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Multimodal electronic textiles for intelligent human-machine interfaces

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Abstract

Smart wearable electronic devices capable of information exchanging (such as human-machine interfaces) have developed into key carriers for the interconnection, intercommunication, and interaction between humans and machines. Multimodal electronic textiles that incorporate multifunctional sensors into daily clothing are an emerging technology to realize smart wearable electronics. This has greatly advanced human-machine interface technology by bridging the gap between wearing comfort and traditional wearable electronic devices, which will facilitate the rapid development and wide application of natural human-machine interfaces. In this article, we provide a comprehensive summary of the latest research progress on multimodal electronic textiles for intelligent human-machine interfaces. Firstly, we introduce the most representative electronic textile manufacturing strategies in terms of functional fiber preparation and multimodal textile forming. Then, we explore the multifunctional sensing capability of multimodal electronic textiles and emphasize their advanced applications in intelligent human-machine interfaces. Finally, we present new insights on the future research directions and the challenges faced in practical applications of multimodal electronic textiles.

Keywords: Electronic textiles, multimodal sensing, human-machine interfaces, intelligent applications

INTRODUCTION

Driven by the Fourth Industrial Revolution represented by intelligent technology, the fields of artificial intelligence, the Internet of Things (IoT), big data, and 5G information technology have ushered in a stage of vigorous development[1-3]. The intelligent interconnection between humans and machines is the foundation and key to the progress of today's era[4-7]. Therefore, the human-machine interface, as an information exchange interface between humans and machines, has become a technology that is now in urgent need of development and is expected to provide a new interactive experience[8-12]. Wearable electronic devices have been proven to be a very effective way to realize the human-machine interface, i.e., the important medium for connecting people to intelligent machines and the key carrier for interconnecting people and everything, which have become a research hotspot in academia and industry[13-18]. Wearable electronic devices that emphasize close human-machine interaction and collaboration have emerged in large numbers to help people achieve the ultimate goal of combining human intelligence with machine intelligence[19-21]. However, they are often limited by issues such as uncomfortable wearing, inconvenience of portability, and poor skin fitting, which leaves a clear boundary in the practical use of human-machine interfaces. The emergence of smart textiles that integrate electronic devices into textiles can effectively solve the shortcomings of other wearable electronic devices. By virtue of the soft, comfortable, and wearable humanized features of textiles, smart electronic textiles can provide humans with a more convenient and natural human-machine interface[22-24].

Therefore, electronic textiles used for human-machine interfaces have developed rapidly, with the continuous maturity of textile, electronic, information, physics, materials, and other technologies. Many researchers have reported integrating fibers with sensing functions into textiles to provide sensing and interaction capabilities for humans and machines[25-28]. Other studies have focused on the use of electronic textiles to digitally analyze the physiological information and motion information of the human body[29-32]. Functional sensors can be placed on various parts of the body assisted by electronic textiles to realize distributed, multi-channel, and multi-parameter sensing. This method of embodying the vital information of the human body in the form of data paves the way for the digital connection between humans and machines and the application of human-machine interfaces.

In recent years, many research achievements on electronic textiles have been reported, and there are also reviews summarizing the research progress of electronic textiles. Some focus on the structural design of textile devices, the textile preparation process, and application in artificial intelligence[33-35], while others emphasize smart textiles for personalized medical care, including wearable point-of-care systems, healthcare, and sustainability[36-38]. However, to our knowledge, the review of electronic textiles with multimodal sensing functions and human-machine interface applications has rarely been reported. With the progress of science and technology and the improvement of living standards, the single functional electronic textile cannot meet people's needs for complicated human-machine interactions. Multimodal sensing capabilities and human-machine interface applications are the main areas of interest at this stage. This urgently requires electronic textiles to develop towards multifunctionality, intelligence, and informatization, which poses considerable challenges in terms of materials selection, structural design, multifunctional integration, and textile manufacturing[22,39]. Currently, multimodal electronic textiles are still an area that has not been fully studied. More and more researchers are centering on the research of multimodal electronic textiles that can simultaneously detect multiple stimulation information to better realize the connection and interaction between humans and machines[40-42]. The motivation of this review is not only to emphasize the research results of multimodal electronic textiles in recent years but also to promote the development of smart electronic textiles in the field of human-machine interfaces and contribute to building an era of intelligent interconnection.

In this review, we logically present the progress of multimodal electronic textiles and summarize their applications in human-machine interfaces, as shown in Figure 1. We first introduce functional fiber fabrication techniques and electronic textile forming strategies. Then, the multimodal electronic textiles with multifunctional sensing capabilities in physical signals, physiological signals, chemical signals, and hybrid signals are summarized. Next, the applications of multimodal electronic textiles in intelligent human-machine interfaces are discussed, including healthcare monitoring, motion recognition, gesture interaction, VR and AR control, and smart home. In the end, we point out the key challenges and future development trends of multimodal electronic textiles in human-machine interface research.

FUNCTIONAL FIBER FABRICATION AND ELECTRONIC TEXTILE FORMING

With the rapid development of smart textiles, increasing fabric manufacturing technologies are used in electronic textiles. According to the required function, the appropriate sensing material, micro-nano processing, and fiber manufacturing technology are selected to prepare the functional fibers. Subsequently, multifunctional fibers are integrated into textiles through various textile processing technologies to form multimodal electronic textiles. In this section, we discuss the common functional fiber fabrication techniques and electronic textile-forming methods in detail.

Fiber fabrication

Fiber is the basic component unit of textiles, so the preparation of functional fiber is the basis for building multimodal electronic textiles. In recent years, various manufacturing technologies, such as coating[58], injecting[59], twisting[60], spinning[61], thermal drawing [62], and coaxial extrusion[63], have been used in the development of fiber. These technologies can combine one or more functional materials to continuously produce multifunctional fibers, as shown in Figure 2.

Coating

The coating is a universal, convenient, and effective fiber manufacturing technology which can transfer functional materials to fiber or yarn substrate[64]. The most common coating methods include spraying[65], dipping[66], electrochemical coating[67], and more. Chen *et al.* used the common textile material polyamide (PA) yarn as the substrate and coated silver on its surface as the conductive electrode[68]. The silver-coated PA yarn was coated with silicone rubber to obtain PA composite yarn with negative friction, as shown in Figure 2A. Park *et al.* also used coating silicone rubber as a negative friction material to design a triboelectric nanogenerator (TENG), which generates electric energy by continuous contact and separation between human skin and silicone rubber[69]. In addition, Liu *et al.* prepared a pressure-sensing fabric based on MXene coating, using cotton fabric as a substrate[70].

Injecting

Injecting is the simplest functional fiber manufacturing technology, which is usually used to inject conductive liquid materials (such as liquid metal[51], conductive ink[71], conductive ionic liquid[72], etc.) into hollow polymer tubes to form functional fibers. Liquid metal (such as gallium, EGaIn, Galinstan, etc.) is widely used in liquid electrodes due to its low Young's modulus, high conductivity, and non-toxicity. As the good fluidity of liquid metals, Wang *et al.* continuously pumped them into homogeneous ultra-fine polymer hollow fibers to propose a large-scale textile-based TENG[73], as shown in Figure 2B. The liquid metal/polymer core/shell fiber structure served as the basic unit of a textile-based TENG for energy harvesting, sensing, and home control. Based on Galinstan, a eutectic alloy consisting of gallium, indium, and tin, Yang *et al.* proposed a TENG with a super-stretchable and structural design[44].

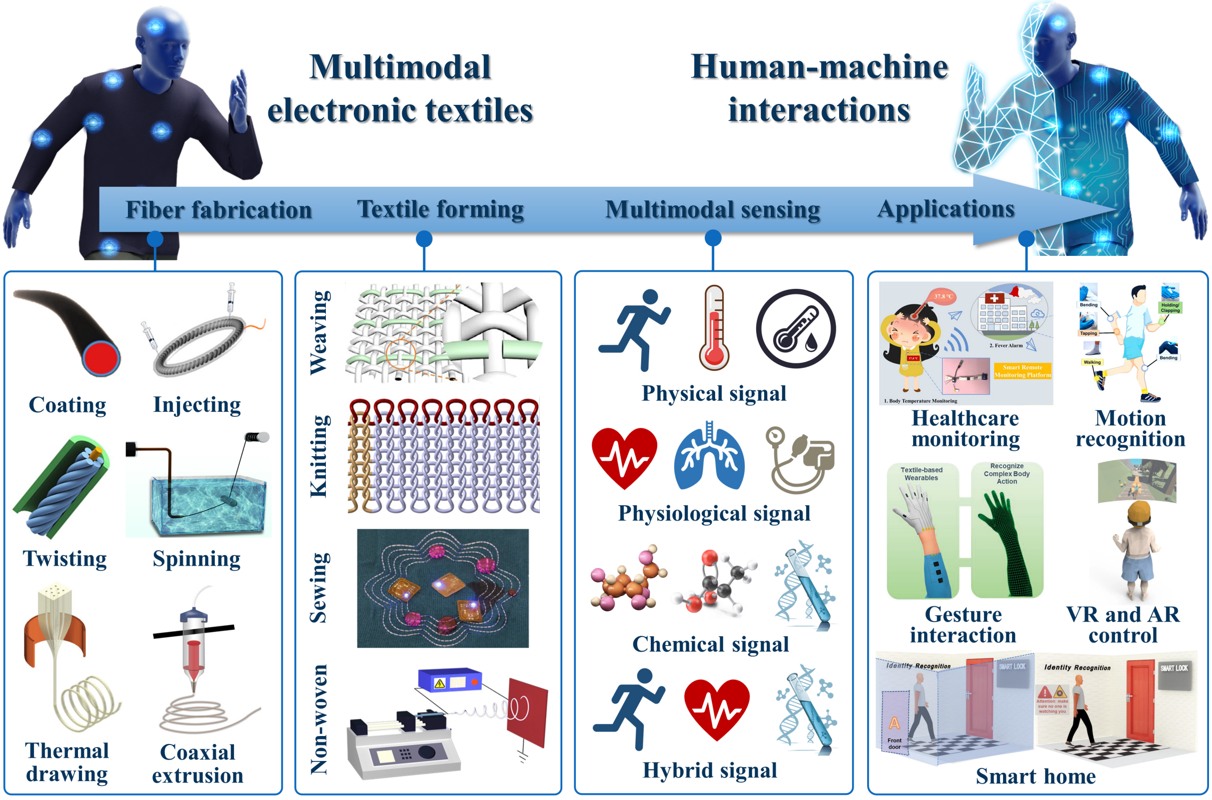

Figure 1. Schematic diagram of multimodal electronic textiles for intelligent human-machine interfaces, including fiber fabrication, textile forming, multimodal sensing, and application for human-machine interfaces. Image for "Coating": Reproduced with permission[43]. Copyright 2022, Elsevier. Image for "Injecting": Reproduced with permission[44]. Copyright 2018, American Chemical Society. Image for "Twisting": Reproduced with permission[45]. Copyright 2020, Elsevier. Image for "Spinning": Reproduced with permission[46]. Copyright 2021, Elsevier. Image for "Thermal drawing": Reproduced with permission[47]. Copyright 2018, Wiley-VCH. Image for "Coaxial extrusion": Reproduced with permission[48]. Copyright 2020, Elsevier. Image for "Weaving": Reproduced with permission[49]. Copyright 2021, American Chemical Society. Image for "Knitting": Reproduced with permission[50]. Copyright 2017, American Chemical Society. Image for "Sewing": Reproduced with permission[51]. Copyright 2022, The Author(s), published by Springer Nature. Image for "Non-woven": Reproduced with permission[52]. Copyright 2020, The Author(s), published by AAAS. Image for "Healthcare monitoring": Reproduced with permission[53]. Copyright 2022, Elsevier. Image for "Motion recognition": Reproduced with permission[54]. Copyright 2022, Wiley-VCH. Image for "Gesture interaction": Reproduced with permission[55]. Copyright 2022, Wiley-VCH. Image for "VR and AR control": Reproduced with permission[56]. Copyright 2020, The Author(s), published by Springer Nature. Image for "Smart home": Reproduced with permission[57]. Copyright 2020, The Author(s), published by Springer Nature.

Twisting

Twisting is a process of winding raw silk into yarn, which is a necessary means to make fiber strips into yarn. The loose filaments can be rotated into yarns in a twisting device, enhancing their flexibility, stretch resistance, and mechanical durability[74,75]. Twisting can also realize the manufacturing of a core yarn, in which conductive fibers are leveraged as core electrodes and other fibers are wrapped around by twisting. In the study of Yang *et al.*, the short sheath fiber was tightly wrapped on the conductive fiber by twisting, forming a core spun yarn[76], as shown in Figure 2C. A triboelectric material was then used to coat the core yarn to design a conductive composite fiber with customizable functions. In the study of He *et al.*, one stainless steel fiber and several polyester fibers were integrated by a multi-twist process for producing the conductive sensing yarn[77]. Also, using the twisting process, Tang *et al.* prepared highly stretchable carbon nanotube (CNT)/thermoplastic polyurethane (TPU) composite nanofiber yarns, which can be further processed for flexible strain sensors[78].

