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REVIEW

Revolutionizing digital healthcare networks with wearable strain sensors using sustainable fibers

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Abstract

Wearable strain sensors have attracted research interest owing to their potential within digital healthcare, offering smarter tracking, efficient diagnostics, and lower costs. Unlike rigid sensors, fiber-based ones compete with their flexibility, durability, adaptability to body structures as well as eco-friendliness to environment. Here, the sustainable fiber-based wearable strain sensors for digital health are reviewed, and material, fabrication, and practical healthcare aspects are explored. Typical strain sensors predicated on various sensing modalities, be it resistive, capacitive, piezoelectric, or triboelectric, are explained and analyzed according to their strengths and weaknesses toward fabrication and applications. The applications in digital healthcare spanning from body area sensing networks, intelligent health management, and medical rehabilitation to multifunctional healthcare systems are also evaluated. Moreover, to create a more complete digital health network, wired and wireless methods of data collection and examples of machine learning are elaborated in detail. Finally, the prevailing challenges and prospective insights into the advancement of novel fibers, enhancement of sensing precision and wearability, and the establishment of seamlessly integrated systems are critically summarized and offered. This endeavor not only encapsulates the present landscape but also lays the foundation for future breakthroughs in fiber-based wearable strain sensor technology within the domain of digital health.

KEYWORDS
advanced fibers, digital health, flexible electronics, strain sensors, wearables

1 | INTRODUCTION

The aging population has underscored the significance of healthcare and the well-being of the elderly, posing vital challenges.[1,2] Real-time physical perception by flexible and stretchable wearable strain sensors plays a vital role in constructing a digital health platform for real-time detection of body activities, interconnection of human health data, expansion of remote and efficient treatment, intelligent health management, and medical rehabilitation.[3–11] Such devices can instantly and directly identify physical responses and convert mechanical motion into an electrical signal with the merits of unrestricted large-scale deformation, outstanding lifetime and serviceability, great safety in contact with human skin, and adaptability to various body structures.[12–17] They surpass the limited sensing range, lack of flexibility, and non-wearability of traditional rigid sensors based on metals and semiconductors.[18–22] It ushers in a novel era for digital health by offering continuous monitoring of dynamic human health information alongside medical care and rehabilitation functionalities.

Sustainable fibers have found applications across a diverse spectrum, spanning electronics, energy conversion, and biomedicine.[23–29] Various fibers, such as cotton,[30–35] silk,[36–41] hemp,[42–44] *Calotropis gigantea*,[45–48] and nylon, have become a popular building block for wearable strain sensors attributed to their attractive structure and performance, such as excellent mechanical property, remarkable skin touch, structure controllability, high flexibility, excellent perspiration conductivity, and good biocompatibility. Multiple works and efforts have been made to manufacture conducive fiber by weaving functional fibers with sensing properties into textiles or implementing electric sensing elements on the fiber surface.[49–59] Fiber-based strain sensors have transcended the limitations of rigidity and adaptability to the human body's curvature.[60–66] They have evolved from experimental prototypes to commercial products like Google garments, capitalizing on their lightweight nature, flexibility, and comfort.[67] These contributions drive a technological revolution for the integrated human–machine ecosystem, smart human health detection and diagnosis, as well as intelligent health management and rehabilitation.

The emergence of digital health has revolutionized the medical health industry and provided innovative solutions to address health challenges and meet patients' requirements. The evolution of wearable fiber-based strain sensors has emerged as a significant factor in the sustainable development of digital health.[68] These sensors, integrated into human clothing, can monitor individual and public health for a long time, thereby achieving effective prevention and improved health management.[69,70] This can further reduce people's dependence on medical centers and contribute to sustainable development. Compared to traditional medical equipment, wearable fiber-based strain sensors have advantages of environmental friendliness, lighter weight, less power consumption, and less waste generated during processing.[31,71] In addition, fiber-based sensors can minimize the need for unnecessary medical examinations, which makes medical healthcare more affordable and accessible. This can achieve economic sustainability by reducing the medical costs of individuals and society.[72,73] In essence, these strain sensors open new sights in a more sustainable future by improving health, reducing the impact of medical consumables on the environment, and making healthcare more affordable.

This review provides an exhaustive overview of the research advancement in fiber-based wearable strain sensors, encompassing material functionalization, device fabrication, and practical applications within the realm of digital health. It introduces various fiber functionalization methods, including spinning technology, surface functionalization, and in situ carbonization techniques. The sensing mechanisms are categorized based on strain sensor modes, namely, resistive, capacitive, piezoelectric, and triboelectric sensors, with a thorough analysis of their strengths and limitations. The potential applications in body area sensing networks, intelligent health management, medical rehabilitation, and multifunctional healthcare systems are also evaluated. Additionally, the indispensable parts of the construction of digital health networks, including data collection and machine learning, were systematically presented. Finally, the review critically summarizes existing gaps and future challenges, anticipating their eventual real-world implementation.

2 | MATERIAL FUNCTIONALIZATION

Conductive fibers play an increasingly vital role in wearable strain sensors, providing a convenient, environment-friendly, and cost-effective means to endow strain sensors with flexibility and sensing ability. Compared with conventional wires, conductive fibers possess lighter weight, less power consumption, and less waste, providing more affordable and accessible wearable strain sensors for sustainable digital health. Conductive fibers can be produced via spinning technology, functionalization of fiber surface, and in situ carbonization. These primarily involve the integration of conductive materials into nonconductive materials or modification of existing fibers. The spinning technology allows the development of conductive fibers with adjustable conductivity, diameter, and shape by changing parameters such as spinning methods, material concentration, spinning pinholes, and spinning speed. However, achieving high electrical conductivity proves challenging due to the necessity of amalgamating more than two materials. Functionalization of fiber surfaces, such as dip-coating and chemical deposition coating, can endow fiber with good electrical conductivity by combining carbon-based materials, conductive polymers, and metals with fibers. Nevertheless, conductive fibers face the challenge of deterioration in conductive stability, durability, and binding force during prolonged usage and in long-term use and pose difficulties in washing. In addition, obtaining conductive fibers with high electrical conductivity by using in situ carbonization technology to induce structural transformation is also an emerging method, whereas it will deteriorate the mechanical properties and flexibility of fibers for long-term use. In addition to electrical conductivity, important characteristics of conductive fibers integral to wearable strain sensors include flexibility, durability, and compatibility with substrates. Flexibility can ensure that fiber-based strain sensors conform intimately to the human skin amidst continuous bodily dynamics and preclude discomfort from movement. The durability of conductive fiber is very important to guarantee that the wearable strain sensor can withstand the rigors of daily wear and resist performance degradation after washing. The compatibility of conductive fiber with substrates can facilitate the seamless integration of conductive fiber into wearable fiber-based devices without affecting its overall functionality and wearing comfort. Furthermore, other properties, such as stretchability, washability, and biocompatibility, are also of significant importance, depending on the specific applications of wearable fiber-based strain sensors.

2.1 | Spinning technology

Spinning techniques for producing conductive fibers, such as wet spinning, mechanical spinning, electrospinning, dry spinning, and thermal drawing, are a promising and sustainable field.[74–82] Wet spinning, in particular, is a traditional and cost-effective fabricate technology that allows for easy industrialization. In this process, a solution is meticulously introduced into a coagulation bath via a microporous spinneret. The coagulation bath facilitates the removal of water from the solution, leading to the solidification of fibers. A previous work reported the wet-spinning coupled with chemical processing (Figure 1A) was illustrated for continuous preparation of graphene oxide (GO) fibers.[83] It was achieved by the introduction of ammonia into GO solution within an innovatively developed coagulation bath comprising methanol and acetone (volume ratio = 1:2). The resulting prepared conductive fiber exhibits impressive mechanical properties, including a tensile strength of 217 MPa and Young's modulus of 5.5 GPa at an elongation of 5.6%. Moreover, it demonstrates good electrical conductivity of 1611 S/m. Another conductive-belt-like fiber for strain sensing was developed from single-walled carbon nanotube (CNT) by employing coaxial wet spinning method (Figure 1B).[84] This fiber, characterized by dimensions of 1050 μm in width and 200 μm in thickness, exhibits superior electrical conductivity of 2804 S cm^{-1}. This fiber, which is coated with a highly stretchable thermoplastic elastomer, can be utilized as deformable and wearable strain sensors capable of detecting and tracking the complicated movements of objects. As shown in Figure 1C, a composite fiber integrating 2D transition metal carbides/nitrides (MXene) with polyurethane (PU) was synthesized by employing the coaxial wet-spinning approach, showing good conductivity and high stretchability.[85] The MXene/PU fiber shows a high gauge factor (GF) of ≈12 900 and a large sensing range of ≈152%. The conductive fibers can be knitted into a one-piece elbow sleeve, which can be applied in digital health to detect various motions from elbows. Additionally, other composite fibers, such as carbon black (CB)/CNT,[86] MXene/aramid nanofibers,[87] aramid nanofibers/polypyrrole/CNT,[88] or thermoplastic polyurethane (TPU)/CNT,[89] can also be produced using wet-spinning for the assembly of strain sensors. These fibers, made of conductive and elastic materials, have good mechanical properties.

In addition to wet spinning, mechanical spinning has also emerged as a viable method for producing strain-detectable fibers. For instance, a conductive yarn with a unique spring-like structure, composed of self-assembled loops, was successfully prepared by slightly over-twisting CNT fibers (Figure 1D). The yarn demonstrates remarkable axial stretchability, is capable of withstanding strain of up to 285% while maintaining stable spring constants, and has great electrical conductivity.[90] Alternatively, elastic conductive fibers produced by using mechanical spinning to wind-align multi-walled CNT sheets on rubber fibers with high and stable electronic properties during stretching were also reported (Figure 1E). It illustrates no obvious damage in the fiber structure under repeated stretching by 100% for over 100 cycles and maintains good electrical resistance (0.27 kΩ/cm).[91] With high stretchability and conductivity, these elastic conductive fibers hold great promise for applications in flexible, stretchable, and wearable strain sensors.

Electrospinning is a straightforward and efficient technique for fabricating micro–nanoscale conductive fibers. It uses a conductive polymer solution or polymer solution with conductive fillers such as graphene, CNT, and silver (Ag) nanoparticles (NPs), which are stretched to form conductive nanofibers under the influence of an electric field. Another way to prepare conductive nanofibers is by coating the nonconductive nanofibers from polymer solution with conductive materials via posttreatment. For example, highly aligned electrospun poly(vinylidene fluoride-*co*-trifluoroethylene) P(VDF-TrFE) fibers were achieved via a stretching-induced alignment method (Figure 1F).[92] These fibers show a high average output voltage (84.96 mV) with 80% alignment. Textiles crafted from these aligned electrospun P(VDF-TrFE) fibers are adept at detecting body gestures such as the articulation of elbow joints and the vector of arm swings. In another study, as depicted in Figure 1G, an electrospun TPU fiber was subsequently

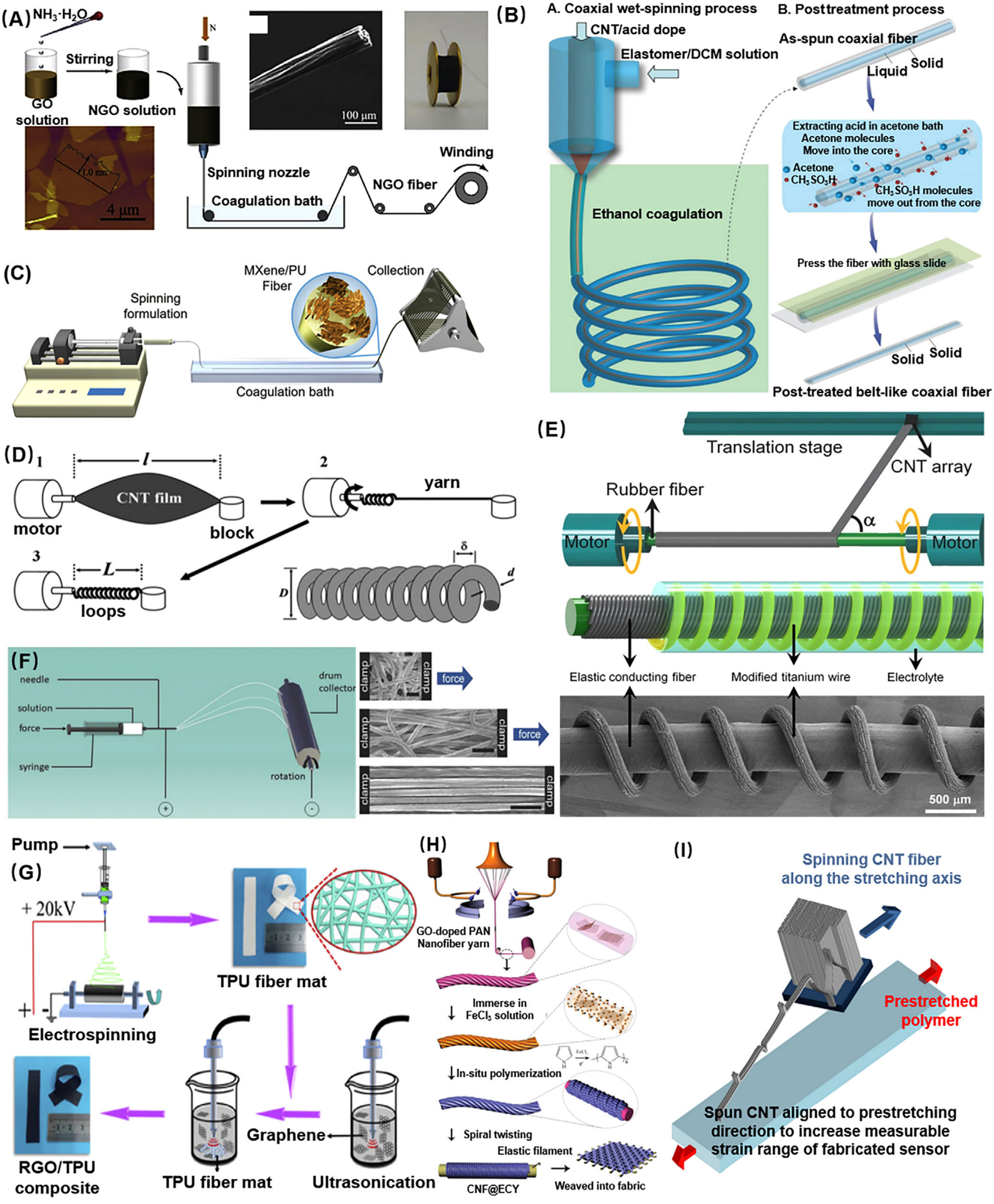


FIGURE 1 (A) The process of preparing graphene oxide (GO) fibers through wet-spinning method. (B) Wet-spinning technology for the preparation of thermoplastic elastomer and carbon nanotube (CNT) composted fibers. (C) The fabrication of coaxial fibers consisting of metal carbides/nitrides (MXene) using wet-spinning. (D) The procedure for fabricating CNT rope by spinning technique. (E) Schematic diagram of mechanical spinning for elastic conductive fibers. (F) The production of highly oriented electrospinning fibers via stretching-induced alignment. (G) Graphene-modified thermoplastic polyurethane (TPU) fibers from electrospinning method for strain sensing. (H) The fabrication of GO-doped PAN nanofibers by using double conjugate electrospinning technology. (I) Dry-spinning process for highly oriented

adorned with reduced graphene oxide (rGO).[93] The electrical resistance of the rGO-decorated TPU mats shows a marked escalation concomitant with the duration of ultrasonic treatment. The electrical resistance can reach about 0.11 ± 0.03 Ω m by the two-probe method after ultrasonication (power is 380 W) for 30 min and can tolerate tensile strain up to 200%. Such strain sensors are poised for integration into intelligent wearable devices, capable of registering large and subtle human movements. Additionally, the concept of double conjugate electrospinning technology was previously employed to prepare GO-doped PAN nanofibers (Figure 1H) and in situ polymerization was employed to coat polypyrrole on the nanofiber surface.[94] The resultant conductive nanofibers were then coiled around elastic yarns to create composite yarns. The composite yarns can be seamlessly interwoven into textiles to create a body-area sensing network. Several other modified electrospinning techniques have been demonstrated to yield similarly strain-responsive fibers.[95–97] Previous studies have also utilized dry spinning[76] and melt spinning[98] to fabricate strain-detectable fibers. As shown in Figure 1I, an ultrahigh stretchable and wearable device was developed using highly aligned CNT fibers fabricated through dry spinning.[76] These devices not only present high sensitivity, large sensing range (>900%), and exceptional durability, but they can also be integrated into a myriad of motion detection systems where their utility is circumscribed by their strain capabilities.

Thermal drawing technique possesses special advantages of the ability to co-draw multiple materials and adjustable structures. A capstan applies an external force to pull the softened or molten materials made of different components in a furnace into fibers, and the size of fibers can be controlled by altering the drawing temperature, feeding speed, and drawing tension (Figure 2A).[106] In 2018, Qu et al. proposed to prepare kilometers-long and superelastic electronic fibers by continuous thermal drawing method to stretch materials assembled with high-viscosity thermoplastic elastomers, metals, or semiconductors.[99] These fibers show a large range of sustained strains beyond 500% and ability to be stretched and twisted without losing structural integrity. The author demonstrated an alternative and simple platform for manufacturing electronic fibers that can be applied to medical, implantable, and wearable devices. After that, Kanik et al. fabricated a tendril-like fiber-based artificial muscle with high-density polyethylene, cyclic olefin copolymer elastomer, and poly(methyl methacrylate) (Figure 2B).[100] It has more than 12 000 cycles under 20% strain, can lift more than 650 times its own weight, and can withstand 1000% strain. By designing and printing a weight-lifting artificial limb to lift dumbbell, verifying the possibility of application in robotics, haptics, and prosthetics for digital health. In 2020, Leber et al. developed stretchable liquid metal transmission lines by injecting liquid metal into a thermoplastic elastomer via thermal drawing technique (Figure 2C).[101] These soft and stretchable liquid metal transmission lines integrated with tens of liquid metal conductors can identify simultaneously multiple mode, magnitude, and position of external pressure and stretch. Furthermore, a large fabric (50 × 50 cm) equipped with a 10-m-long soft transmission line was fabricated to demonstrate the potential for deciphering convoluted mechanical stimulation.

