Huang *et al*. *Soft Sci* 2024;4:40
DOI: 10.20517/ss.2024.37

Soft Science

Review Article

Open Access

Textile electronics for ubiquitous health monitoring

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How to cite this article: Huang FC, Sun XD, Shi Y, Pan LJ. Textile electronics for ubiquitous health monitoring. *Soft Sci* 2024;4:40. https://dx.doi.org/10.20517/ss.2024.37

Received: 2 Sep 2024 **First Decision:** 18 Oct 2024 **Revised:** 3 Nov 2024 **Accepted:** 20 Nov 2024 **Published:** 28 Nov 2024

Academic Editors: Huanyu Cheng, YongAn Huang **Copy Editor:** Pei-Yun Wang **Production Editor:** Pei-Yun Wang

Abstract

The emergence of wearable electronics, along with an increased emphasis on personal health, has catalyzed a transformation in conventional health monitoring methods. Textile electronics are attracting significant attention due to their good flexibility, breathability, biocompatibility, portability and wearability, positioning them as a promising platform for human health monitoring. Consequently, substantial efforts are being dedicated to developing multifunctional, integrated, and reliable health monitoring systems based on textile electronics. This review summarizes recent advancements in textile electronics, focusing on materials, preparation techniques for functional fibers and fabrics, design strategies for textile-based health monitoring systems, and applications in ubiquitous health monitoring. Additionally, some emerging strategies for integration are presented. Moreover, the challenges and future outlook of textile electronics, along with potential solutions are discussed.

Keywords: Textile electronics, functional fiber, healthcare monitoring, integration strategies, wearable electronics

INTRODUCTION

As artificial intelligence (AI) evolves and human demands increase, wearable electronics are emerging as platforms for the next generation of multifunctional and user-friendly intelligent devices[1-4]. Ideal wearable electronics possess properties of excellent wearability and durability[5-8]. Consequently, researchers are striving to develop wearable technologies that exhibit superior electrical performance while ensuring excellent deformability and comfort. Textile electronics, a crucial component of the smart wearable devices sector, integrates textile technologies with electronic engineering principles to facilitate the generation, transmission, assessment, and modulation of electronics on fibrous substrates[9-11]. Characterized by their inherent softness, comfort, breathability, and washability, textile electronics have been extensively integrated into various applications, particularly in human health monitoring[12-15].

Health is fundamental to human survival and development, and health issues present societal concerns and scientific challenges. The advent of textile electronics has ushered in a new era for adaptable health monitoring solutions within consumer electronics markets[16,17]. These advanced devices integrate functional fibers to facilitate the transmission of information between the human body and the surrounding environment, as well as *in vivo* and *in vitro*, with exceptional interactive capabilities[18-20]. In contrast to conventional thin-film patch sensors, textile-based health monitoring systems offer superior breathability and enhanced wearability, which are essential for comprehensive large-scale sensing capabilities[18,21,22]. Textile electronics for health monitoring can be realized through two primary pathways. The first approach involves directly affixing electronic components onto the surface of textiles or integrating them as hybrid electronic elements within the textiles[23,24]. Subsequently, flexible or fabric circuits are employed to establish wired connections between microelectronic components and textiles. The alternative approach entails producing fibers with electronic functionalities, which are then woven into textiles[25-28].

Research on textile electronics for health monitoring dates back to the 1960s and 1970s[29], with the introduction of concepts such as shape memory fiber materials and intelligent fiber materials, which laid the groundwork for the field. Most textile electronics were developed by attaching electronic components to textiles using the first approach in the early stage[30]. For example, the Georgia Tech Wearable Motherboard was developed in 1999, and the firefly dress was created by the MIT Media Laboratory around 2000[23,31]. In the early 2000s, the EU-funded project WEALTHY developed a textile sensor system to monitor patients' physiological signals, such as electrocardiograms (ECG) and breathing, in real time[32-35]. This system represents a significant advancement in the use of textile electronics for medical health monitoring. Subsequently, more textile electrodes for physiological monitoring arose, and textile electronics with wireless personal area networks were progressively utilized in health monitoring[36,37]. In 2012, researchers at Ohio State University developed textile antennas and circuits with a precision of 0.5 mm[24]. Subsequent advancements improved this precision to 0.1 mm, representing a significant milestone in textile electronics[38]. These wearable antennas can transmit and receive digital information, significantly enhancing communication capabilities for health monitoring systems[24,39-41]. With advancements in internet technology, cloud computing platforms have been incorporated into textile-based health systems for efficient processing of health big data. Subsequently, smart platforms based on various functional fibers have been successfully developed for electromyography (EMG) and sleep monitoring[42,43]. These studies demonstrate that textile electronics obtained through the second approach not only maintain the comfort and functionality of traditional clothing but also integrate advanced electronic functions, contributing to the realization of a fully electronic textile system. In recent years, the development of smart textile electronics has entered a flourishing stage[44-48]. Machine learning algorithms and advanced integration technology have greatly advanced the intelligence and integration of health monitoring systems[49-52]. Figure 1 illustrates the above evolution of textile electronics in health monitoring applications. Moving forward, the realization of a fully textile-based health monitoring system will be a primary research direction. It is anticipated that textile electronics will transform human lifestyles through real-time health management and remote medical care, in conjunction with AI, human-computer interaction, and cloud computing technology.

In this review, we systematically introduce innovative textile electronics and summarize their latest advancements in health monitoring systems. We begin with an overview of the materials utilized in textile

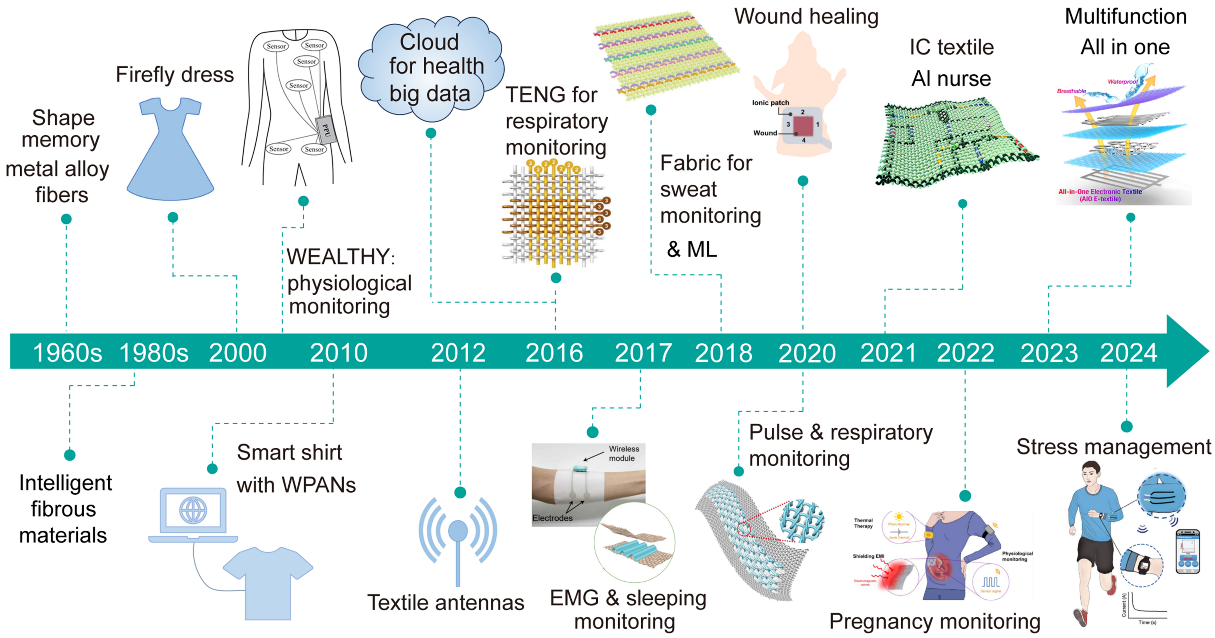

Figure 1. Timeline of textile electronic developments for health monitoring. Figure "WEALTHY: physiological monitoring"[35], reprinted with permission. Copyright 2011, Elsevier; Figure "TENG for respiratory monitoring"[53], reprinted with permission. Copyright 2016, John Wiley and Sons; Figure "EMG"[43], reprinted with permission. Copyright 2017, John Wiley and Sons; Figure "Sleeping monitoring"[42], reprinted with permission. Copyright 2017, John Wiley and Sons; Figure "Fabric for sweat monitoring"[47], reprinted with permission. Copyright 2018, John Wiley and Sons; Figure "Wound healing", reprinted with permission. Copyright 2020, Elsevier; Figure "Pulse & respiratory monitoring"[45], reprinted with permission. Copyright 2020, Science Advances; Figure "IC textile"[51], reprinted with permission. Copyright 2021, Springer Nature; Figure "Pregnancy monitoring"[44], reprinted with permission. Copyright 2022, American Chemical Society; Figure "Multifunction"[52], reprinted with permission. Copyright 2023, Elsevier; Figure "Stress management"[49], reprinted with permission. Copyright 2024, John Wiley and Sons. TENG: Triboelectric nanogenerator; EMG: electromyography; IC: integrated circuit.

electronics, followed by an analysis of the fabrication techniques for functional fibers and fabrics. Next, we discuss various design strategies for developing textile-based health monitoring systems. Furthermore, recent applications of textile electronics in ubiquitous health monitoring are discussed. The latest integration strategies are then presented, representing pivotal advancements toward the commercialization of textile electronics. Finally, we emphasize the critical challenges faced by health monitoring systems based on textile electronics. Our discussion aims to cover advanced materials, fabrication techniques, applications, and integration strategies in this promising field.

MATERIALS OF TEXTILE ELECTRONICS

Functional materials

The performance of textile electronics is significantly influenced by functional materials, which endow textiles with conductive and sensing properties. The selection of materials demands a meticulous assessment of pivotal attributes, such as electrical conductivity, mechanical resilience, thermal stability, specific weight and density, thermal dissipation capacity, and the reliability and longevity essential for integration with conventional wire interconnections[54,55]. These characteristics are fundamental to ensuring the functionality and robustness of textile electronics in various applications. Figure 2 presents an overview of the prevalent functional materials for the preparation of textile electronics, categorized into metals, conductive polymers, carbon materials, and semiconductors[54,56].

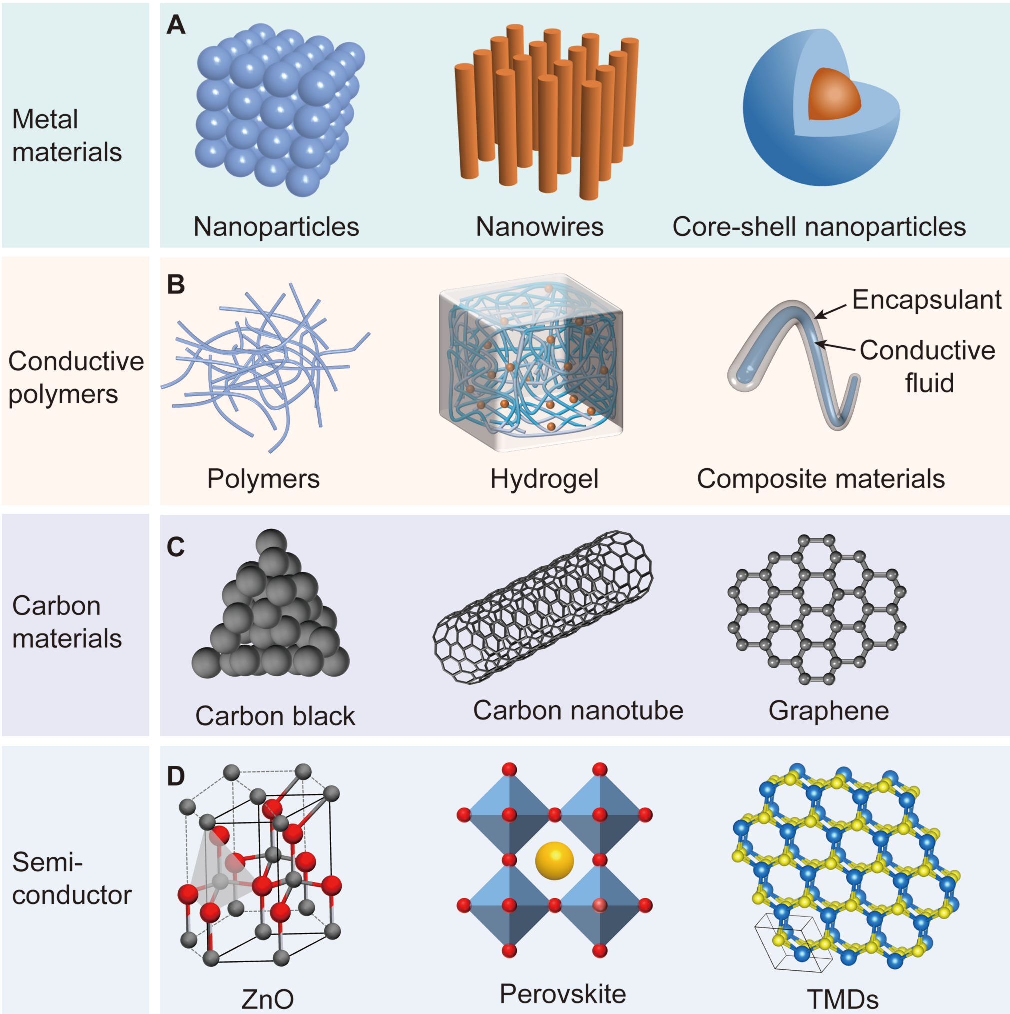

Figure 2. Images of various functional materials for textile electronics.