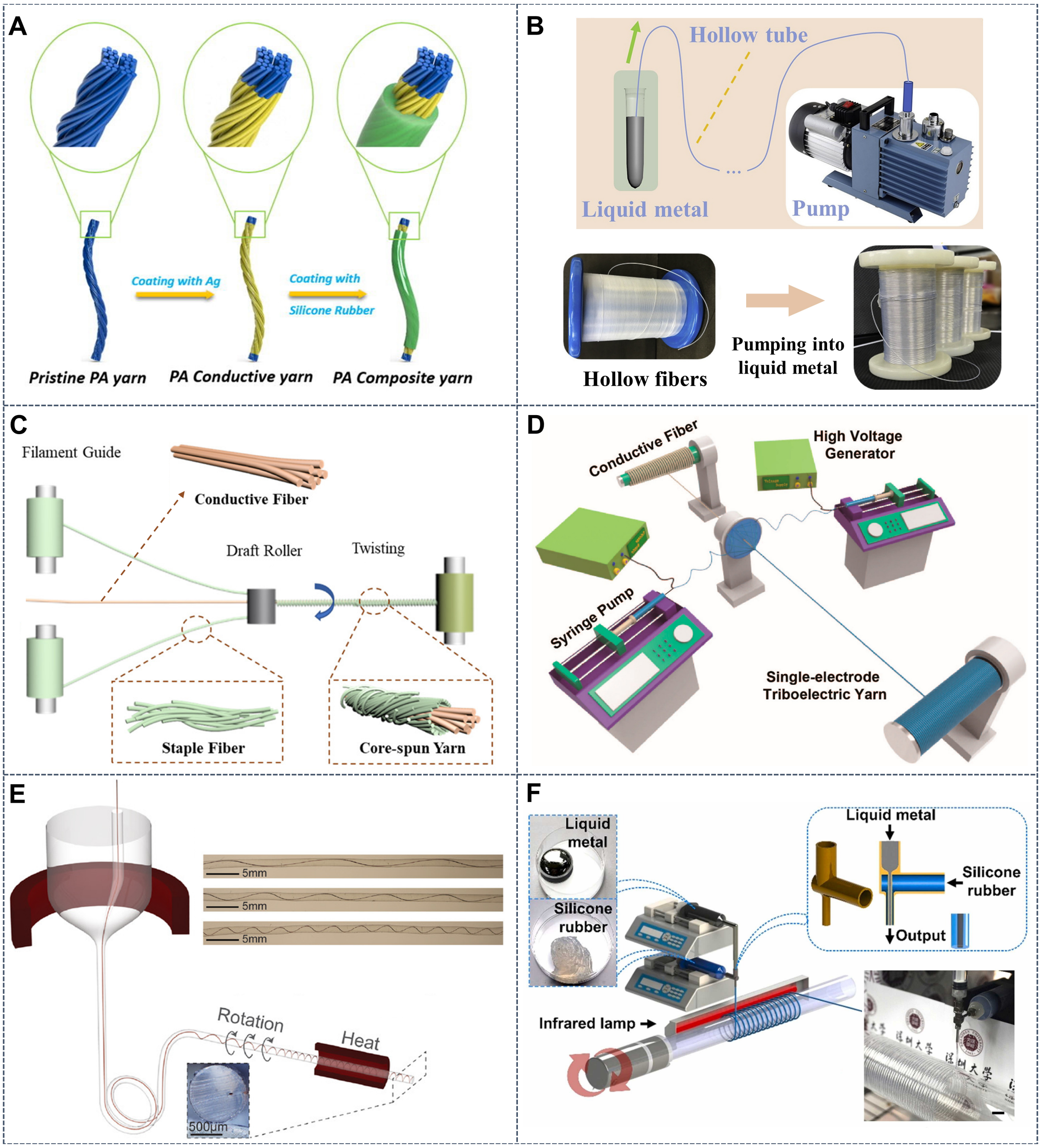

Figure 2. Functional fiber manufacturing technology. (A) Coating technique. Process flow for preparing core-shell functional yarn by coating functional materials. Reproduced with permission[68]. Copyright 2019, Elsevier; (B) injecting technique. The fabrication process of the liquid-metal/polymer core/shell fibers by injecting technique. Reproduced with permission[73]. Copyright 2020, Elsevier; (C) twisting technique. The fabrication method of conductive polymer fibers by twisting technique. Reproduced with permission[76]. Copyright 2021, American Chemical Society; (D) spinning technique. The fabrication method of single-electrode triboelectric yarn by spinning technique. Reproduced with permission[83]. Copyright 2020, American Chemical Society; (E) thermal drawing technique. Process flow of thermally drawn high conductive fibers with controlled elasticity. Reproduced with permission[91]. Copyright 2022, Wiley-VCH; (F) coaxial extrusion technique. Preparation of stretchable conductive core/shell fibers by coaxial extrusion technique. Reproduced with permission[94]. Copyright 2022, Elsevier.

Spinning

Spinning manufacturing processes, such as conjugated spinning[79], melt spinning[80], and wet spinning[81], can realize continuous manufacturing of functional fibers and large-scale industrial production. Conjugated spinning is to apply a high voltage of opposite polarity to two spinnerets, and the nanofibers ejected from the two spinnerets are attracted and wound together to obtain continuous yarn[82]. As shown in Figure 2D, Ma *et al.* reported a triboelectric yarn with helical hybridized nano-micro core-shell fiber bundles, which was fabricated by a continuous conjugated spinning technology[83]. Polyvinylidene fluoride (PVDF) and polyacrylonitrile (PAN) hybrid nanofibers were uniformly wound on the conductive yarn at a certain angle to form a tightly wrapped core-shell structure. Melt spinning is a yarn preparation method that uses a polymer melt as raw material to spin through a melt spinning machine[84]. Wang *et al.* developed an activated carbon fiber by using melt spinning technology, presenting a good application prospect in the field of flexible electronics[85]. Wet spinning is to dissolve the polymer in a solvent, and then the solution is ejected from the spinneret and solidified into fiber in the coagulation bath[86]. Using wet spinning technology, Wu *et al.* prepared a highly stretchable and conductive CNTs/MXene-TPU hybrid fiber electrode with a porous structure[61]. TPU molecular chain was the main skeleton, while CNTs and MXene form conductive networks, which could be further applied to flexible strain sensors.

Thermal drawing

Thermal drawing is another way that can be available for the industrial production of fibers, which is to draw preforms into miniaturized fibers[87-90]. During the drawing process, fibers of different sizes can be achieved by setting different parameters. In the study of Marion *et al.*, the preform made of two thermoplastic elastomers was thermally drawn into fibers, and the conductive copper wire was fed into the hollow channel of the preform[91]. Subsequently, the elastomer fiber was twisted to produce helical metal electrodes embedded in a stretchable yarn, as shown in Figure 2E. Zhang *et al.* proposed thermoelectric micro/nanowires by thermally drawing inorganic thermoelectric materials in a flexible fiber-like substrate[92]. The thermoelectric fibers were highly flexible, ultralong, and mechanically stable and could meet the requirements of large-scale preparation. Thermal drawing technology has been regarded as a platform for the industrialized manufacturing of fiber electronic devices. By combining metals, insulators, and semiconductors all in one fiber, fibers with optical, electrical, acoustic, and optoelectronic functions can be easily produced.

Coaxial extrusion

Coaxial extrusion is also a common fiber manufacturing technology. Typical coaxial extrusion technology is that conductive materials and insulating materials are extruded at the same time to form core electrodes and triboelectric layers, respectively, after drying[93]. In the study of Wu, the liquid melts and silicone rubber were respectively injected into the central channel and the outer channel of a coaxial needle[94]. Subsequently, by coaxial extrusion, stretchable conductive core/shell fibers were prepared for strain sensing and self-powered smart textiles, as shown in Figure 2F. 3D printing technology is an emerging technology in recent years, which is also another form of coaxial extension[95]. Chen *et al.* have prepared stretchable elastic fibers with a coaxial core-sheath structure by a 3D printing method, which consisted of a conductive core and an insulative sheath[63].

Textile forming

The functional fibers produced by continuous production have good machine manufacturing properties and can be made into multimodal electronic textiles by various textile processing technologies (including weaving[49], knitting[96], sewing[97], non-woven[98], etc.). Owing to its salient merits of mechanical deformation and adaptability, the textile can be integrated into ordinary clothing to achieve multimodal sensing.

Weaving

Weaving is a textile processing technology in which warp and weft are vertically crossed to form a textile. Weaving technology has been widely used, with the intersection of warp and weft often designed as a sensing unit[99,100]. Based on the shuttle-flying weaving technique, Gong *et al.* weaved polylactic acid fibers into a reconfigurable green electronic textile, as shown in Figure 3A. Due to the excellent mechanical properties of polylactic acid fiber, the designed textile is applicable for large-scale production and possesses good washability[101]. In the study of Zeng, through scalable industrial textile weaving routes, fabricated metal fabric presented satisfactory mechanical strength, breathability, and waterproofness[102]. Moreover, Choi *et al.* fabricated a smart textile system by weaving processes, including wireless power transmission, touch sensing, photodetection, environmental/biosignal monitoring, and energy storage. The system design and integration strategies based on the weaving process lay a foundation for large-scale smart home and IoT applications[103].

Knitting

Knitting is the process of intertwining yarns to form a textile, which mainly includes weft knitting and warp knitting. As the structure of knitted textiles can be easily stretched in different directions, it is regarded as a very effective manufacturing method for strain-sensing textiles[104]. Yang *et al.* developed a graphene textile strain sensor with a weft-knitted textile substrate, possessing high sensitivity and wide-range tensile response[105]. As shown in Figure 3B, Dong *et al.* reported a facile and all-yarn-based knitting power textile that enabled both biomechanical energy harvesting and simultaneous energy storing[50]. With the weft-knitting technique, the textile had the characteristics of the high elasticity, flexibility, and stretchability and was qualified with adaptability in complex mechanical deformation. Moreover, Uzun *et al.* coated cellulose yarns with MXene to produce highly conductive and electroactive yarns[106]. By using an industrial knitting machine, the yarns were knitted into textiles, providing a new method for the preparation of flexible and wearable capacitive pressure sensors.

Sewing

Sewing is the simplest way to integrate functional fibers into textiles and provides great flexibility for textile structure and function design. Functional fibers can be designed to various structural patterns and placed on any position of the textile by sewing[107]. As shown in Figure 3C, Lin *et al.* developed electronic textile systems with near-field wireless power and communication capabilities, which are realized by the digital embroidery of liquid metal fibers onto clothing[51]. The compatibility of liquid metal fibers with the digital embroidery process allowed the design of radio-frequency patterns on clothing by utilizing established computer-controlled textile manufacturing. By sewing a sensing yarn into the designer pattern on the garments, He *et al.* integrated electronic textile-based triboelectric sensors with versatile commercial garments[77]. With this scalable method of sewing, any commercial clothes can be easily converted into intelligent wearable systems.

Non-woven

Non-woven is a technique that makes textiles by winding discontinuous staple fibers or filaments in a random manner. Electrospinning is the most representative technology in the non-woven process[52,108]. As shown in Figure 3D, electrospinning was adopted to manufacture nanofiber non-wovens, realizing an all-fiber synergistic electronic textile[109]. Through a self-assembly technology based on wet heterostructured electrified jets, Zhang *et al.* developed versatile electrospinning micropyramid arrays. Self-assembly far-field electrospinning apparatus was used for the design of the electrospinning pyramid array structure, which was a new electrospinning method[110]. A ferroelectric-enhanced triboelectric textile and the directional moisture-wicking fabric were made by electrospinning non-woven. This new type of electrospinning

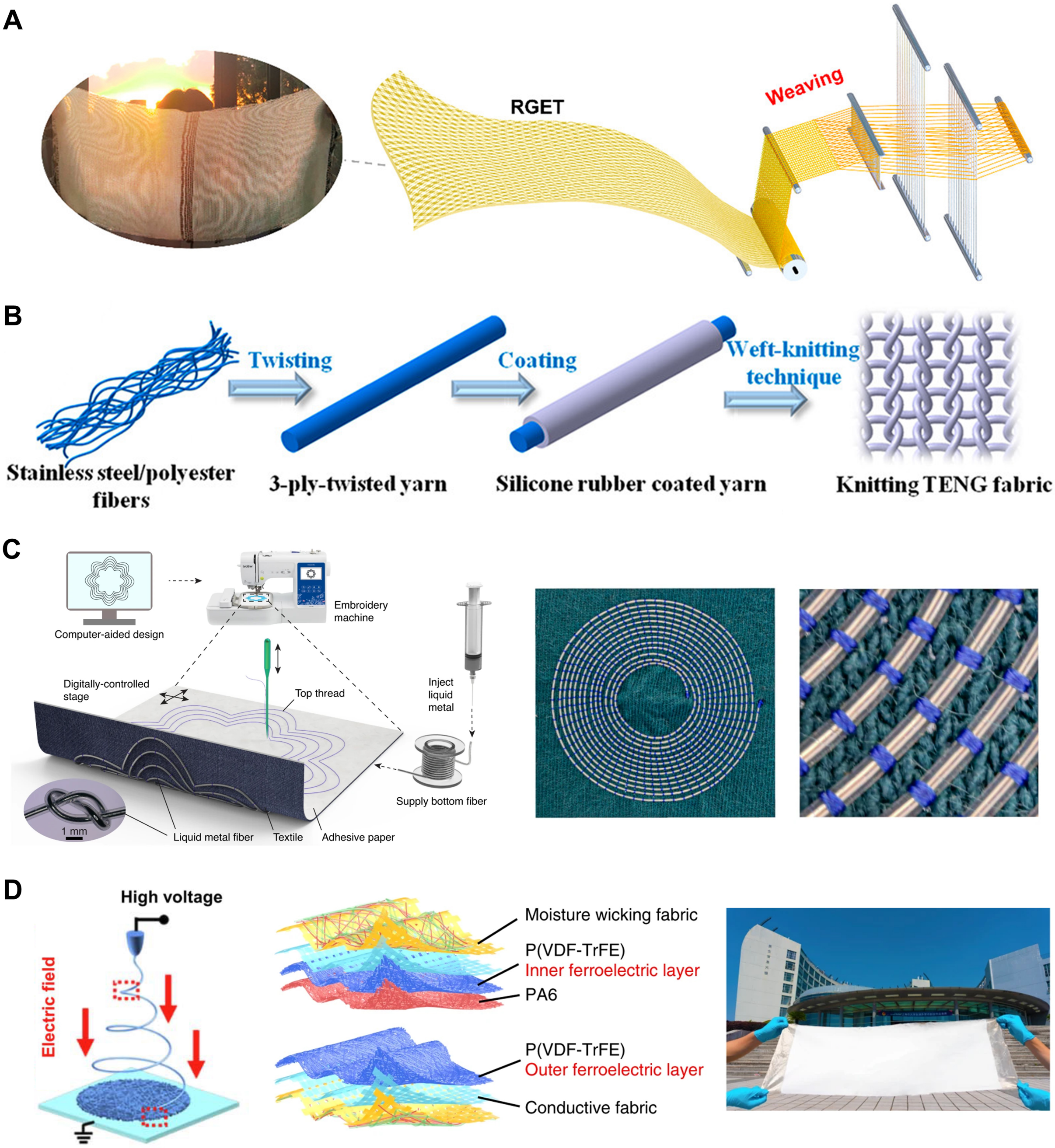

Figure 3. Electronic textile forming strategies. (A) Weaving technology. The process of manufacturing electronic textiles through the shuttle-flying weaving technique. Reproduced with permission[101]. Copyright 2022, American Chemical Society; (B) knitting technology. The fabrication process of the all-yarn-based knitting power textile by knitting technology. Reproduced with permission[50]. Copyright 2017, American Chemical Society; (C) sewing technology. Schematic diagram of digitally-embroidered liquid metal electronic textiles designed by sewing technology for wearable wireless systems. Reproduced with permission[51]. Copyright 2022, The Author(s), published by Springer Nature; (D) non-woven technology. The fabrication process of the all-fiber tribe-ferroelectric synergistic electronics by non-woven technology. Reproduced with permission[109]. Copyright 2019, The Author(s), published by Springer Nature.

non-woven presented broad application prospects in fast-drying clothes, cooling textiles, and wireless motion monitoring insoles[111].