Figure 2D showcases the preparation of hundreds-meter fibers, adorned with an array of both regular and intricate surface patterns, achieved through direct imprinting in the thermal drawing process.[102] This technique achieved high-resolution micro and nanostructures upon the fiber surface. A wearable, self-powered, multipoint touch sensor integrated with patterned functional fiber-based triboelectric nanogenerator (TENG) has demonstrated superior efficacy compared to TENGs utilizing flat-surfaced fibers, showing the bright future of direct imprinting in thermal drawing technology in wearable electronics and intelligent textiles. Similarly, super-elastic fibers used as TENG were fabricated by injecting liquid metal gallium indium (GaIn) eutectic alloy into hollow styrene–ethylene–butylene–styrene (SEBS) fibers drawn by thermal drawing method (Figure 2E).[103] This fiber shows outstanding flexibility and excellent conductivity under 1900% strain, in addition to their capacity to endure a 1.5 kg load or impact from a free fall at a height of 0.8 m. They were attached to sports gear to monitor sports performance while enduring sudden impacts, providing more possibilities to achieve large-area, high-dimensional device integration for digital health. As shown in Figure 2F, stretchable piezoelectric fibers were prepared by thermal drawing the SEBS-encapsulated $BaTiO_3$ NPs-loading P(VDF-TrFE) and carbon-loaded polyethylene containing four copper wires.[104] The high sensitivity was achieved when the fiber is mounted on a Mylar membrane,

CNT fibers. *Source*: (A) Reproduced with permission: Copyright 2018, Elsevier.[83] (B) Reproduced with permission: Copyright 2018, Wiley-VCH.[84] (C) Reproduced with permission: Copyright 2020, Wiley-VCH.[85] (D) Reproduced with permission: Copyright 2018, Elsevier.[90] (E) Reproduced with permission: Copyright 2014, Wiley-VCH.[91] (F) Reproduced with permission: Copyright 2018, Wiley-VCH.[92] (G) Reproduced with permission: Copyright 2016, Elsevier.[93] (H) Reproduced with permission: Copyright 2019, Wiley-VCH.[94] (I) Reproduced with permission: Copyright 2015, American Chemical Society.[76]

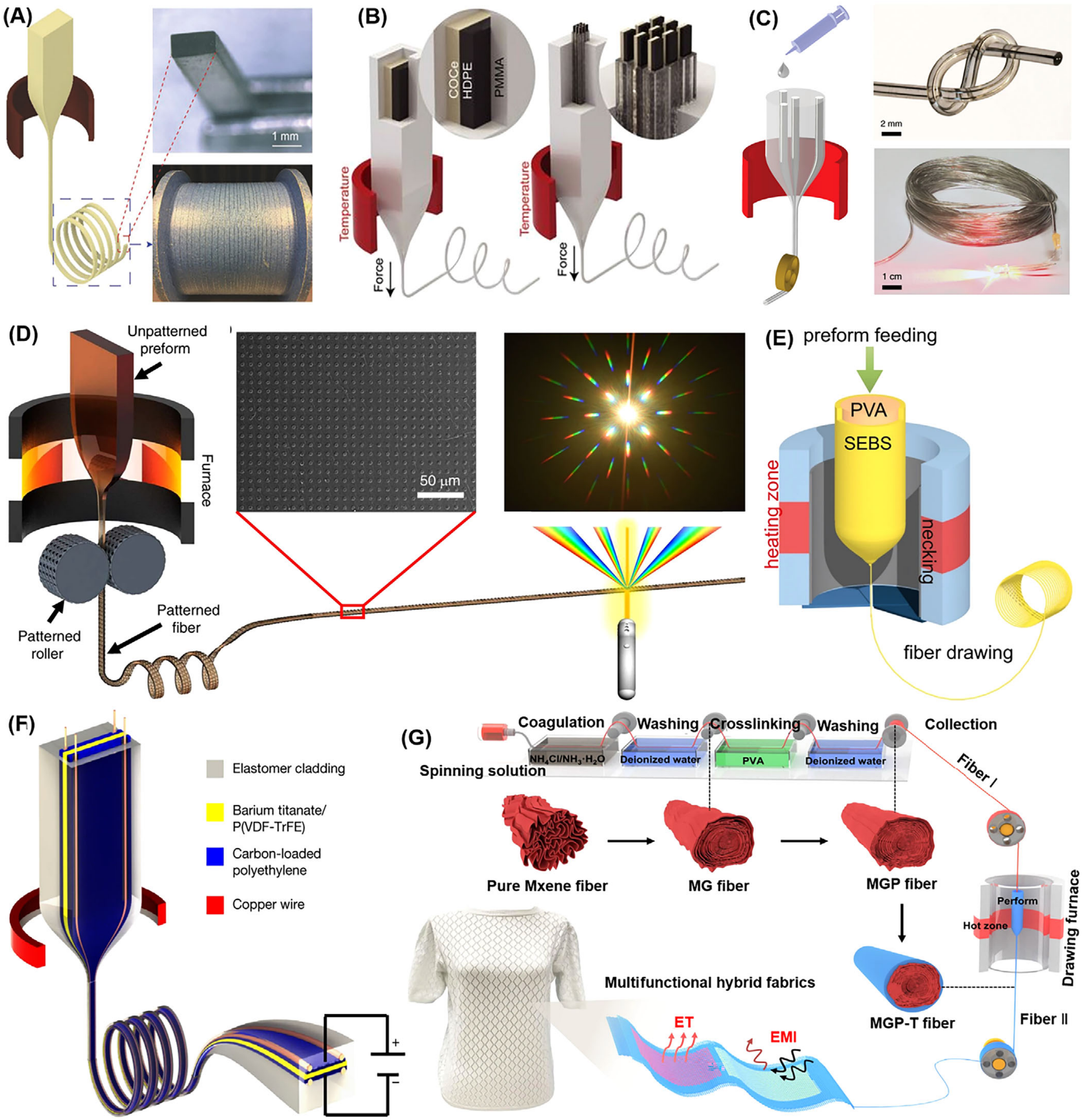


FIGURE 2 (A) Schematic of a preform drawn into a superelastic electronic fiber along with an optical microscope image of fiber. (B) The procedure of fiber-based artificial muscle via two-step thermal drawing. (C) Schematic of the thermal drawing method for preparation of fiber made of metal-thermoplastic elastomer and photograph of conductive fiber used to light the bulb. (D) Illustration of the procedure of preparing 2D diffraction grating on fiber surface using thermal drawing technique, SEM image, and diffraction patterns of fibers. (E) Schematic diagram of fiber drawing process in the thermal fiber drawing tower. (F) The production of piezoelectric fiber via thermal drawing technique. (G) Fabrication of ultracompact metal carbides/nitrides (MXene) fiber using wet spinning and thermal drawing that can be integrated into textiles. *Source*: (A) Reproduced with permission: Copyright 2018, Wiley-VCH.[99] (B) Reproduced with permission: Copyright 2019, Science.org.[100] (C) Reproduced with permission: Copyright 2020, Springer Nature.[101] (D) Reproduced with permission: Copyright 2020, Springer Nature.[102] (E) Reproduced with permission: Copyright 2021, Springer Nature.[103] (F) Reproduced with permission: Copyright 2022, Springer Nature.[104] (G) Reproduced with permission: Copyright 2022, Springer Nature.[105]

allowing the sensors can efficiently detect audible sounds. In addition, the woven Twaron/cotton fabric with single functionalized fiber enables sound-direction detection, sound transmission, and heartbeat monitoring. Figure 2G shows ultracompact MXene fibers were developed via wet-spinning method and thermal drawing technique,[105] the fiber exhibits high electrical conductivity, formidable tensile strength, and extraordinary toughness. Moreover, textiles of meter-scale dimensions, crafted from these ultracompact fibers, were constructed to demonstrate the potential of this strategy for applications in electromagnetic interference shielding and personal thermal regulation within the digital health sphere.

2.2 | Functionalization of fiber surface

Functionalization of fiber surface is a low-cost, low-energy consumption, and effective method that mainly adopts physical and chemical techniques to deposit fibers with conductive materials.[107] This suite of processes includes, but is not limited to, dip-coating, chemical plating, electroplating, and printing techniques.[108–112] Strain sensors that utilize the functionalization of fiber surfaces offer several advantages such as a wide working range and exceptional sensitivity. One example is the modification of Kevlar fiber using poly(styrene-block-butadiene-styrene) (SBS) polymer, followed by coating silver precursors into the SBS layer. Then, a large amount of Ag ions experience a direct reduction into Ag nanoparticles (AgNPs) within the SBS polymer, fabricating conductive fibers (Figure 3A).[113] These conductive fibers exhibit excellent electrical properties, as evidenced by a resistance of 0.15 Ω/cm, attributable to the dense network of electrical pathways provided by the AgNPs. They also exhibit commendable resilience to repetitive mechanical stress, as verified by enduring 3000 bending cycles. Similarly, another work adopted a dip-coated method to develop an Ag nanowire (AgNW)/PU composite fiber with a sheath–core structure (Figure 3B).[114] The rich AgNPs formed a dense shell on the fiber surface with the assistance of the adhesive properties of the pre-cured PU. The resulting strain sensor displays excellent sensitivity (GF = 9557), durability, and ultrastability (over 10 000 cycles at a strain of 50%). Additionally, previous work reported a strain sensor characterized by high breathability and robust anti-interference capabilities, based on a copper-deposited viscose fiber synthesized via the polymer-assisted metal deposition (PAMD) method (Figure 3C).[115] The PAMD process involved polymer functionalization, ion pairing with palladium moieties as an activation step, followed by a chemical reaction to yield a dense congregation of metal NPs on the substrate's surface. In one research, hierarchical hairy conductive fibers with highly stretchable and conductive properties were fabricated by printing microscale cylinder-shaped patterns on the surface of PU/AgNW fibers using a pressure-assisted imprinting technique.[116] The prepared strain sensor possesses remarkable stretchability (<200%), sensitivity to diverse stimuli (including pressure, stretching, and bending), and can withstand multiple cycles of testing across various modes (<2200 cycles for each stimulus). Another work developed a stretchable and conductive fiber by coating cobblestone-shaped gold NPs on the CNT/MXene/PU fiber surface for multifunctional sensing (Figure 3D).[117] The fiber has high elasticity, stretching up to 250%, and good conductivity (≈2 S/cm), showing its auspicious potential in the realm of fiber-based wearable strain sensors.

Furthermore, this concept is readily adaptable to yarns modified with graphene and CNT. Intriguingly, the combination between elastic and conductive yarns can form a helix structure, which enables strain-sensing ability through the dynamic interplay of contact and separation within the conductive yarns. As depicted in Figure 3E, a graphene-coated composite yarn consisting of two disparate strands of yarns, silk and PU, is used to establish a core–sheath structure.[118] During the stretching process, the elastic yarn drives the separation between the adjacent fibers in spiral shapes, endowing it with strain-sensing ability. The sensor exhibits fast response (≈80 ms), remarkable durability (>1500 cycles), and a linear response characteristic (R^2 = 99.8%) across its entire operational range (from 0% to 120% strain). Alternatively, a work reported a graphene-coated composite yarn comprising a highly elastic PU core with polyester fibers wound helically.[119] The elastic PU triggers the separation of spring-like covering yarns during the deformation process, leading to a variation in electrical resistance. The strain sensor shows super-stretchability (up to 200% strain), excellent durability (>10 000 cycles), and the potential to detect body motions. Previous research developed CNT-coated cotton yarns and silicone fibers sheathed with polytetrafluoroethylene threads for strain detection.[120] Similarly, a safely functionalized jute fiber was coated with CNT to prepare conductive fibers after the treatment with citric-acid-assisted oxygen plasma.[121] The fiber shows great electrical conductivity (5 S/m) and tensile strength (55 MPa). These fibers can be used as conductive fillers in various electrical and electronic devices, as well as in polymer composites as conductive fillers. Additionally, strain sensors based on functionalized fiber with CNT have also been developed.[122,123] Moreover, there is still much research to prepare strain sensors by modifying insulating fiber materials through spinning technology, functionalization of fiber surface, and in situ carbonization. The fabrication and performance of these strain sensors are summarized in

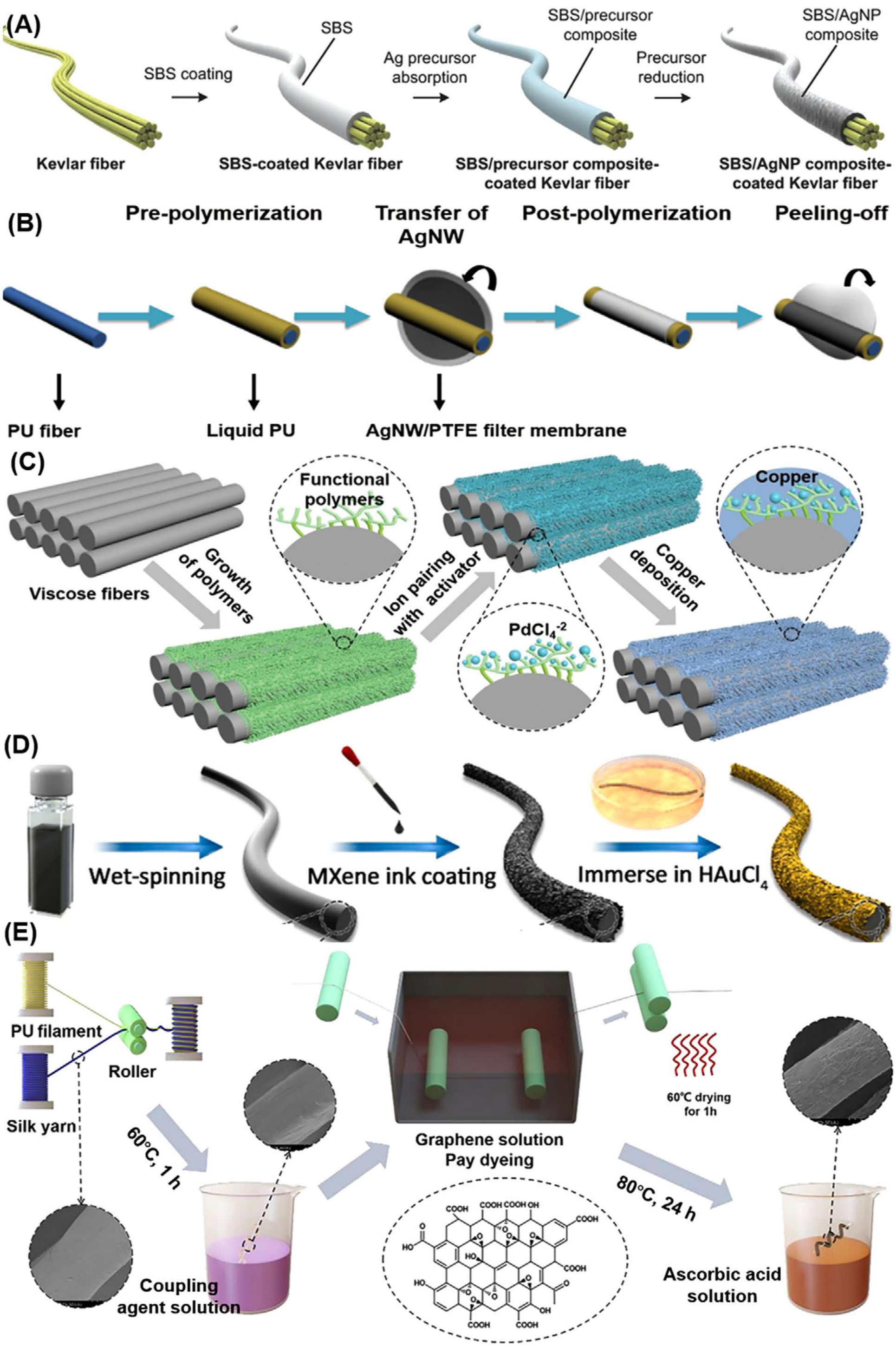


FIGURE 3 (A) Illustration of poly(styrene-block-butadiene-styrene) (SBS)/Ag nanoparticles (AgNPs) composite-coated Kevlar fibers for strain sensor. (B) Illustration of fabrication of the Ag nanowire (AgNW)/polyurethane (PU) composite fiber with a sheath–core architecture via dip-coated method. (C) Schematic diagram of the fabrication of copper-deposited viscose fiber. (D) Schematic diagram of the fabrication strategy of stretchable and conductive carbon nanotube (CNT)/metal carbides/nitrides (MXene)/PU fiber with gold nanostructure for multifunctional sensing. (E) The production of graphene-coated silk/PU fibers core–sheath structure for strain sensing. *Source*: (A) Reproduced with permission: Copyright 2015, Wiley-VCH.[113] (B) Reproduced with permission: Copyright 2018, American Chemical Society.[114] (C) Reproduced with permission: Copyright 2021, Wiley-VCH.[115] (D) Reproduced with permission: Copyright 2021, Elsevier.[117] (E) Reproduced with permission: Copyright 2023, Elsevier.[118]

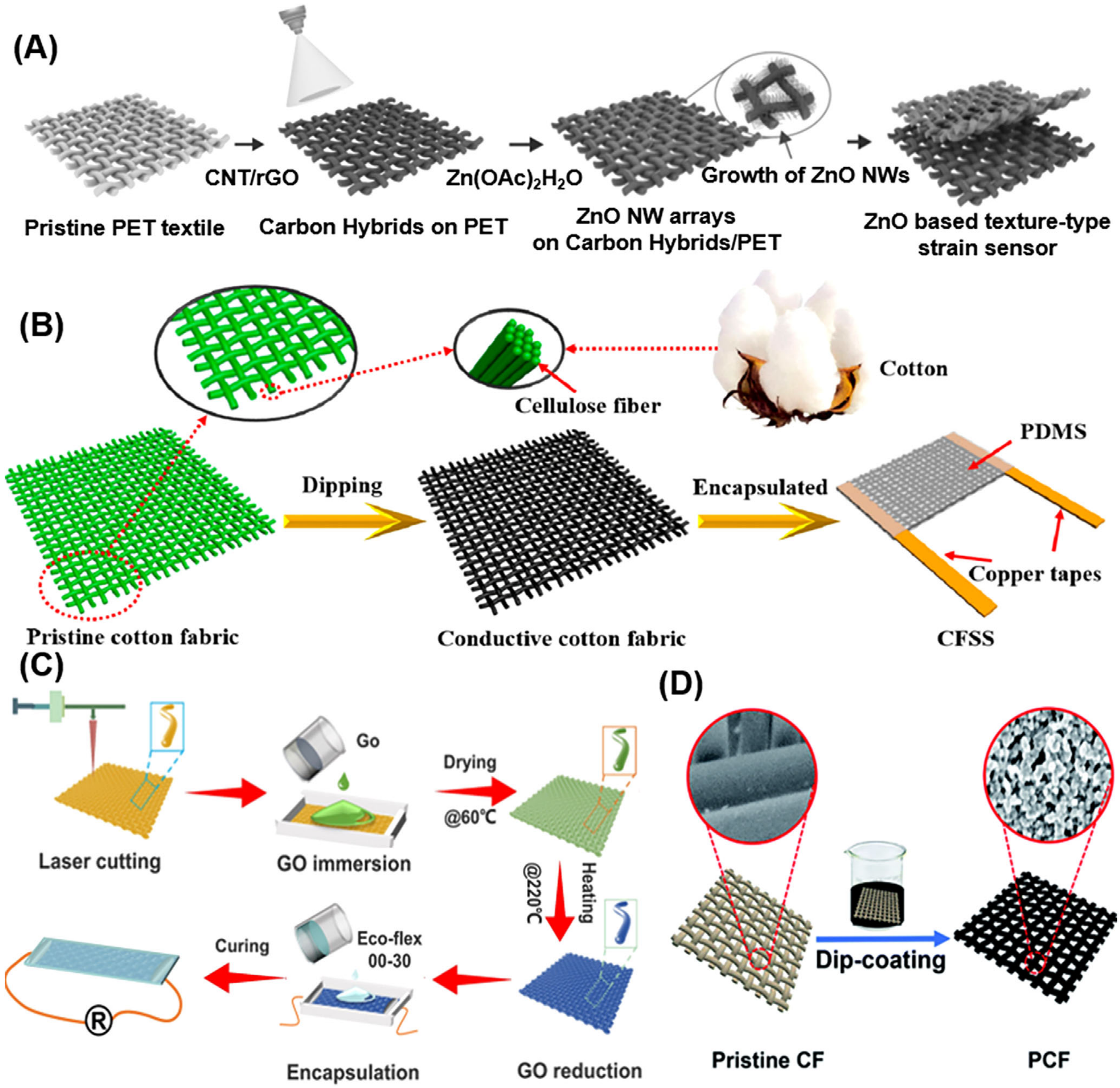


FIGURE 4 (A) Illustration of nonwoven fabric strain sensor for strain sensing. (B) Schematic diagram of the preparation process of the cotton fabric-based strain sensor. (C) Procedure for fabricating the fabric strain sensor. (D) Schematic of the fabrication of the multifunctional strain sensor. *Source*: (A) Reproduced with permission: Copyright 2019, Elsevier.[146] (B) Reproduced with permission: Copyright 2019, American Chemical Society.[32] (C) Reproduced with permission: Copyright 2022, American Chemical Society.[147] (D) Reproduced with permission: Copyright 2018, Royal Society of Chemistry.[148]

Table 1, and they also show good reliability for application in digital health.