Metals such as Au, Ag, and Pt are highly valued for their exceptional electrical and thermal conductivity. These metals are available in a spectrum of dimensions, from 0D to 3D structures, as shown in Figure 2A. Among them, Ag nanoparticles have garnered extensive applications due to their remarkable electrical conductivity, stability, and the simplicity of their synthesis process[57,58]. Furthermore, the core-shell structured composite metal nanoparticles offer a viable alternative for the fabrication of textile electronics. Although metal alloying can improve strength and corrosion resistance, it potentially decreases conductivity relative to pure metals, alongside elevated costs and enhanced processing complexity[59,60].

As shown in Figure 2B, conductive polymers involve conventional varieties [such as polyaniline, polypyrrole, polythiophene and poly(ethylene dioxythiophene)][61-65], conductive hydrogels[66-68], and conductive liquids encapsulated by polymers[69]. These materials are notably lightweight and highly flexible, making them suitable candidates for textile electronics and their interconnects[70,71]. Although their conductivity can be adjusted through physical or chemical means, it remains lower than that of metals, necessitating doping for performance enhancement[72].

Carbon materials, such as carbon black, carbon nanotubes (CNTs), graphene, and reduced graphene oxide (rGO), are known for their inherent electrical conductivity, excellent thermal conductivity, and low weight [Figure 2C][73-76]. However, they may present challenges related to dispersibility and compatibility with other materials[77,78]. Moreover, as depicted in Figure 2D, zinc oxide (ZnO)[79,80], organic/inorganic perovskites[81,82], and transition metal dichalcogenides (TMDs)[83,84] have shown considerable potential for applications in sensing and display modules of health monitoring systems.

Mechanical polymers

In textile electronics, mechanically flexible/stretchable polymers play an important role, especially as flexible substrates, conductive fibers and encapsulation layers. The three-dimensional network structure of polymeric matrixes can be used to carry, support and protect other materials, such as the previously mentioned functional materials. In textile electronics, mechanical polymers should be selected based on requirements for flexibility, stretchability, biocompatibility, and compatibility with functional materials.

For fabricating flexible substrates, there are some examples provided for consideration, such as using polyimide (PI) as a substrate directly[85], coating polyvinyl chloride (PVC)/polyurethane (PU) on textiles to be suitable for lithographic processes[86], and using polyethylene terephthalate (PET) fiber as a substrate for coaxial configuration[87,88]. Besides, the polymers are employed for fabricating conductive fibers, such as Au nanowires@styrene-ethylene/butylene-styrene (SEBS)[89], Ag nanoparticles@poly(styrene-block-butadienstyrene) (SBS)[90], GO@PU[91], *etc.* Moreover, the polymers are employed for encapsulation layers such as ecoffex[92], polydimethylsiloxane (PDMS)[93], PI[94], *etc.*

In addition to the functional materials and mechanical polymers, other materials are also employed to enrich the functionality of textile electronics. For instance, pharmaceuticals are being embedded into fibers to enable long-term therapeutic applications[95]. Furthermore, efforts are underway to integrate antibacterial materials into textiles to suppress or eliminate bacteria and provide additional protection for users[96], especially in scenarios where strict hygiene standards are crucial.

FABRICATION TECHNIQUES

Textiles are complex hierarchical materials requiring specialized knowledge of manufacturing processes. As the fundamental units of textiles, fibers can be processed into yarns through twisting or texturing[97,98]. These yarns can be crafted into fabrics using various techniques, including weaving, knitting, or bonding[99]. Given the importance of electrical performance in textile electronics, it is crucial to innovate and enhance the fabrication techniques of textile electronics according to the framework of traditional textile production processes. This section introduces fabrication techniques for functional fibers and fabrics, highlighting their significance in developing textile electronics.

Fabrication of functional fibers

Surface treatment for commercial fibers

Conductive fibers are typically obtained through wire drawing, which involves elongating metal wires into fiber forms. Metals such as stainless steel, copper, and aluminum are commonly used in this method. Fibers with diameters ranging from a few to tens of microns can be fabricated by drawing the metal wires through a series of precision dies[100,101]. However, most commercial fibers are primarily insulators[102-106], so their conductivity can be achieved by applying conductive materials via dip-coating[90,107]. Lee *et al.* employed this technique for the fabrication of conductive fibers[90]. In their method, theSBS polymer was immersed in a silver-containing solution ($AgCF_3$ COO). This immersion allowed for the infiltration of Ag into the SBS, enhancing electrical conductivity of SBS. Thereafter, the silver nanowire (Ag NW)-coated fiber was coated using the poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) solution. This approach was demonstrated as an effective strategy for integrating electrical conductivity with the inherent properties of insulating fibers.

Certain fibers, such as polyacrylonitrile (PAN) and cellulose, can be rendered conductive through carbonization, a method commonly employed to fabricate high-performance carbon fibers[108,109]. For instance, Gupta *et al.* reported on the impact of carbonization temperature on the crystallinity and electrical conductivity of PAN fibers[110]. The conductivity of PAN fibers carbonized at 1,000, 1,800, and 2,200 °C increased monotonically from 5.32 to 51.01 $S \cdot m^{-1}$ and 75.91 $S \cdot m^{-1}$, respectively. Thus, by controlling the carbonization temperature, it is feasible to achieve fibers with the desired level of conductivity.

Additionally, electroless deposition and electrodeposition are also common methods for the surface functionalization of fibers[111-113]. Electroless deposition employs a potent reducing agent in a solution of metal ions to reduce the metal ions to their metallic form, which subsequently deposits onto the surface of materials[114,115]. Electrodeposition, referred to as electroplating, is a method of depositing a metal layer onto the surface of a material through electrolysis[116,117]. Both electroless deposition and electrodeposition have their respective advantages. The former does not require an external power source, and it can form a uniform coating on substrates of complex geometry, making it suitable for surface metallization of complex shapes or insulating materials[118,119]. The latter allows for the control of metal layer thickness and deposition rate, making it appropriate for applications requiring a thicker metal layer[120-123].

Inherently functional fiber making

Previous methods focused on surface treatment of insulating fibers to achieve functional fibers. Extensive experimental evidence has demonstrated that it is also feasible to produce inherently functional fibers through various processes, including thermal drawing, spinning, and 3D printing.

The thermal drawing technique, derived from the technology used in optical fiber fabrication, can also be employed to manufacture functional fibers[124]. Loke *et al.* have demonstrated the preparation of a preform integrating conductors, semiconductors, and polymer insulators, as depicted in Figure 3A[125]. Upon heating and stretching the preforms, the functional fiber exhibiting seamless material integration and exacting dimensional precision was achieved. Various methods can be employed for fabricating these preforms, including thin-film rolling for cylindrical fiber production, extrusion, lamination, drawing, and integrating different material components through hot pressing or advanced 3D printing technology[126]. Furthermore, various post-processing methods have been developed to overcome the mechanical property mismatch between different materials[127,128], such as laser and thermal annealing, as depicted in the second fiber of Figure 3A.

Spinning is a prevalent process for converting polymers into fibers, including melt spinning, wet spinning, dry spinning, dry-jet wet spinning, and coaxial extrusion. Melt spinning is a process that involves using the apparatus shown in Figure 3B to incorporate conductive fillers into easily meltable polymers or to blend conductive polymers with matrix polymers[129]. Common matrix polymers used in the spinning process include polypropylene (PP), PU, thermoplastic PU (TPU), and Ecoflex[130-132]. Probst *et al.* blended highly elastic TPU with conductive CNTs to fabricate conductive fibers via the melt-spinning process[132]. These fibers exhibit high elongation, mechanical properties comparable to conventional elastic fibers, and electrical conductivity on par with conductive liquid. Notably, melt spinning focuses on using the blends of conductive polymers with thermoplastic polymers suitable for this process due to the inadequate stability, toughness, and processability of pure conductive polymers[129,133].

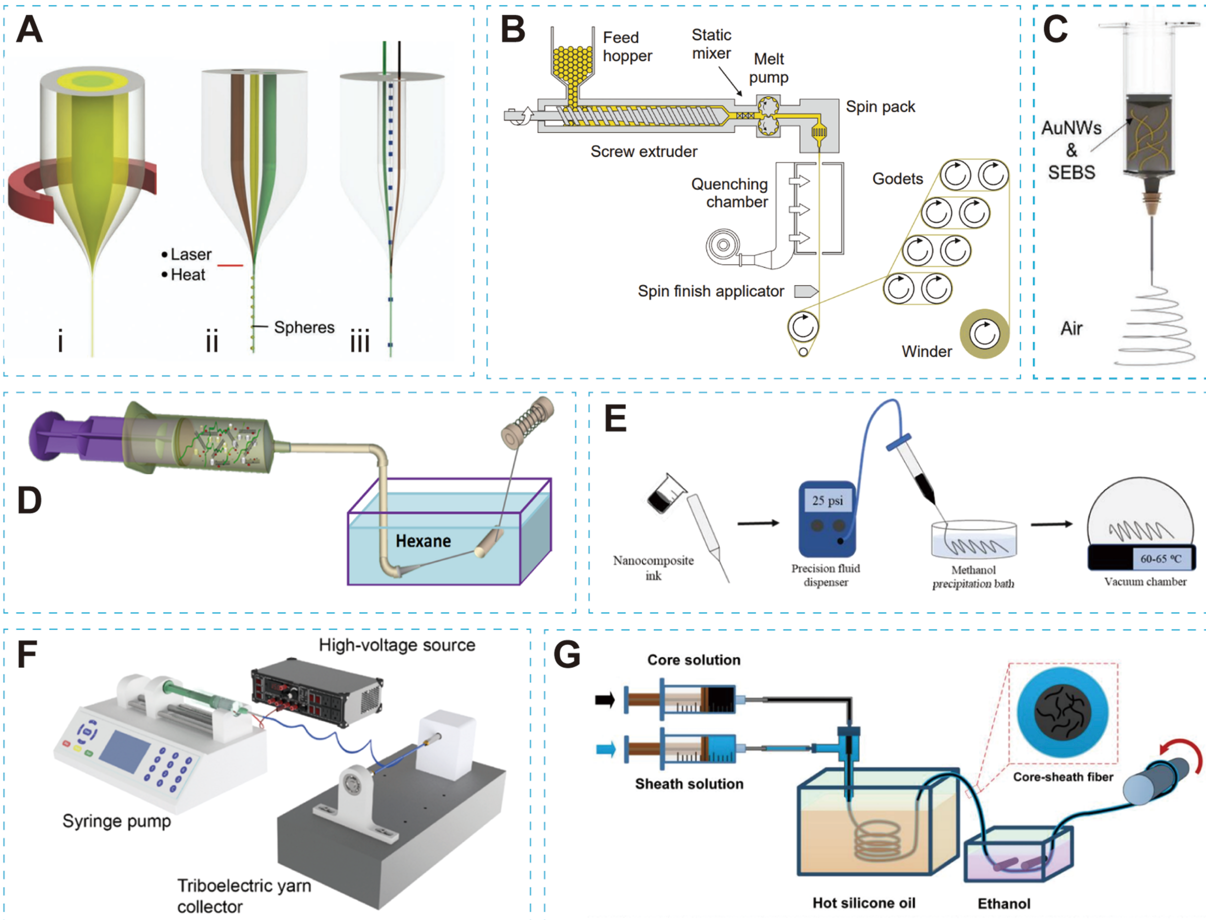

Figure 3. Thermal drawing and various spinning techniques. (A) Thermal drawing[125]. Reprinted with permission. Copyright 2019, John Wiley and Sons; (B) Melt spinning[129]. Reprinted with permission. Copyright 2020, MDPI; (C) Dry spinning[134]. Reprinted with permission. Copyright 2018, John Wiley and Sons; (D) Wet spinning[138]. Reprinted with permission. Copyright 2014, American Chemical Society; (E) Dry-jet wet-spinning[141]. Reprinted with permission. Copyright 2023, MDPI; (F) Electrospinning[143]. Reprinted with permission. Copyright 2021, American Chemical Society; (G) Coaxial extrusion[144]. Reprinted with permission. Copyright 2018, American Chemical Society.