MULTIMODAL SENSING

Functional fibers with stimulus-response capabilities are prepared through advanced fiber fabrication techniques, and then multiple functional fibers are integrated into electronic textiles using textile-forming methods to achieve multimodal sensing functions. Electronic textiles manufactured by textile-forming methods have a vertical cross structure, a loop structure, and a non-woven fabric structure, which can improve the sensing performance of the device. In addition, electronic textiles have the advantages of softness and large areas, facilitating the integration of multiple sensing mechanisms to achieve multimodal sensing. In this section, we focus on the multimodal sensing capabilities of electronic textiles, including physical, physiological, chemical, and hybrid signals.

At present, researchers have investigated multiple ways of converting stimuli information into electrical signals, and Figure 4 depicts six types of common sensing mechanisms. The capacitance sensing mechanism is the use of the capacitance variations of dielectric materials between conductive electrodes to characterize stimulus information[112-114]. Piezoresistive sensing mechanism refers to the change in the resistance of the device under external mechanical stimuli[115-117]. The piezoelectric sensing mechanism relies on polarization phenomena inside the material to represent stimulus information in the form of electricity generation[118-120]. The triboelectric sensing mechanism uses contact electrification and electrostatic induction coupling effects to convert mechanical stimuli into electrical output[34,121,122]. The electrochemical sensing mechanism is a method to convert chemical stimuli signals into electrical signals via chemical reactions[123-125]. Electromagnetism is a sensing mechanism that converts magnetic signals into electrical signals[126-128].

Physical signal sensing

Sensors based on electronic textiles have been widely used to detect various physical signals. Physical signals are converted into detectable electrical signals through various methods, including the triboelectric effect[129], the piezoelectric effect[130], the thermal resistance effect[131], etc., to detect physical signals, such as pressure[132-134], strain[135,136], temperature[137], humidity[138-140], and more. Nowadays, the detection of electronic textiles with a single signal can no longer meet the needs of accurate monitoring and advanced applications. Therefore, people began to study multimodal electronic textiles that can simultaneously detect two or more physical signals.

Multimodal electronic textiles for physical signals can be divided into two categories. One is to detect different manifestations of the same type of signals (such as pressure and strain[141,142]), and the other is to detect different types of signals (such as temperature and strain[143]). According to the designed device structure and sensing mechanism, it is very significant to utilize different methods to measure the same physical signal. For example, we can choose methods such as triboelectric, piezoelectric, capacitive, and piezoresistive effects to measure pressure and strain signals. We can also choose thermal resistance and piezoresistance effect methods to measure temperature and strain signals. Triboelectric and piezoelectric effects have the advantage of fast response time based on the acquisition and analysis of the output transient voltage signal for dynamic information detection. For capacitance, piezoresistive and thermal resistance effects have the advantage of high sensitivity and wide response range based on the acquisition and analysis of continuous capacitance or resistance signals for static information detection.

TENG not only can convert mechanical signals into electrical signals when triboelectric fiber materials contact and separate but also has the characteristics of being self-powered, which is a good choice for mechanical sensors[63,144]. As shown in Figure 5A, the pressure-strain multimodal electronic fabric combined with the triboelectric nanogenerator is presented[68]. Cotton yarn and PA composite yarn are used as positive and negative triboelectric materials, respectively, wherein PA yarn coated with high-conductivity silver is

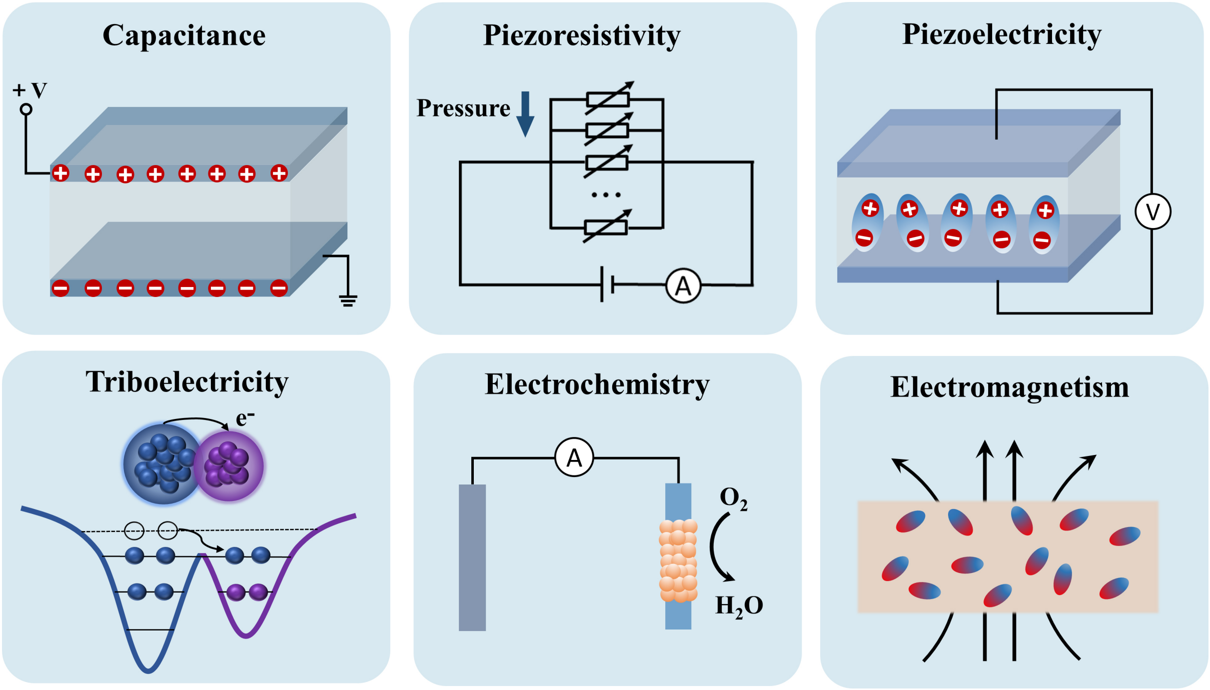

Figure 4. Schematic illustrating the six types of common multimodal sensing mechanisms: capacitance; piezoresistivity; piezoelectricity; triboelectricity; electrochemistry; and electromagnetism.

used as a conductive electrode, which is coated with silicone rubber to obtain composite yarn. The two materials are compiled together in a special structure that is a double-faced interlocking structure. Figure 5A shows the power generation mechanism of the textile sensor with a double-faced interlocking structure under pressure and stretch. When pressure or stress is applied to the fabric, PA and cotton yarns come into contact and separate from each other, which will result in charge movement, thus enabling multimodal sensing functions. On this basis, the fabric has good performance as a pressure and strain sensor. Figure 5B shows a temperature-strain multimodal sensing textile, which is made by supersonic spraying reduced graphene oxide (rGO) and silver nanowires (AgNWs) on wearable fabrics[143]. As a thermal fabric, the low junction resistance produced by supersonic cold spraying coating makes rGO/AgNW fabric have high conductivity, which enables it to measure temperature in real-time accurately. As a strain fabric, the rGO/AgNW fabric can be used for wearable or body-attachable electronic devices.

The detection of multimodal signals can be divided into two cases. One case is that the same fiber/textile can detect two signals, respectively, as shown in Figure 5C[145]. The fiber is obtained by integrating Kevlar nanofiber with MXene nanosheet (KM) through wet spinning. And the conductive fiber can be packaged in two dielectric elastomers with a sandwich structure to make a sensitive piezoresistive sensor, which can be used for Morse code recognition. In addition, MXene has the characteristics of negative thermal coefficient behavior, which can be sewn on gloves and other textiles with alarm devices to prevent scalding and other risks. The other case is to use different signal-sensing fibers and weaves them into textiles to achieve simultaneous detection of the two signals, as shown in Figure 5D[146]. Temperature sensing is achieved with the help of CNTs and ionic liquid temperature-sensitive materials, while pressure sensing is achieved by detecting the capacitance at the yarn crossing point. The temperature-pressure sensor array is a layered sensing textile, which is obtained by integrating temperature and pressure sensing yarns. The two layers of textiles are used for temperature sensing and pressure sensing, respectively. The position accuracy of the temperature pressure signal sensed by the sensor array is 1 mm^2, which shows that it has a good resolution.

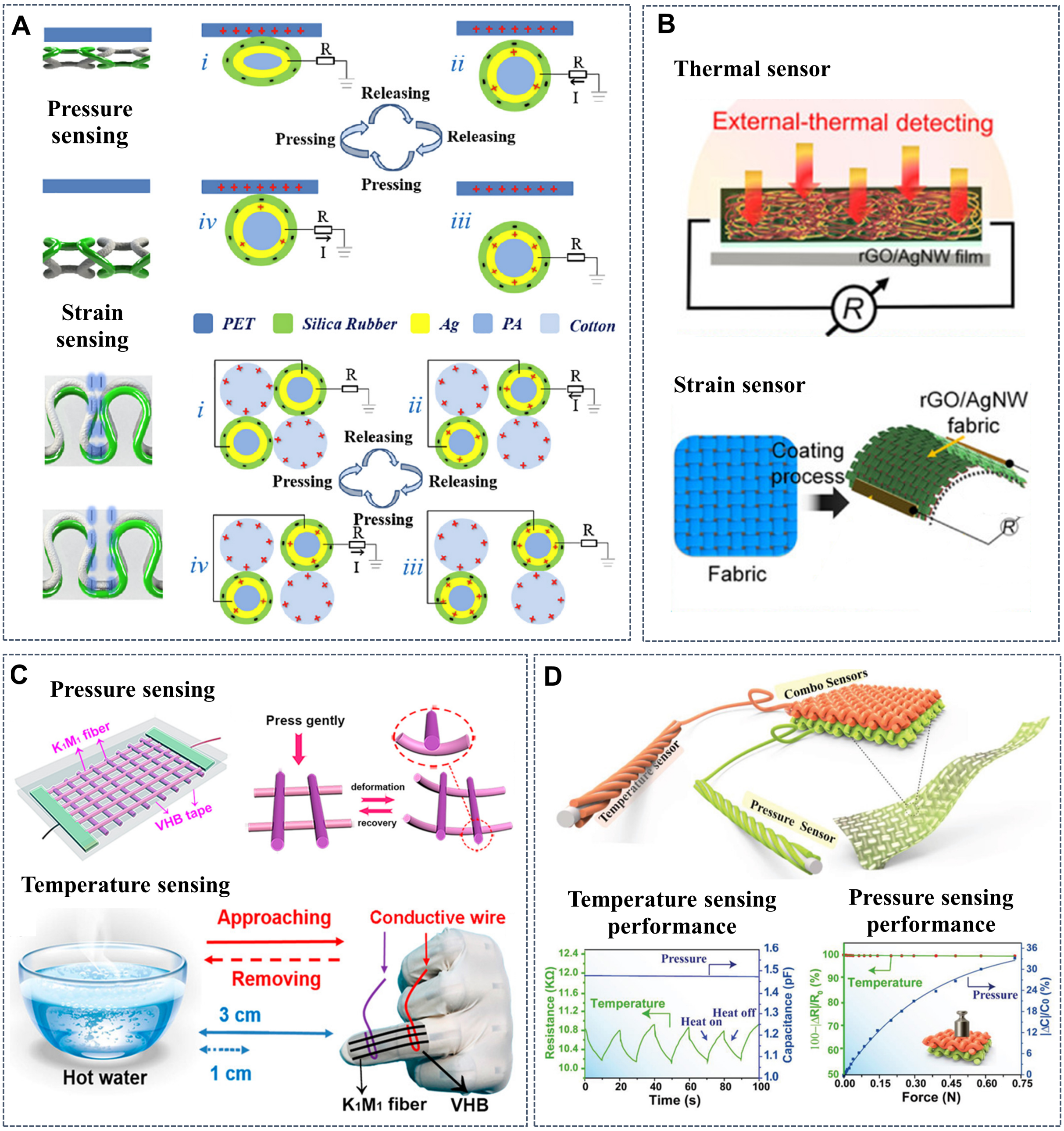

Figure 5. Physical signal sensing textile. (A) Schematic diagram of the working principle of double-faced interlocking structure TENG under pressure and stretch. Reproduced with permission[68]. Copyright 2020, Elsevier; (B) wearable rGO/AgNW textile as a thermal sensor and a strain sensor. Reproduced with permission[143]. Copyright 2022, American Chemical Society; (C) schematic diagram of pressure and temperature sensing of textile sensor manufactured by K_1M_1 fiber. Reproduced with permission[145]. Copyright 2021, American Chemical Society; (D) schematic diagram of a temperature-pressure electronic textile sensor and its temperature and pressure sensing performance. Reproduced with permission[146]. Copyright 2019, Wiley-VCH.