Recently, much research has also focused on functional fabric coatings imparting fabrics with electrical conductivity to develop strain sensors due to simple procedures, low cost, and high efficiency. The substrates are modified with conductive materials, such as metals, graphene, CNT, and MXene. For example, a polyester fabric coated with CNT and rGO was used as active layers in Figure 4A. The active layers were further modified with ZnO NW arrays to produce a conductive network.[146] With the protection of polydimethylsiloxane (PDMS), the strain sensor is able to detect a maximum bending strain of 6.2% and achieve a superior GF of approximately 7.6. In Figure 4B, woven cotton fabric was modified with graphene and encapsulated with PDMS to fabricate a strain sensor.[32] The prepared strain sensor exhibits a fast response time (≈90 ms) and a high detection limit (≈0.4% strain). Figure 3C shows a

TABLE 1 Summary of the strain sensors by modifying insulating fiber materials.

Fabrication technology	Substrate	Active materials	Strain range	GF	Cycling stability	Refs
Surface functionalization	Polyurethane fiber	Ag	200%	35 (0%–140%) 659 (140%–200%)	10 000	124
Surface functionalization	Polyurethane fiber	AgNW	100%	128 (0%–15%) 800 (15%–25%) 1553 (25%–50%) 3.2×10^5 (50%–70%) 3×10^6 (70%–87%) 1.6×10^7 (87%–100%)	1000	125
Surface functionalization	Nylon/spandex fabric	CNT/MoO_3	80%	46.3 (0%–60%)	10 000	126
Surface functionalization	Spandex fiber	Ag/CNT	400%	740 (0%–335%) 48 310 (335%–400%)	10 000	127
Surface functionalization	*Juncus effusus* fiber	CNT	600%	24.95 (0%–20%) 76.79 (20%–70%) 28.08 (70%–80%)	13 000	128
Surface functionalization	Carbon fiber	CNT/CB	1100%	20.3 (0%–200%) 99 (200%–500%) 217 (500%–700%) 143.9 (700%–900%) 921.4 (900%–1100%) 1096 (1100%)	25 000	129
Surface functionalization	Thermal plastic elastomer composite	CNT	1135%	21.3 (0%–150%) 34.22 (100%–1135%)	20 000	130
Surface functionalization	Cotton fabric	CNT	120%	42 (5%) 8470 (120%)	5000	131
Surface functionalization	Polyester yarn	Ag	50%	140 (0%–30%) 10 (30%–50%)	2000	132
Spinning/Surface functionalization	Polyurethane fiber	CNT	530%	57.2 (430%–530%)	40 000	133
Spinning	Polyimide hydrogel fiber	Ion	120%	0.76 (0%–100%)	1000	134
Spinning	Thermoplastic elastomer	CNTs	100%	48 (0%–5%) 425 (5%–100%)	3005	84
Spinning	Polyurethane fiber	Acrylamide	750%	0.58 (0%–100%) 1.08 (100%–300%) 1.62 (300%–500%)	800	135
Spinning	Polyurethane fiber	rGO	10%	51 (0%–5%) 87 (5%–8%)	6000	136
Spinning	Polyacrylamide fiber	Ion	400%	0.5–2.7 (0%–400%)	10 000	137
Spinning	Ecoflex	CB	210%	61 (100%–200%)	3000	138
Spinning	Polyurethane fiber	CNT/CB	1468%	2.3×10^6 (0.5%–100%)	7200	139
Spinning	Polycaprolactone and polyurethane fiber	CNT	300%	3.81 (0%–50%) 9.78 (50%–100%) 21.11 (100%–300%)	2000	140
Spinning/Carbonization	Polyacrylonitrile	Carbon	30%	180	2500	141
Carbonization	*Juncus effusus* fiber	Carbon	100%	4.5 (0%–30%) 10.1 (30%–65%) 31.0 (65%–80%)	3500	142
Carbonization	Loofah	Carbon	10%	203.37 (0%–2%) 6830.39 (2%–4.5%) 14 639.06 (4.5%–10%)	2000	143
Carbonization	Cellulose fiber	Liquid metal/carbon	500%	2.51 (0%–150%) 4.76 (150%–400%) 6.65 (400%–500%)	1000	144
Carbonization	Silk	Carbon	200%	8.81	12 000	145

Abbreviations: AgNW, Ag nanowire; CB, carbon black; CNT, carbon nanotube; GF, gauge factor; rGO, reduced graphene oxide.

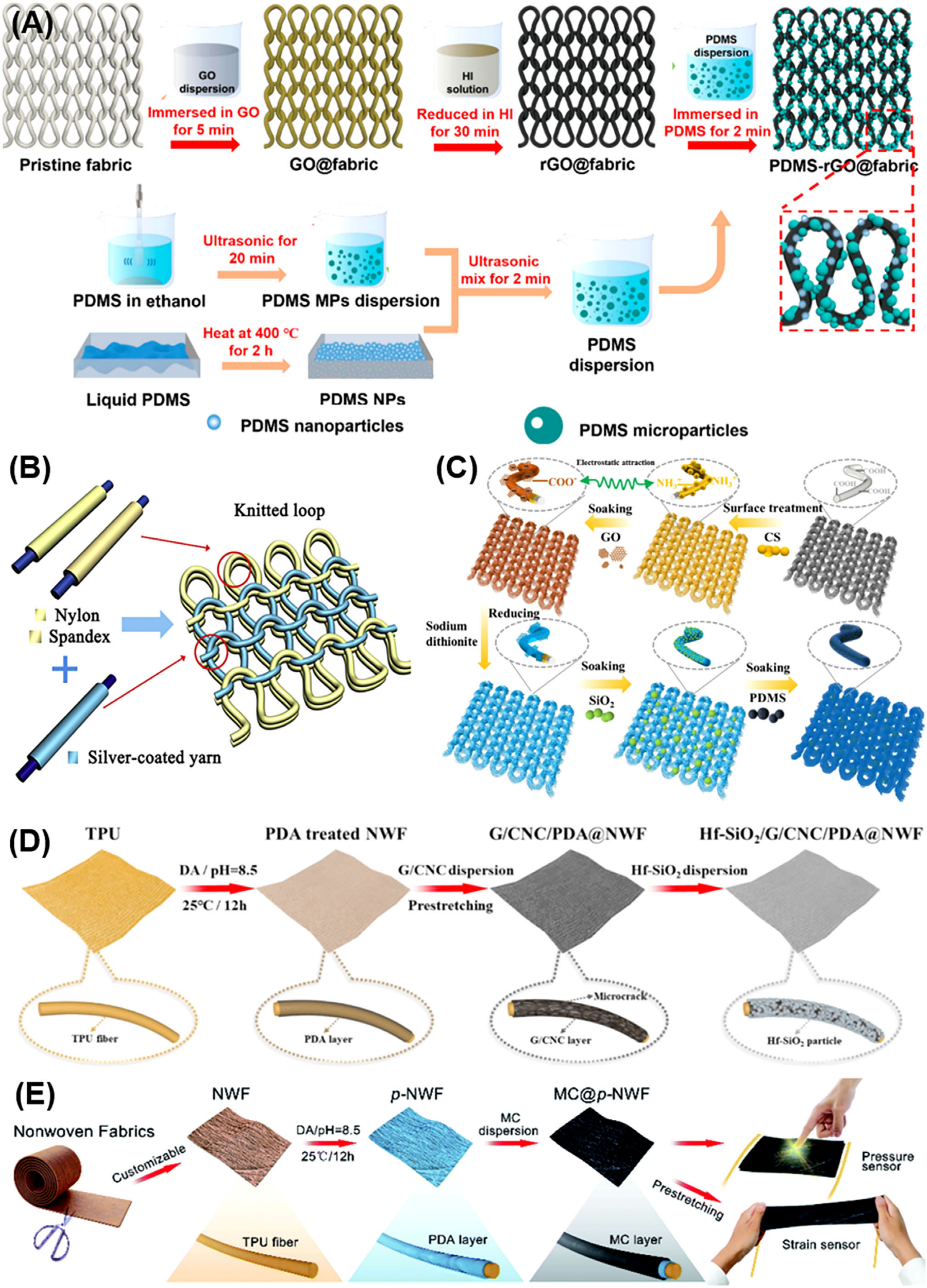
woven fabric made of basalt fibers coated by graphene and wrapped with Ecoflex to develop a strain sensor (Figure 4C).[147] A large number of cracks in the graphene generates under an external strength, and the contact resistance of overlapping graphene changes during stretching, endowing the strain sensor with excellent sensitivity (GF = 138.10) and high durability (>40 000 cycles). A Cupra fabric was coated with carbonic pen ink solution, acting as a strain sensor with a GF of 2.63 (strain = 23%) after coating for seven cycles (Figure 4D).[148] The water absorption of the cellulose-based substrate affects interconnections between intermolecular bonds and disrupts electron transport in the graphite networks. This leads to the strain sensor with high sensitivity to water and different solvents (ethanol and perspiration) due to the water absorption. This characteristic is significant for digital health applications in intelligent health management and medical rehabilitation. Nevertheless, such strain sensors made of the woven fabric have limited strain sensing range due to restrictive fiber slip in the tight structure of the woven fabric.

Knitted fabric-based strain sensors possess a wider sensing range and better flexibility due to yarns being bent into loops and nested, which creates more stretching space during the knitting process. As shown in Figure 5A, a knitted polyester fabric-based strain sensor was fabricated by coating GO and PDMS, showing superhydrophobicity (water contact angle is 156°) and stable signal output in the stretching process.[149] This fabricated strain sensor can detect underwater behaviors via Bluetooth such as swimming. It shows great potential in digital health for remote and efficient detection in potentially dangerous scenarios. Another work reported the silver-coated spandex fiber and nylon fiber were knitted into a highly stretchable strain sensor via weft-knitting full-shaping technology (Figure 5B).[150] This knitted strain sensor possesses 3D surface sensing function, which is more suitable for real-life applications on the human body surface and offers a wider sensing range than 2D sensing. Figure 5C exhibits electrostatic self-assembly of chitosan and rGO, followed by dip-coating of SiO_2 and PDMS functionalized polyamide/spandex knitted fabric.[151] This functionalized fabric shows strain-sensing ability due to a decrease in the distance between the adjacent fibers under stretching. The change in distance causes a change in the graphene contact area, thus leading to an electrical resistance change.

Besides, nonwoven fabrics have also garnered considerable attention for their application in flexible wearable strain sensors, attributed to their excellent air permeability and low cost. In Figure 5D, the graphene and cellulose nanocrystals were coated as an active layer, and polydopamine (PDA) was used as the binding agent for a nonwoven fabric to produce a conductive network. Then, it was endowed with superhydrophobicity via hydrophobic fumed silica (Hf–SiO_2) ethanol solution.[152] The prepared strain sensor is capable of discerning strains up to 98%, exhibiting a high GF ≈ 7.6. Figure 5E exhibits a nonwoven fabric-based strain sensor that was prepared by coating MXene and cellulose nanocrystals on the TPU fabric surface.[153] The dynamic modulation of the MXene layer's pronounced cracks during tensile deformation bring changes in the conductive pathways. This change in the conductive network endows the strain sensor with the ability to sense strain change. The strain sensors have a broad sensing range (83%) and high sensitivity (GF = 3405), indicating their promising utility in digital health.

2.3 | In situ carbonization

Some fibers can be directly converted into highly conductive carbon fibers through in situ carbonization treatment while maintaining their original integrity and flexibility.[145,154,155] A fundamental study systematically reported the structural and chemical changes of silk proteins during heating at different temperatures. The β-sheet structure is transformed into a sp^2-hybridized carbon hexagonal structure at 350°C, and a highly ordered graphitic structure is further formed when the temperature reaches 2800°C.[156] This carbonization treatment provides silk with excellent electrical conductivity. In another research, the highly conductive nanofibrillated cellulose was prepared using GO as a template via the carbonization method (Figure 6A).[157] The fiber accomplishes the conversion from cellulose to carbonaceous materials at high temperatures and achieves excellent electrical conductivity (649 ± 60 S/m) through the carbonization of well-aligned GO. Exploiting this carbonization approach, another group developed a high-performance wearable strain sensor using carbonized cotton fabric containing Ecoflex encapsulation (Figure 6B).[158] The cotton fabric, rendered flexible and highly conductive through a straightforward annealing process, shows a large workable strain range and high sensitivity. This sensor is capable of detecting minute strains as low as 0.02%, with a GF of 10, and can sense lightweight items down to 0.3 mg. Similarly, an ultrastretchable and highly sensitive strain sensor using carbonized silk fabrics containing Ecoflex encapsulation was fabricated (Figure 6C).[159] The silk's β-sheet crystallite structure underwent a heating-induced reconstruction, converting it into hexagonal carbon rings and a highly ordered graphitic framework. This sensor exhibits an extensive sensing range (>500% strain), high sensitivity, rapid response time (<70 ms), and robust durability (10 000 cycles). Consequently, it holds great application


(A)
GO dispersion
Immersed in GO for 5 min
HI solution
Reduced in HI for 30 min
PDMS dispersion
Immersed in PDMS for 2 min
Pristine fabric
GO@fabric
rGO@fabric
PDMS-rGO@fabric
Ultrasonic for 20 min
PDMS in ethanol
PDMS MPs dispersion
Ultrasonic mix for 2 min
Heat at 400 °C for 2 h
Liquid PDMS
PDMS NPs
PDMS dispersion
PDMS nanoparticles
PDMS microparticles
(B)
Knitted loop
Nylon
Spandex
Silver-coated yarn
(C)
Electrostatic attraction
Soaking
GO
Surface treatment
CS
Sodium dithionite
Reducing
Soaking
SiO2
Soaking
PDMS
(D)
TPU
PDA treated NWF
G/CNC/PDA@NWF
Hf-SiO2/G/CNC/PDA@NWF
DA / pH=8.5
25°C / 12h
G/CNC dispersion
Prestretching
Hf-SiO2 dispersion
TPU fiber
PDA layer
Microcrack
G/CNC layer
Hf-SiO2 particle
(E)
NWF
p-NWF
MC@p-NWF
Nonwoven Fabrics
Customizable
DA/pH=8.5
25℃/12h
MC dispersion
Prestretching
Pressure sensor
Strain sensor
TPU fiber
PDA layer
MC layer

potential in digital health for intelligent health management and medical rehabilitation. Figure 5D illustrates the process of fabricating a highly aligned GO/polyacrylonitrile composite fiber membrane for exercise monitoring by the microfluidic spinning method and carbonization.[160] Their work investigated flexible strain sensors derived from the carbon fiber membrane with varying fiber orientations, showing excellent sensing performance and pronounced anisotropic electromechanical properties. Significantly, this research has been instrumental in advancing the production of strain sensors by employing carbonized fibers and textiles. This includes the utilization of carbonized cotton fabrics, modal fabrics, and silk georgettes for the development of sensors sensitive to tensile strain, as well as the use of carbonized crepe paper specifically for sensors detecting bending strain.[156,161–163] Although controllable electrical conductivity is achieved by altering carbonization temperature and time, the insufficient mechanical strength of carbonized fibers necessitates the use of elastic polymers for encapsulation and fixation during sensor fabrication. Therefore, gaining a balance between electrical conductivity and mechanical performance remains an urgent challenge for future research.

3 | CLASSIFICATION AND SENSING MECHANISM

Continuous monitoring of vital and subtle body motions using a sustainable fiber-based strain sensor attached to the epidermis is a vital technology in digital health for body area sensing networks, intelligent health management, and medical rehabilitation. A fiber-based strain sensor, an electronic device, can measure strain by transforming the deformation of an object into an electrical signal. Various types of strain sensors, such as resistive (Figure 7A),[164,165] capacitive (Figure 7B),[166,167] piezoelectric (Figure 7C),[168] triboelectric (Figure 7D),[169] and optical strain sensors,[170,171] have been reported. Among them, capacitive strain sensors are expressed by common parallel-plate technology that is easy to develop and build simple models. The mechanism of triboelectric strain sensors can be displayed, for example, via contact-separation mode. They rely on different mechanisms to detect mechanical deformation,[172–174] enabling them to provide an accurate monitor for human health in a wide range of signals.[175–181] Table 2 exhibits advantages and disadvantages of these fiber-based strain sensors.

3.1 | Resistive sensors

Wearable resistive strain sensor is primarily composed of conductive materials and flexible substrates.[189,190] Such strain sensors can respond to strain deformation based on the change in the micro-conductive network structure of conductive materials when strain is applied to the sensor.[4,191] Application of strain to the fiber electrode induces separation or slippage between the adjacent conductive materials, resulting in a measurable fluctuation in the sensor's electrical resistance. Upon release of the sensor, the electrical resistance of the sensor recovers as conductive materials return to their original states or structures.[93,192] The resistive strain sensor boasts a plethora of merits, including easy fabrication, an uncomplicated structure design, broad operational range, high precision, and long service life, as well as disadvantages of nonlinearity and weak output signal to large strain range. The resistance variation (R) is attributed to the geometric modifications—namely, alterations in the area (A) and length (L) of the conductive fiber and fabric—occasioned by the stretching and bending. In addition, it could also be influenced by piezoresistive deformation, as the change in resistivity (ρ) and conductivity of the fiber-based sensor presented in the following equation:

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

Resistive strain sensors are renowned for their excellent durability, wide sensing range, great sensitivity, and fast response time, rendering them suited for accurate monitoring of human movements.[193] Lee et al. fabricated a stretchable resistive fiber strain sensor with a multi-microfilament structure and Ag-rich shells by embedding AgNPs into the polymeric fiber surface.[124] This sensor exhibits remarkable sensitivity (GF = 659), a wide strain detection range (200%), and great durability (>10 000 stretching cycles). As shown in Figure 8A, the external strain causes the crack of the Ag-rich shells, leading to

FIGURE 5 (A) Schematic diagram of a knitted textile-based strain sensor for strain sensing about drowning alarming. (B) Schematic diagram of the preparation of a highly-stretchable knitted sensor consisting of spandex/silver-coated yarn. (C) A graphene and SiO_2-coated fabric for the detection of athletes' actions without being affected by water. (D) Illustration of a nonwoven fabric strain sensor for strain sensing. (E) The preparation procedure of a nonwoven fabric-based strain sensor. *Source*: (A) Reproduced with permission: Copyright 2022, American Chemical Society.[149] (B) Reproduced with permission: Copyright 2021, Elsevier.[150] (C) Reproduced with permission: Copyright 2023, Springer Nature.[151] (D) Reproduced with permission: Copyright 2019, Elsevier.[152] (E) Reproduced with permission: Copyright 2020, Royal Society of Chemistry.[153]