Dry spinning is a method that usually uses hot gas to process the spinning solution for solidification. After the solvent evaporates, the polymer solidifies to form conductive fibers [Figure 3C][134]. For polymers and their solvents that are stable at high temperatures, dry spinning may be the preferred method. If the polymers are sensitive to high temperatures, such as PVC melt (melting point: ~80-85 °C), dry spinning is also possible under strict processing conditions. For those polymers that can be easily dissolved in a specific solvent but are not easily melted, wet spinning offers a suitable alternative. For instance, the cellulose acetate (melting point: ~160-190 °C) is dissolved in acetone (boiling point: ~56 °C) for fabricating a wet spinning solution[135-137]. First, a spinning solution containing conductive nanomaterials or conductive polymers is extruded through a spinneret into a coagulation bath. Subsequently, the solvent diffuses into the bath, facilitating the solidification and formation of conductive fibers [Figure 3D][138]. The earliest single-walled CNT (SWCNT) fibers were successfully assembled through wet spinning[139]. By adjusting parameters such as injection rate, flow speed, and the size of the needle or capillary tube, the morphology of the spun fibers can be controlled, allowing for the fibers with diameters ranging from a few micrometers to 100 μm. Eom *et al.* extruded a high-concentration MXene dispersion through a nozzle into a coagulation bath containing NH_4Cl and NH_4OH, forming a gel-like MXene fiber[140]. Subsequent post-treatment in a water bath yielded highly conductive MXene fibers with excellent electrical conductivity (7,713 $S \cdot cm^{-1}$) and good mechanical properties.

Additionally, the dry-jet wet spinning technology combines both dry and wet spinning characteristics. Unlike conventional wet spinning, in dry-jet wet spinning, the fine filament stream exits the nozzle and traverses a defined air gap without encountering any solidifying medium, as illustrated in Figure 3E. This intervention is beneficial for curtailing fiber stretching and enhancing fiber orientation[141]. Consequently, dry-jet wet spinning can significantly reduce solvent consumption, boost production efficiency, and is applicable to a broad spectrum of polymers, including those that present processing challenges in traditional wet spinning setups.

Electrospinning involves continuously drawing fibers using static electricity [Figure 3F][142,143]. Although electrospinning shares a reliance on solvent evaporation for fiber solidification with dry spinning, traditional dry spinning is limited in producing nanoscale fibers. Furthermore, advances in spinneret design have led to the development of coaxial extrusion techniques, such as coaxial electrospinning and coaxial wet spinning [Figure 3G][144,145]. Coaxial extrusion can create multi-layered fibrous structures, typically with a conductive layer at the core and an insulating layer as the sheath.

Moreover, 3D printing technology, with its exceptional design flexibility and manufacturing adaptability, enables on-demand customization. For example, composite fibers of boron nitride nanofiber/polyvinyl alcohol (BNNS/PVA) have been successfully produced via 3D printing, boasting high mechanical strength and excellent thermal conductivity[146]. The functional fibers can be further integrated into textiles with diverse structures for personal cooling applications. As shown in Figure 4A and B, the BNNS/PVA ink is continuously extruded through a metal needle into a methanol bath at 0 °C for cooling, forming a continuous printed fiber. In this process, PVA serves as a dispersing agent to achieve uniformly dispersed BNNSs, as shown in Figure 4C.

Similar to the coaxial extrusion, coaxial fibers can also be prepared by 3D printing. As shown in Figure 4D, a conductive core ink is formulated by blending graphene powder with a PDMS prepolymer, while an insulating sheath ink is concocted by combining polytetrafluoroethylene (PTFE) particles with the same PDMS prepolymer. The core and sheath printing inks are extruded through the coaxial printing nozzle of the 3D printer. The printed fibers were heat-cured at 170 °C, and then highly elastic coaxial fibers with 300% strain were obtained[147]. Moreover, 3D printers can design various 3D shapes and even directly print a complete device[148,149]. Figure 4E shows the step-by-step process of 3D printing to fabricate a pressure sensor. In this process, a base layer was printed using silicone rubber. A sensing layer was printed using a composite material with specific silver content. The ratio of silver to polymer can be adjusted to achieve the desired conductivity and pressure sensitivity. The electrode layer was printed using a composite material with high Ag content to ensure optimal conductivity. An isolation layer was employed in the device to separate the sensing layer and the electrode layer. Notably, the support layer should be removed through hydrolysis after printing.

In general, the preparation of multifunctional fibers often requires the participation of various technologies. Consequently, in the specific preparation process, these technologies should be strategically selected and combined based on the actual requirements of the application.

Fabrication of functional fabrics

Functional fibers can be obtained using the fabrication techniques previously presented, preparing for the

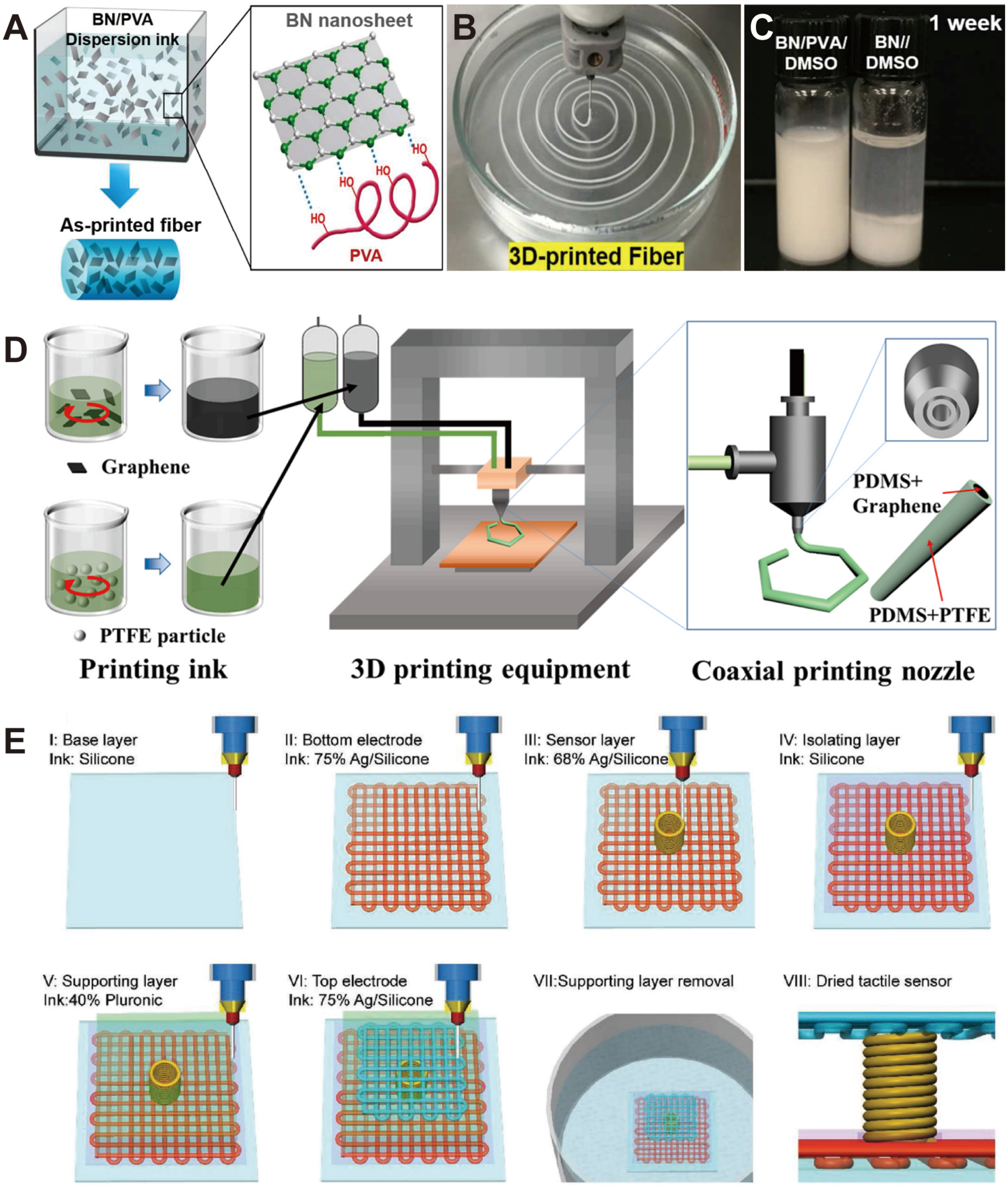

Figure 4. (A) Schematic of the fabrication of as-printed fiber; (B) Photo image of 3D-printed fiber cooling in methanol; (C) Photo image showing DMSO/BNNSs dispersion and PVA/DMSO/BNNSs dispersion after standing for one week[146]. Reprinted with permission. Copyright 2017, American Chemical Society; (D) Schematic of the 3D printing process of coaxial functional fiber[147]. Reprinted with permission. Copyright 2021, Elsevier; (E) 3D printing procedure of different functional fibers for a sensor[148]. Reprinted with permission. Copyright 2017, John Wiley and Sons. DMSO: Dimethylsulfoxide; BNNSs: boron nitride nanofibers; PVA: polyvinyl alcohol.

fabrication of yarns and fabrics. Four production stages are shown in Figure 5A, ranging from the initial fiber stage to the finalization of apparel products. As shown in Figure 5B, the classification of fabric structures is delineated into five distinct categories[150-153].

Weaving is a prevalent technique for the integration of textile electronics into fabrics due to the minimal deformation that occurs during the weaving process[154,155]. Woven structures can be formed by vertically interweaving warp and weft threads through a loom, resulting in a fabric with a uniform texture, including

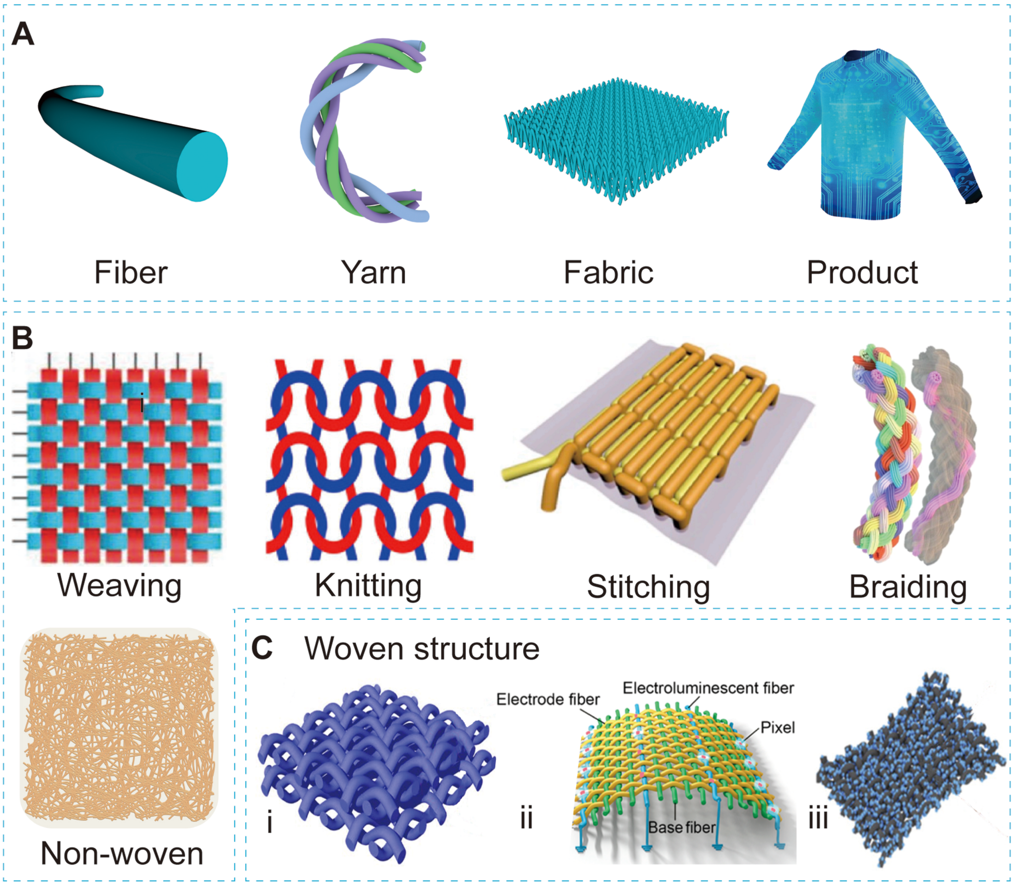

Figure 5. (A) Production stages from fibers to products; (B) Summarization of various fabric structures. Figure "Weaving"[150], reprinted with permission. Copyright 2018, John Wiley and Sons; Figure "Kitting"[151], reprinted with permission. Copyright 2013, Elsevier; Figure "Stitching"[152], reprinted with permission. Copyright 2020, Elsevier; Figure "Braiding"[153], reprinted with permission. Copyright 2020, Springer Nature; (C) Woven structures obtained by individual functional fiber, complex fibers and carbonization, respectively. Figure (i)[168], reprinted with permission. Copyright 2017, Springer Nature; Figure (ii)[169], reprinted with permission. Copyright 2021, American Chemical Society; Figure (iii)[170], reprinted with permission. Copyright 2019, Elsevier.

plain, twill, satin, basket, leno, and mock leno[156-158]. The most popular woven structure is the plain weave due to its simplicity, minimal repeat dimensions, and ease of formation and identification[159]. This structure integrates various electronic components such as pressure sensors, strain sensors, circuit boards, logic operations, solar cells, *etc.*[51]. However, the precise control of the weft yarn presents a challenge for the positioning of microelectronic devices[160].