All of the above are dual-mode sensing textiles, while three-mode sensing textiles can adapt to more complex environments and achieve better sensing effects. To realize temperature-humidity-strain sensing textiles, a resistive sensor and capacitive sensors can be integrated[147]. Carbon particles are coated on nylon/spandex textiles as a strain-sensing layer. The original intermediate textile is sewn by conductive textiles, which can be further made into a capacitive pressure sensor. By combining a resistive sensor and a capacitive sensor, a hybrid sensor with a special sandwich structure is made, and a multimodal electronic textile with a humidity-temperature-strain sensor is realized.

Physiological signal sensing

Electronic textiles based on sensors have been widely used in the biomedical field. They have the same permeability and comfort as conventional clothing and can directly make contact with the skin for a long time without causing discomfort. The biosensor based on electronic textiles can continuously detect the signal of the human body. It can detect the pulse[148,149], heart rate[150,151], respiration[152], and other signals of people by making textile sensors into clothing and other daily textiles to achieve disease diagnosis, healthcare[153,154], and other functions. In disease diagnosis and medical care, multimodal signal detection can monitor human body status more comprehensively and accurately. Therefore, increasing multimodal sensing textiles for pulse, respiration, and other signals have been developed.

Sleep time accounts for approximately 1/3 of the daily time. Good sleep is of great significance to human health, but sleep apnea syndrome (SAS) seriously threatens human health. SAS can be effectively monitored[155] by detecting the respiratory-pulse signal[156] or respiratory-heart rate signal[157,158] during sleep. There are two directions for monitoring the SAS of electronic textiles. The one is to make sheets into electronic textiles, which enables the conversion of pressure to electrical signals through the triboelectric sensing mechanism based on silicone rubber and polyester, as shown in Figure 6A[45]. Sixty-one independent sensing units are integrated into the single-layer textile, and 60 small sensing units are evenly distributed on the textile to detect the posture of people during sleep. A larger sensing unit is located below the chest area to detect physiological signals. The system then transmits these signals to the computer to monitor the respiratory signals and pulse signals. The figure shows that when SAS occurs, the respiratory signal will change significantly, which can be combined with the heart rate signal to accurately diagnose SAS. The second is to integrate the sensor into the clothing, as shown in Figure 6B[96], and combine two triboelectric all-textile sensor arrays (TATSA) to the chest and wrist of the clothing to continuously collect and monitor the pulse signal and respiratory signal in real-time. The respiratory signal can directly display whether the patient has SAS. In addition, the analysis of pulse transmission time (PTT) based on this can determine which SAS the patient has so as to provide targeted treatment for the patient. In addition to SAS, electronic textiles can also diagnose other diseases, such as cardiovascular diseases diagnosed by pulse wave[159], COVID-19 diagnosed by respiratory activity[160], etc.

In addition to disease diagnosis, they can contact the human body for long-term signal monitoring due to the good compatibility between electronic textiles and the human body, which can play a good role in healthcare. As shown in Figure 6C[161], installing perfluorooctyltriethoxysilane modified TiO_2 nanoparticles incorporated textile conductor (PTCCS) on the human chest can upload the detected electrocardiogram (ECG) signal through Bluetooth to promote its application in health monitoring. In addition, based on the Arduino platform, the platform is connected with two PTCCS textile electrodes of the biceps brachii belly and elbow joint. The electromyography signals of the three biceps brachii contraction movements, namely fist clenching, elbow lifting, and forearm supine, are obtained by a series of processing. When the conductive fabric is used as a strain sensor, a stable resistance signal can be generated according to the reorganization of the conductive network. When the conductor is used as a physiological electrical sensor, it can effectively monitor ECG and electromyogram (EMG) signals. The combination of ECG and EMG can play a good role in monitoring people's physical condition in sports. It can be seen that this long-term signal monitoring has a good application prospect in medical care and sports.

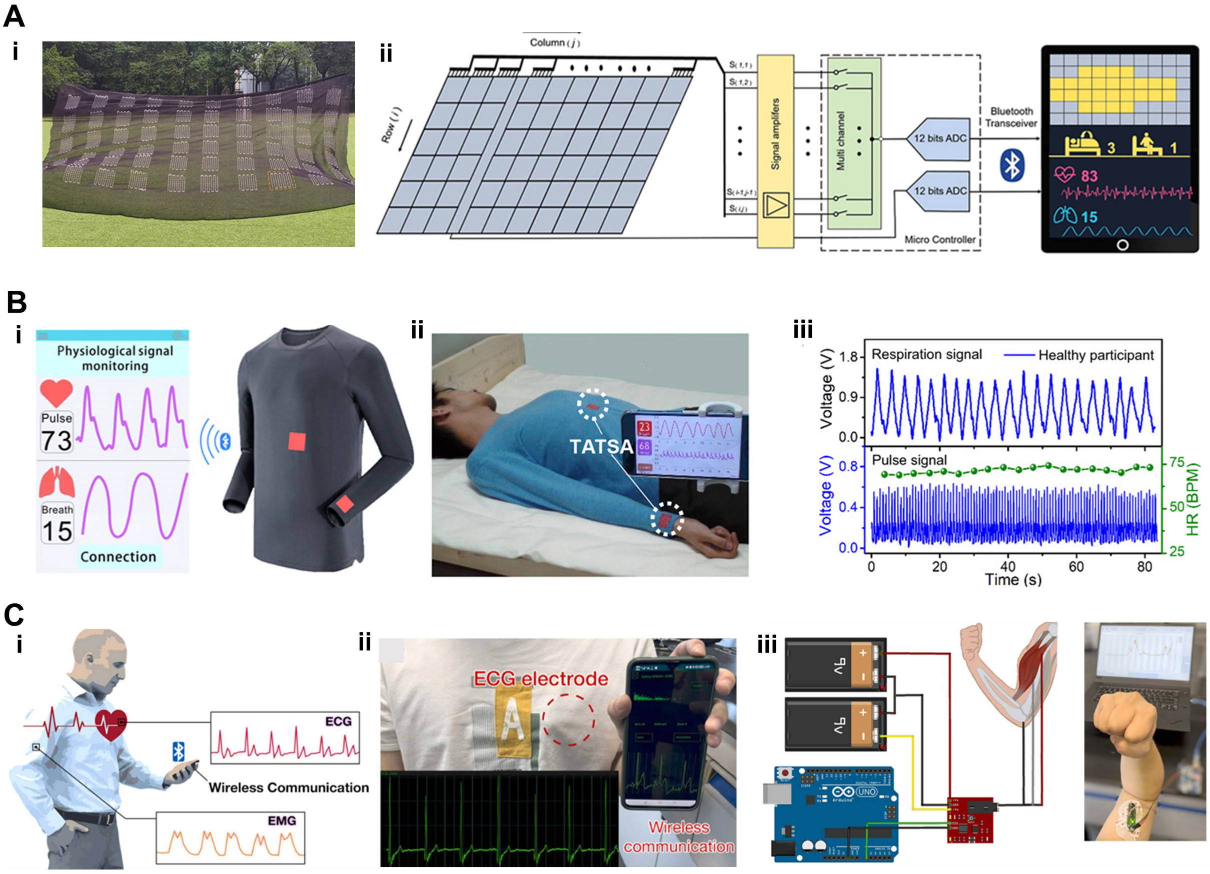

Figure 6. Physiological signal sensing textile. (A) (i) Schematic diagram of the smart textile with 61 sensing units; (ii) schematic diagram of the real-time physiological signal monitoring system. Reproduced with permission[45]. Copyright 2020, Elsevier; (B) (i) schematic diagram of two TATSA combined on clothes to detect pulse and respiratory signals; (ii) photo and data map of pulse and respiratory signals measured by TATSA during sleep; (iii) respiratory and pulse signals of a healthy participant. Reproduced with permission[96]. Copyright 2020, The Authors, published by AAAS; (C) (i) schematic diagram of sensors used to detect ECG and EMG; (ii) real-time ECG signal displaying on the phone; (iii) detection of electromyography with bioelectrode. Reproduced with permission[161]. Copyright 2022, Elsevier.

In a word, textile sensors can monitor some physiological signals of people without affecting people's normal life and play a good role in disease diagnosis and healthcare. In order to adapt to the complex situation in life, the robustness of textile sensors will be another focus of research. In addition, the combination of fabric sensors and the Internet of Things is also one of the main development directions in the future.

Chemical signal sensing

Aside from the aforementioned physical signal sensing and physiological signal sensing, the multimodal chemical sensing textile is another kind of extensively studied fabric sensor. Such sensors are often used for disease diagnosis or personal health monitoring[162-166], emotional status assessment[167], and detecting harmful gases from the environment[168]. Sensors in the form of fabric can be conveniently integrated into traditional textile products such as clothes[162,163], headbands[165,166], and masks[168], improving comfort and biocompatibility. As integrated wearable platforms that can simultaneously collect multiple chemical signals from a human body or the environment, these sensors give the basis for comprehensive monitoring and judgment. In this section, we classify the textile-based multimodal chemical sensors into three categories according to their working principles, namely electrochemical sensing, optochemical sensing, and chemiresistive sensing, as shown below.

Electrochemical sensing is the most studied and widely-applied type of chemical signal sensing textiles. This is due to its simplicity, reliability, and direct conversion of analyte concentrations to potential or current signals. There are two main types of these multimodal electrochemical sensors, which are standard electrochemical sensors and organic electrochemical transistors (OECTs).

Based on the measurement of electrode potential or current, the standard electrochemical sensors collect concentration information according to the Nernst relationship between analyte concentration and electrochemical potential or current, convert chemical signals into electrical signals, and then submit them to the readout circuit for amplification and further processing. If different electrodes capable of measuring multiple signals are integrated into the same textile, multimodal chemical sensing can be realized. For example, a textile-based bimodal sensing textile was fabricated for in-situ analysis of Na^+ and K^+ concentrations in human sweat simultaneously (as shown in Figure 7A)[162]. The chemical sensing ranges of the device covered the typical Na^+ and K^+ concentrations in human perspiration during the whole course of a physical workout, providing an effective indicator for hydration status and a potential diagnostic tool for electrolyte imbalance.

Going a step further, a higher-integrated multimodal electrochemical sensing textile with five analyte-detecting channels was reported (as shown in Figure 7B)[163]. Coaxial structured sensing fibers and their corresponding fiber-based reference electrodes were made by coating different active functional materials onto CNT fibers, respectively. By weaving together all the functionalized fibers into an ordinary fabric, a conformable and breathable integrated multimodal electrochemical fabric detecting a variety of physiological chemicals (namely glucose, Na^+, K^+, Ca^{2+}, and pH) was developed, which can be used to collect synthetic information of component concentrations in human sweat.

Apart from standard-type electrochemical sensors, another alternative realization of electrochemical sensing is an OECT-based sensor. OECT is a kind of dual-functional device that simultaneously collects and amplifies electrochemical signals, simplifying the subsequent signal processing circuits[169]. When it comes to multimodal sensing, a promising textile-based sensor is a bimodal sensing fabric produced by integrating two OECT devices on a single fabric cloth for selectively monitoring ions and adrenaline molecules in human sweat (as shown in Figure 7C)[167]. Each OECT device featured a metallic gate and a conductive fiber-based channel. When an appropriate gate voltage was applied, the Ag-gate participated in the redox reaction involving Cl^- in the electrolyte, whereas the Pt-gate surface underwent the oxidation reaction of adrenaline, which ultimately enabled analyte-concentration-dependent OECT channel currents in both devices. Due to the mechanism difference between the two devices, the Ag-gate OECT and Pt-gate OECT were sensitive and selective to ions and adrenaline molecules, respectively. This combined OECT sensor could be applied to evaluate hydration state and psychological status (by evaluating adrenaline level) in a non-invasive way, which is of great application value in personal healthcare management.

Optochemical sensing converts the concentration signals of chemical substances into corresponding optical signals, such as chromatic or spectral changes[165,166]. Such sensors often have simple structures and low manufacturing costs. Multimodal sensors can be easily fabricated by combining multiple optochemical sensing units on one textile substrate. A noteworthy example is a thread/fabric-based microfluidic multi-sensing band functioning in a method of a colorimetric assay, which could be used to detect pH, Cl^- and glucose concentrations in sweat[165], as is shown in Figure 7D. After colorimetric treatment, hydrophilic threads, working as sweat-transporting channels as well as sweat storage sites, were embroidered into a

