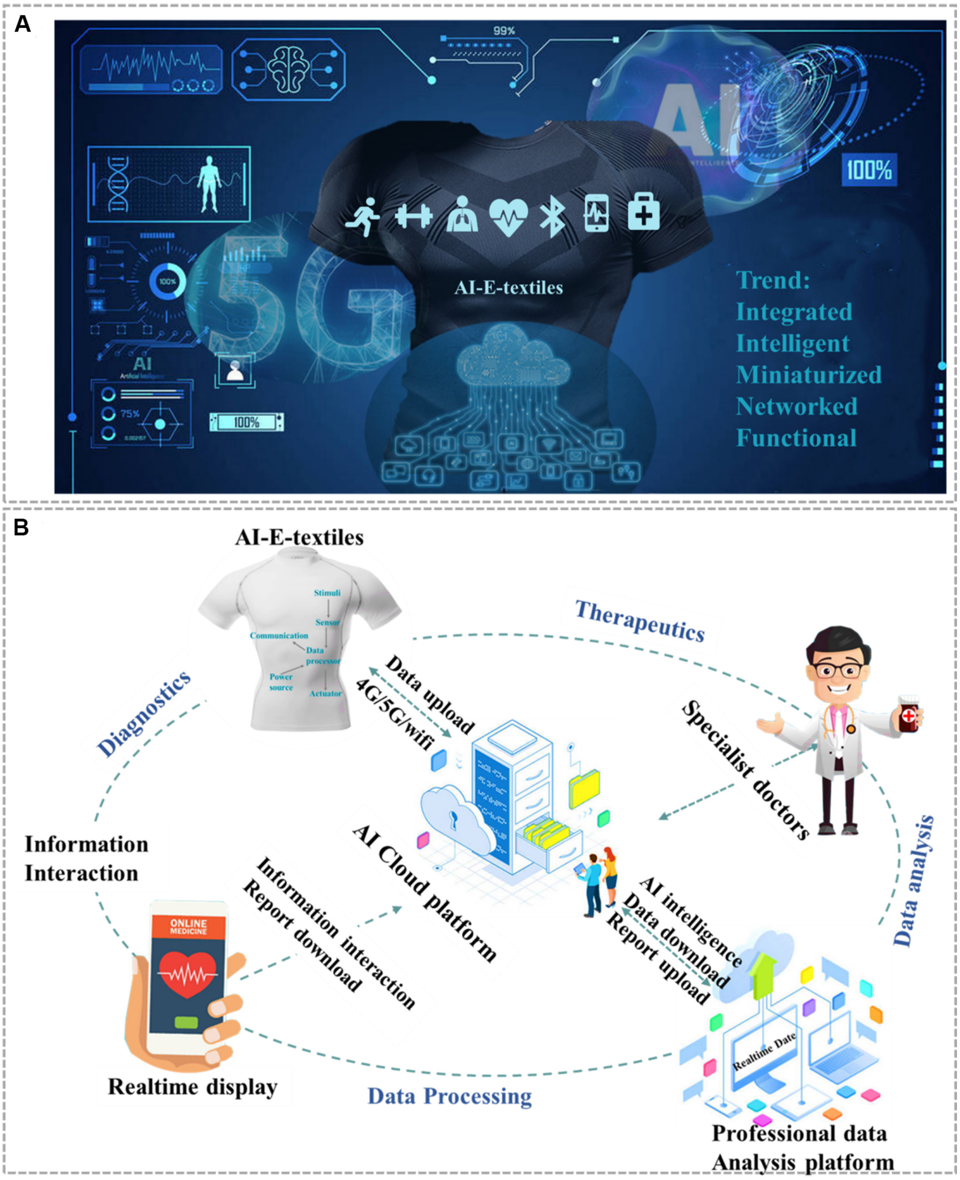


**Figure 12.** Anticipated advancements in smart medical textiles. (A) E-textiles integrated with 5G networks, big data, and AI cloud network platforms; (B) E-textiles create big data on health among users, doctors, and web-based platforms to achieve diagnostic and therapeutic integration. AI: Artificial intelligence.

materials and advanced manufacturing technologies must be developed to meet the requirements for preparing advanced e-textiles[120]. Two or more functional properties can be combined into a new multifunctional material[121]. Smart textile devices often require integrating available materials with higher requirements for mechanical properties. To address the deposition of functional layers, interfacial engineering can be implemented during the overall manufacturing process. This approach aims to achieve stable interfacial bonding and minimize the occurrence of fiber cracks and delamination. In addition, textile technologies for improving comfort and weaving structures can be consulted with several experts or technical departments, replacing the complexity and high cost of redeveloping the technology. Superior structural design is expected to lead to better overall healthcare applications, yielding structural properties with inherent robustness, flexibility, softness, and porosity.

From a processing technology perspective, there is a need for the development of a number of efficient processing technologies, and combining a variety of e-textiles with comfortable designs will be one way to manufacture complex e-textiles[122,123]. The research focus should be directed toward scalable and automated processes that leverage existing low-threshold manufacturing technologies. The textile industry can scale and prepare intelligently using top-down and bottom-up scaling approaches. Top-down manufacturing strategies can offer significant advantages for diagnostic solutions. In this context, economies of scale factors will play a dominant role and be implemented through continuous production models. These models encompass advantages such as reduced raw material costs and increased availability, standardized production design, compatibility with existing machinery, and the replication of established protocols. Cheaper functional materials and platform technologies will also be easier to scale[102]. Manufacturing strategies such as spinning have already been proven in scale production and can be used to develop standardized garments with predefined sensing regions; e.g., integrated gloves can be used to detect blood oxygen saturation and finger sensing data, chests can be used to detect heart and respiratory rates, and multipoint multidirectional fabrics can be used for body movement parameters and for rehabilitation training. Developing these products on a large scale to replace hospital gowns and ensuring their easy recyclability can be achieved. Due to the choice of materials, these solutions are also best suited for everyday use in terms of washability and long-term comfort.

Furthermore, from the perspective of healthcare providers, e-textiles play an important role as a bridge between users and healthcare providers, so they not only monitor users' physiological parameters but also provide a multifaceted assessment of their health status conveniently, creating big data on health among users, doctors, and web-based platforms to achieve diagnostic and therapeutic integration [Figure 12B][114,124]. For AI algorithms, data management is a key factor for successful application in healthcare. These algorithms should be trained with high-quality data to learn relevant patterns[125]. The data must be updated promptly to ensure the latest information is fed into the database.

Finally, ensuring that scientific and clinical outcomes are recognized is key to adopting e-textiles in the medical community. Clinicians and patients need to be trained to understand how e-textiles work. To optimize future development and integration, it is crucial to develop optimized user interfaces, web integration, and accessibility in close collaboration with clinicians. The multidisciplinary nature of e-textiles in personalized medicine necessitates cross-collaboration among materials scientists, electrical engineers, apparel industry experts, regulatory agencies, clinicians, patients, user interface developers, and government entities. This collaborative approach is essential for achieving optimal outcomes in terms of functionality, usability, and regulatory compliance of smart textile technologies.

## DECLARATIONS

### Authors' contributions

Initiated the idea: Dong K
Conducted the literature review: Zhao C, Sheng F
Outlined the manuscript structure: Sheng F, Dong K
Wrote the manuscript draft: Sheng F, Dong K
Designed and formatted the figures: Sheng F, Tan Y
Reviewed and revised the manuscript: Dong K, Zhang B

### Availability of data and materials

Not applicable.

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**Conflicts of interest**
All authors declared that there are no conflicts of interest.

**Ethical approval and consent to participate**
Not applicable.

**Consent for publication**
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