In the knitting process, yarns are formed into a looped structure through either mechanical knitting machines or manual knitting techniques[161,162]. Owing to their looped construction, fabrics with knitted structures exhibit high extensibility, enabling them to withstand external forces better[160]. Additionally, knitting makes it easy to obtain circular or tubular structures in a bi-layer configuration. It is beneficial for the fabrication of devices that require the integration of multiple materials in contact.

Stitching, a method that employs sewing threads to bind multiple layers of material, is employed to enhance the thickness, strength, and durability of fabrics[163,164]. This process not only significantly amplifies the reinforcing effect but also elevates the permanent recovery ratio[152]. Furthermore, braiding is a simple technique for intertwining three or more strands of yarn to create narrow strips or flat fabrics, used for rope, shoelaces, and net-shape composite preforms[153,165]. Furthermore, non-woven structures stand apart from traditional weaving or knitting. They are formed by fixing fibers together using adhesives, heat pressing, or electrospinning, resulting in anisotropic, inhomogeneous fabrics with porosity and permeability[41,166,167].

Regardless of the structures, functional fabrics can be formed by individual functional fibers/yarns, or by weaving functional fibers/yarns with insulating fibers/yarns, which are then made into garments. Moreover, the previously discussed techniques for the functionalization of insulating fibers, such as carbonization and deposition, are equally applicable to insulating fabrics. Taking the woven structure as an example, as shown in Figure 5C, the fabrication of functional fabrics can be achieved through weaving with individual functional fibers, weaving with different fibers, and carbonization[168-170].

DESIGN STRATEGIES OF TEXTILE HEALTH MONITORING SYSTEM

The design and fabrication of textile electronics constitute a complex endeavor, as they involve integrating electronic systems with a textile platform. A simple health monitoring system includes a power module, sensing module, interconnections, data processing module, communication module, and display module. In such integrated systems, the design of textile electronics necessitates well-considered manufacturing decisions, which involve selecting appropriate materials and processes to ensure adherence to design specifications under specific constraints.

Power module

The power module serves as the energy core of the system, providing the necessary power to other modules. The power management circuitry is responsible for voltage regulation, current control, and power distribution. Recently, beyond conventional commercial energy devices, a variety of textile-based energy harvesting and storage devices, such as solar cells, supercapacitors and batteries, has emerged.

The energy harvesting devices effectively capture ambient energy sources, including solar radiation, thermal gradients, mechanical vibrations, and kinetic energy from human motion, to power wearable health monitoring systems. They typically leverage specialized materials optimized for energy conversion, such as photovoltaic, triboelectric, piezoelectric, and thermoelectric materials, to achieve efficient energy management in wearable applications. The use of photovoltaic materials to create solar cells is the primary technology for solar power generation[171]. When two triboelectric materials come into contact and then separate, they generate electrical energy due to the triboelectric effect[172]. Additionally, piezoelectric materials generate an electric charge when subjected to mechanical stress, also leading to the production of electrical energy[173,174]. Furthermore, thermoelectric materials are capable of converting thermal energy into electrical energy, making them particularly useful for waste heat recovery or in environments with significant temperature differences[175].

When ambient energy is insufficient, energy storage devices become essential to maintain reliable operation of health monitoring systems. Critical factors in designing these devices include volume, weight, flexibility, safety, charge-discharge rate, and cycle life. For example, Li *et al.* demonstrated that zinc-ion batteries are highly suitable for textile applications due to their high theoretical capacity and low redox potential, making them effective for powering display modules[176]. In an intelligent health monitoring system, energy storage devices should be capable of working in tandem with energy harvesting systems to enable seamless transitions during periods of low energy supply.

Sensing module

The sensing module is designed to monitor various parameters related to physical health. Sensing fibers can be integrated into textiles to establish direct contact with the skin or other body parts. For textile-based pressure sensors, the working principle relies on the increased contact area between sensing fibers and electrode fibers, as well as the interactions between the sensor fibers themselves[177]. The contact and compression within and between the fibers lead to an increase in the conductive pathways, thereby enhancing the overall conductivity of the sensor. Additionally, the sensitivity of acoustic sensors to sound pressures and frequencies at various distances suggests the potential for harnessing energy from ambient noise and vibrations[178]. In addition, ultraviolet (UV)-sensitive textile electronics are mainly realized through materials that respond to UV exposure[179]. Temperature sensors can be created using temperature-sensitive materials as textile electrodes[180]. If the body's electrolyte balance, kidney function, or breath odor needs monitoring, sensors can be designed to detect biochemical signals related to liquids or gases[181,182].

Interconnections

Textile-based sensors require connection to other circuit elements, additional sensors, and/or data acquisition circuits to function effectively. Therefore, flexible or rigid interconnects and connectors are critical to ensuring the functionality and durability of the final monitoring system. Interconnects are conductive pathways that link various textile electronics within or between textiles. These pathways can be made from conductive fibers, tracks printed with conductive inks, or other forms of conductive materials[70]. Typical interconnects found in textile electronics that are suitable for textile-based sensors are conductive yarns[40]. Connectors are physical interfaces used to connect conductive pathways in textiles to rigid electronic components, such as integrated circuits (ICs) and sensors. These connectors provide a reliable electrical connection between the softness of the textile and the rigidity of the electronic components. Connectors can be categorized into three types: physical connections (such as soldering and welding)[31], mechanical connections (such as gripping, crimping, and sewing)[183], or connections using conductive adhesives (such as conductive epoxy)[184,185]. Moreover, the electrodes in textile electronics, often integrated as conductive fibers or yarns, play a crucial role in the detection, collection, and transmission of signals[186]. The synergistic integration of the various textile electronics, electrodes, interconnects and connectors holds great promise for realizing a comprehensive textile-based health monitoring system.

Data processing module

The data processing module serves as the central component of the health monitoring system. After capturing the initial sensing signals, a signal conditioning circuit that includes amplifiers, filters, and analog-to-digital converters (ADC) is utilized to process these signals. Subsequently, the processed data is transmitted to the microcontroller for further analysis and processing.

This module is underpinned by a suite of algorithms that leverage statistical analysis, machine learning, and other sophisticated data analysis techniques to enhance the accuracy and efficiency of health monitoring protocols. In textile-based health monitoring systems, machine learning provides a range of powerful data analysis techniques. Compared to traditional data processing methods, machine learning can handle datasets with high complexity and multiple variables, which is critical for processing extensive health monitoring data. Algorithms such as support vector machines (SVM), convolutional neural networks (CNN), K-nearest neighbors (KNN), and decision trees can make predictions about new, unseen data after undergoing training. Although the data processing module is crucial, it often receives less attention in the literature compared to the more prominent sensing modules. Table 1 summarizes several machine learning algorithms utilized in textile-based health monitoring systems, providing a reference for the future development and optimization of new algorithms.

Table 1. Some machine learning algorithms for healthcare monitoring systems

Textile	Sensor	Function	Machine learning models	Ref.
Fabric	Pressure sensor	Biometric gait recognition	SVM	[187]
Muscle pants	Stretch sensor	Human motion recognition	Random forest, neural network, SVM	[188]
Chest band	Stretch sensor	Talking detection	Random forest, neural network, linear discriminant analysis	[189]
Fabric	Gas sensor	Gas sensing identification	Machine learning-enabled principal component analysis	[190]
Vest	Triboelectric sensor	Sitting position recognition	Random forest	[191]
Cuff	Triboelectric Sensor	Cardiovascular monitoring	Neural network	[192]
Wristband, socks	Pressure sensor	Respiration and gait recognition	CNN	[193]
Garment	Polymer optical fiber sensor	Activity classification	KNN classifier	[194]
Knee covers, sleeves	Strain sensor	Human motion recognition	1D CNN	[195]

SVM: Support vector machines; CNN: convolutional neural networks; KNN: K-nearest neighbors.

Communication module

The function of the communication module is to realize the transmission and communication of health data. Communication modules can be categorized into two types based on transmission mode: wired and wireless. Wired communication modules, such as Ethernet, are ideal for scenarios demanding stable and high-speed data transfer. On the other hand, wireless communication modules, including Bluetooth, Wi-Fi, near field communication (NFC), and radio frequency identification, are suited for situations that call for mobility and flexibility in data transmission. Textile antennas, designed for the transmission and reception of radio waves, have garnered considerable research attention. To meet specific design requirements, the antenna's geometry and dimensions are developed using electromagnetic simulation software to predict the performance of the antenna[196]. Subsequently, the conductive material is applied to the substrate material using printing technology (such as screen printing or inkjet printing) or coating technology to create the antenna[197].

Display module

To present visual health management and analysis, the collected monitoring data is transmitted to an external display device, such as a smartphone or computer interface. In recent years, preliminary display fabrics have been realized. There are two approaches to fabricating textile displays. The first approach involves directly manufacturing thin-film light-emitting diodes (LEDs) onto the fabrics. For optimal LED performance, it is essential that the underlying substrate is extremely smooth. Consequently, a critical step is applying a polymer buffer layer to the textile's uneven surface through methods such as heat pressing or UV-induced photopolymerization[198,199]. Alternatively, light-emitting fibers can be created and then woven directly into the fabric to serve as displays[200,201]. The advancement of light-emitting fabrics for real-time health status display is anticipated to drive significant progress in health monitoring system development.

In summary, the design of all modules must consider compatibility, size, shape, and flexibility to facilitate their integration with textiles. The existing textile-based health monitoring systems still combine rigid and flexible components. Numerous challenges remain in the development of a fully textile-based health monitoring system.

APPLICATIONS OF TEXTILE ELECTRONICS IN HEALTH MONITORING

In health monitoring systems, textile electronics play an essential role, necessitating one or more such components. These fundamental components can be categorized into four types based on their functionality: sensors, displays, energy devices, and memory devices[160,202]. They are integrated with some commercial hardware and software to achieve a comprehensive health monitoring workflow. Notably, the applications introduced in this review are just a few emerging examples. The health monitoring systems based on textile electronics are rapidly evolving, and an increasing number of applications are expected to be developed. The integration of diagnostic and therapeutic capabilities in healthcare systems represents a future trend for the advancement of textile electronics.

Human motion monitoring

Currently, technologies for detecting human motion are predominantly divided into two principal categories: stationary and mobile monitoring. The stationary monitoring approach is contingent upon equipment positioned at designated sites, including depth cameras and far-infrared cameras. However, this approach has several limitations, including high costs, data accuracy, extensive data storage and processing, restricted monitoring range, and potential privacy concerns[14]. In contrast, mobile monitoring technologies facilitate the unrestricted movement of subjects within an environment, typically employing wearable sensing systems. In these systems, the application of textile electronics is revolutionizing the way of human motion monitoring. These intelligent textile electronics demonstrate high sensitivity to minute variations in tension or pressure. Moreover, they can be custom-tailored into various configurations and dimensions to meet the diverse requirements of human motion monitoring[203]. In human motion monitoring systems, textile electronics are integrated into the seams of garments to capture the movements of the limbs (such as the knees or elbows), and they can also be positioned on the dorsal region to monitor spinal posture and upper body position[191,204,205].