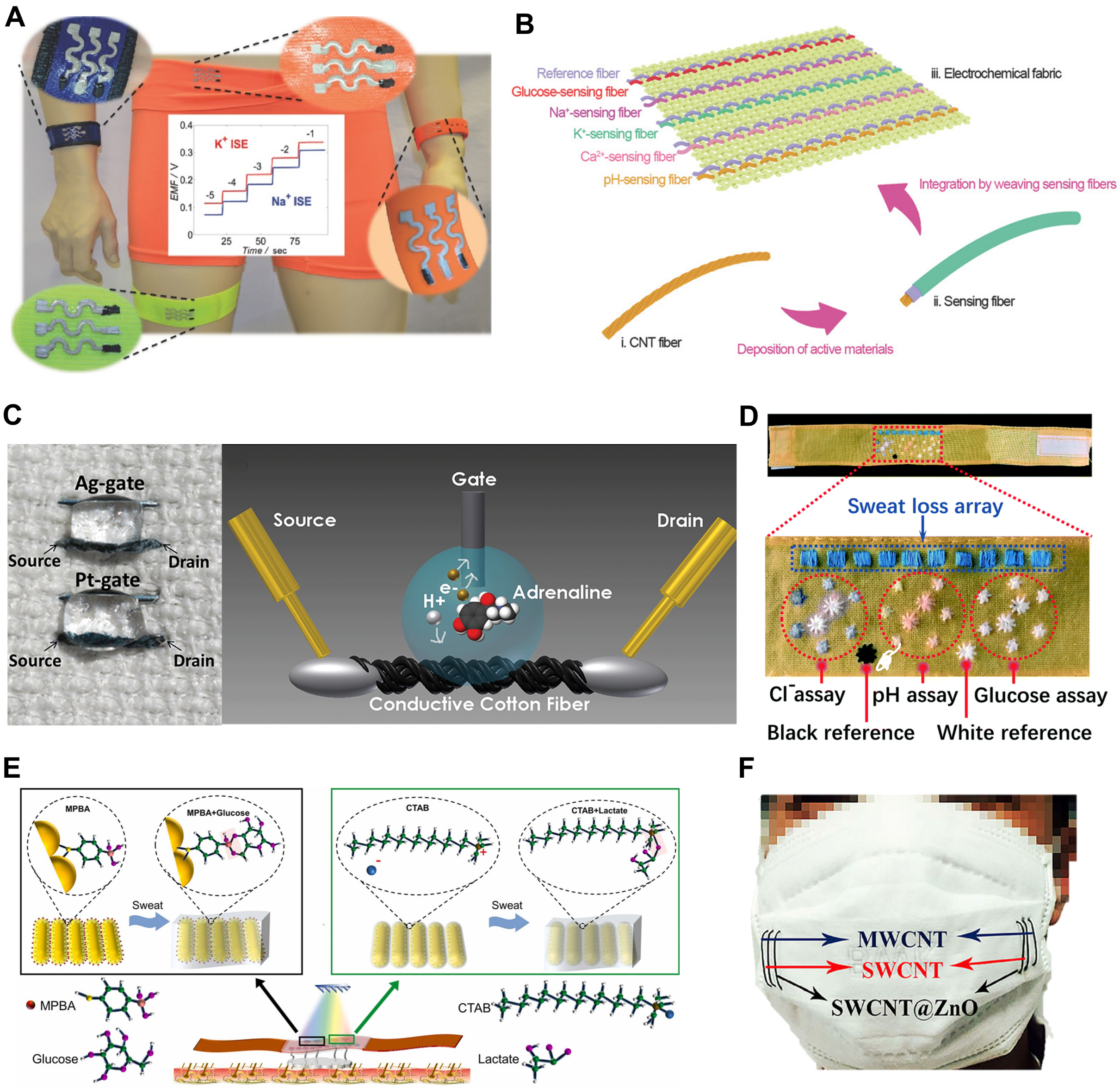

Figure 7. Chemical signal sensing textiles. (A) Image of highly stretchable and printable textile-based bimodal ion sensors arranged on different detection sites. The inserted diagram shows linear relationships between ion concentrations and output voltages. Reproduced with permission[162]. Copyright 2016, Wiley-VCH; (B) schematic of a five-channel textile-based multimodal sensor array for sensing glucose, Na^+, K^+, Ca^{2+}, and pH. Reproduced with permission[163]. Copyright 2018, Wiley-VCH; (C) image and schematic of an OECT-based sweat sensing textile. Reproduced with permission[167]. Copyright 2014, Royal Society of Chemistry; (D) images of a thread/fabric-based microfluidic multi-sensing band based on the colorimetric assay. Reproduced with permission[165]. Copyright 2021, Royal Society of Chemistry; (E) schematic of the working principles of a SERS technology-assisted thread/fabric-based microfluidic sensor. Reproduced with permission[166]. Copyright 2021, Elsevier; (F) image of a tri-modal gas sensing mask based on fiber gas sensors. Reproduced with permission[168]. Copyright 2017, Tsinghua University Press and Springer-Verlag GmbH Germany.

hydrophobic textile. Different colorimetric treatment methods endowed the threads with the ability to sense different chemicals; namely, the concentrations of chemical analytes were reflected through their color changes. Three groups of detection patterns were arranged for the detection of pH, Cl^-, and glucose concentrations, which could be determined by visual observation of color changes or by analyzing RGB values of the sensing sites through a smartphone APP.

In addition to the colorimetric assay method, a novel optochemical sensing mechanism combining thread/fabric-based microfluidic device and surface-enhanced Raman scattering (SERS) technology was reported, allowing simultaneous detection of glucose and lactate concentrations in human sweat with high accuracy[166]. A textile-based microfluidic device was made by embroidering mercerized cotton thread into a hydrophobic cotton fabric to build the sensing site, with a viscose thread attached to serve as a microfluidic channel. To detect certain biomolecules, SERS tags targeting glucose and lactate were deposited onto two as-prepared microfluidic devices (as shown in Figure 7E). After human sweat was absorbed and chemical reactions occurred between sweat analytes and SERS tags, the devices were used to measure Raman spectra. The concentrations of the analytes were then correlated to the characteristics of the Raman spectra. These relationships can be generalized as exponential functions for further analysis.

The textile chemical sensor can also be realized based on the principle that the resistance of the sensor changes due to its interaction with chemical substances. An example of multimodal textile chemical sensors that operate according to the chemiresistive principle is a face mask integrated with three fiber sensors with different sensing functions [Figure 7F][168]. Flexible nylon fiber substrates were wrapped with different types of CNT-based functional materials to produce sensing fibers whose resistances were sensitive to certain types of chemical concentrations in the air. Combining these sensing fibers into a face mask, three different gas signals can be detected and distinguished by monitoring resistance changes, realizing multimodal sensing to poisonous gases from the environment.

Hybrid signal sensing

As shown in the previous sections, wearable textile sensors can realize multimodal sensing of physical signals, physiological signals, and chemical signals, providing users with a great variety of valuable information, including human motions, physiological or health status, and environmental variables. On this basis, wearable device designers further organically integrate these signals to provide simultaneous monitoring of physical and physiological signals realized on the fabric platform[55,170-173] or multimodal acquisition of physical and chemical signals[174,175]. Hybrid signal sensing is enabled by integrating multiple types of fabric sensors on a single sensing textile or arranging sensors at different locations on the human body. While outputting information in different dimensions, these mixed-signal textile sensors also have the advantages of comfort, breathability, and biocompatibility, which are inherent in fabric-based sensors, thus enabling broad prospects in future wearable applications.

Physical/physiological-type hybrid sensing textile combining physical signals and physiological signals is ideal for the evaluation of overall body conditions in exercise or resting state. For instance, a fabric pressure sensor with high sensitivity based on rGO decorated carbonized cellulose fabric (CCF@RGO) was created for multimodal detection of bending motion and pulse signals[170]. As shown in Figure 8A, the CCF@RGO material was obtained by a high-temperature reduction process. Two stacked layers of this material could be sandwiched between Ecoflex layers to form an eco-friendly pressure sensor with high performance. The inserted diagrams respectively show that the sensor could be used to detect joint bending angles and measure pulse signals. Therefore, by arranging the pressure sensors on different positions of the human body, multimodal sensing of physical signals and physiological signals could be realized, thus providing comprehensive information of body status during physical movements.

Another noteworthy example is a bimodal fabric sensor that can simultaneously detect physical and physiological signals on the same sensor unit (as shown in Figure 8B)[171]. A nylon-coated graphene/$Fe_2(MoO_4)_3$/TPU-based micro/nano-porous fiber was manufactured and woven into a fabric. The core porous fiber in the fabric was used as a thermal resistance sensor to measure temperature, while the whole

Figure 8. Hybrid signal sensing textiles. (A) Schematic of fabric pressure sensors with high sensitivity based on CCF@RGO for pulse monitoring and body motion detection. Reproduced with permission[170]. Copyright 2020, Royal Society of Chemistry; (B) schematic of a bimodal fabric sensor that simultaneously detects temperature and pulse signals on one sensor unit. Reproduced with permission[171]. Copyright 2022, Elsevier; (C) schematic of a sericin-graphene decorated biocompatible sensor for strain and EMG detection. Reproduced with permission[55]. Copyright 2022, Wiley-VCH; (D) a skin-tight e-shirt integrating a strain sensor, an ECG sensor, and an EMG sensor for multiple signals monitoring. Reproduced with permission[172]. Copyright 2019, American Chemical Society; (E) a design concept of a highly integrated multimodal electronic garment and different working principles of the sensors attached. Reproduced with permission[173]. Copyright 2019, Wiley-VCH; (F) schematic of a bimodal textile sensor for pressure and gas detection. Reproduced with permission[176]. Copyright 2018, Wiley-VCH.

fabric was used as a single electrode TENG to deliver pulse output. The two output variables of the sensor were independent and did not interfere with each other, which could be used for bimodal sensing.

The combination of physiological and physical signal sensing can reflect multimodal hybrid information that cannot be displayed by only one signal detection. As an example, a multifunctional sensing fabric decorated with hydrophilic sericin-graphene ink was applied to simultaneous sensing of strain and EMG signals (as shown in Figure 8C)[55]. The textile could function as a strain sensor due to its strain-dependent resistance change and as an electrode with low contact resistance for detecting EMG signals. Strain and EMG sensors, based on this textile, were arranged on both human fingers and a wristband to identify three types of complex human motions that are impossible to be distinguished by a single strain sensor or EMG sensor.

Another example of a physical/physiological hybrid sensing system is a skin-tight electronic shirt integrating a strain sensor, an ECG sensor, and an EMG sensor on it. Direct stencil printing was used to apply a silver-fluoroelastomer-mixed composite ink onto an electrospun PVDF nanofiber sheet in order to form a nanofiber-reinforced elastic conductor[172]. Then the as-prepared elastic conductor was transferred onto a shirt using a press process to fabricate a strain sensor, an ECG sensor, and an EMG sensor on appropriate sites of the shirt (as shown in Figure 8D). After a wireless transmission module was integrated, the e-shirt could be used as a multimodal electronic fabric sensor system for long-term continuous monitoring of physiological activities.

To achieve a higher-level integration of sensing textile platforms, integrating multiple signals sensors on one garment may reflect a development trend of wearable fabric sensors in the future. For example, Kapoor *et al.* put forward a design concept of integrating multimodal fabric sensing units on one long-sleeved shirt (as shown in Figure 8E)[173]. They arranged resistance-type fabric sensors for pulse monitoring or fabric electrodes for measuring bioelectrical signals on the chest. They also placed humidity sensors based on impedance changes under the armpit to monitor sweat and weaved tactile input sensors based on capacitance changes on the inner arm. At the same time, the author proposed that all fabric sensors could be realized by fibers based on a continuous extrusion printing process and could be assembled into sensor arrays by commercial roll-to-roll weaving process for mass production.

The physical/chemical-type multimodal sensing textile is another aspect of hybrid signal sensing that is worth exploring. Many previous studies have already involved this idea. A well-known study is a multi-channel fully integrated sweat sensor reported by Gao *et al.*, which can selectively detect sweat electrolytes (Na^+ and K^+) and metabolites (glucose and lactic acid) with a temperature sensor embedded in to correct the response of the bio-enzyme sensing unit[174]. In addition, a multi-sensor device, integrating strain, ultraviolet light, and NO_2 gas sensing, was manufactured to conveniently monitor signals from the human body and environment[175]. However, previous efforts are mainly focused on non-textile platforms.

For textile-based sensing, Tang *et al.* proposed a bimodal sensor that detects pressure and gas concentration signals, which could be used to detect and distinguish tactile and olfactory stimuli on a single sensing unit (as shown in Figure 8F)[176]. The polyaniline (PANI) fabric was sensitive to the concentration of ammonia in the air, while the contact area between the fabric and the interdigital electrode was related to the pressure applied to the sensor. This allowed for the realization of the pressure-dependent resistance change. The resistance of the dual-mode sensing fabric increased with the increase of ammonia concentration in the environment and decreased with the increase of pressure applied. This allowed for the detection and distinction of both tactile and olfactory stimuli.

To the best of our knowledge, although hybrid signal sensing textiles have been widely studied, multimodal textiles that combine physical and chemical signals, as well as physical, physiological, and chemical signal multi-sensing, are rarely reported; therefore, further research is warranted.

APPLICATION IN HUMAN-MACHINE INTERFACE

The development of smart textile manufacturing processes has facilitated the rise of multimodal electronic textiles, providing a viable strategy for multimodal sensing of physical, physiological, chemical, and hybrid signals. Designed through fiber fabrication and textile forming techniques, multimodal electronic textiles provide a more natural interface for human-machine interaction, which is the key to connecting the human physical world and the digital space of machines to better support human life. The electronic textile with multimodal sensing function shows its potential application in intelligent human-machine interface and plays an important role in the coming intelligent era. In this section, we summarize the exciting applications of multimodal electronic textiles in health monitoring, motion recognition, gesture interaction, VR and AR control, and smart home.

Healthcare monitoring

A mainstream application of intelligent human-machine interfaces is the healthcare monitoring system. With the growing demand of consumers for improving the quality of life, more flexible and comfortable healthcare monitoring devices are attracting extensive attention in the consumer electronic market. The healthcare monitoring system can be divided into three categories based on its shape: patch[51,177,178], wearable device[155,179,180], and clothing[26,181]. Through monitoring various physiological indicators, including ECG, pulse, body temperature, and sweat components, and by algorithms on smartphones or cloud computing platforms, the health status of users can be comprehensively analyzed.

The patch is a widely used shape by various flexible sensors because it is easy to manufacture and has a flexible structure. In the field of healthcare monitoring, patch sensors are often used in physical signal sensing (such as stress, temperature, etc.). Film sensors and textile-based patch sensors are two types of patch sensors. Traditional film patch sensors are designed on flexible substrates such as PDMS. Zhou *et al.* designed a stress sensor patch[177] based on the magnetoelastic effect to generate electricity through the magnetic changes of the material. They attached the patch on the wrist to better fit the artery, and then it can measure weak signals such as wrist pulse. This design has better performance and a more flexible design but poor air permeability, so it is not suitable for large-area sensing. The textile-based patch sensor has better air permeability and wearing comfort. Fang *et al.* have designed a multi-layer textile-based stress sensor patch[178], in which the CNTs-coated cotton fabric substrate and the non-woven fluorescent ethylene propylene textile are used as the triboelectric layers, and the outermost layer is encapsulated by PDMS and fabric. The textile-based patch can be used to measure wrist pulse signals and send them to mobile phones to calculate blood pressure and other physiological information. At the same time, the device has good waterproof performance due to the outer PDMS layer, so it can be used by sportsmen such as swimmers and divers. Lin *et al.* designed a liquid metal-based conductive fiber by injecting liquid metal into a hollow flexible pipe, and a clothing surface embroidery antenna was designed by using a computer-aided design and embroidery machine[51]. This customizable embroidery pattern can transmit data from the temperature sensor on the clothing to the smartphones through the NFC function of smartphones or other devices, as shown in Figure 9A.