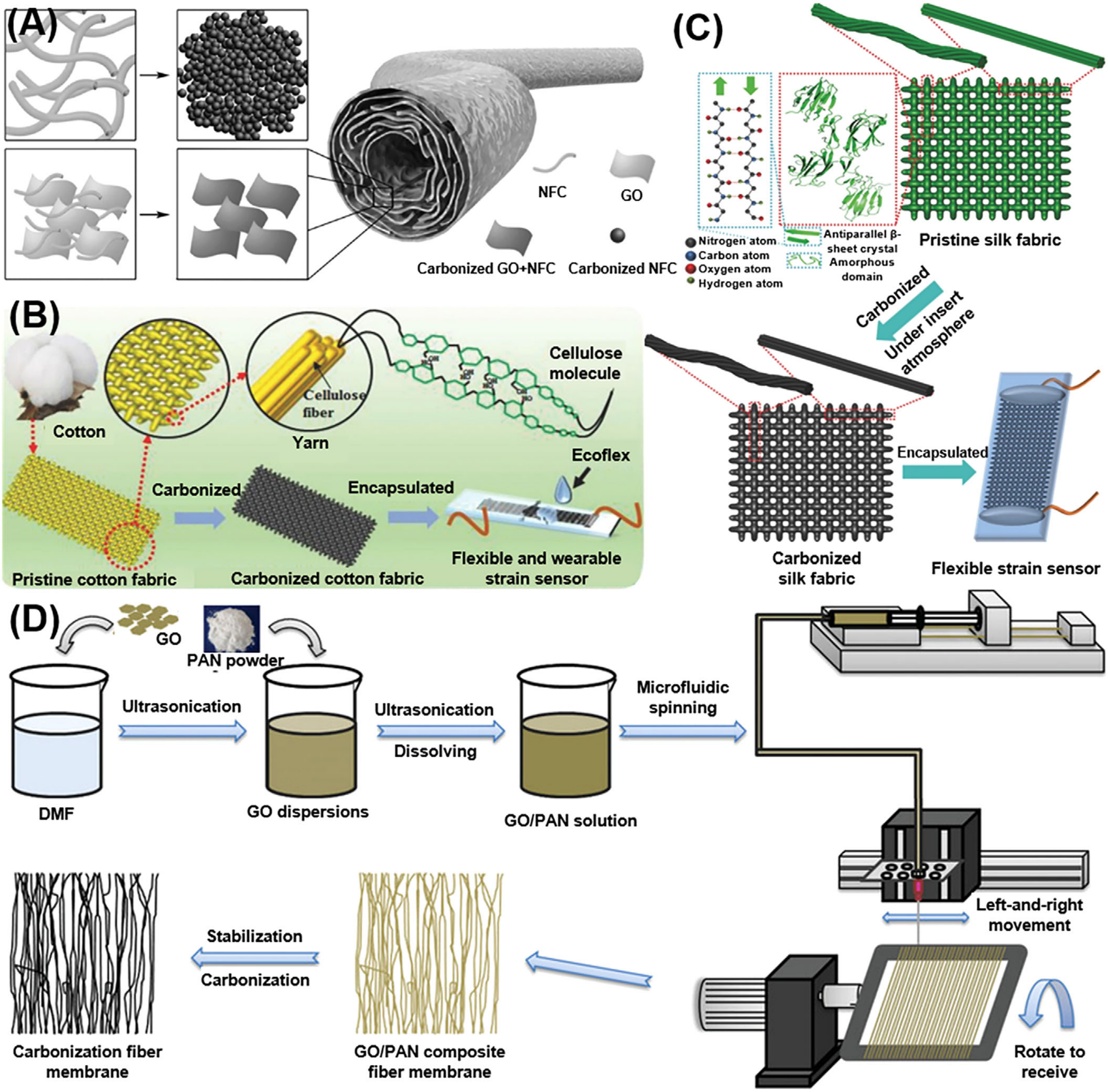


FIGURE 6 (A) Illustration of highly conductive microfiber of the graphene oxide (GO) templated carbonization of nanofibrillated cellulose. (B) Illustration for fabricating wearable carbonized cotton fabric strain sensors. (C) Schematic diagram of carbonized silk fabric for wearable strain sensors. (D) The production of highly aligned GO/polyacrylonitrile composite fiber membrane for strain sensing. *Source*: (A) Reproduced with permission: Copyright 2014, Wiley-VCH.[157] (B) Reproduced with permission: Copyright 2017, Wiley-VCH.[158] (C) Reproduced with permission: Copyright 2016, Wiley-VCH.[159] (D) Reproduced with permission: Copyright 2021, Wiley-VCH.[160]

Ag-rich shell grabbing a region between the AgNPs and the polymeric fiber and the exposure of the inner conductive composite. The resistance of fiber-based sensors changes with continuous stretching and more contact between the Ag-rich shells from the increasing number of filaments. Similarly, a multilayer structured fiber resistive strain sensor was prepared through coating waterborne PU, AgNW, and MXene ink via layer-by-layer method.[125] The prepared strain sensor presents excellent sensitivity (GF = 1.6×10^7), broad strain range (>100%), exceptional reliability and stability (beyond 1000 cycles), and swift response time (344 ms). Figure 8B exhibits the sensor's operational mechanism, highlighting the predominance of crack propagation in the sensing process rather than

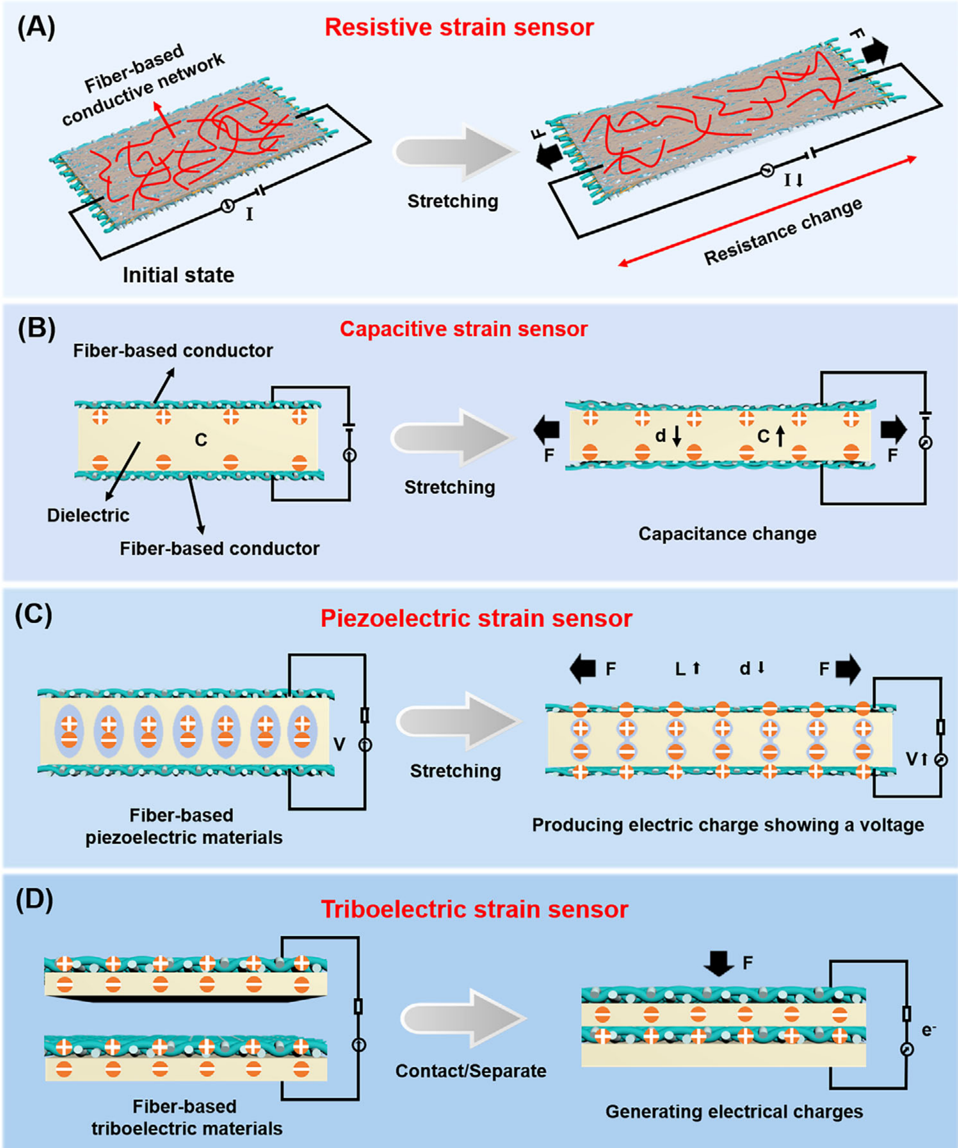


FIGURE 7 Classification and mechanism of strain sensors: (A) resistive sensor, (B) capacitive sensor, (C) piezoelectric sensor, (D) triboelectric sensor.

slippage. Originally, the sensor remained integrated without the cracks appearing, then the crack grew gradually with increasing strain up to 30%. The crack gaps further expand with the strain further increases and cracks come into contact again when the strain recovers. The sensor's resistivity fluctuations are attributable to the variations in the total area of the cracks engendered during the stretching process. Additionally, fiber slippage can change the contact area of conductive material for strain sensing. For example, a resistive strain sensor was fabricated by using PDMS to encapsulate weft-knitted fabric coated with graphene.[194] During the stretching process (Figure 8C), the yarns from the sensor experience significant compaction in the *Y*-axis, a direct consequence of the more pronounced deformation along the *X*-axis relative to the *Y*-axis (Figure 8D). The *X*-direction slippage of fiber causes a negative differential resistance response.

3.2 | Capacitive sensors

Capacitive strain sensors, unlike resistive strain sensors, are composed of a pair of fiber electrodes separated by an elastic dielectric layer, typically arranged in a parallel-plate configuration. It shows low input energy, strong adaptability to harsh environment, great dynamic response, and noncontact measurement, but nonlinearity in wide range and sensitivity to electromagnetism. Upon the application of a direct current voltage to the capacitive strain sensors, the external pressure will change the parallel area between

TABLE 2 Summary of advantages and disadvantages of fiber-based strain sensors.

Classification	Advantages	Disadvantages	References
Resistive strain sensor	Small size, light weight, low cost, simple structure, high sensitivity, wide range, electromagnetic immunity, multiplexing capability, available to static, and dynamic strains	Sensitive to temperature changes, nonlinearity for large strain, low output signal, external power requirement	41, 182
Capacitive strain sensor	High sensitivity, available to static and dynamic strains, low power consumption	Complex circuitry, high cost, sensitive to humidity and temperature changes, affected by electromagnetic interference, limited range	183, 184
Piezoelectric strain sensor	Available to dynamic strains, high sensitivity, without an external power	Complex circuitry, cannot measure static strains, sensitive to temperature changes, affected by electromagnetic interference, output drift over time	173, 185
Triboelectric strain sensor	Light weight, low cost, high sensitivity, available to static and dynamic strains, high energy-converting efficiency, without an external power	Complex circuitry, sensitive to humidity and temperature changes, output drift over time	186–188
Optical strain sensor	Small size, light weight, high sensitivity and accuracy, electromagnetic immunity, available to static and dynamic strains, distributed sensing capabilities	Complex circuitry, high cost, external power requirement	170, 171

two parallel plate electrodes (A) and the overlapping length between the two fiber electrodes (d). These changes can affect both the capacitance value (C) and the signal change of the capacitive strain sensor. The capacitance (C) of the fiber-based sensor is contingent upon the parallel surface area between the parallel plate electrodes, the overlapping length between the fiber electrodes, and the relative permittivity of the dielectric (ε). The relationship between these factors can be expressed in the following equation:

$$C = \frac{\varepsilon A}{d} \tag{2}$$

Capacitive strain sensor has the advantages of low power consumption, good stability, and easy multipoint identification.[195] Previous work has unveiled the creation of a stretchable capacitive sensor by filling liquid metal into hollow fiber elastomeric capillaries.[196] In this method, the capacitance can be changed through twisting, stretching, and touching processes. The double-helix fibers experience changes in the geometry when twisting two fibers without altering the end-to-end distance (Figure 9A), leading to changes in capacitance. Another work reported that a capacitive sensor was fabricated by cross-stacking using PDMS-encapsulated polymers that were deposited with AgNPs. When external stress is applied onto the fiber, it induces deformation in the fiber thickness (Figure 9B). The substitution of micropores with PDMS causes a decrease in permittivity, endowing the sensor with capacitance-sensing ability.[197] In addition, coating PDMS onto two stretchable AgNPs-coated fibers with a hollow double helical structure can develop capacitive strain sensors.[198] When tensile strain is applied to the unstretched fiber-based strain sensor, the two double helical conductive fibers within the sensor progressively straighten and move nearer to each other, culminating in an augmentation of the capacitance between the two conductive fibers, as shown in Figure 9C. A capacitive strain sensor, compatible with skin, was successfully prepared by electrochemically co-depositing the polypyrrole-CNT on the rGO/Cr–Au current collectors.[199] The microstructure in the microsensor is analogous to a series of parallel capacitors, $C_1, C_2, \ldots, C_n$. The gel dielectric layer, upon deformation by an applied force, infiltrates the interstices between the interdigitated electrode's fingers, lowering both interface contact resistance and charge transfer resistance (Figure 9D). This results in an enhanced pseudocapacitance and electric double-layer effect, generating a current response to external pressure. Frutiger et al. fabricated a novel variety of soft capacitive strain sensor fibers with four-layer configuration, utilizing a bespoke printhead composed of four coaxially aligned cylindrical nozzles for elongational strain detection.[200] Figure 9E exhibits the analogous circuit of sensor, which can be interpreted in terms of a triad of components—a cylindrical resistor, capacitor, and ring resistor—arranged in series. When an external strain is exerted on the structure, the capacitance and resistance

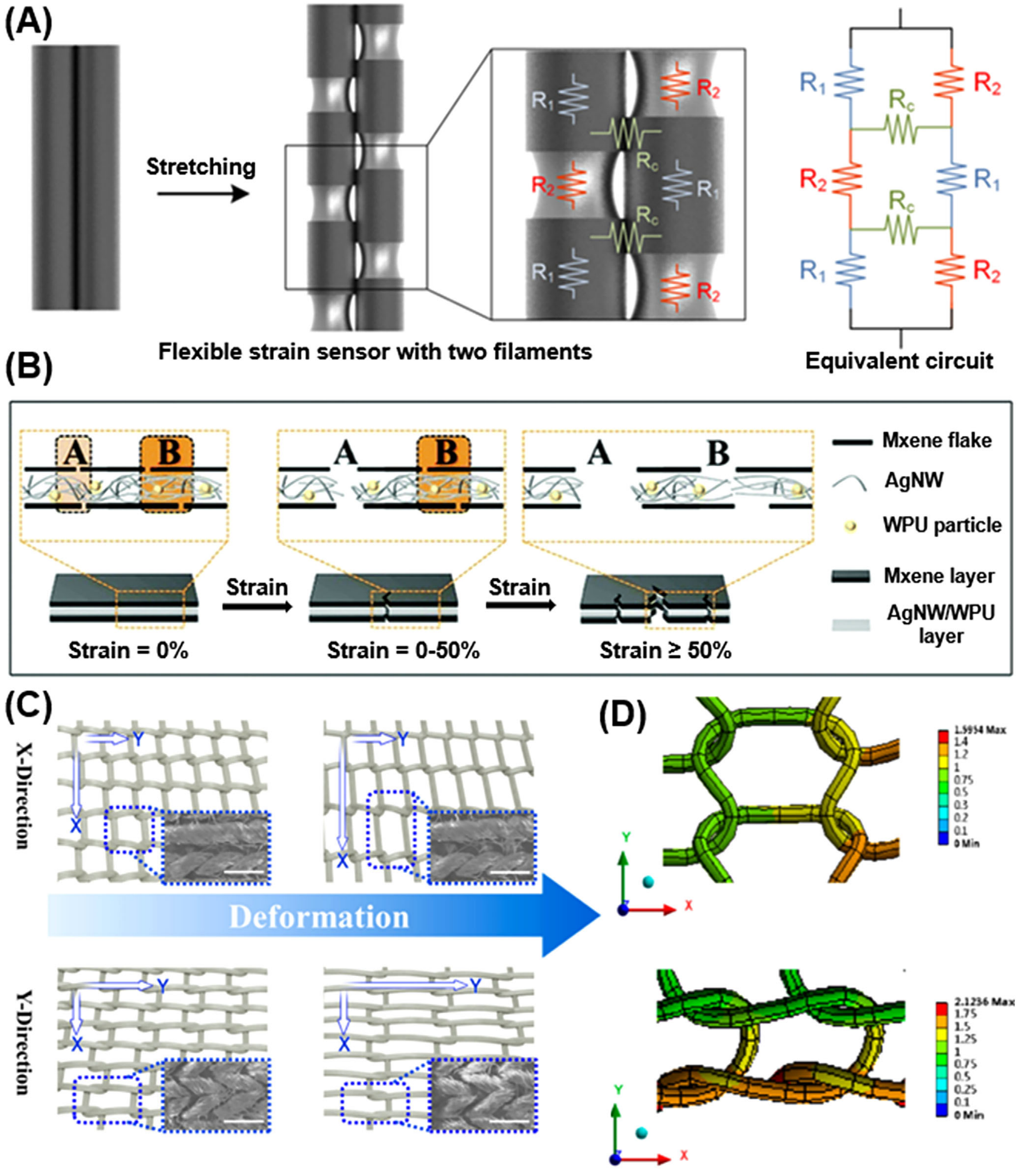


FIGURE 8 (A) Illustration of the resistance model and the corresponding equivalent circuit of the fiber sensor. (B) Schematic diagram of the crack propagation mechanism in the multilayer strain sensor. (C) Schematic diagram of fabric structure deformation along different directions. (D) Mechanical simulation of relative deformation of adjacent fibers under X and Y direction loading tension. *Source*: (A) Reproduced with permission: Copyright 2018, American Chemical Society.[124] (B) Reproduced with permission: Copyright 2019, Royal Society of Chemistry.[125] (C and D) Reproduced with permission: Copyright 2022, American Chemical Society.[194]