For instance, to motivate individuals with obesity or cardiovascular conditions to engage in increased physical activity, the development of lightweight and comfortable sensing textiles is imperative. These smart textiles can monitor their daily activity levels, providing a means to track progress and encourage a more active lifestyle[206]. Regarding Parkinson’s disease, although a complete cure is not possible, active treatment and management can help patients maintain a good quality of life and work capacity[207]. Precise measurement of their movements is crucial for assessing the effectiveness of treatment. By monitoring specific motion patterns, physicians can better understand the patient’s condition and adjust the treatment plan accordingly.

In clinical monitoring applications, textile electronics designed for human motion monitoring are integrated with motion analysis algorithms. In 2020, Lin *et al.* developed an innovative near-field responsive sensing network by integrating near-field relays, commercial NFC tags, wireless battery-free temperature and strain sensors, conductive threads, connections using conductive epoxy (CW2460, Chemtronics), and wireless readers[208]. This state-of-the-art wireless garment enables the real-time assessment of spinal posture and the continuous monitoring of body temperature and gait during the exercise period. In 2022, Jiang *et al.* used machine learning algorithms for the design of a self-powered posture monitoring vest (SPMV) integrating conductive fibers, nylon yarns, sensor array [triboelectric nanogenerators (TENGs)] with protection layer[191]. In addition, a step motor for periodic contact-separation movement and LabView and Python software platforms for real-time data processing are applied. Precise, real-time posture recognition and correction are achieved using the SPMV. Besides, the deployment of a random forest classifier has yielded an impressive accuracy rate of 96.6%, surpassing the accuracy of logistic regression and decision tree classifiers. In 2023, the same research group developed a self-powered multi-point body motion sensing network (SMN) based on a fully textile structure, enhancing pressure response sensitivity and breathability [Figure 6A][187]. Similar to their previous study, the body motion sensing system consists of a sensing fabric, a linear motor, and a human-computer interface platform based on LabView software. The sensing fabric was fabricated using Ag-polyethylene core-sheath composite yarns through 3D knitting techniques,

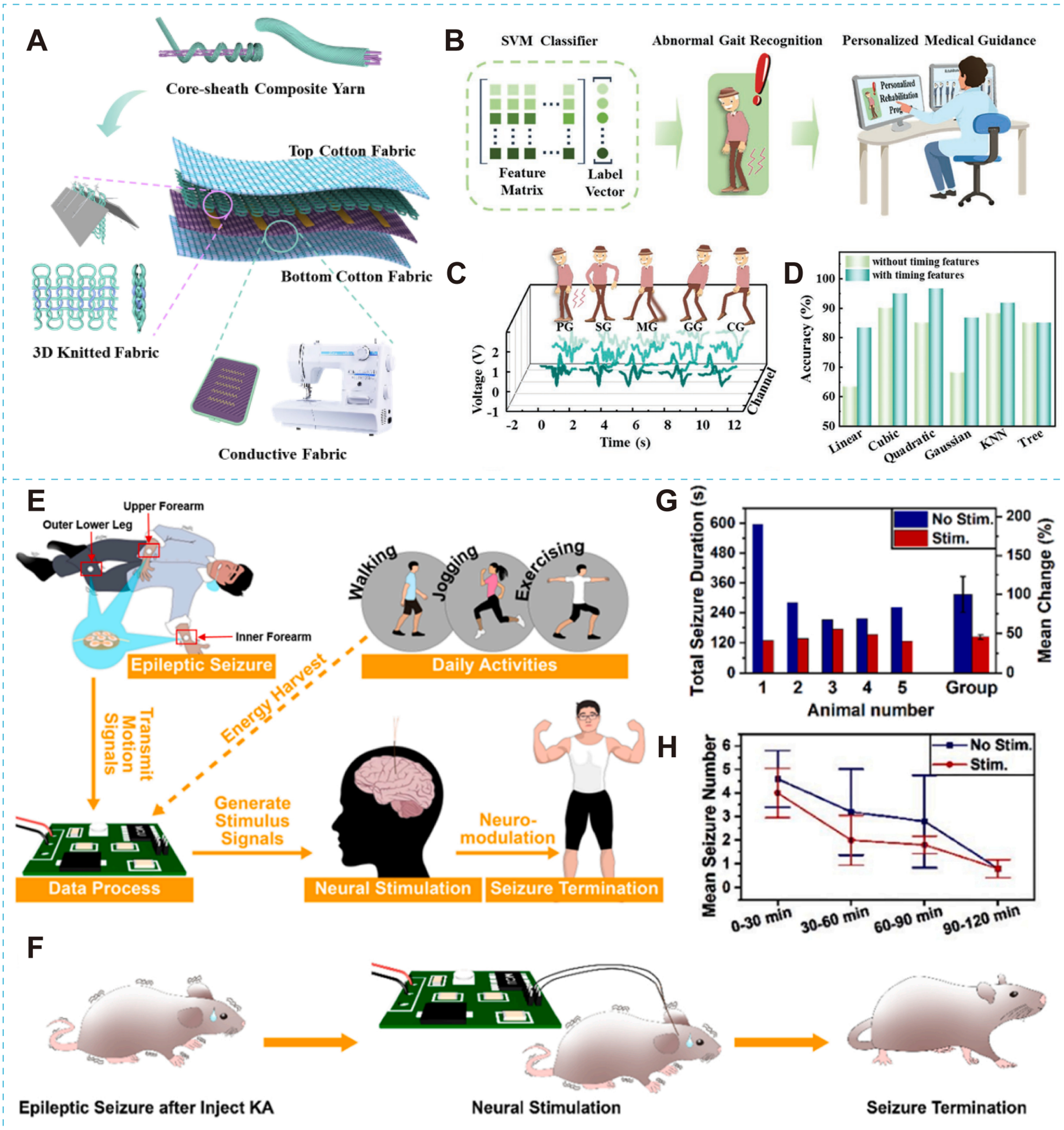

Figure 6. (A) The structure of SMN for body motion sensing. The sensitivity of the SMN is 1.56 V·kPa^{-1} under pressure below 2 kPa; (B) SVM classifier for gait recognition and auxiliary rehabilitation training; (C) Multi-channel test results of five deformed gaits containing PG, SG, MG, GG, and CG; (D) Classification accuracy of five gaits using different machine learning algorithms[187]. Reprinted with permission. Copyright 2023, John Wiley and Sons; (E) The working process of an epilepsy treatment system; (F) *In vivo* experiment to relieve epileptic seizures in mice; (G) Total epileptic seizure duration under two conditions; (H) The mean epileptic seizure number during 0-120 min under two conditions[210]. Reprinted with permission. Copyright 2023, Elsevier. SMN: Self-powered multi-point body motion sensing network; SVM: support vector machines; PG: Parkinson's gait; SG: scissors gait; MG: mopping gait; GG: gluteus maximus gait; CG: cross-threshold gait.

ensuring each sensing node exhibits high linear sensitivity to pressure. Additionally, a SVM algorithm was integrated into the SMN for processing the sensory data [Figure 6B]. By analyzing the time series and dynamic parameters of five deformed gaits [Figure 6C], gait recognition and classification with an accuracy rate of 96.7% are effectively achieved [Figure 6D]. Constructing a real-time human-computer interaction platform based on the SMN holds the potential to assist in the diagnosis of neurological disorders, such as Parkinson's disease and dystonia.

In everyday scenarios, human limbs may exhibit vibrations at approximately 1-3 Hz, whereas epileptic seizures are characterized by vibrations at varying frequencies, reaching up to 7 Hz[209]. Therefore, it is possible to distinguish between the signals of normal movement and epileptic seizures by analyzing the frequencies associated with different human behaviors. A self-powered, wearable epilepsy monitoring system for potential epilepsy treatment is shown in Figure 6E[210]. This system is capable of real-time monitoring of human motions and delivering neural stimulation signals to mitigate epileptic seizures. In this system, the energy harvesting module converts mechanical energy generated from human motions into electrical energy, with the rectifier subsequently charging the capacitors. The motion detection sensor detects subtle human motions and transmits signals to the data processing center. The data processing center can identify epileptic seizures and generate neural stimulation signals. As shown in Figure 6F, the system operation successfully suppressed the epilepsy of the mouse. By stimulating the dentate gyrus of the mouse with a stimulation electrode, the total duration of epileptic seizures in the mouse can be reduced by 40%-50% [Figure 6G and H].

The research findings highlighted the potential of merging textile electronics for human motion monitoring. With the assistance of AI algorithms, a motion monitoring system based on textile electronics is equipped to offer personalized health advice and exercise prescriptions to individuals.

Physiological monitoring

Textile electronics have revolutionized the conventional rigid design of physiological monitoring devices, enabling the development of textile electronics that provide real-time, continuous, non-invasive, and comfortable monitoring of vital physiological signals[211]. These devices stand out for their efficacy in monitoring chronic conditions, including cardiovascular diseases and diabetes[192,212]. To intuitively understand the applications of textile electronics in physiological monitoring over the past five years, Table 2 presents a comprehensive overview of physiological monitoring devices with the materials employed, the fabrication techniques utilized, the product developments realized, and the monitoring locations.

ECG represents a medical diagnostic technique designed to capture the electrical activity of the heart. Unlike the mechanical vibration sensing of acoustic sensors, ECG sensing is adept at detecting alterations in the action potentials of cardiomyocytes. The integration of textile electrodes has become the cornerstone for ECG monitoring, allowing for a more comfortable and continuous assessment of cardiac activity. In an early study[229], emulating the traditional Yuzen dyeing technique of Japanese kimono, researchers employed PDMS as a template to directly imprint conductive polymer patterns of PEDOT:PSS onto textiles, as illustrated in Figure 7A. The textile electrodes were utilized for ECG recordings with the SandsResearch system (EA68 or EA136 amplifiers) and a data processing module (LabView software). The realization of the precise tracking of cardiac activity in motion [Figure 7B] and good stability in ambient air [Figure 7C] represents a significant development to textile electronics for ECG monitoring applications.

EMG signals are typically acquired from the arms or legs [Table 2]. For instance, muscle activity monitoring using a leg sleeve for detecting EMG signals is illustrated in Figure 7D[230]. For EMG recordings, the textile electrodes and reference electrodes were connected to a wireless EMG acquisition system that included a wireless transmitter and a BIOPAC system with a wireless receiver. Then, the results were shown on the user terminal through an Ethernet connection. Moreover, an investigation into embroidery techniques for

Table 2. Summary of representative physiological monitoring devices in the past five years with materials, preparation methods, products and monitoring location

Signals	Materials/components	Fabrication	Products	Monitoring location	SEI	SNR/sensitivity	Ref.
ECG	Ag-plated fibers	Electrostatic flocking	T-shirt	Chest	A few hundred k Ω at 100 Hz and 1,000 Pa	/	[213]
ECG	Ag/M-PETF	Electroless deposition	T-shirt	Chest	/	/	[214]
ECG	Ag/AgCl	Screen printing	Polyester fabric	Hand and leg	A few hundred Ω within 100 Hz	/	[215]
ECG/EMG	rGO, sericin, water retention polymer	Knitting	Sports undergarment, sleeve	RA, RL, LL	24 kΩ at 1,000 Hz	35-40 dB at pH = 4.3	[216]
ECG	Fabink-TC-C4001, MOS TitanRF	Screen printing	Mattress	Back	~200 kΩ at 10Hz; 50 kΩ at 100-1,000 Hz	-40 dB	[217]
EMG	Graphene	Dip-coating	Sleeve	Arms and legs	~90 kΩ at 1-5 Hz	19.23 dB	[218]
EMG	PEDOT:PSS	Screen printing	Sleeve	Legs	3-20 kΩ at 30 Hz	/	[219]
EEG	Ag flakes/SIS	Screen printing	Headband	Forehead	< 10 kΩ	-32.7 dB	[220]
EEG	Ag	Knitting	Cap	Head	5-30 kΩ at 0.1-30 Hz	33.6 dB	[221]
EOG	Graphene	Dip-coating	Headband	Forehead	/	/	[183]
ECG/EOG	LIG, AgCl, carbon inks	Screen printing	Fabric	Forehead	~700 Ω at 0.1-500 Hz	/	[222]
EEG/EOG	Ag	Knitting	Headband	Forehead	/	/	[223]
Temperature	Polycarbonate, battery, thermistors	Thermal drawing	Digital fiber, T-shirt	Body	/	/	[224]
Temperature	PEDOT:PSS, PU/graphene	Wet spinning, weaving	Fabric	Arm	/	-1.72%/°C	[225]
Temperature	Thermal-sensitive ink PDMS	Etching, coating	Fabric	Lower limb	/	62.3 V/K	[226]
Respiratory Rate	Functional yarns	Wrapping	Mask	Face	/	82.4 pF/% RH	[227]
Respiratory Rate	Ag NPs	Drop casting	Chest strap	Chest	/	0.043	[228]

SEI: Skin-electrode impedance; SNR: signal-to-noise ratio; ECG: electrocardiograms; M-PETF: modified polyester fabric; EMG: electromyography; rGO: reduced graphene oxide; RA: right arm; RL: right leg; LL: left leg; Fabink-TC-C4001: silver conductive polymer ink; MOS TitanRF: self-adhesive conductive textile fabric; PEDOT:PSS: poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate); EEG: electroencephalographic; SIS: styrene-isoprene-styrene; EOG: electrooculogram; LIG: laser induced graphene; PU: polyurethane; PDMS: polydimethylsiloxane; RH: relative humidity; NPs: nano-particles.

textile electrodes found that the moss stitch method produced a lower skin-electrode impedance (SEI) than the lock stitch method. SEI, or the resistance at the skin-electrode interface, is crucial for efficient signal transmission and high accuracy, which is mainly reflected in the signal-to-noise ratio (SNR). Thus, the moss stitch method enhances reliable EMG signal acquisition.