Wearable devices are a relatively mature technology at present, such as wristbands, smart bracelets, and smart glasses. With the developed system of wearable devices, sensors can work and transmit signals with smartphones or other personal terminals more stably. Wristband healthcare monitoring devices are mostly used for pulse monitoring. Convenience and small size are the main advantages of this monitoring device. In addition, the wristband can also be compatible with traditional wearable devices such as watches to achieve functional integration. Meng *et al.* developed a fabric-based stress sensor using silver-plated fabric as the substrate and conductive yarns wrapped with insulating fibers as triboelectric layers[155]. They designed a wrist strap and a headband that can detect and collect people's pulse signals by wearing these devices and connecting them to a smartphone, as shown in Figure 9B. Zhao *et al.* designed a flexible magnetoelastic material by dispersing solid nanomagnets in silica gel and obtained the magnetoelastic fiber through an adjustable nozzle[180]. By textile layout designing, the crossed conductive fibers form an induction coil and wrap the magnetoelastic fibers in it to make a stress sensor fabric. At the same time, a pulse-sensing

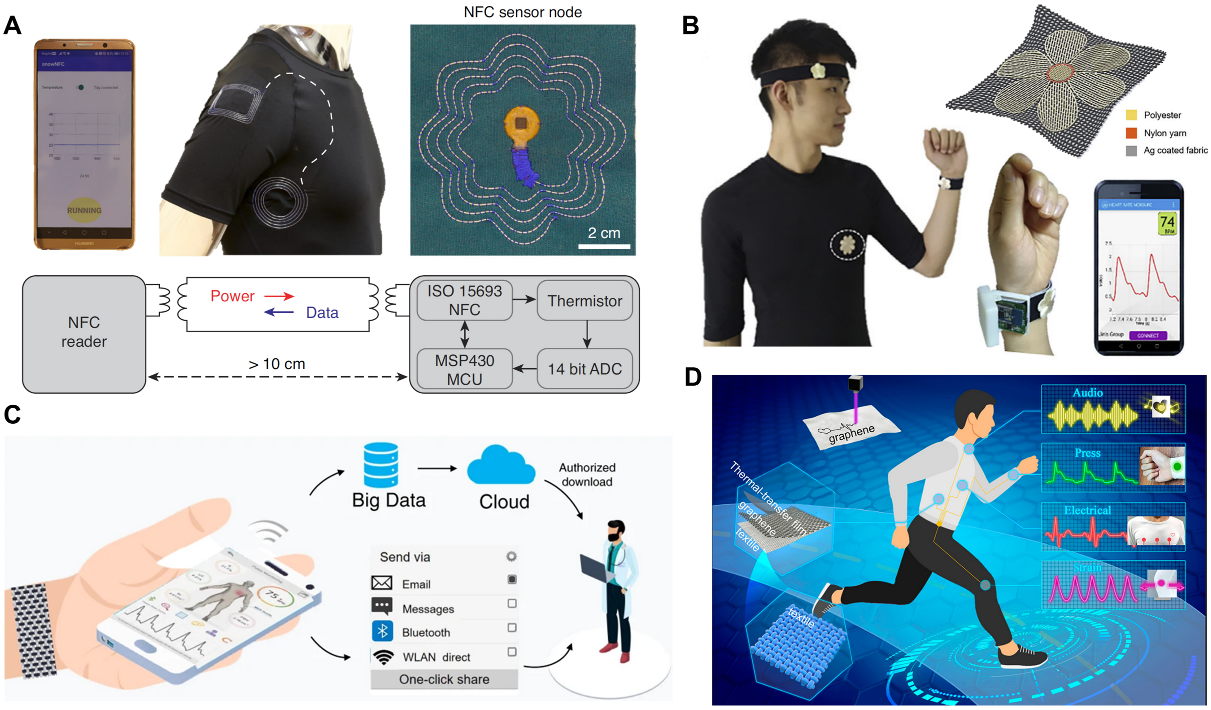

Figure 9. Application of multimodal electronic textiles in healthcare monitoring interface. (A) NFC antenna on clothing based on liquid metal conductive fiber for clothing surface temperature sensing. Reproduced with permission[51]. Copyright 2022, The Author(s), published by Springer Nature; (B) pulse monitoring wrist strap and pulse monitoring application displayed on a smartphone. Reproduced with permission[155]. Copyright 2019, Elsevier; (C) the pressure-sensing wrist strap based on magnetoelastic material for telemedicine systems and personal healthcare monitoring. Reproduced with permission[180]. Copyright 2021, The Author(s), published by Springer Nature; (D) intelligent healthcare monitoring clothing based on laser scribing with sound, pulse, ECG, and joint activity monitoring. Reproduced with permission[181]. Copyright 2021, American Chemical Society.

wrist strap and a telemedical system are designed based on this fabric, which can collect and analyze heart rate and pulse data, as shown in Figure 9C.

Since Google Glasses came out, intelligent eyewear devices have been attracting increasing attention. As a device near the head, eyewear healthcare monitoring devices can monitor more physiological signals. Homayounfar *et al.* sewed conductive silver wire on the surface of the hydrophobic and coated a layer of AgCl as an ionic interface to collect ophthalmic signals[179]. At the same time, a pressure sensor is formed by pasting silver-plated nylon fabric on both sides of cotton fabric to collect pulse signals. Based on the above devices, the bioelectricity pulse monitoring glass is designed to comprehensively monitor the health state of users.

Clothing is an indispensable part of daily life and a better form of a healthcare monitoring system. Smart clothing, integrated with various sensors and electronic systems, has a more comprehensive monitoring range and better-wearing comfort. He *et al.* coated graphite and lithium cobalt oxide (LCO) slurry on copper and aluminum wires, respectively, wrapped the two wires and then encapsulated them with polymers to develop fiber lithium-ion batteries[26]. At the same time, they prepared sweat ion monitoring fibers by coating Na^+ and Ca^{2+} selective membrane precursors on Ag/AgCl reference electrodes. Then, they designed a healthcare monitoring jacket with sensing, display, communication, and energy storage functions. It can monitor the ion concentration in the user's sweat in real-time and display the data on the jacket, while the textile-based battery can ensure its all-day work. Wei *et al.* presented a graphene-based textile based on laser scribing technology[181]. Through graphene oxide (GO) drop-casting, laser-scribing, GO removal, and thermal transfer processes, an item of clothing with a multifunctional graphene device has been obtained. This clothing contained a strain sensor, actuator, and ECG electrode, allowing the healthcare monitoring clothes to monitor pulse, ECG, body motion, and people's voices, as shown in Figure 9D.

Motion recognition

In the field of exercise healthcare, motion recognition is important to protect athletes from injury. By monitoring and analyzing joint activities[54,94,182], body posture[183], and micro movements[184-186] of users, the system can analyze their physical conditions in real time and provide a necessary warning. In the field of medical health, motion recognition can also be used for first-aid training[187]. Due to the inflexible mechanical characteristics of traditional sensors, it can be challenging to miniaturize and lighten motion recognition devices; however, textile sensors can effectively solve this problem.

Human activities are mainly carried out through various joints, such as knee activities during running and elbow joint activities during fetching; therefore, monitoring the activities of the main joints can help recognize most human motions. Wu *et al.* designed a highly integrated TENG by injecting liquid alloy and silicone rubber into a coaxial needle[94]. This liquid alloy/silicone rubber core/shell structure has better stability and higher sensitivity. Based on this TENG, they developed wearable devices such as wristbands and kneepads to monitor the activities of joints. When joints bend, sensors attached to them detect the activity and then translate it to electrical potential, as shown in Figure 10A. In addition, the simple manufacture makes it possible for mass production, which makes it possible to put on the consumer electronics market. Jiang *et al.* developed a stretchable, breathable, and stable nanofiber composite based on perovskite/poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) and styrene-ethylene-butylene-styrene (SEBS)[54]. Based on this composite, a textile-based triboelectric nanogenerator was designed through screen printing and electrospinning. This TENG has high sensitivity, searchability, and breathability and can be used in motion-recognizing devices such as kneepads, insoles, and elbow pads, as shown in Figure 10B. These sensors can also be attached to clothes and trousers, collecting joint motion and producing electrical signals to monitor joint activities throughout the day. Moreover, Li *et al.* developed a textile-based strain sensor by using sliver-coated yarn and nylon-wrapped spandex for the re-design layout of the textile[182]. The sensor provides a wide sensing range, and it can be strained up to 120%. They developed a motion-monitoring kneepad based on the sensor to collect activities of the knee during walking, running, and other exercises. Notably, it can collect more data than other flexible sensors based on its 3D sensing ability. Data collection and processing allow for the analysis of people's exercise habits and the provision of appropriate exercise advice, as shown in Figure 10C.

Human motion is not only related to joint activities but also related to the posture of the human body. The body posture determines the initial state and movable range of human motion. Therefore, monitoring human body posture and the force of the body surface can better monitor the state of body activity and can identify the potential risk of sports injury. Luo *et al.* used low-cost piezoresistive coating conductive wire to create a coaxial fiber by scalable and automated fabrication process[183]. Then, through the machine knitting process, they developed the textile-based stress sensors array, in which each pair of fibers are orthogonally overlapped to create a stress sensor unit. This sensor array can be used to collect pressure distribution information of large areas such as the plantar, back, or abdomen for posture analysis. Moreover, Lan *et al.* provided a stretchable fiber-shaped TENG (FTENG) for a wearable cardiopulmonary resuscitation training system[187]. The stretchable FTENG was obtained by coating silicon rubber and AgNWs ink on PU fiber, and it performed effectively in energy collecting during the stretch. They developed a wearable cardiopulmonary resuscitation training system based on the FTENG, which can monitor gestures during chest compression for cardiopulmonary resuscitation and recognize interruptions in chest compression.

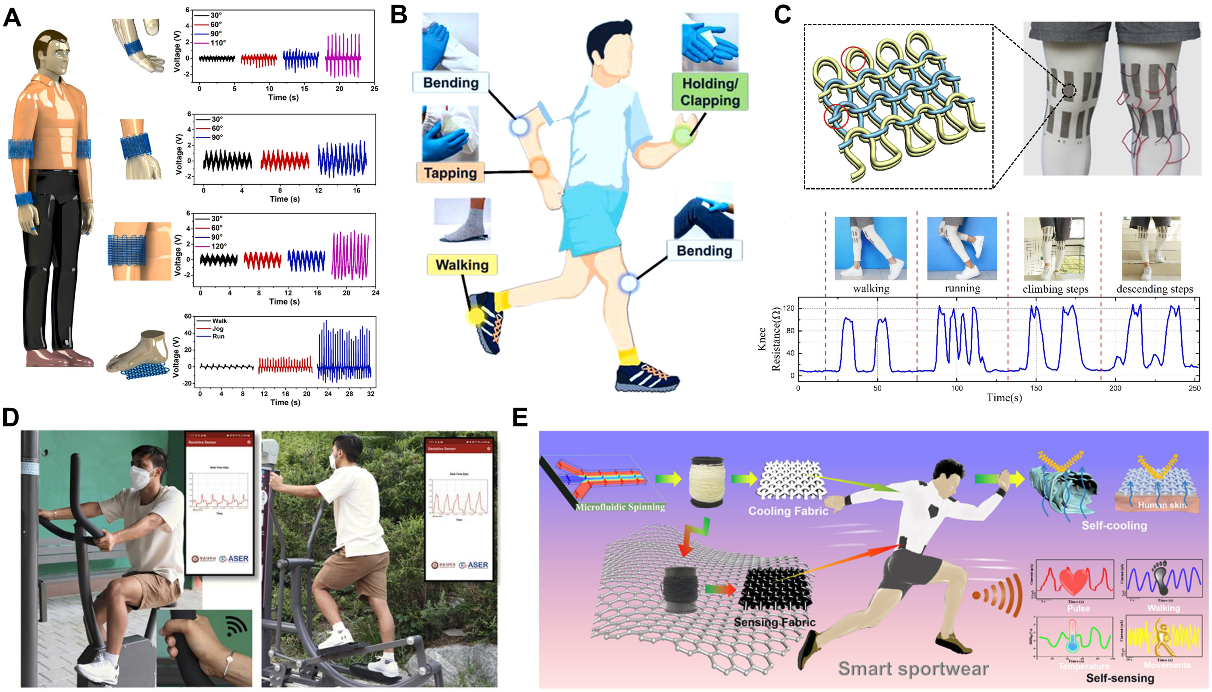

Figure 10. Application of multimodal electronic textiles in motion recognition. (A) Wristbands and insole based on TENG for human motion signal detection. Reproduced with permission[94]. Copyright 2022, Elsevier; (B) motion monitoring system consisting of elbow pads, knee pads, wristbands, and insoles based on textile-based TENG. Reproduced with permission[54]. Copyright 2022, Wiley-VCH; (C) kneepads based on textile-based strain sensors for monitoring signals of knee activities during walking and running. Reproduced with permission[182]. Copyright 2020, The Author(s), published by Elsevier; (D) personalized wireless motion detection system for detecting human body information. Reproduced with permission[185]. Copyright 2022, Elsevier; (E) smart clothing based on highly sensitive strain sensors for body motion monitoring. Reproduced with permission[186]. Copyright 2019, American Chemical Society.