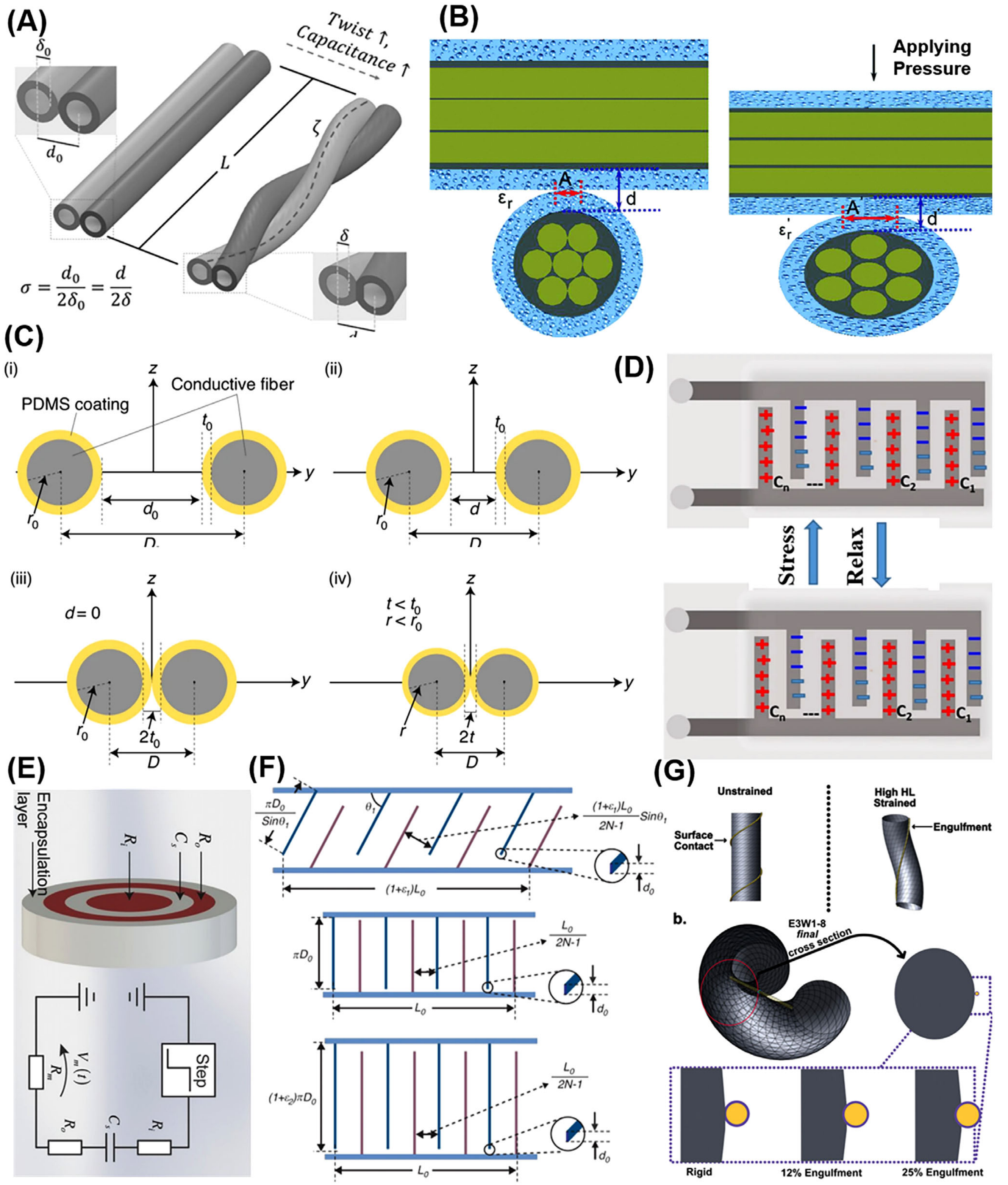


FIGURE 9 (A) Schematic of the torsion sensing mechanism. (B) Schematic diagram of structural variation sensing unit. (C) Schematic illustrations showing the change in cross-sectional view of elastic fibers in the strain sensor during stretching. (D) Schematic of working mechanism for flexible capacitive micro-strain sensor. (E) Equivalent circuit diagram displaying the mechanism of capacitive soft strain sensor fibers. (F) The geometrical illustration of the strain sensor of two strain sensing modes. (G) Schematic illustration showing mechanism of strain sensors associated with point contact and engulfment examples. *Source*: (A) Reproduced with permission: Copyright 2017, Wiley-VCH.[196] (B) Reproduced with permission: Copyright 2017, Royal Society of Chemistry.[197] (C) Reproduced with permission: Copyright 2021, Springer Nature.[198] (D) Reproduced with permission: Copyright 2023, Springer Nature.[199] (E) Reproduced with permission: Copyright 2015, Wiley-VCH.[200] (F) Reproduced with permission: Copyright 2023, Springer Nature.[201] (G) Reproduced with permission: Copyright 2023, Wiley-VCH.[183]

of sensor rise linearly and quadratically with elongation, respectively, owing to a reduction in the neighboring distance. Zhang et al. prepared a dual-mode fiber-shaped capacitive strain sensor by using $BaTiO_3$@Ecoflex encapsulate Ag-modified TPU fiber for human physical signals monitoring and human–machine interaction.[201] The axial tensile strain sensing mode is solely associated with the angle between the helical electrode's trajectory and the TPU fiber axis (θ). During the axial tensile strain, the alteration in the area and distance (d) between electrodes results in a change in angle, endowing the yarn with capacitance sensing (Figure 9F). A recent work reported capacitive strain sensors with helical auxetic yarn by wounding copper wire around polypyrrole-treated elastic yarn,[183] showing significant promise for applications in the realm of wearable technology and exoskeletons. In Figure 9G, the stretching process engendered a gap between the copper wire and polypyrrole-treated elastic yarn, leading to a decrement in capacitance because of the increased electrode separation.

3.3 | Piezoelectric sensors

Piezoelectric strain sensors can provide power by generating electric charges when piezoelectric materials generate deformation by applied pressure, which leads to polarization and spatially separated movement of opposite charges inside the piezoelectric materials.[202,203] Such sensor possesses simple manufacturing process, uncomplicated sensor configuration, high precision, fast response time as well as sensitive to environment change, low sensitivity, and limited sensing range.[204] The intrinsic piezoelectric voltage (V_0) is given in the following equation:

$$V_0 = g\sigma h \tag{3}$$

where g represents the piezoelectric constant, σ symbolizes the exerted pressure, and h represents the material's thickness. A bamboo-inspired piezoelectric sensor from conductive carbon nanofiber/PDMS foam was prepared, featuring a hierarchical arrangement of pore structures with hierarchical pore structures. The applied stress causes hollow-skeleton wall deforming, generating many conductive paths when adjacent outside/inside walls contact (Figure 10A).[205] These emerging conductive paths endow sensors with high sensitivity to tiny pressures (~0.6 kPa^{-1} at 0–1 kPa). Figure 10B demonstrates the preparation of a self-powered piezoelectric sensor by transferring $Pb(Zr_x,Ti_{1-x})O_3$ to an ultrathin polyethylene terephthalate (PET) substrate.[206] The pressure from the human body can generate polarization and spatially separated movement of opposite charges, which can be converted into electric energy. This energy can be used for sensors to detect critical physiological parameters, such as arterial pulsations, respiratory patterns, and phonation vibrations can be identified at a pressure of 10–100 kPa. Sun et al. fabricated a piezoelectric strain sensor by putting the poly(vinylidene fluoride) membrane deposited with ZnO between two perforated PET layers.[207] The resistance changes from ZnO induced by a local pressing action make the strain sensor respond to various local pressing actions at specific positions (Figure 10C). Figure 10D displays an aerogel piezoelectric sensor from AgNWs and nanofibrillated cellulose with good sensitivity (3.86 kPa^{-1}), swift response time (180 ms), and excellent durability (>10 000 cycles). The sliding, separation, and rearrangement of AgNWs from compression and stretching condition change the numbers of AgNWs contact points.[208] An augmentation in the sensor's resistance is precipitated by an increase in contact points. Wu et al. prepared a piezoelectric yarn suitable for wearable energy harvesting applications by adorning polyvinylidene fluoride nanofibers with cesium lead halide perovskite and assembling them with a stainless-steel yarn.[209] As stress is applied or released, the bound charges on the surface of nanofibers wrapped perpendicular to the yarn decrease or increase, leading to generation of current (Figure 10E). The piezoelectric yarns can provide electrical signals for flexible electronic textiles during twisting, bending, knotting, braiding, and weaving.

3.4 | Triboelectric sensors

The operational principle of triboelectric sensors is predicated upon the conjunction of the triboelectric effect and electrostatic induction to transform external deformations arising from frictional interactions between two fiber-based materials—each possessing disparate electron affinities—into electricity.[210] The advantages of triboelectric sensor are simple structure, low cost, high precision, and wide sensing range as well as disadvantages are easy to be affected by temperature changes, bad stability, and limited measurement. Moreover, when two fiber-based materials with opposite tribopolarity bring into a frictional contact, electrical charges undergo segregation and transference at their juncture. The external frictional contact cyclically propels the charged surfaces, engendering a relative shift between the surfaces and the electrodes, thereby causing the creation of output potential between the electrodes.[211] TENGs can be classified into four distinct categories predicated on the type of contact and number of electrodes, including the contact-separation mode, contact-slide mode, single-electrode mode, and freestanding triboelectric-layer mode.

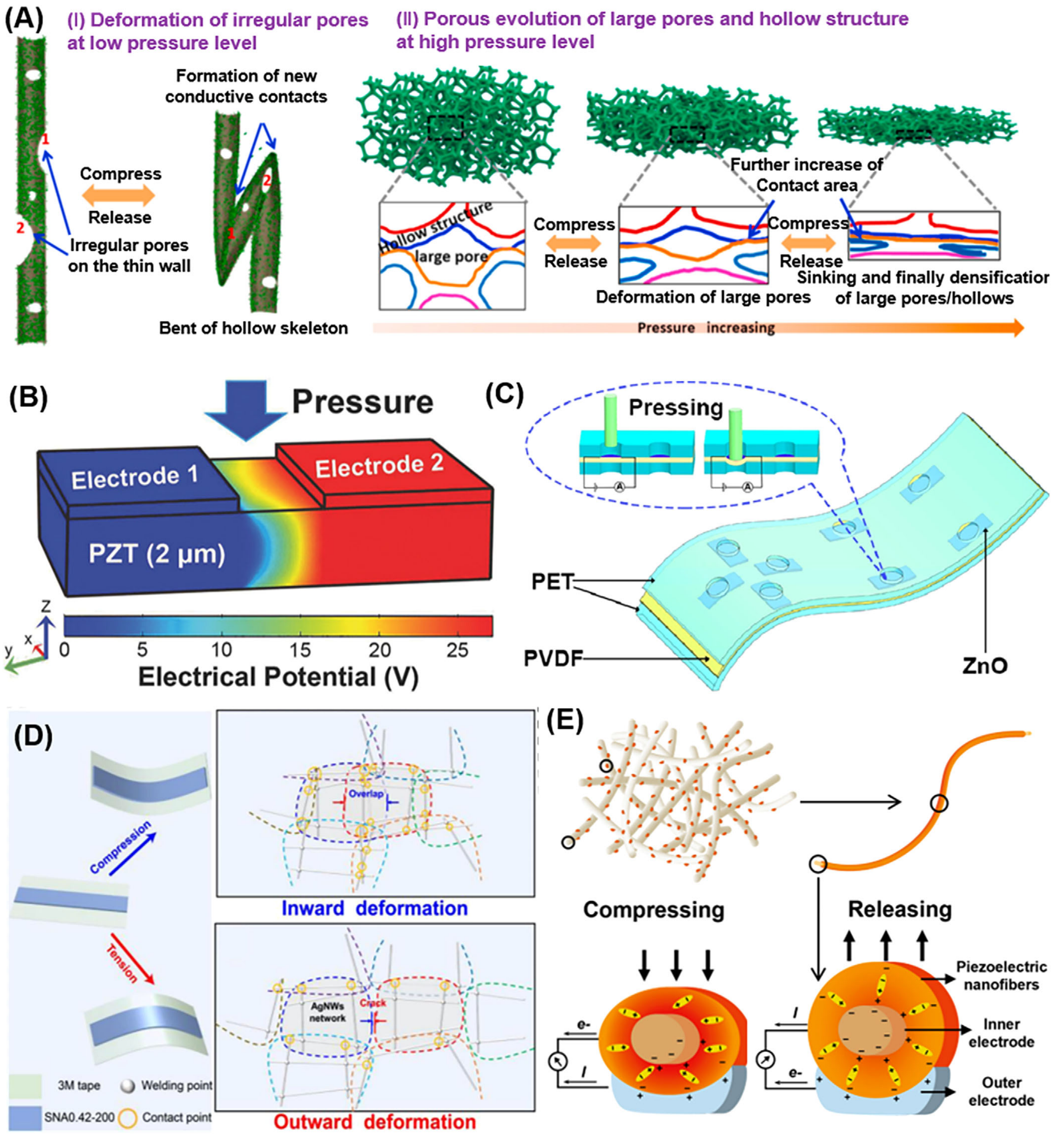


FIGURE 10 (A) Sensing mechanism of the bamboo-inspired piezoresistive sensor. (B) Schematic illustration of piezopotential distribution inside the sensors. (C) Illustration of the response mechanism of the sensor for a press-excitation on the sensor. (D) Schematic illustration of the sensing mechanism of an aerogel piezoelectric sensor. (E) Schematic illustration to show the sensing mechanism of piezoelectric yarn. *Source*: (A) Reproduced with permission: Copyright 2021, Elsevier.[205] (B) Reproduced with permission: Copyright 2017, Wiley-VCH.[206] (C) Reproduced with permission: Copyright 2021, Elsevier.[207] (D) Reproduced with permission: Copyright 2021, Elsevier.[208] (E) Reproduced with permission: Copyright 2023, American Chemical Society.[209]

In a previous work, a highly stretchable coaxial structure TENG was developed by successively depositing AgNWs/CNTs and PDMS on the spandex fiber surface for human body movement monitoring and real-time pressure distribution distinguishment.[212] The continuous contact and separation between active object and PDMS bring the equivalent negative and positive electrostatic charges as well as a new equilibrium state, resulting in generation of an electrical current (Figure 11A). Another work reported a fabric TENG was fabricated with PDMS-treated yarn and multiaxial winding yarn achieved by the 3D braiding machine, it can be applied to identity recognition carpet in a self-powered visitor identification system.[213] In Figure 11B, the continuous compression and release motion between braided braced frame and axial core column induces the neutralization of positive and negative electrostatic, generating an instantaneous alternating current. In addition, an all-fiber iontronic triboelectric sensor was developed with TPU and ionic liquid [EMIM][TFSI] via two-step electrospinning method.[214] As shown in Figure 11C, when contact and separation occur between fingers and the triboelectric sensor, it will cause the contact electrification and electrostatic induction, thus generating electric signals. Moreover, Fang et al. prepared a permeable and moisture-proof textile triboelectric sensor for real-time respiratory monitoring.[215] Breathing changes between expiratory and inspiratory states make two adjacent yarns contact and separate (Figure 11D). This brings about the generation of the equivalent electrification with opposite polarities, resulting in the conversion of breathing pressure into electricity. Another study proposed a stretchable triboelectric sensor made of elastomeric fiber filled with liquid metal for the application of electromagnetic energy collection, self-powering sensing device, and human–machine interface.[216] The SEBS and liquid eutectic GaIn function as the triboelectric materials and the conducting single-electrode (Figure 11E). As the SEBS and other dielectrics contact and separate each other, electrons move between the SEBS surface and liquid eutectic GaIn to provide useful electricity.

3.5 | Performance assessment

The sensing performance of strain sensors based on fiber can be measured by several performance parameters, including sensitivity, minimum detection limit, strain range, linearity, response time, cyclic stability, and wearing comfort. These performance parameters are crucial in determining whether the fiber-based strain sensor can maintain reliability and accuracy in practical applications. Sensitivity is one of the most critical performance evaluation parameters used to assess strain sensor performance, reflecting the change of resistance/capacitance of the strain sensor during the stretching and recovery process as well as its ability to respond to external stimuli (quantified by GF). Higher sensitivity means that the strain sensor can clearly and accurately monitor large and small strain changes. In addition, minimum detection limit of 0.2% is also very important for subtle human motion signals such as pulse beating, heart beating, eye movement, contraction, and expansion of blood vessels. It is expressed by Equations (4) and (5).

$$GF = \frac{\Delta R/R_0}{\varepsilon} \tag{4}$$

where R_0 denotes the strain sensors' resistance in their unstrained state, ΔR signifies variation in resistance with applied strain, and ε represents the applied strain.

$$GF = \frac{\Delta C/C_0}{\varepsilon} \tag{5}$$

where C_0 is the capacitance of strain sensors without applied strain, ΔC indicates the alteration in capacitance consequent to strain application, and ε denotes the applied strain.

Fiber-based sensors are not merely expected to withstand considerable elongation but also to preserve consistent mechanical and sensing performance amidst extensive strain. Linearity refers to the sensor's capacity to produce an output that is in direct proportion to the input strain, quantified by the coefficient of determination (R^2) ascertained from linear regression analysis. Higher linearity between the sensor response and the strain elongation can mitigate the intricacies and cost of data processing and circuit design, resulting in a predictable and reliable electrical signal output of the fiber-based strain sensor. Furthermore, the response time—the interval requisite for the sensor to respond a variation in strain—determines the sensing speed of the strain sensor. A shorter response time is desirable because it means the strain sensor can detect strain deformation more quickly and enable real-time monitoring more reliably in practical applications. Moreover, cyclic stability represents the ability of the strain sensor to maintain its initial performance over repeated cycles of stretching and releasing process. Excellent durability is essential for wearable sensors because human joints are always in a large, complex, and dynamic deformation state. Ideally, the fiber-based strain sensor should be able to maintain stable performance after at least 100 000 stretch-release cycles, which ensures its suitability for prolonged monitoring endeavors. The continuous movement of human body produces heat and sweat, which will bring irritation and allergic reaction to human skin due to the sealed sensor. Last but not least, great wearing

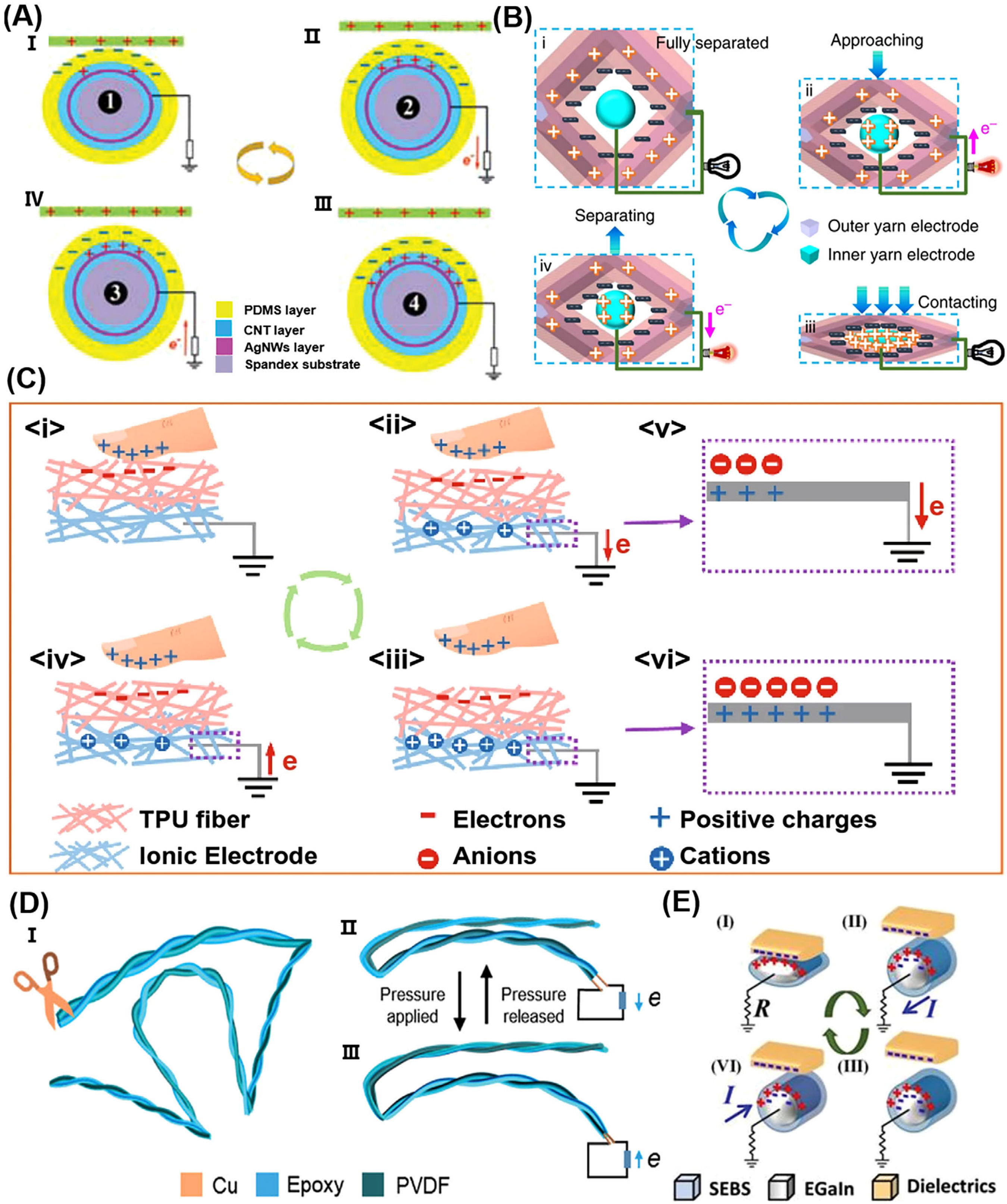


FIGURE 11 (A) Illustration of working mechanism of coaxial structure triboelectric nanogenerator (TENG). (B) Schematic diagram of the working principle of the 3D fabric TENG. (C) Schematic diagram of the mechanism the all-fiber iontronic triboelectric sensor. (D) Schematic diagram showing sensing mechanism of a triboelectric sensor. (E) Schematic illustration to show the working mechanism of stretchable triboelectric sensor. *Source*: (A) Reproduced with permission: Copyright 2021, Wiley-VCH.[212] (B) Reproduced with permission: Copyright 2020, Springer Nature.[213] (C) Reproduced with permission: Copyright 2022, Springer Nature.[214] (D) Reproduced with permission: Copyright 2021, Wiley-VCH.[215] (E) Reproduced with permission: Copyright 2021, Wiley-VCH.[216]

comfort can quickly discharge sweat and heat generated by human body to create a comfortable microenvironment between skin and sensors. Therefore, these abovementioned parameters should be carefully considered while designing strain sensors as well as selecting functional materials and device structures.