Electroencephalographic (EEG) signals capture the electrical activity of the brain, playing a crucial role in the diagnosis of neurological disorders such as epilepsy, sleep disorders, and brain injury. Tseghai *et al.* developed washable and flexible textile electrodes for detecting EEG signals emanating from cerebral activity[231]. The textile electrodes demonstrate lower SEI compared to conventional Ag/AgCl dry electrodes after three minutes [Figure 7E] due to sweat permeating the textile, rendering them highly suitable for long-term EEG monitoring applications. In Figure 7F, three textile electrodes and two reference electrodes are

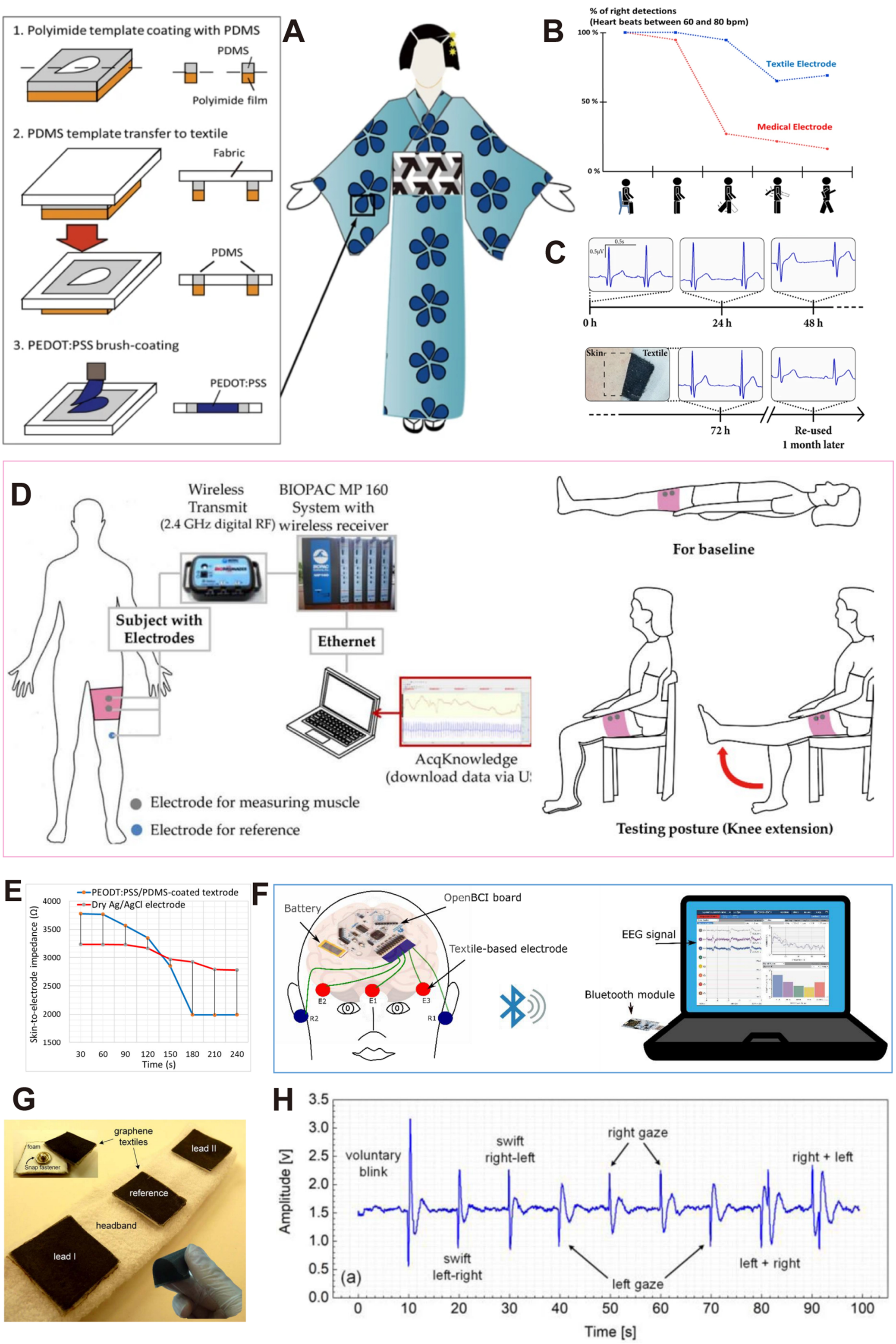

Figure 7. (A) Process of PEDOT:PSS coating on textiles; (B) Percentage of accuracy of heartbeat detection for five human behaviors; (C) Evolution of ECG signals over time[229]. Reprinted with permission. Copyright 2015, Springer Nature; (D) Schematic illustration of the measuring process for EMG signals and the testing postures[230]. Reprinted with permission. Copyright 2023, Springer Nature; (E) Skin-to-electrode impedance condition of different EEG electrodes over time; (F) Schematic illustration of the EEG measurement system [231]. Reprinted with permission. Copyright 2021, IEEE; (G) Photograph of an EOG headband; (H) EOG trace showing the

different types of eye movement[183].Reprinted with permission. Copyright 2019, IOP Science. PEDOT:PSS: Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate); ECG: electrocardiograms; EMG: electromyography; EEG: electroencephalographic; EOG: electrooculogram.

connected to a battery and an OpenBCI board to record EEG waveforms. The EEG signals are then displayed on a laptop using the OpenBCI GUI software via a Bluetooth module. Notably, these textile electrodes enable skin contact without the requirement for conductive gels and exhibit robust stability in EEG signal acquisition, even following multiple wash cycles and bending.

Electrooculogram (EOG) records the electrical activity linked to eye movements, serving as a valuable diagnostic tool for investigating the visual system and analyzing sleep patterns. As shown in Figure 7G, a smart headband using graphene is used for EOG signal monitoring. The graphene textile electrodes are secured in an elastic headband with adhesive foams by a metallic snap fastener. The EOG-based human-computer interaction interface is obtained by a front-end readout circuit and a smart headband for signal acquisition, a microcontroller unit for processing signals, and a laptop computer for display. Furthermore, an automated algorithm has been developed to detect and classify ocular movements [Figure 7H]. The integration of the algorithm with the bright headband has expanded its applications in human-computer interaction and human-machine interfaces, achieving impressive recognition accuracies ranging from 85% to 100%.

Additionally, variations in human body temperature are indicative of metabolic activity and can reflect pathophysiological information[226,232]. Zhang *et al.* fabricated a thermosensitive micro/nanoporous fiber with an unprecedented high thermal sensitivity (β = 4,994.55 K, α = -5.58%/K at 26 °C) and the fastest response/recovery times (97/239 ms) recorded for textile-based temperature sensors[233]. The fiber was achieved by growing $Fe_2(MoO_4)_3$ nanostructures on graphene using a wet spinning method. Compared to the conventional direct mixing of $Fe_2(MoO_4)_3$ and graphene, the fibers produced by this method exhibit enhanced thermal sensing performance. The core thermoresistive micro/nanoporous fiber strand acts as both the temperature sensor and the working electrode of the textile TENG. The output signals are displayed on a mobile phone screen through a wireless system that includes an analog-to-digital conversion module, Bluetooth, and an accompanying app. Ultimately, real-time wireless monitoring of body temperature and pulse is achieved through textile electronics.

Respiratory rate, a vital sign, varies with age, health status, and activity levels. Anomalies in respiratory rate could be symptomatic of various conditions, including cardiac, pulmonary, metabolic disorders, or infections[234]. In respiratory rate monitoring systems, the humidity sensors[227] and pressure sensors[235] are fundamental and critical components. For instance, Lin *et al.* developed a pressure sensor based on ultrasoft helical functional fibers, demonstrating high sensitivity (1.726 V/N) and rapid response time (20 ms)[236]. They have successfully developed a real-time respiratory monitoring system, which includes a pressure sensor, an analog-to-digital conversion module, and a signal processing unit, and utilizes LabView software for further data processing. The system can continuously record vital parameters such as respiratory intensity, frequency, and intervals.

Biochemical monitoring

Sweat, as a biological fluid, provides a wealth of health-related biomarkers[237-239]. The rapid production and renewal rate of sweat implies that it can provide nearly real-time information on physiological status[240]. Therefore, long-term continuous monitoring of sweat can help track the trend of individual health status changes and detect abnormalities in time.

Recently, Li *et al.* developed a Janus nanoprocessed electronic textile (JNET) for comfortable sweat monitoring[241]. By combining radiative cooling with moisture-wicking capabilities, substantial enhancements in wearing comfort have been realized [Figure 8A]. The structure of JNET, as shown in Figure 8B, involves weaving different fiber sensors to detect various substances in sweat. The novel integration of the optimized substrate and sensing fibers ensures a comfortable physiological microenvironment for sweat monitoring under sweating and hot conditions. Compared with traditional fabrics, experimental results have shown that Janus nanoprocessed silk (JNPS) achieves significant cooling effects and reduces skin surface humidity [Figure 8C]. Figure 8D demonstrates that the textile electronics can simultaneously detect pH, uric acid (UA), and Na^+ biomarkers. In practical applications, the JNET is connected to a printed circuit board (PCB) via fiber electrodes. The PCB primarily consists of an MS02 chip, Bluetooth module, power supply, and other functional modules, enabling the real-time wireless transmission of sensing signals to be displayed on a smartphone [Figure 8D].

Additionally, cortisol can be detected in sweat, correlating with the stress levels experienced by individuals. Hu *et al.* developed textile electronics based on CNT fibers for populations troubled by depression[49]. In the research, Prussian blue as an oxidation-reduction probe was deposited onto molecularly imprinted polymers (MIP) to directly detect cortisol upon contact with sweat. As shown in Figure 8E, the textile includes three functional fibers. MIP/CNT fiber serves as the working electrode, while Ag/AgCl/CNT fiber and Pt/CNT fiber act as the reference and counter electrodes, respectively. Then, the integrated textile electronics and other modules of a complete sweat monitoring system are illustrated in Figure 8F. The sweat sensor converts variations in cortisol concentration into electrical signals, which are subsequently transmitted to the flexible PCB for data processing. These signals are amplified, filtered, and converted into readable data, and then sent to the display module via a wireless module (such as Bluetooth). Users can view real-time monitoring reports of cortisol through the user interface (UI). An application scenario of real-time stress management is shown in Figure 8G. After the stress test, the cortisol levels of participants gradually decrease. If participants exercise, their cortisol levels will also decrease after exercise.

Multifunctional health monitoring system

Conventional health monitoring systems with single-function monitoring are inadequate for some special situations, such as pregnancy and sleep monitoring that necessitate simultaneous tracking of various human motions and physiological signals[44,226]. Hence, the necessity for multifunctional health monitoring systems arises to meet the intricate demands of such scenarios[242-244]. In this section, a multifunctional health monitoring system for sleep monitoring as an example is discussed.