In addition to joint activities and body movements, small movements (such as breathing and vocalization) may reveal the overall state of the body. However, these small movements can be difficult to detect and require highly sensitive sensors for identification. Yue *et al.* developed a highly stretchable carbon black/ thermoplastic polyurethane fibrous strain sensor by an efficient coaxial wet-spun approach[184]. This sensor has a large strain range, less response time, and ultrahigh sensitivity. Then, the strain sensor fiber was pasted on the surface of the neck, cheek, and finger to monitor micro-movements during talking, breathing, and head bowing. Signals collected from sensors showed that the strain sensor can recognize inhalation, exhalation, and other small-range movements of the head. Moreover, Sharma *et al.* created a flexible, highly sensitive piezoresistive material by depositing PANI-nanospines on hybrid hierarchical nanofibers, which were comprised of cellulose, PAN, and MXene[185]. They developed a personalized wireless motion detection system based on this fiber sensor, which can continuously monitor micro-motion signals such as breathing, talking, and pulse on a mobile platform for the diagnosis of cardiovascular diseases, as shown in Figure 10D. Hu *et al.* designed a highly sensitive strain sensor by a phase-separate-based microfluidic spinning method[186]. Based on this fiber sensor, they developed smart clothing for body motion monitoring, as shown in Figure 10E. This smart clothing can detect the micro-movement of the whole body, including breathing, chewing, swallowing, and talking, and record these signals through the application on a smartphone for further analysis.

Gesture interaction

Gesture recognition and interaction could mitigate the communication barriers between signers and non-signers, who are often unable to communicate through sign language due to its lack of universality as a conversation medium. Therefore, electronic textiles used for the recognition of hand gestures, sign-to-speech translation, and human-machine gesture collaboration have been broadly explored in recent years[88,188-192]. Liu *et al.* developed fiber-type sensors made of the Ecoflex/CNT composite and integrated them with gloves through sewing and printing to make a smart glove[193]. With the help of deep learning and control systems, a smart glove can precisely identify gestures with a high accuracy of 98.4%, as shown in Figure 11A.

The accurate recognition of gestures lays a solid foundation for gesture interaction and sign language communication. To meet the urgent demand for gesture interaction, Veeramuthu *et al.* proposed conductive fibers produced through electrospinning[194]. The conductive fibers are mounted on a commercial glove to design a hysteresis-free smart glove that converts biomechanical gestures into electrical signals to establish a wearable gesture interaction interface between people (as shown in Figure 11B). Furthermore, using a continuous, mass-producible, and low-cost spinning technology, a full-fiber auxetic-interlaced yarn sensor is designed by Wu *et al.*[195]. With the sensor array, an ultrafast full-letter sign-language translation glove is developed to translate daily dialogues and complex sentences, which can eliminate the communication barriers between signers and non-signers (as shown in Figure 11C). The overall accuracy of all letters is 99.8%, and the average recognition time is less than 0.25 s, demonstrating excellent potential for practical applications. Also, in sign-to-speech translation, Zhou *et al.* demonstrated a translation system consisting of yarn-based stretchable sensor arrays and a wireless printed circuit board[144]. Assisted by machine learning, the wearable sign-to-speech translation system allowed real-time translation of signs into spoken words with an accuracy of 98.63%.

In order to achieve intelligent development of machines, human-machine gesture collaboration is another focus of researchers in addition to gesture interaction between people. As shown in Figure 11D, Yang *et al.* reported scalable fiber electronics that could be designed as an optoelectronic synergistic smart data glove for human-machine interaction[196]. The smart glove could manipulate hands in virtual space and further control manipulators in real-life scenarios. Moreover, Zhang *et al.* designed a textile-based electronic device that can control machine hands by human hand gestures[197], showing the significant potential of wearable electronic textiles for reliable human-robot interaction.

VR and AR control

The rapid development of VR and AR technologies has paved the way for diverse applications in social activities, sports training, leisure and entertainment, games, and other fields[198-202]. Smart textiles represent an ideal human-machine interface for VR/AR applications. As shown in Figure 12A, a wearable human-machine interface smart textile, driven optically, was developed by Ma *et al.*, which could feel slight finger slip and classify the touch manners with the help of machine learning, achieving a recognition accuracy as high as 98.1%[203]. When the smart textile was attached to a doll, the virtual doll on the computer could express various emotional expressions according to the touch mode perceived by the real doll. To realize AI-enabled sign language recognition and VR space bidirectional communication, Wen *et al.* proposed an intelligent system comprising sensing gloves, an AI block, and a VR interaction interface[204]. It is worth noting that the intelligent system can recognize new sentences created by recombining new-order word elements, with an average accuracy rate of 86.67%. The results of sign language recognition in the real world were mapped in virtual space and translated into visual text or voice, showing the potential applications of intelligent sign language recognition and communication systems in the future [Figure 12B].

As the standard of living increases, people’s expectations for entertainment services are also increasing. Mapping human motion signals into virtual space to enable VR games is currently the key direction for the

Figure 11. Application of multimodal electronic textiles in gesture interaction interface. (A) A smart glove with a fiber sensor for hand gesture identification by deep learning networks. Reproduced with permission[193]. Copyright 2022, Elsevier; (B) schematic diagram of smart glove framework and working mode for gesture interaction. Reproduced with permission[194]. Copyright 2022, Elsevier; (C) sign-language translation glove for a signer communicating with a person. Reproduced with permission[195]. Copyright 2022, The Author(s), published by Springer Nature; (D) a smart data glove for human-machine gesture collaboration, including control of a virtual hand and control of a robotic hand. Reproduced with permission[196]. Copyright 2021, Wiley-VCH.

development of living entertainment. Zhang *et al.* proposed a triboelectric smart sock equipped with sensing capabilities of monitoring the user's physical status[56]. The smart sock could provide information about the user's gait, with an accuracy rate of 96.67%. This technology was used to create an immersive experience for VR/AR scene, as demonstrated in a VR fitness game with the smart sock as the control interface, as seen in Figure 12C. In addition, their research group also reported a glove based on triboelectric textile sensors with human motion sensing capabilities[205]. By employing machine learning technology, various gesture recognitions with an accuracy of 96.7% were completed in real-time by using a textile glove

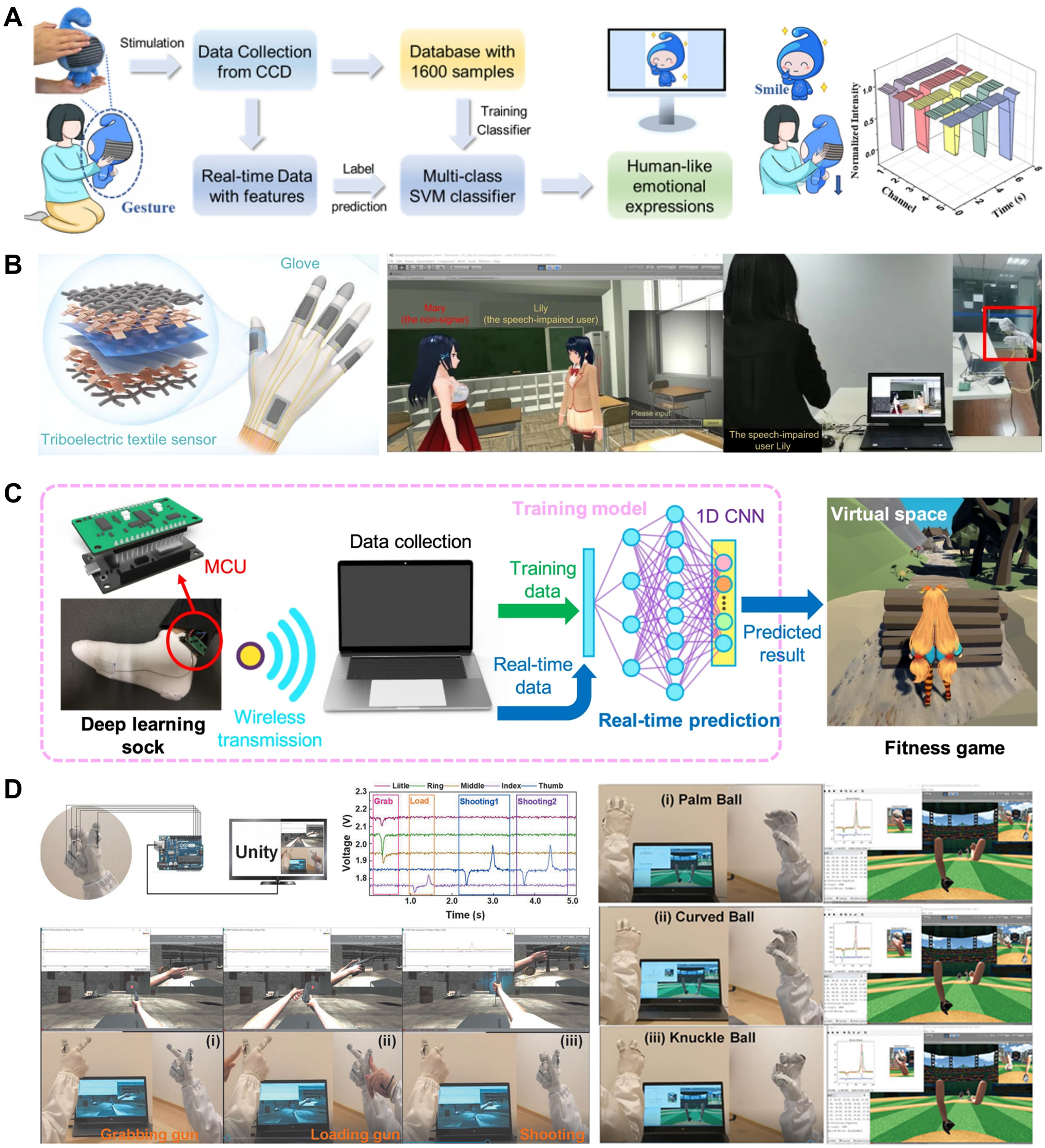

Figure 12. Application of multimodal electronic textiles in VR and AR control interface. (A) Emotional virtual interaction interface based on smart textiles. Reproduced with permission[203]. Copyright 2022, Donghua University, Shanghai, China; (B) intelligent interaction system for AI-enabled sign language recognition and VR space bidirectional communication using a triboelectric smart glove. Reproduced with permission[204]. Copyright 2021, The Author(s), published by Springer Nature; (C) smart socks for IoT-based gait analysis and VR fitness game. Reproduced with permission[56]. Copyright 2020, The Author(s), published by Springer Nature; (D) triboelectric textiles for gun shooting and baseball pitching in VR space of Unity. Reproduced with permission[205]. Copyright 2020, The Authors, published by WILEY-VCH.

to implement highly accurate virtual VR/AR game controls, including gun shooting and baseball pitching, as shown in Figure 12D. Also, for motion control within the game interface, Choi *et al.* weaved conductive fibers into a smart glove to reveal a pressure and gesture-discernible wearable controller for the VR game interface[206].

Smart home

A smart home connects various devices in the home through the Internet of Things technology to provide intelligent human-machine interaction[2,207,208]. It not only has the traditional living function but also has network communication, information appliances, and equipment automation to offer a full range of information interaction functions. Therefore, smart home has extensive research in the field of flexible electronic devices[209-211]. In the modern information society, home security is an important part of the smart home. He *et al.* showed a safety warning carpet based on 3D angle-interlock woven structural TENG[212]. The TENG textiles are mounted on a coded array, where the sole contacts and separates the textile to generate signals for transmission to the programming system. When someone walks by, an outsider will trigger the alarm without realizing it, as shown in Figure 13A. Further, in order to maintain home security and prevent intrusion by an outsider, Dong *et al.* developed an identity recognition carpet using 3D braided TENG[57]. The recognition system consisted of a carpet for energy harvesting, a multi-channel module for data acquisition, and a real-time platform for data analysis that enabled password path setting and real-time travel path recording (as shown in Figure 13B).

In addition to being used for home security, smart carpets have also shown application potential for escape and rescue. As shown in Figure 13C, a self-powered escape and rescue carpet was demonstrated by Ma *et al.*, which could pinpoint the location of survivors and indicate escape routes to assist victims in timely search and rescue[213]. Moreover, Niu *et al.* designed a multifunctional system based on bionic scales knitting triboelectric generators, which could realize personal outdoor rescue with wireless signal transmission[214].

Intelligent control of home devices to enrich human life is a hot topic in smart home research. A smart home system was reported by Zhang *et al.*, constructed for elderly health protection, intelligent control of household appliances, and security management of access control[215]. Chen *et al.* proposed an automated fabrication of a braided electronic cord to realize natural, convenient, and efficient user interfaces[216]. Because the braided electronic cord was a miniaturized form, it was suitable to be combined with various occasions in life, including a control music player App, emergency call, musical instruments playing, and control light (as shown in Figure 13D).