4 | APPLICATIONS FOR DIGITAL HEALTH

The intersection of digital health and sustainable development is increasingly being shaped by the application of fiber-based strain sensors in various wearable scenarios such as body area sensing networks and intelligent health management to medical rehabilitation and multifunctional healthcare systems.[217–220] These devices can convert strain-induced deformation into visible electrical signals to monitor body motions and vital signs, providing a more efficient and effective healthcare system. This not only promotes a more streamlined and efficient digital health system but also resonates the goal of ensuring the sustainable development of individuals' healthy lives. Furthermore, it supports economic sustainability by conserving medical resources and reducing medical costs.

4.1 | Body area sensing networks

The integration of skin-attached, fiber-based wearable strain sensors upon various body locations enables real-time monitoring of physical dynamics, encompassing a series of deformations from the small to the pronounced. A previous research has unveiled a porous graphene fiber strain sensor made with polymer nanoballs and PU (Figure 12A), which can detect eyeball movement.[136] The gauze-decorated sensor with more comfort was worn around the eyes to sense subtle muscle movements associated with blinking and rotation of the eyes. The outcomes exhibit that eyelid blinking yields a small resistance fluctuation, but the eyeball rotation induces bigger variation, revealing a high consistency of resistance variation in concert with the respective motions. Figure 12B presents a strain sensor affixed to a subject's cheek for detecting the electrical signals resulting from cheek bulging.[133] These signals exhibit a rise and fall pattern in sync with the cheek bulging, demonstrating the potential application in monitoring human facial micro-expressions. Wearable strain sensors are also capable of capturing the cutaneous vibration of the throat caused by speaking, drinking water, and swallowing. The placement of a sensor upon the throat allows for the monitoring of head movements, drinking, and swallowing.[221] However, the signals garnered from strain sensors exhibit an inverse pattern, attributable to the diversity in human throats and sensing positions. Further investigation is needed in this area.[158,222,223] In Figure 12C, the real-time detection of the delicate pulse is showcased through attaching a core–sheath fiber strain sensor from CNT and thermoplastic PU elastic materials to arm surface.[224] The pulse rate, calculated from the resistance change rate, was recorded at a quiescent 75 beats per minute, aligning remarkably with the established vital signs for adult males.

The realm of larger deformation detection has witnessed considerable advancements. For instance, a polyimide hydrogel fiber was developed to monitor finger bending on an artificial hand (Figure 12D).[134] As the finger bent through a range of angles (0°, 30°, 45°, 90°, 135°, and 180°) and held at an angle for about 30 s, the sensor showed gradual and ladder-shaped changes in relative resistance. The sensor can identify finger bending at different angles and shows great potential in health management for athletes. As shown in Figure 12E, a strain sensor fabricated from woolen fabric modified with GO was mounted on the wrist for health detection.[222] The resistance changes presented via Bluetooth device fluctuate up and down when the wrist movements at certain angles. A multilayered AgNW/waterborne polyurethane-MXene fiber strain sensor, when adhered to a human neck, enabled the monitoring of neck motion (Figure 12F).[125] It exhibits an efficient increase in resistance when the neck moved forward while remaining low resistance when the neck reverted to a neutral stance. This strain sensor could also identify the different patterns of leg bending (walking and running).[127,225–227] Figure 12G exhibits a fabric-like strain sensor consisting of rGO-enhanced interwoven with elastic yarn, which was fixed on the leg to detect walking and running.[48] With repetitive leg actions, the resistance change reveals a reduplicative pattern, accurately discriminating the movements based on the response frequency and intensity of the sensor. Some strain sensors have been applied to sports monitoring, which is very important for the combination of digital sports in the future. In 2021, a highly breathable and stretchable strain sensor (Figure 12H) was attached to a ball and the wrist to capture the signal profiles during basketball play.[115] Owing to its acute sensitivity across an expansive sensing range. This sensor system could discern two modes of dribbling (high-path dribbling and low-path dribbling), highlighting its potential for applications in athletic coaching and body area sensing networks. In 2022, a continuous, helically twisted graphene fiber (Figure 12I), boasting an impressive tensile strength of 369 MPa and extraordinary elongation at 48.5%, was reported to monitor people's underwater motion.[228] The strain sensors seamlessly integrated into elbow and knee pads were connected with Bluetooth

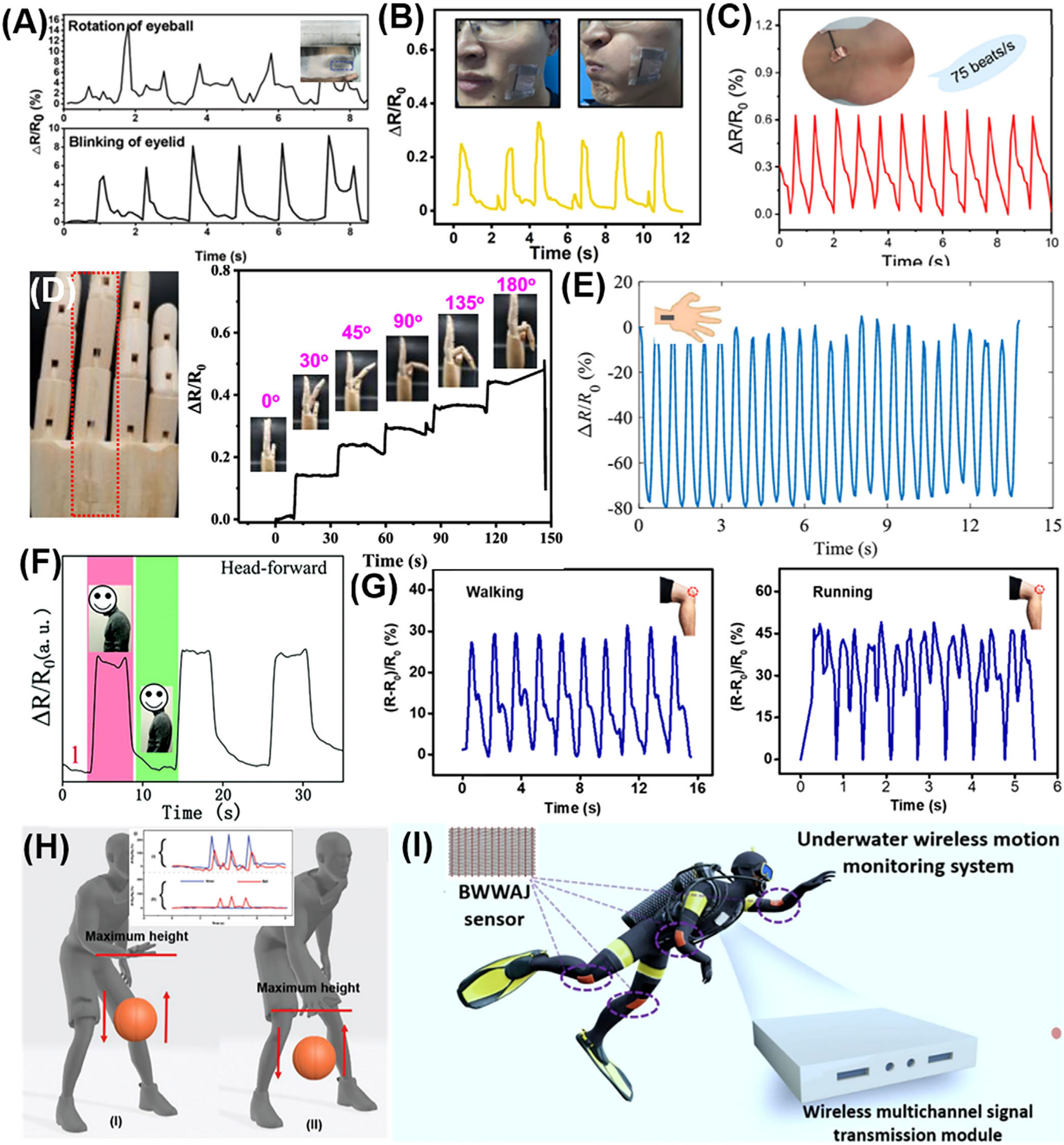


FIGURE 12 (A) Detection of the blinking and rotation by wearing a strain sensor around eyes. (B) Monitoring of the signals from cheek bulging. (C) Real-time recording and recognition of pulse movement. (D) Detection of finger motions via a facile strain sensor assembled by polyimide hydrogel fiber. (E) Capturing the signals of wrist bending by using the wool-knitted fabric strain sensor. (F) Detection of neck movements through a multilayer structured strain sensor. (G) Detections of walking and running via a strain sensor attached on the knee surface. (H) Real-time detection of two modes of dribbling by fixing a sensor to a ball and the wrist. (I) Detecting the people's underwater motion by sewing strain sensors onto the elbow and knee. *Source*: (A) Reproduced with permission: Copyright 2019, Wiley-VCH.[136] (B) Reproduced with permission: Copyright 2023, Elsevier.[133] (C) Reproduced with permission: Copyright 2020, Wiley-VCH.[224] (D) Reproduced with permission: Copyright 2021, American Chemical Society.[134] (E) Reproduced with permission: Copyright 2020, American Chemical Society.[222] (F) Reproduced with permission: Copyright 2019, Royal Society of Chemistry.[125] (G) Reproduced with permission: Copyright 2023, Springer Nature.[48] (H) Reproduced with permission: Copyright 2021, Wiley-VCH.[115] (I) Reproduced with permission: Copyright 2022, Elsevier.[228]

devices, enabling people to detect real-time motion signals about different motions and frequencies on their phones. Different swimming postures and distinct motion signals from different limbs were accurately recorded on the mobile interface. This work demonstrates the heightened sensitivity and stability of the strain sensors in water, making them essential for precise assessment of digital health within multifaceted external environments.

4.2 | Intelligent health management

With the advancement of technology, personal and public digital health have become increasingly crucial in areas such as social governance, epidemiological surveillance, and the control of communicable diseases. The integration of wearable strain sensors offers a discreet yet efficacious means for the mass monitoring and identification of people's health accurately and unobtrusively, positioning these devices as health barometers to manage human health intelligently. Medical diagnosis and health management are poised for a shift toward greater expediency if people can get access to a wealth of physical exercise and health information through smartphones.[229,230]

In Figure 13A, a design for long-term monitoring and identification of five-finger movements is shown by mounting a strain sensor made with PDMS/PU-encapsulated helical metal fiber on the skin surface.[231] The relative resistance changes reveal that the signal waves, caused by the skin strain on the middle metacarpophalangeal joint, correspond to five distinct signal waveforms for five tapping actions. The unique features of these waveforms, caused by the five-finger movements, are easily identifiable. This strain sensor can be applied to build a more concise, efficient, and interpretable intelligent health management system. Moreover, a continuous coaxial hydrogel fiber strain sensor via wet spinning was fixed on the finger joint for collecting finger movement data by a Bluetooth module (Figure 13B).[135] The data from finger bending at different angles was transmitted and processed to the cell phone via Bluetooth device, and then it was simultaneously displayed on the screen. This demonstrates the potential in real-time detection and identification of human movement. A previous work introduced a highly sensitive strain sensor based on a multifunctional fabric for respiration monitoring, the fabric was prepared through carbonization and polymer-assisted copper deposition method (Figure 13C).[232] The sensor, combined with a convolutional neural network model, was attached to the chest for collecting the respiration signals. The sensor with a learning network can distinguish three classic respiration models with high classification accuracy (up to 93.3%). The sensor could be used as an emergency alarm system for COVID-19 patients, significantly contributing to managing health in an intelligent way.

Song et al. engineered a textile-based covalently cross-linked sensing network (Figure 13D) for discerning multidirectional strain.[233] By integrating five separate fiber strain sensors into a glove, the signals from different gestures of various letters and words are sequenced. This glove could assist the visually impaired in typing or converting language into information that machines can comprehend and make sound. Another work reported a helical fiber strain sensor that can monitor subtle vibration from thoracic and abdominal respiration for disease prevention and medical diagnosis.[186] When the signals from human breathing stop for 6 s, the mobile communication system will automatically request the help of the preset number to ensure that the patient can get timely medical care (Figure 13E), ensuring the patient achieves prompt medical attention. Figure 13F exhibits real-time detection and identification of the continuous motion of a badminton player by the sleeve knitted with Joule-thermochromic Ecoflex fiber strain sensors.[138] The badminton players' actions under three postures (high ball, forehand flick, and backhand flick) can be successfully distinguished, demonstrating the real-time motion capture capabilities of the strain sensors. Real-time motion monitoring provides timely and intelligent health management when athletes suffer from injuries.

4.3 | Medical rehabilitation

The swift advancement in wearable electronics has promoted the application of medical rehabilitation systems such as remote medical treatment and rehabilitation training, which play an important role in digital health.[234–238] These applications are usually centered around human movement and health management, whereas traditional electronic products face the dilemma of matching the flexibility of the human body. Within this context, wearable strain sensors have emerged as significantly popular owing to their exceptional adaptability and great properties in medical rehabilitation, particularly in human–machine interaction.[95,239] They are essential for monitoring and controlling the interaction between patients and rehabilitation devices, ensuring the safety and effectiveness of the treatment.

Figure 14A presents poly(3,4-ethylenedioxythiophene)-coated fibers prepared through in situ polymerized method. These fibers are integrated into a piece of fabric and used for wireless user-interface (UI) devices.[240] Researchers embedded the sensors into the glove and interfaced them to a controller affixed to the wearable for the application of human–machine interface devices. The

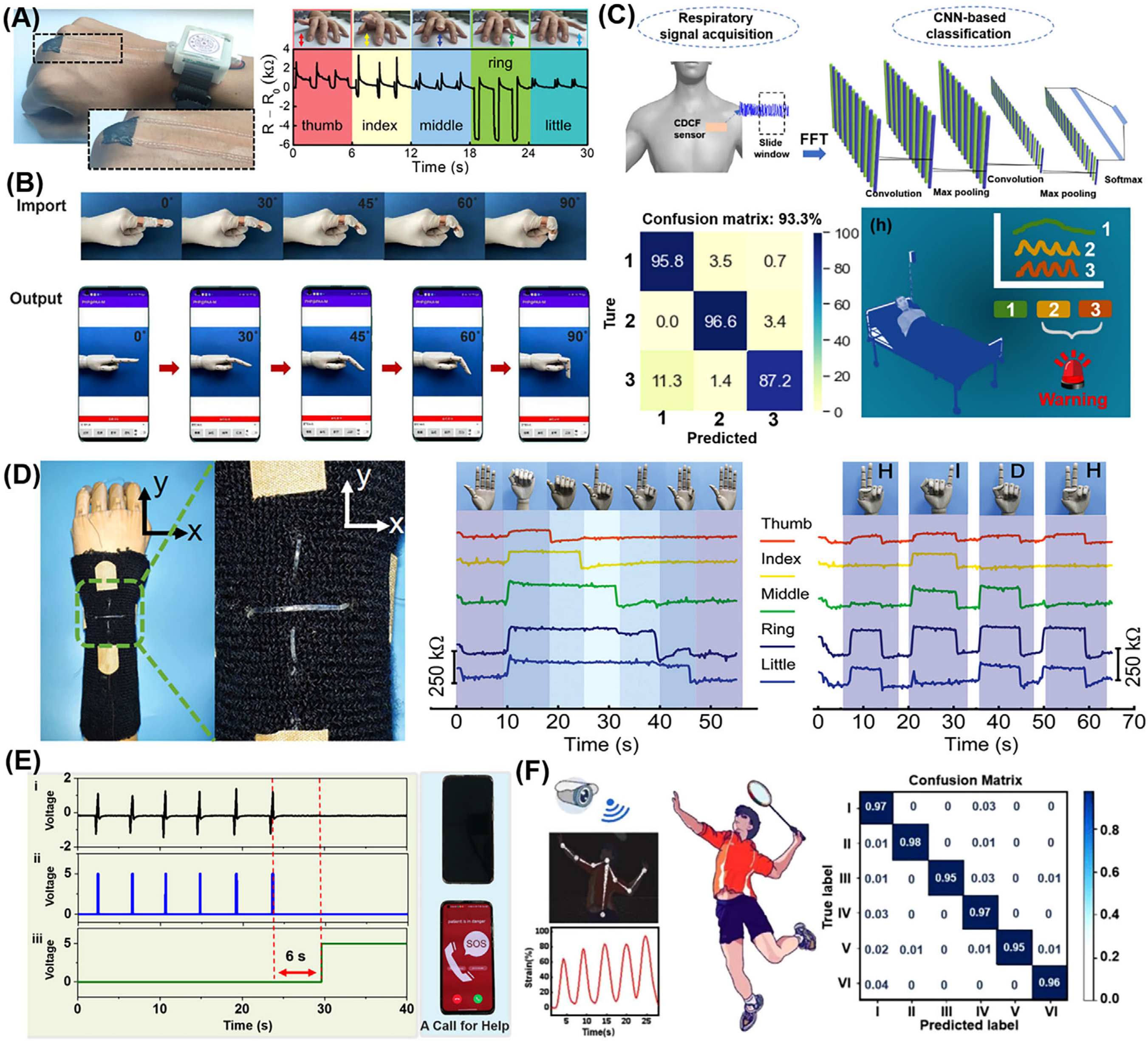


FIGURE 13 (A) The motion detection of five tapping actions from fingers. (B) Detection and identification of the finger bending with different angles. (C) A integrated detection and warning system using a strain sensor. (D) The recognition of gesture by gloves with strain sensors. (E) Identification of chest breathing and abdominal breathing by a type of helical fiber strain sensor. (F) Detection and identification of badminton players' actions by sleeve with Joule-thermochromic Ecoflex fiber strain sensors. *Source*: (A) Reproduced with permission: Copyright 2023, Wiley-VCH.[231] (B) Reproduced with permission: Copyright 2023, Elsevier.[135] (C) Reproduced with permission: Copyright 2021, Elsevier.[232] (D) Reproduced with permission: Copyright 2020, Wiley-VCH.[233] (E) Reproduced with permission: Copyright 2022, American Chemical Society.[186] (F) Reproduced with permission: Copyright 2023, Royal Society of Chemistry.[138]

wearable UI device should be designed to generate a series of output voltages, each corresponding to different finger states. Figure 14B showcases an intelligent glove containing PU yarn strain sensors with Ag-rich shells and a multifilament structure on fingers for hand robot controlling.[124] By wearing this glove integrated with sensors, the research group successfully measured a distinguishable response to finger bending without significant sensor interference. The sensor could display real-time images, mirroring the glove's movements to control a robotic hand, thereby providing an innovative option for rehabilitation training and remote medical treatment. The pursuit of gesture detection with heightened precision for digital health has continued to seek further improvement. A conductive network dispersing multi-walled carbon nanotubes (MWCNTs) in Ecoflex was reported to provide reliable sensing in

FIGURE 14 (A) The motion detection of different bending states of the fingers. (B) Detection and identification of the finger bending with different angels. (C) Detection of several gestures using the sensor-computer system. (D) Illustration of recognizing gestures and commanding the manipulator to interact with objects. (E) Photograph of multidimensional sensor-integrated gloves for surgical training and human–humanoid interactions. *Source*: (A) Reproduced with permission: Copyright 2017, Wiley-VCH.[240] (B) Reproduced with permission: Copyright 2018, Wiley-VCH.[124] (C) Reproduced with permission: Copyright 2022, Elsevier.[241] (D) Reproduced with permission: Copyright 2022, Wiley-VCH.[132] (E) Reproduced with permission: Copyright 2020, American Association for the Advancement of Science (AAAS).[242]

wearable microclimates and multidirectional mechanical fluctuation.[241] Researchers integrated the prepared sensor with a smart glove by sewing and printing to identify hand gestures and control a robot wrist's bending. As shown in Figure 14C, the sensor-computer system detects several gestures, including deviations from a wrist neutral position to the "down-back-up-back" movements, showing its potential in the domain of movement rehabilitation and physical therapy for human injury. Li et al. reported a deterministic-contact-resistance braided structure-based stretchable strain sensor for human–machine interaction (Figure 14D).[132] The sensors were integrated into a fabric glove and connected to wirelessly to a manipulator. The smart glove is adept at recognizing gestures and commanding the manipulator to interact with objects, showing fantastic utility in human motion monitoring, medical rehabilitation, and robotic control. In Figure 14E, a glove equipped with multidimensional sensors and sophisticated haptic feedback was reported for human–machine interfaces, which includes finger sensors and a palm sensor. The finger sensor can project the movement of fingers on a 30° scale by the virtual hand, and the palm sensor can detect normal force and shear force when in contact with an external object.[242] In identification tests, the prepared gloves were used to conduct the demonstration of VR surgical training program and AR-based human–humanoid interactions. The left glove controls the entire arm and hand movements and switches operation modes, whereas the right glove is used for object recognition and surgical operation, which provides an effective approach for remote medical treatment and rehabilitation.