Lin *et al.* developed a smart mattress based on pressure-sensitive TENG arrays for real-time monitoring of sleep behaviors[42]. The smart mattress is constructed with conductive fibers and elastic materials, exhibiting high sensitivity, rapid response time, durability, and waterproof performance. The configuration of the sensor array is illustrated in Figure 9A, with individual addressing for each TENG unit. The conductive fibers are linked to the signal amplifier via the row/column data bus. The amplified signals are subsequently transmitted to the analog multiplexer and then fed into the ADC The microcontroller receives the digital signals from theADC for further processing. As the scanning progresses from the first row to the *i*th column, an $i \times j$ pressure image is constructed. This sequence of images forms a continuous data stream, which is subsequently transmitted to an external device such as a medical terminal or a personal mobile phone via the Bluetooth module.

When a user lies on the smart mattress, the body posture, position, and pressure distribution can be visualized on the graphical UI, as shown in Figure 9B. Figure 9C illustrates the distribution of pressure

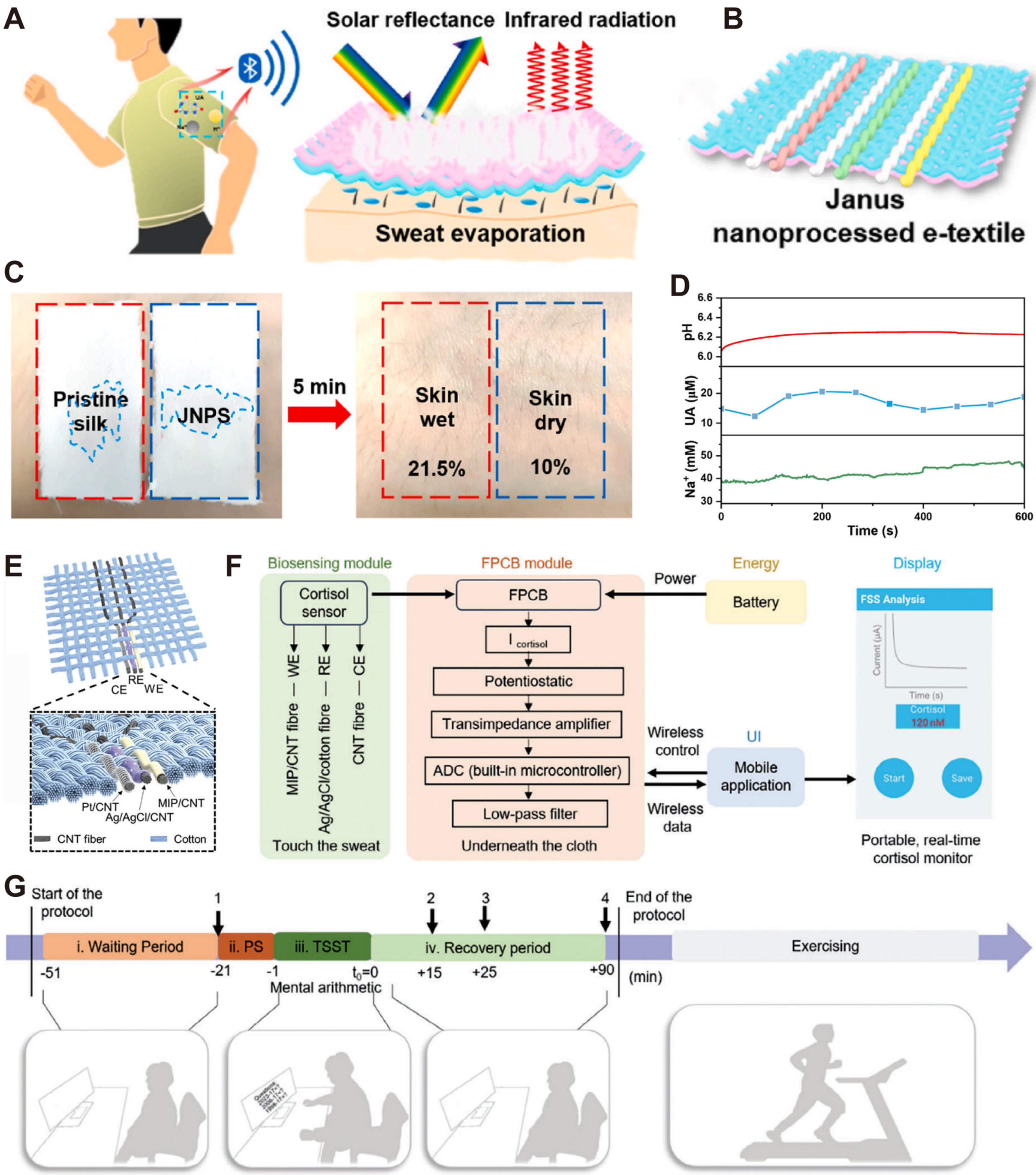

Figure 8. (A) JNET with function of radiative cooling and anisotropic wettability; (B) The JNET is fabricated by different functional fibers and exhibits high sensitivity: 81.03 mV·pH^{-1} for pH, 0.08 μA/μM for UA, and 108.93 mV/decade for Na^+; (C) Comparison of hygroscopic properties between pristine silk and JNPS; (D) The results of real-time sweat monitoring by JNET[241]. Reprinted with permission. Copyright 2023, Elsevier; (E) Schematic illustration of a fabric sensor for cortisol monitoring, with a detection limit of 1 pM for cortisol; (F) Design of an integrated system containing a biosensing module, FPCB module, Energy module and display module; (G) Different stages of stress monitoring and management[49]. Reprinted with permission. Copyright 2024, John Wiley and Sons. JNET: Janus nanoprocessed electronic textile; UA: uric acid; JNPS: Janus nanoprocessed silk; FPCB: flexible printed circuit board.

values for a sleeper throughout the night, indicating the sleep quality. In addition to sleep monitoring, the intelligent textile can serve as a fall warning system for the elderly or patients. If an elder or patient falls

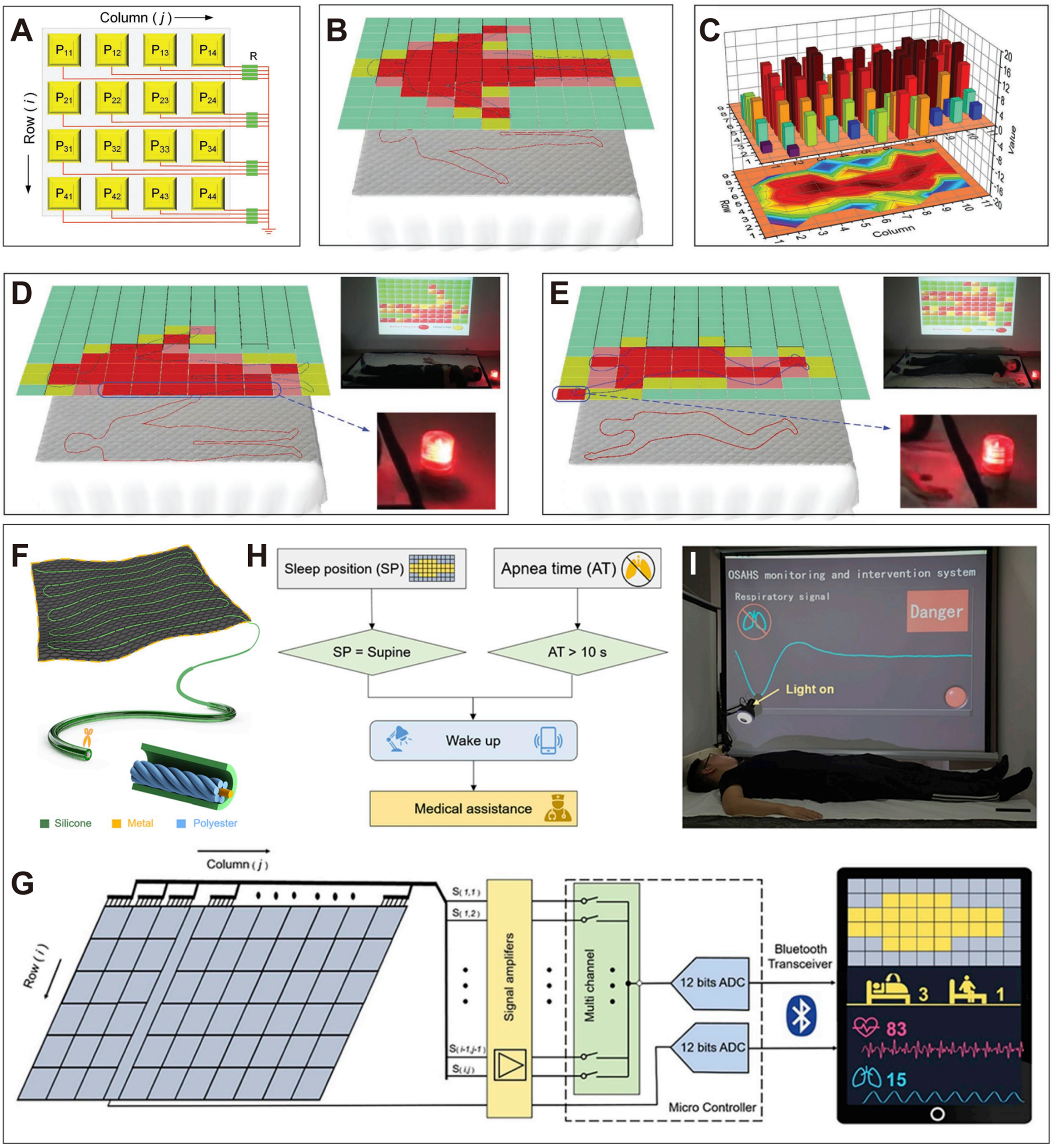

Figure 9. (A) Multi-channel data acquisition system for sleep state monitoring. One pixel corresponds to one TENG unit with a pressure sensitivity of 0.77 V·Pa^{-1}; (B) The UI showing sleep states information including posture, position, and pressure distribution; (C) The diagram showing the press number distribution of a sleeper throughout the night; (D) Automatic warning function of smart bedsheet; (E) Auxiliary warning function of smart bedsheet[42]. Reprinted with permission. Copyright 2017, John Wiley and Sons; (F) Schematic illustration of a smart bedsheet integrated functional fibers with a high sensitivity of 10.79 mV·Pa^{-1}; (G) Design of an integrated system containing sensing array, signal amplifiers, multi-channel processing, ADC, Bluetooth transmitter, and mobile terminal; (H) The flowchart of the obstructive sleep apnea-hypopnea syndrome monitoring and intervention system; (I) Photograph showing the patient is awakened by the system in abnormal situations[243]. Reprinted with permission. Copyright 2020, Elsevier. TENG: Triboelectric nanogenerator; UI: user interface; ADC: analog-to-digital converters.

from the bed, signals from five TENGs along the edge of the mattress are sent to a computer or mobile terminal, triggering an alarm signal [Figure 9D]. Besides, they can autonomously call for help by touching the TENG in the upper left corner of the mattress when experiencing discomfort, thereby alerting family members or healthcare professionals [Figure 9E]. These advancements carry significant implications for remote healthcare.

However, multi-layered electronic fabrics can increase the weight of the detection system. Recently, the same group optimized the textile electronics. They first prepared a single functional fiber, and then multiple fibers were woven into a black textile substrate with a serpentine structure design, ultimately creating a single-layer, ultra-soft intelligent bedsheet [Figure 9F]. The operation of the monitoring system is shown in Figure 9G. Similar to their previous study, the pressure signals generated by each sensing unit are independently addressable and can be recorded through a customized multi-channel data acquisition circuit. After analog-to-digital conversion, the electric signals are transmitted to a mobile terminal via Bluetooth. The real-time images of sleep postures and various physiological signals are shown on mobile terminal displays.

Furthermore, the group also designed an obstructive sleep apnea-hypopnea syndrome monitoring and intervention system and demonstrated its reliability [Figure 9H]. In cases where the apnea duration exceeds a predetermined threshold, an alarm is activated immediately [Figure 9I]. Compared with their previous study, this monitoring system has demonstrated advancements in enhancing monitoring accuracy, broadening the scope of surveillance, and improving user comfort. In addition to tracking sleep posture and behavior, it has further expanded to include the monitoring of respiratory rate and heart rate.

INTEGRATION OF TEXTILE HEALTH MONITORING SYSTEM

Integration strategies

If fiber- or yarn-based sensors and LEDs are employed in the sensor module and display module, they can form multiple sensing and display pixels through the previously described five textile structures. However, if other flexible electronic devices are integrated into textiles, two connection steps require attention: the mechanical connection with the textile material and the electrical connection integrated into the conductive structure. Both connections must be functionally reliable. The mechanical connection involves securely attaching electronic components to the textile, considering the stability and durability of the connection while ensuring the softness and comfort of the textile. Mechanical connections can be achieved through sewing, adhesive bonding, or other textile processing techniques, similar to traditional ICs and multifunctional devices on two-dimensional wafers. Currently, limitations on scaling down and challenges in electronic circuit configuration remain significant obstacles.