CONCLUSION AND OUTLOOK

Considering its salient merits, such as softness, comfort, wearability, and portability, electronic textiles with multimodal sensing functions have shown wider application potential than other wearable electronic devices, which are regarded as an important research direction for future human-machine interfaces. The electronic textiles reported at present can detect human body information in a full range from small signals such as pulse, ECG, and respiratory rate to large deformation signals such as joint bending and limb movements. They can also analyze the chemical components in human body fluids[54,155,163]. The durability of electronic textiles is crucial to ensure their long-term normal operation in practical applications. Electronic textiles are often required to be in contact with the skin and exposed to the external environment; therefore, the impact of human sweat, mechanical wear, and environmental factors on durability needs to be considered. At present, many electronic textiles with excellent durability have been reported through structural design, material selection, and packaging technology. Some of these textiles have a cycle life exceeding 10,000 cycles[149,178,217]. In order to promote the development of electronic textiles, we discuss the advanced manufacturing technologies in this review in detail. We cover information from the manufacturing of functional fibers (including coating, injecting, twisting, spinning, thermal drawing, and coaxial extrusion) to the textile forming process (including weaving, knitting, sewing, and non-woven). In

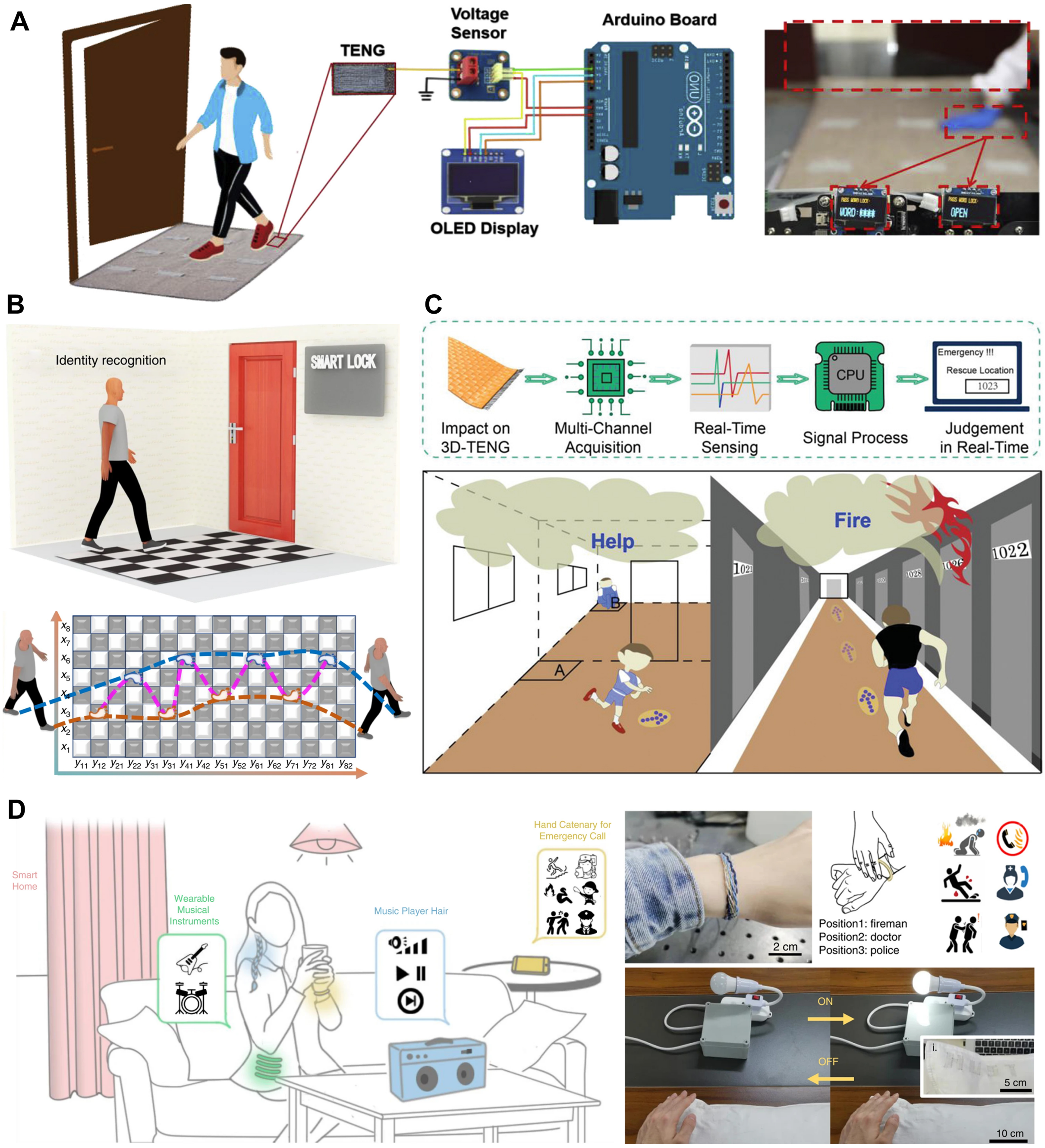

Figure 13. Application of multimodal electronic textiles in a smart home. (A) Working diagram of a safety warning carpet signal monitor. Reproduced with permission[212]. Copyright 2020, Elsevier; (B) a self-powered identification carpet for entrance protection, intrusion warning, and path tracking. Reproduced with permission[57]. Copyright 2020, The Author(s), published by Springer Nature; (C) a machine-fabricated flame-retardant triboelectric fabric to help fire escape and rescue in a home. Reproduced with permission[213]. Copyright 2020, Wiley-VCH; (D) a braided electronic cord-based interaction system for smart home control. Reproduced with permission[216]. Copyright 2022, The Author(s), published by Springer Nature.

addition, the multimodal sensing capabilities of electronic textiles in physical, physiological, chemical, and hybrid signals are summarized from the perspective of functional material selection, device structure design, and multimodal sensing mechanisms. Finally, the applications of multimodal electronic textiles in intelligent human-machine interfaces are highlighted, especially in health monitoring, motion recognition, gesture interaction, VR and AR control, and smart home.

Although great progress has been made in theoretical research and application demonstration of electronic textiles in recent years, there are still great challenges in their practical industrial application. The problems that need to be solved in the practical application of electronic textiles are listed in the following six aspects: materials, manufacture, sensing, circuit, wearability, and intelligence, as shown in Figure 14.

(1) Material: Flexible materials are the basis and core of flexible electronic devices, so the progress of electronic fabrics should first focus on the innovation of materials. In order to achieve a balance between softness, high sensitivity, and stability, the design and synthesis of new composite-sensitive materials are urgently expected to realize multimodal sensing of electronic textiles by modulating the amount of material doping and the interface binding state. The composite doping of flexible substrate materials and functional materials is currently the main way to achieve multimodal sensing[218]. Representative flexible substrate materials include silicone rubber, PDMS, polyurethane elastomer, hydrogel, and more[219,220]. Commonly used functional materials include 1D/2D/3D nanomaterials, conductive polymers, ionic liquids, and more[221,222]. However, the applicability, adhesion stability, and durability of these flexible substrates and functional materials with textile substrates need to be improved.

(2) Manufacture: At present, most functional yarns cannot be mechanically manufactured, which limits the large-scale mechanized production and practical application of electronic textiles. In addition, functional yarn encapsulation technology has been the focus of the manufacturing process, which is an important guarantee for the stability, woven and mechanical properties of electronic textiles. How to realize the integration and weaving of multimodal functional yarns and reduce the wear in machine weaving manufacturing is also a problem to be considered. The structural design and integration of functional yarns in commercial knitting machines is one way to achieve large-scale manufacturing of smart textiles[30,213,223]. Functional yarns, such as silver-plated conductive yarns, cotton yarns, PA yarns, PP yarns, and more, are typically available for commercial purchase, machine-knittable, and durable. However, when using this approach, the resulting strain sensing function is limited, which makes it challenging to integrate multimodal sensing. Additionally, the applicable sensing mechanism is single.

(3) Sensing: There is a lack of a fully integrated textile design solution that implements multi-signal sensing on a piece of clothing for monitoring more comprehensive information about human movement, physiology, health, environment, etc. When electronic textiles are used for human monitoring, multi-channel information is often measured at the same time, which poses a great challenge in terms of crosstalk-free, accurate decoupling of information and freedom from external interference. As we conclude in this review, most multimodal sensing textiles only implement a few stimulus-response functions. Further research is needed for the detection of information in the whole human body domain. In addition to functional integration, accuracy is a key issue to consider, particularly in human-machine control. This is especially important in industrial applications, where there are high risks involved.

(4) Circuit: In terms of circuits, mainstream electronic textiles still have not got rid of the traditional electronic circuit boards. Fiber shape sensors still need to be connected with rigid or semi-rigid circuit boards to achieve various detection functions. The development of intelligent clothing in the future requires the weaving of the circuit system. The connecting wires between devices and circuits have developed from traditional wires to high-performance conductive yarns or fibers. The whole clothing is used as a circuit board, and various electronic components are arranged on the clothing surface. Further, all kinds of basic components, such as resistors, capacitors, diodes, etc., will be fiberized, and then the complete circuit system

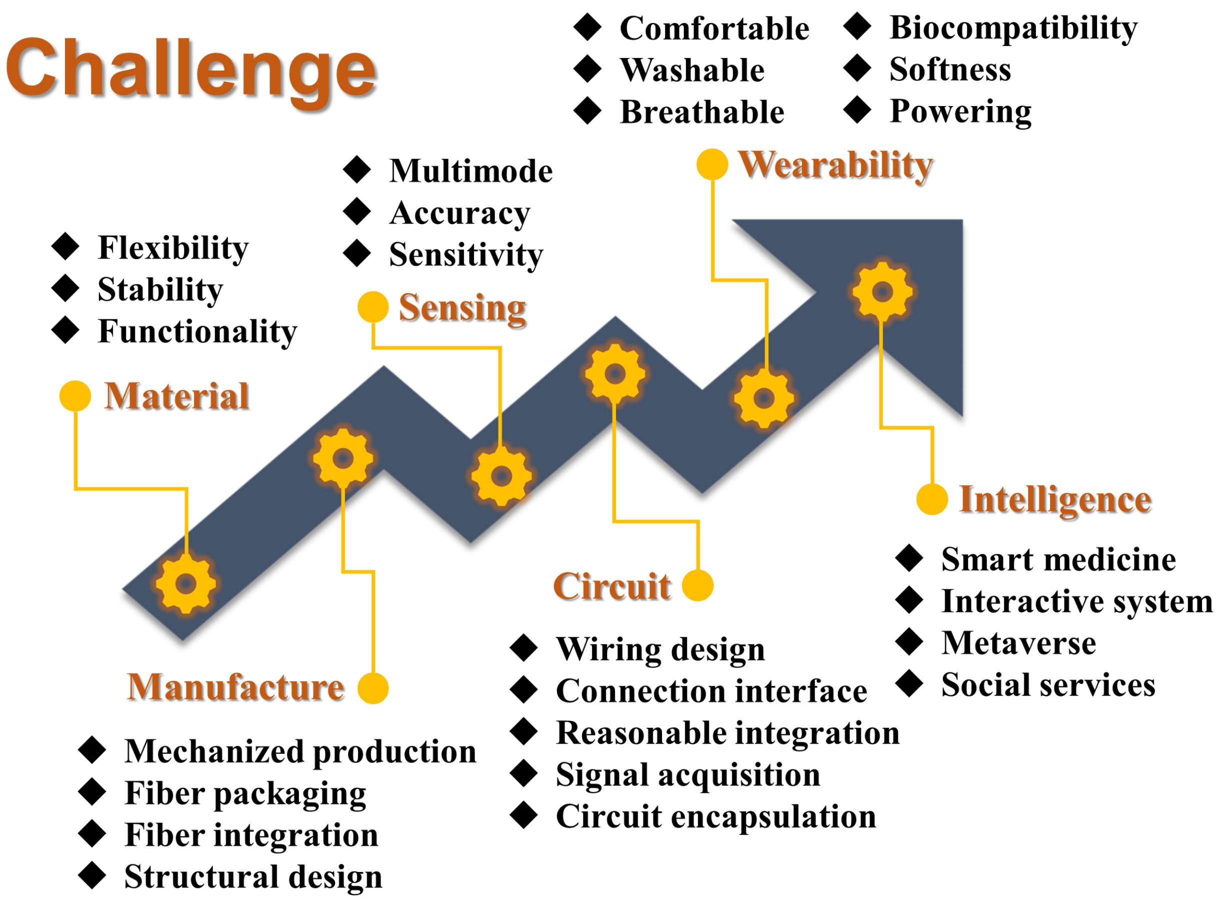

Figure 14. Potential difficulties and challenges of electronic textiles in the practical application of human-machine interfaces, including materials, manufacture, sensing, circuit, wearability, and intelligence.

can be realized only by fiber weaving. In addition, for woven circuits, there is a lack of mechanized processing like printed circuit boards, including circuit design, analysis methods and tools, and support for automated design and analysis. Placing hard or flexible circuit boards on textiles is currently the main method for collecting electronic textile signals, and the collection circuit system for fabric morphology still needs further development[28,224]. In recent studies, a non-printed integrated-circuit textile for wireless theranostics has been reported, promising to replace the traditional circuit board[225]. However, the stability, durability, versatility, and manufacturing process of this method need to be further verified.

(5) Wearability: Electronic textiles need to be in contact with human skin, which puts forward higher requirements for wearability. Comfortable, soft, anti-friction, breathable, biodegradable, and biocompatible materials are selected to comply with fabric wearability. In addition, smart textiles need to meet special mechanical properties, such as the ability to be bent, twisted, pleated, heavily pressed, washed, and more. Among these, the washability of textiles is the issue that needs to be focused on. In addition, powering is also a limiting factor for the development of electronic textiles, as the ordinary power supply cannot meet the wearability needs. In order to solve the two major problems of washing and powering, the self-powered sensing system based on waterproof fabric TENG and washable electronic textiles wirelessly powered by omniphobic silk-based coils has been reported[79,226]. In addition, fiber rechargeable batteries, fiber supercapacitors, fiber solar cells, fiber photovoltaic cells, etc., also provide feasible solutions for electronic texts harvesting wireless energy[227-229]. Current research has improved the single property of electronic

textiles; however, the balanced development of electronic textiles in wearability, multimode sensing, power supply, and other properties is a problem that needs to be solved.

(6) Intelligence: With the progress of artificial intelligence technology, electronic textiles have become an ideal platform for human-machine interfaces. This is accelerating the practical applications in fields such as smart medicine, interactive system, metaverse, and social services. In the future, we can expect to see even more innovative uses of this technology. In the context of IoT and the 5G era, data processing technologies are more advanced, such as cloud computing, big data, edge computing, etc. These technologies provide convenient conditions for rapid data collection and information processing. The combination of electronic textiles and artificial intelligence technology to construct a multimodal intelligent perception system is an effective way to achieve intelligence. The current research focuses on the processing and analysis of collected information by machine learning algorithms, including convolutional neural networks, artificial neural networks, support vector machines, and more[230,231]. However, further research is needed for efficient data fusion and decoupling of multimode information, as well as intelligent transmission and feedback of information.

Although some problems and challenges have hindered the practical application of electronic textiles in human-machine interfaces, their development potential as wearable electronic devices is enormous. With the progress of science and technology, we firmly believe that the current challenges faced by electronic textiles will be solved soon. To sum up, electronic textiles, as a new generation of wearable electronic devices, will play an important role in our current era of intelligent interconnection.

DECLARATIONS

Authors' contributions

Initiated the reviewing idea and outlined the manuscript structure: Wu J, Shi Q, Wei X
Conducted the literature review and wrote the manuscript draft: Wei X, Liang X, Meng C, Cao S
Involved in the discussion and revised the manuscript: Wu J, Shi Q
All authors have read the manuscript and approved the final version.

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

Not applicable.

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