The soft tissues within the human form, encompassing musculature, tendons, and ligaments, are prone to damage during vigorous outdoor activities.[243–245] Without vigilant oversight of delicate structures, physical recovery may be detrimentally affected. The rehabilitation of ruptured muscles, tendons, and ligaments has garnered great attention, highlighting the importance of an effective assessment method for early recovery exercise and repair.[246] The growing popularity of flexible and wearable electronics has been propelled by the demand for personalized continuous sports monitoring and health management.[191,247,248] Even though various formats of skin-mounted wearable strain sensors have been designed for nonintrusive, perpetual detection, there is a common issue concerning the mechanical mismatches between the devices and supple tissues of the human body, which will lead to inaccurate and unstable responses. Therefore, mechanically super-elastic and compatible sensors based on implantable electronics for digital health are urgently required.

Li et al. presented a highly stretchable, swift in response, sensitive, and enduring strain sensor composed of MWCNT and thermal plastic elastomer (TPE) (Figure 15A).[130] The fabrication process involves wrapping an ultralight MWCNT/TPE composite film around a pre-stretched TPE elastic rubber fiber, followed by the alleviation of the tensile force, forming a buckled sheath–core structure.[249,250] The periodic buckling formed along the axial direction of fiber by releasing the pre-stretched TPE core endows the fiber strain sensor with a wide strain sensing range, and the higher concentration of MWCNTs forms a denser conductive path. To verify the feasibility of tendon rupture rehabilitation, a TPE encapsulated strain sensor was attached to the hamstring of a laboratory rat with a compromised limb, serving as an implantable apparatus for the real-time, quantitative evaluation of tendon recovery. The angle between the tibia and metatarsus in the relaxed and stretching state is successfully detected by the strain sensor (as illustrated in Figure 15B), showing formidable potential in digital health assessment for guiding rehabilitation training.

In the domain of pliable implantable medical apparatuses, there has been noteworthy advancement toward devices for rapid diagnosis and continuous detection of vital physiological parameters. These devices provide valuable medical information about various related diseases.[198,251,252] Recently, soft and extensible polymeric substances have been increasingly employed in the fabrication of flexible implantable sensors.[253,254] Sheng et al. prepared a fiber-helical sensor by twisting the cured organogel fiber via ultraviolet and Ecoflex into a spiral for real-time ligament strain monitoring.[255] The organogel fiber and a silicone tube were proved to foster an optimal microhabitat conducive to cellular adhesion and proliferation and have no cytotoxicity, which was chosen as the core and encapsulating tube for implantation within the rabbit patellar ligament (Figure 15C). As shown in Figure 15D, the self-powered sensor exhibits stable and repeatable electrical signals under varied cycles and angles of stretching and bending of the rabbit's limb at the same and varying velocities via Bluetooth. This novel technology provides a significant stride toward an intelligent, implantable, and self-powered sensing system. To obviate the necessity for surgical retrieval, a sensor entirely made from biodegradable materials is desirable.[256,257] Boutry et al. prepared an implantable sensor by assembling biodegradable poly(octamethylene maleate (anhydride) citrate) (POMaC) layers, biodegradable pressure sensor (square pyramid-structured elastomers poly(glycerol sebacate) layer), and strain sensor (biodegradable metal electrodes (polylactic acid/Mg layer)).[5] The sensor can independently discriminate strain and pressure due to two vertically stacked sensors. Meanwhile, this device shows desirable degradation kinetics because they used excellent materials renowned for their great biocompatibility upon decomposition. In Figure 15E, the sensors were subcutaneously

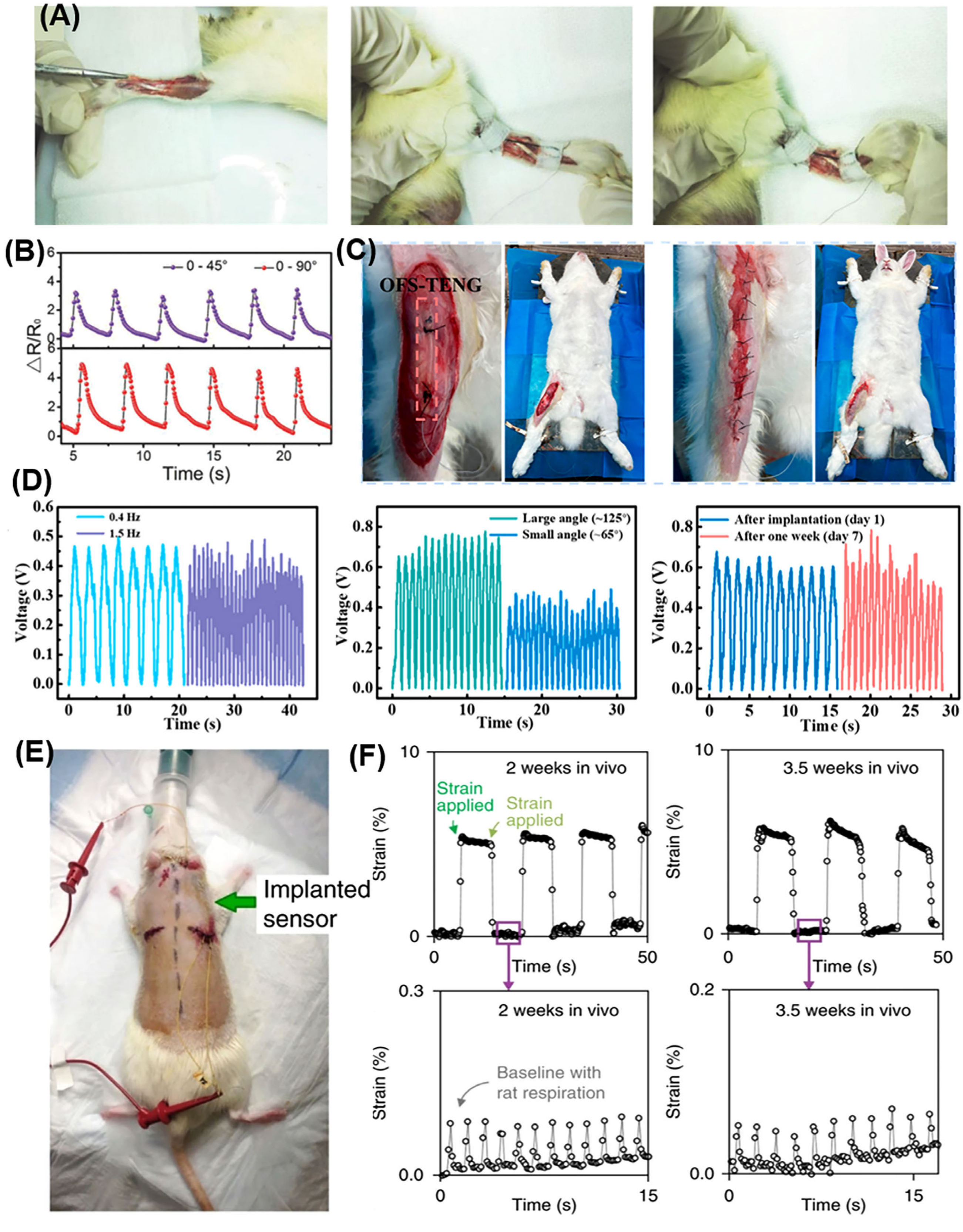


FIGURE 15 (A) The images showing the process of fixing the sensor to the hamstring of a lab rat. (B) Strain sensor response the cyclic leg stretching exercises from rats. (C) Images displaying the sensors were implanted on the ligament of the rabbit knee. (D) The electrical outputs of the rabbit leg's bending and stretching. (E) Photos exhibiting the biodegradable sensor implanted on the back of a rat. (F) The varying signal for different weeks after sensor implantation. *Source*: (A and B) Reproduced with permission: Copyright 2018, Wiley-VCH.[130] (C and D) Reproduced with permission: Copyright 2022, American Chemical Society.[255] (E and F) Reproduced with permission: Copyright 2018, Springer Nature.[5]

implanted into the backs of rats to record the respiration of the animal and assess adverse inflammatory reaction after 2 and 3.5 weeks. The corresponding baseline exhibits electrical outputs of rat's respiration, with the rats exhibiting tolerance toward the sensor without prolonged inflammatory reactions tolerated the presence of the sensor without long-term adverse inflammatory reactions (Figure 15F). The POMaC layers effectively protect the sensor from body fluids, preventing premature degradation of the metal electrodes. This work opens up possibilities for the development of a wholly biodegradable wireless system, inclusive of the circuit employed for transmission of recorded signals through the skin.

4.4 | Multifunctional healthcare system

The continuous physiological process of respiration, including inhalation and exhalation, is a critical aspect in healthcare system throughout human life. Clinically, the mechanics of breathing can act as a significant biomarker for the early detection of various diseases, such as chronic lung disease, asthma, and pulmonary hypertension.[258,259] The real-time and rapid detection of life-threatening gaseous compounds is particularly important for digital health as it can prevent and prohibit dangerous occurrences.[260–263] Compared to costly, bulky, and energy-intensive apparatuses, wearable strain sensors for gas sensing have the advantages of affordability, small size, flexibility, and reasonable life, and guarantee chemical safety and human health protection.[70,264–266]

Guo et al. developed a multilevel structure fiber containing a porous sensing core with MXene-coated microspheres, rending gas-sensing capabilities requiring large surface areas (Figure 16A).[267] The respiration rates of 16 and 64 breaths per minute before and after exercise can be successfully recorded by this integrated fiber sensor, which aligns with the frequencies observed in normal breathing patterns.[268] Compared to pristine MXene, which exhibits a limited response to gas adsorption, this multilevel structured fiber is sensitive to volatile organic compounds and some inorganic gases owing to its substantial specific surface area (285.1 m^2 g^{-1}) and highly porous inner core. The fiber sensor can detect acetone at a concentration as low as 100 ppb, with a sensing response of 0.18% ($\Delta R/R_0$) at this concentration. Xie et al. prepared an on-skin strain sensor by depositing a thin layer of polyvinyl alcohol fibers on the welded MXene/PU fiber mate for harmful gas sensing (Figure 16B)[269] and sensors can be easily fixed on any curved human skin surface without external paste. The welded matrix, with porous and conductive properties, was fashioned into a serpentine structure. It makes the mate possess excellent electrical stability against stretching, with resistance change rate of less than 0.01 when stretching reaches up to 20% strain. As shown in Figure 16C, the serpentine mate displays high sensitivity to an array of organic and inorganic gases, a phenomenon ascribed to the hydrogen bonding interactions between the MXene layers and the gas analytes. In Figure 16D, a multifunctional stretchable strain sensor was prepared by in situ polymerization of dopamine onto the rGO/TPU film for detecting various human motions and some organic gas sensing.[270] The stretching process induces an increase in the distance between the neighboring rGO nanosheets on the TPU fiber surface, leading to the increase in resistance, and the introduction of PDA endows sensors with a large sensitivity.[271,272] The accumulated organic gas on the fiber surface causes TPU and PDA to swell gradually. The swelling of the fiber alters the rGO conductive network on the TPU fiber surface, engendering a change in resistance. Figure 16E shows the vapor sensing behaviors of the fibrous mat sensors toward the four solvents. The prepared sensor reveals distinct sensitive responses and relative resistance changes, showing considerable potential in detection of organic gas leaks and preventing people from danger in time.

Incorporating self-powering functions into textiles offers new opportunities for wearable electronic devices in the realm of digital healthcare.[273–276] By combining electronic components with durable and lightweight fiber, these textiles can supply power to wearable electronic devices, thereby stimulating the demand for compact, flexible power solutions that are also lightweight.[277–279] Concurrently, they can minimize the necessity for battery replacements or charging, enhancing human health by making the devices more user-friendly and less intrusive for patients.[280–283] However, it remains a challenge for fiber batteries to escape from the limited lifespan to cater to the ever-increasing power demand of wearable devices designed for continuous human activity monitoring and health management.[284–286] Self-powered strain sensors can aid in the creation of novel and groundbreaking digital health technology, thereby advancing the field of medical care.

A self-recharging aqueous Zn-ion battery fiber, capable of functioning in ambient air, was developed by assembling V_6O_{13}/CNT fiber (VCF) as the cathode with a Zn anode fiber (Figure 17A).[287] The prepared battery fiber displays a formidable specific capacity, excellent durability, maintaining 91% capacity after 5000 charge–discharge cycles at 5 A g^{-1}. The VCF/Zn battery fibers were used to energize a thermometer and, in tandem with a strain sensor, were incorporated into a wearable fingertip. The strain sensor can quickly respond to the repeated curving of the finger, validating the practicality of this rechargeable battery fiber for autonomous powering of wearable technologies.

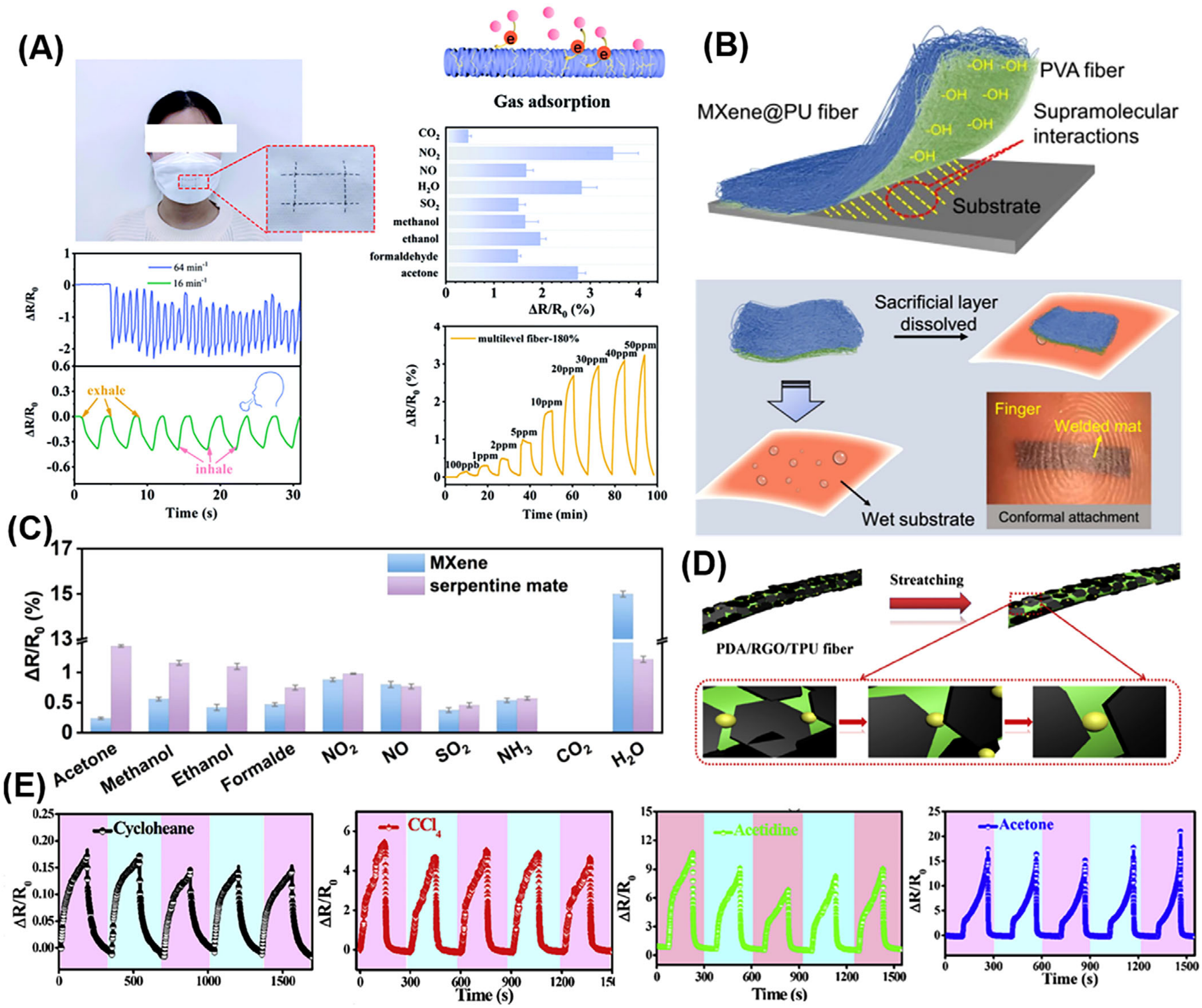


FIGURE 16 (A) Demonstrating gas sensing of the multilevel fiber sensor. (B) Schematic diagram of the welded mate sensor attached onto the skin. (C) Sensing response of the sensors for different gas species. (D) Schematic illustration of the stretching process of the polydopamine (PDA)/reduced graphene oxide (rGO)/thermoplastic polyurethane (TPU) fiber. (E) Sensing response of a multifunctional sensor for cyclohexane, CCl_4, acetidine, and acetone. *Source*: (A) Reproduced with permission: Copyright 2022, Royal Society of Chemistry.[267] (B and C) Reproduced with permission: Copyright 2022, Elsevier.[269] (D and E) Reproduced with permission: Copyright 2020, Elsevier.[270]

To fabricate the fiber with liquid alloy/silicone rubber core/shell structure (LCF), liquid alloy and silicone rubber were injected simultaneously into the output ports via coaxial spinning method. The LCF exhibits a wide tensile strain of 300%, good tensile force (500 g), great repeatability, and resistance-strain sensitivity (Figure 17B).[288] Furthermore, the LCFs were weaved into highly integrated fabric used as TENG by warp/weft weaving. This wearable device presents excellent electrical output performance, including open-circuit voltage (175 V), short-circuit current (15 μA), and short-circuit transferred charge (66 nC) under the frequency of 3 Hz, with a commercial latex glove serving as the triboelectric material. Various sizes of fabrics are worn on different body parts to monitor bodily movements as self-powered sensors (Figure 17C). The movement of limbs can be accurately detected by these sensors without external power supply, indicating the potential application in body area sensing networks and intelligent health management.