Recently, Hwang *et al.* proposed a technology for integrating electronic devices such as transistors, inverters, ring oscillators, and thermocouples onto the outer surface of a one-dimensional microfiber substrate, as shown in Figure 10A[245]. Using capillary-assisted coating methods and high-resolution maskless lithography techniques, multiple micro-devices can be rapidly integrated onto a very narrow and thin fiber surface. Subsequent evaluations of the electronic characteristics of the micro-devices on the fiber included assessments of switching and data processing capabilities, as well as units for sensing or converting light and thermal signals. Test results indicate that this mechanical connection technology provides the device with good stability and flexibility, presenting a viable strategy for manufacturing high-density electronic microfibers.

Notably, while functional fiber assembly has advanced, current wireless modules and microelectronics still rely on silicon chips and batteries, which are bulky and rigid, adversely affecting textile functionality and comfort. Yang *et al.* addressed this challenge by proposing a human body coupling energy interaction

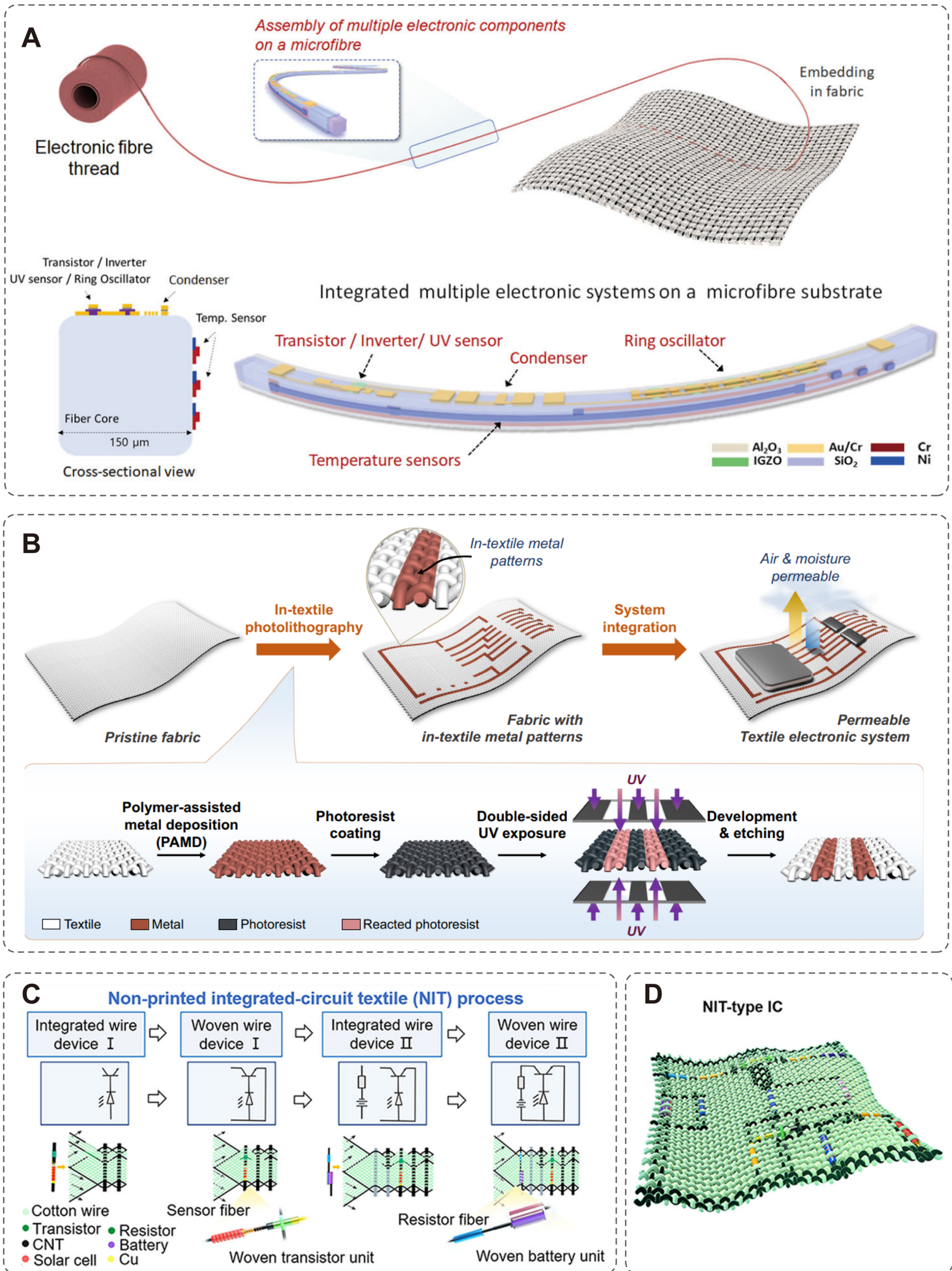

Figure 10. (A) Integration of multiple electronic components on a microfiber[245]. Reprinted with permission. Copyright 2022, Springer Nature; (B) The process of in-textile photolithography technology[247]. Reprinted with permission. Copyright 2024, Springer Nature; (C and D) The process of NIT and NIT-type IC[51]. Reprinted with permission. Copyright 2021, Springer Nature. NIT: Non-printed integrated-circuit textile; IC: integrated circuit.

mechanism for smart fibers, enabling wireless signal transmission via environmental electromagnetic energy[246]. By integrating an electrostatic-sensitive photoelectric medium, these fibers consolidate sensing and actuation, allowing for light-emitting displays and touch interaction without the need for chips or batteries, thereby offering a novel integration strategy for textile health monitoring systems.

To establish electrical connections in textiles, PCBs play a crucial role. Over the past two years, Wang *et al.* have reported innovative fabrication methods for creating circuit patterns on textiles, specifically double-sided photolithography technology and in-textile photolithography technology[247]. The latter represents an optimization of the former, enabling the fabrication of finer metal patterns (sub-100 μm) that can penetrate the interior of the textiles. This advancement maintains the three-dimensional porous structure of the textiles, thereby preserving their breathability and comfort [Figure 10B]. The optimized circuit patterns have been utilized to construct a multiplex sweat sensing system fully integrated into the textile framework, successfully monitoring physiological signals.

Additionally, Yang *et al.* prepared a non-printed integrated-circuit textile (NIT) for biomedical and therapeutic diagnostic applications[51]. This system comprises devices such as transistors, sensors, diodes, solar cells, and batteries, all constructed in the form of fibers or crossover nodes [Figure 10C]. These devices are woven into a deformable textile IC [Figure 10D]. The NIT employs fiber-based transistors for logic operations, incorporates various sensors for health and environmental monitoring, and integrates photovoltaic and battery fibers for self-powered energy. Wireless data transmission is facilitated via infrared or advanced communication fibers. The NIT represents a fully self-powered, wearable monitoring system, simulating an AI "nurse" for health oversight and emergency assistance. This non-printing approach offers a novel manufacturing process distinct from traditional PCBs, promising for future wearables and personalized healthcare.

Security and reliability of the components

The safety of textile-based health monitoring systems encompasses two primary aspects: human safety and environmental friendliness, as well as data security and privacy protection. Given that health monitoring devices are intended for integration on the human body or even for implantation, the functional fibers and fabrics must be non-toxic and harmless at a cellular level. Materials that are green, harmless, and environmentally friendly should be prioritized. Devices implanted in biological tissues must exhibit excellent biocompatibility to prevent scarring and inflammation.

In the data processing module, UI, and software, devices should undergo regular calibration to maintain data accuracy. In accordance with data protection regulations, such as the General Data Protection Regulation[248], personal health information should be encrypted for storage and transmission. Access control measures should be implemented to ensure that only authorized users can access sensitive data. To guard against cyber-attacks, firewalls and intrusion detection systems should be employed to enhance data security.

As textile electronics continue to evolve, future health monitoring systems are expected to develop into more powerful telemedicine solutions and smart wards. Therefore, for systems closely linked to medical care, the entire system design must comply with the safety and reliability standards of medical devices, such as obtaining Food and Drug Administration (FDA) approval[249].

CONCLUSION AND OUTLOOK

Textile electronics hold substantial potential for development in the field of wearable health monitoring. This review provides an overview of the materials and fabrication methods associated with textile electronics. Key design strategies for developing textile-based health monitoring systems are discussed. Furthermore, the applications of textile electronics in ubiquitous health monitoring are also introduced, including human motion monitoring, physiological monitoring, biochemical monitoring, and multifunctional monitoring. Moreover, current strategies for integrating health monitoring systems are explored, along with the security and reliability of their components. Despite the significant advancements made in textile-based health monitoring systems over the past two decades, considerable challenges remain to be addressed, spanning from material selection to system integration and eventual commercialization.

Performance improvement

In the development of textile electronics, active substances are typically endowed with specific functions through deposition onto textile substrates or polymer fibers. However, material compatibility issues may result in weak interactions at the interface between these active substances and their carriers, leading to a tendency for the active substances to detach under mechanical stress such as bending, stretching, or washing. This detachment adversely affects the operational stability of textile electronics. To enhance stability and durability, comprehensive optimization of material selection, fabrication processes, and textile structures is essential. For instance, improving coating techniques or utilizing more compatible binders can strengthen adhesion between active substances and fiber substrates, thereby enhancing the reliability of textile electronics during prolonged use. Additionally, the stability of energy storage fibers warrants attention, as passivation of electrode surfaces and biological contamination can lead to erroneous operational responses.

Integration

The integration of textile electronics is a pivotal step in achieving a multifunctional and efficient health monitoring system. Through integration, a variety of functionalities such as energy harvesting, signal processing, data storage, and wireless communication can be realized on a compact and wearable platform. Reliable connection technologies and textile-compatible ICs contribute significantly to the high degree of integration within electronic textiles. Although some integration technologies have been discussed in previous sections, there remains substantial room for improvement in the current level of integration compared to the demands of practical applications. Therefore, developing more effective integration strategies is essential for achieving high-performance textile electronics.

Large-scale fabrications

Industry reports indicate that numerous enterprises have developed a variety of smart textile electronics. Examples include Sergers heat socks designed for alpine skiing, Skin brand underwear capable of recording real-time heart rate, resting heart rate, and heart rate variability, and Siren’s washable smart socks tailored for individuals with diabetes. However, the manufacturing of these electronic textile products remains largely confined to laboratory settings. To facilitate commercial application, a transition to industrial-scale production is imperative. This transition necessitates not only the development of manufacturing technologies suitable for mass production but also considerations of cost-effectiveness. Laboratory-level manufacturing often fails to meet the cost and efficiency demands of large-scale production. Industrial manufacturing must address issues such as automation, standardization, and quality control. Additionally, the development of textile machinery adapted for functional fibers is crucial for realizing mass production. For instance, traditional textile machinery may require modification or redesign to accommodate the production of new types of textile electronics.

Health delivery

From a user-centric perspective, textile electronics must be sufficiently resilient to withstand regular use, including daily wear and washing, and yet remain comfortable and unobtrusive for patients. Therefore, standardized guidelines for the deployment and maintenance of these systems are essential. For these devices to be widely adopted in healthcare, they must comply with regulatory standards for medical devices, such as those established by the FDA. Furthermore, user adoption plays a crucial role in health delivery effectiveness. Patients may require training on proper use and maintenance of these wearable textiles, and healthcare providers must adapt to new patient data streams generated by these systems. Addressing these challenges can contribute significantly to improved patient outcomes and the efficient delivery of care resources.

To sum up, the advancement of textile electronics necessitates collaborative efforts from researchers across multiple disciplines, including materials science, textile engineering, electronic engineering, and biomedical engineering. By consistently overcoming pivotal material and technical challenges, future textile electronics will possess the capacity to integrate diverse functionalities and establish a closed-loop medical care system that delivers personalized, real-time, and comprehensive health management services. This progress not only fosters innovation in the healthcare sector but also enhances convenience and well-being in the daily lives of individuals.

DECLARATIONS

Authors' contributions

Wrote the original draft: Huang FC

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Availability of data and materials

Not applicable.

Financial support and sponsorship

This work was supported by the National Key Research and Development Program of China under Grant 2021YFA1401100 and the National Natural Science Foundation of China under Grant 61825403 and 61921005.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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