A bis-condensed, dual-carbon fiber strain sensor from MWCNTs, carbon blank, and poly(styrene-b-isoprene-b-styrene) was proposed based on the synergistic interaction and tunneling effect.[129] The strain sensor presents excellent sensing ability for human motion detection, including good electrical stability, ultra-stretchability (>1100%), high sensitivity, and great durability (Figure 17D). The fiber

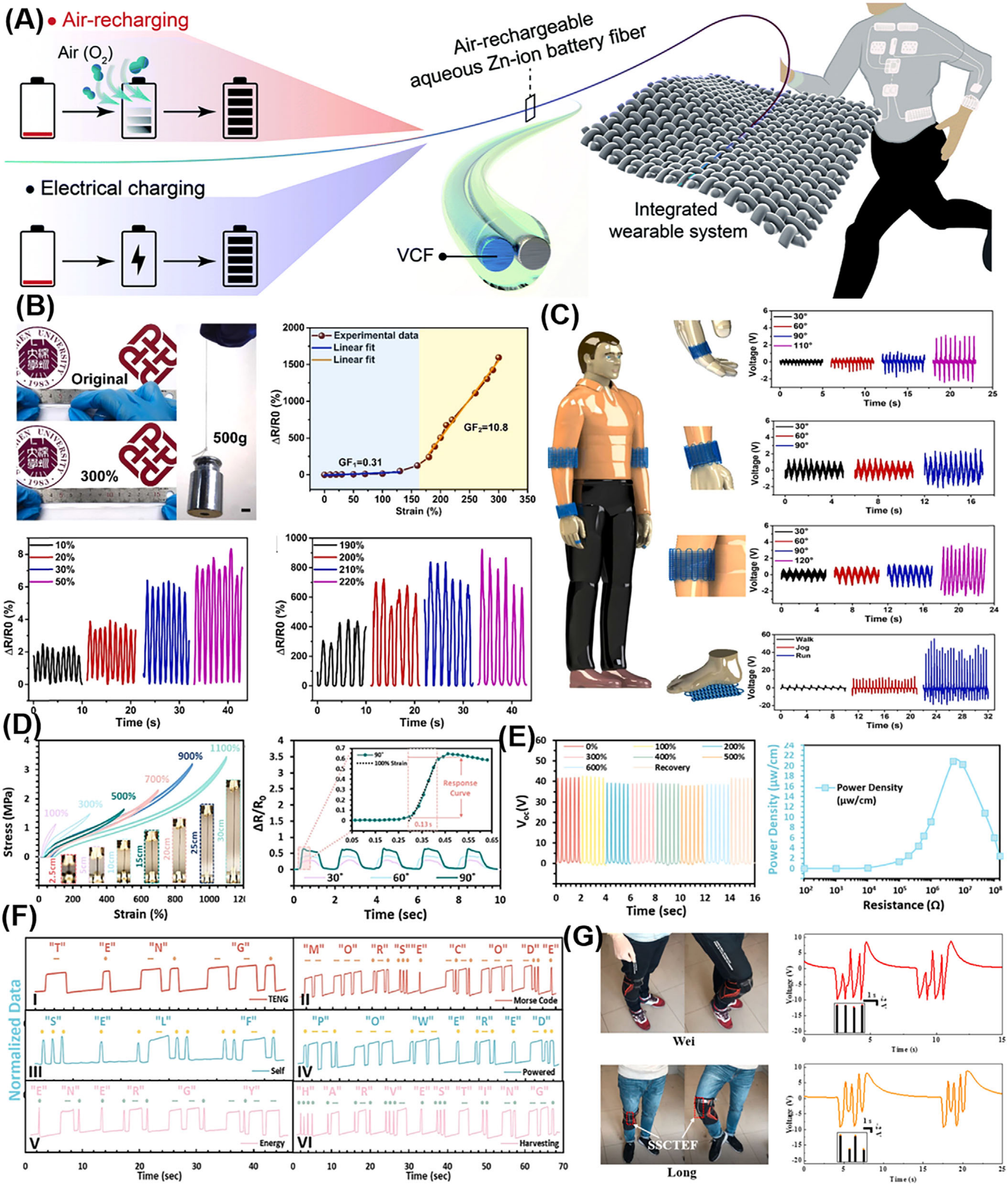


FIGURE 17 (A) Schematic of the battery fiber with air-rechargeable ability integrated into multifunctional wearable systems. (B) Performances of composited liquid fiber sensor with core/shell structure. (C) Application of motion monitoring by the triboelectric nanogenerator (TENG) and data corresponding to different bending. (D) Stress–strain curve and the electrical response of the fiber strain sensor during bending. (E) V_{OC} of the fiber-TENG at different strain and dependence of the output power with different external load resistance. (F) Reliable sensing signals of the fiber-TENG in different Morse codes. (G) Applications of the sheath–core structural fiber as a self-powered sensor for motion monitoring. *Source*: (A) Reproduced with permission: Copyright 2021, Royal Society of Chemistry.[287] (B and C) Reproduced with permission: Copyright 2022, Elsevier.[288] (D–F) Reproduced with permission: Copyright 2023, Elsevier.[129] (G) Reproduced with permission: Copyright 2017, Elsevier.[289]

TABLE 3 Summary of the fiber-based strain sensors for different applications.

Applications	Substrates	Active materials	Cycling stability	Data collection method	Refs
Body area sensing	TPU	CNTs	>40 000	Wireless	133
	PU	CB/Ag	>32 000	Wired	290
	Loofah	Carbon	>2000	Wired	143
	TPU	CNTs	>10 000	Wired	291
Intelligent health management	Polytetrafluoroethylene/Nylon	Ag	>20 000	Wireless	186
	Ecoflex	CB	>3000	Wired	138
	Woven fabrics	Carbon/Copper	>12 000	Wired	232
	Poly(ethylene glycol)	Poly(ethylene glycol) diacrylate	>1000	Wired	233
Medical rehabilitation	Polyester yarns	Ag	>2000	Wireless	132
	Ecoflex	CNTs	>4000	Wireless	241
	Silicone fiber	ZnS/Cu	>10 000	Wireless	292
Implantable medical devices	PDMS	rGO	>10 000	Wireless	293
	Ecoflex	Organogel	>30 000	Wireless	255
	Ecoflex	Ag	>2000	Wireless	198
Self-powered devices	Poly[styrene-b-isoprene-b-styrene]	CNTs/CB	>10 000	Wired	129
	Silicone rubber	Liquid alloy	>5000	Wired	288
	Polyacrylonitrile	Ag	>2300	Wired	294

Abbreviations: CB, carbon black; CNT, carbon nanotube; PDMS, polydimethylsiloxane; PU, polyurethane; rGO, reduced graphene oxide; TPU, thermoplastic polyurethane.

strain sensor is able to generate repeatable signals for monitoring subtle facial expressions and large joint movements (limb movement, sitting, jumping, and squatting), which is important for medical rehabilitation in clinical treatment. Meanwhile, the fiber sensor was also used as TENG via single-electrode mode, with Ecoflex-silicone rubber as a triboelectric layer, dual-carbon fiber strain sensor as an electrode, and an active object (e.g., hand and glove) connected to the ground through a wire. Based on the strong and stable interconnection of MWCNTs and CB, the TENG shows good electric output performance in various stretching levels (0%–600%), and the power density reaches 20.95 μW cm^{-1} (Figure 17E). Due to its static responsiveness, it can generate corresponding voltages to numerous phrases and show a stable capacity for longer phrases about the Morse code sequences, revealing significant potential in human–computer interaction (Figure 17F). By combining a built-in wavy core fiber (nylon fiber) with an intrinsically stretchable sheath fiber tube (silicone rubber/AgNW/PDMS), a sheath–core structural fiber strain sensor was prepared.[289] The unique configuration endowed the fiber sensor with high stretchability (>300%) and heightened sensitivity to various mechanical deformations. The physical contact from the differential retraction ratios between the sheath fiber tube and core fiber generates an alternative current. It can provide enough power to guarantee the sensor serves as a human kinematic sensor to differentiate the movements of distinct individuals. In Figure 17G, the fiber sensor fixed on a soft knee pad was worn by walkers (Wei and Long) to identify their accustomed walking manner. The device not only discriminated the walkers but also quantitatively recorded the dynamic alterations throughout the gait cycle. It provides a new way for developing wearable and self-powered sensing fiber in body area sensing networks and intelligent health management. In summary, we provide the applications, substrate materials, active materials, cycling stability, data collection methods, and applications of fiber-based strain sensors in recent years, as shown in Table 3.

5 | DATA COLLECTION AND PROCESSING

Extensive research has been conducted on wearable strain sensors using sustainable fibers, primarily focusing on device preparation and practical application in digital health. High-efficiency data collection and processing have greatly affected the confluence of digital health and sustainable development, enabling the seamless integration of wearable electronics into our everyday lives. Various data collection methods, such as wired, Bluetooth, and near-field communication (NFC), can be used to gather data from human body. Then these data are integrated into learning networks for analysis and processing, and a comprehensive digital health network can be established. These advances in technology are revolutionizing digital health and providing critical insights for early warnings, diagnosis, and personalized treatment.

5.1 | Data collection

Integrating data collection function with fiber-based strain sensors is an indispensable part in building digital medical networks. The main data collection methods for wearable strain sensors include wired and wireless (Bluetooth, NFC, etc.). Continuous real-time data collected from wearable devices can provide rich personalized health information, enabling personalized medical care, early detection and prevention, higher patient participation, cost-effectiveness, and real-time monitoring.

Sun et al. developed a superhydrophobic conductive rubber modified with CNT, rGO, and hydrophobic fumed silica for full-range monitoring of human motions and physiological signals.[295] As shown in Figure 18A, the sensor attached to various body positions via wired method can achieve corresponding data related to knee deformation, underwater training, throat muscle movement, pulse, and head at different angles. Similarly, a fiber strain sensor fabricated via warping carbon yarns onto the PU fibers was employed to detect various human movements.[296] The sensor was connected to the circuit and attached to the body skin via electrical wires, and the data were achieved via the digital multimeter (Figure 18B). Although the body deformation signals can be transferred to the terminal data collector, many wires around body skin will interface the stability of the sensors.

To avoid inference from external wires and create a more professional digital health system, researchers began to use wireless devices to collect the data. As shown in Figure 18C, a remote patient/elderly medical diagnosis and treatment system was created by connecting a stretchable pressure sensor with a motorized robotic arm via Bluetooth device.[297] Doctors can conduct remote diagnosis and surgery by controlling the robot hand to apply well-controlled contact to the patient's body. Fang et al. integrated sensors into mask and created a wireless transmission system for data collection and respiratory monitoring.[215] The real-time data from human respiratory can be collected and analyzed by a lab-designed circuit (Figure 18D), then it is transferred into phone via a wireless device and displayed on a customized application. The previous work reported a remote human–machine interaction system established by integrating fiber sensors, wireless transceiver, and battery into a glove.[298] Signals from each finger are transformed into digital signal and transmitted into a smartphone via wireless transceiver (Figure 18E), enabling the manipulator and display pressure under multichannels in real scenes. Another work developed a wireless system for human-centered healthcare system by attaching stretchable electronics on the skin.[299] The electrical signals can be collected by smart phone or personal computer terminal to monitor electrocardiograph (ECG) and electromyography (EMG) (Figure 18F). Alternatively, textile-based bioelectrodes modified by CB and CNT also completed ECG and EMG detection via wireless device (Figure 18G).[64] These devices can wirelessly transmit real-time human body deformation signals via the NFC to the central hub or health care providers so as to continuously monitor the health status of patients. Shao et al. developed an all-MXene-printed integrated system with capability of wireless communication, energy harvesting, and smart sensing.[300] By directly integrating the MXene components, PDMS, and flexible printed circuit board into a flexible integrated device (Figure 18H) and then connecting it with smart phone, an NFC platform used to sense and energy transmission was prepared. To build a digital health network, much work also realized the data transmission of real-time human deformation signals via NFC.[222,301,302] This innovative technology facilitates seamless data exchange between electronic devices without physical contact, making it an ideal choice for various applications. These include wearability, battery-free operation, one-time use, low-cost implementation, recyclability, and compatibility with smart phones.

5.2 | Machine learning networks

Machine learning significantly contributes to the enhancement of the functionality and significance of wearable fiber-based strain sensors in the realm of digital health. Through machine learning, these sensors incorporated into wearable devices can generate extensive data pertaining to body movement and strain patterns. Machine learning algorithms can be trained to identify potential injuries or health issues, thereby alerting individuals or medical centers. This facilitates timely intervention and improved health outcomes. Furthermore, machine learning enables the creation of personalized healthcare solutions, utilizing data gathered from wearable fiber-based strain sensors.

COVID-19 swept across the world, causing unprecedented interference to people's lives and health. Some work began to focus on developing wearable strain sensors that can identify human breathing patterns. Liu et al. integrated a highly sensitive sensor with a learning network, enabling respiratory monitoring and identification for various breathing modes,[232] revealing significant promise for the medical oversight of COVID-19-infected patients. Fang

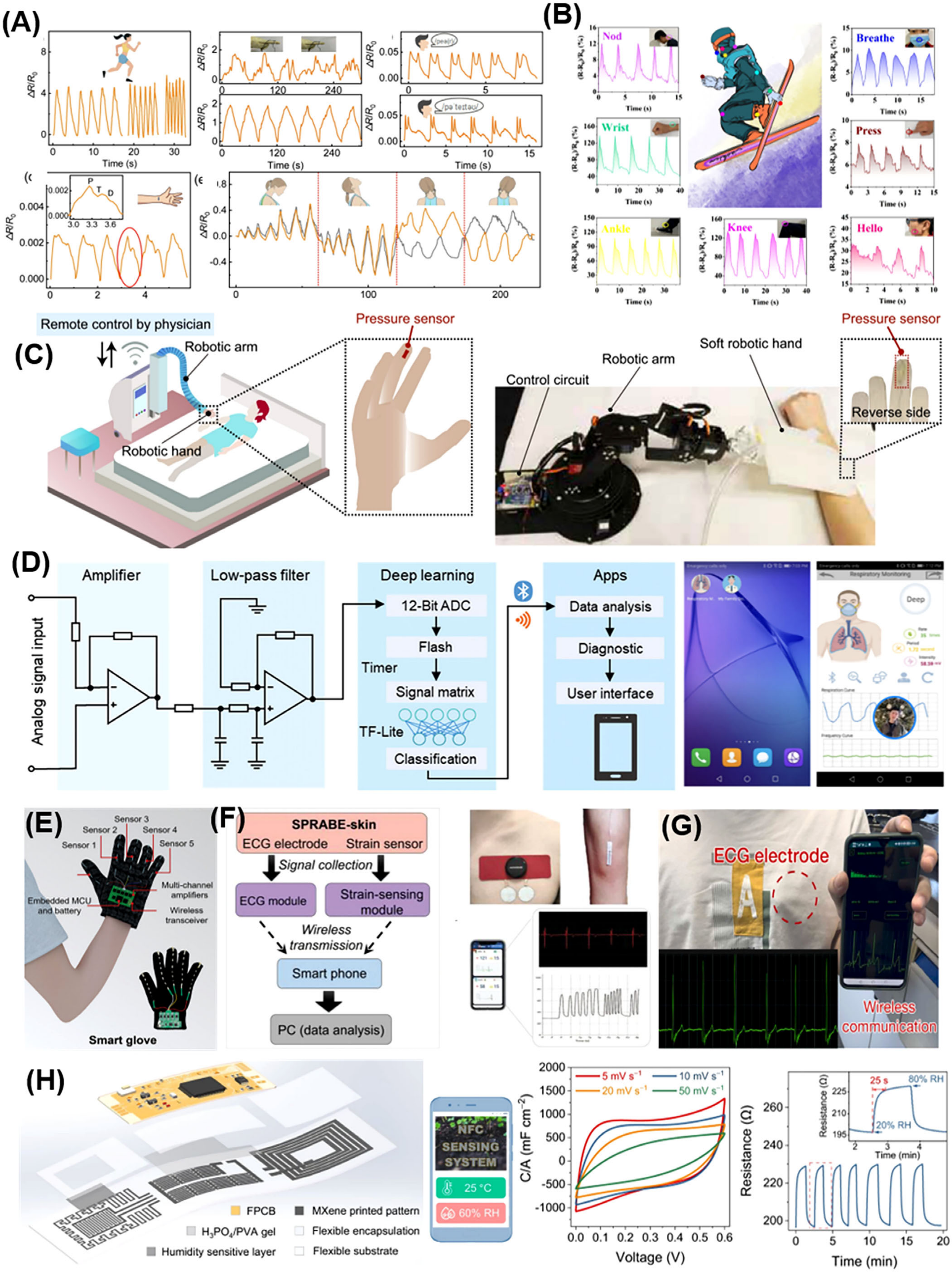

(A)
Time (s)
(B)
Nod
Breathe
Wrist
Press
Ankle
Knee
Hello
Time (s)
Remote control by physician
(C)
Robotic arm
Robotic hand
Pressure sensor
Control circuit
Soft robotic hand
Reverse side
(D)
Amplifier
Low-pass filter
Deep learning
Apps
Analog signal input
12-Bit ADC
Flash
Timer
Signal matrix
TF-Lite
Classification
Data analysis
Diagnostic
User interface
(E)
Sensor 1
Sensor 2
Sensor 3
Sensor 4
Sensor 5
Multi-channel amplifiers
Embedded MCU and battery
Wireless transceiver
Smart glove
(F)
SPRABE-skin
ECG electrode
Strain sensor
Signal collection
ECG module
Strain-sensing module
Wireless transmission
Smart phone
PC (data analysis)
(G)
ECG electrode
Wireless communication
(H)
FPCB
MXene printed pattern
H3PO4/PVA gel
Flexible encapsulation
Humidity sensitive layer
Flexible substrate
NFC SENSING SYSTEM
25 °C
60% RH
5 mV s-1
10 mV s-1
20 mV s-1
50 mV s-1
C/A (mF cm-2)
Voltage (V)
Resistance (Ω)
Time (min)
25 s
80% RH
20% RH

FIGURE 18 (A) Real-time monitoring of human motions via wired method. (B) Connecting wires with strain sensor to detect human body movements. (C) Schematic scenario of a remote patient/elderly medical diagnosis and treatment system. (D) Schematic illustration of wireless learning network for data collection and respiratory monitoring via mobile phone application. (E) Schematic diagram of a remote human–machine interaction system by integrating fiber sensors, wireless transceiver, and battery into a glove. (F) Schematic illustration of a health monitoring system and photos of real-time signal monitoring. (G) Detection of ECG and EMG via a textile-based bioelectrodes. (H) Demonstration of sensor structure, integrated sensing system, and electrical response. *Source*: (A) Reproduced with permission: Copyright 2022, Science.[295] (B) Reproduced with permission: Copyright 2023, Springer Nature.[296] (C) Reproduced with permission: Copyright 2021, Science.[297] (D) Reproduced with permission: Copyright 2022, Wiley-VCH.[215] (E) Reproduced with permission: Copyright 2021, Wiley-VCH.[298] (F) Reproduced with permission: Copyright 2023, Wiley-VCH.[299] (G) Reproduced with permission: Copyright 2022, Elsevier.[64] (H) Reproduced with permission: Copyright 2022, Springer Nature.[300]

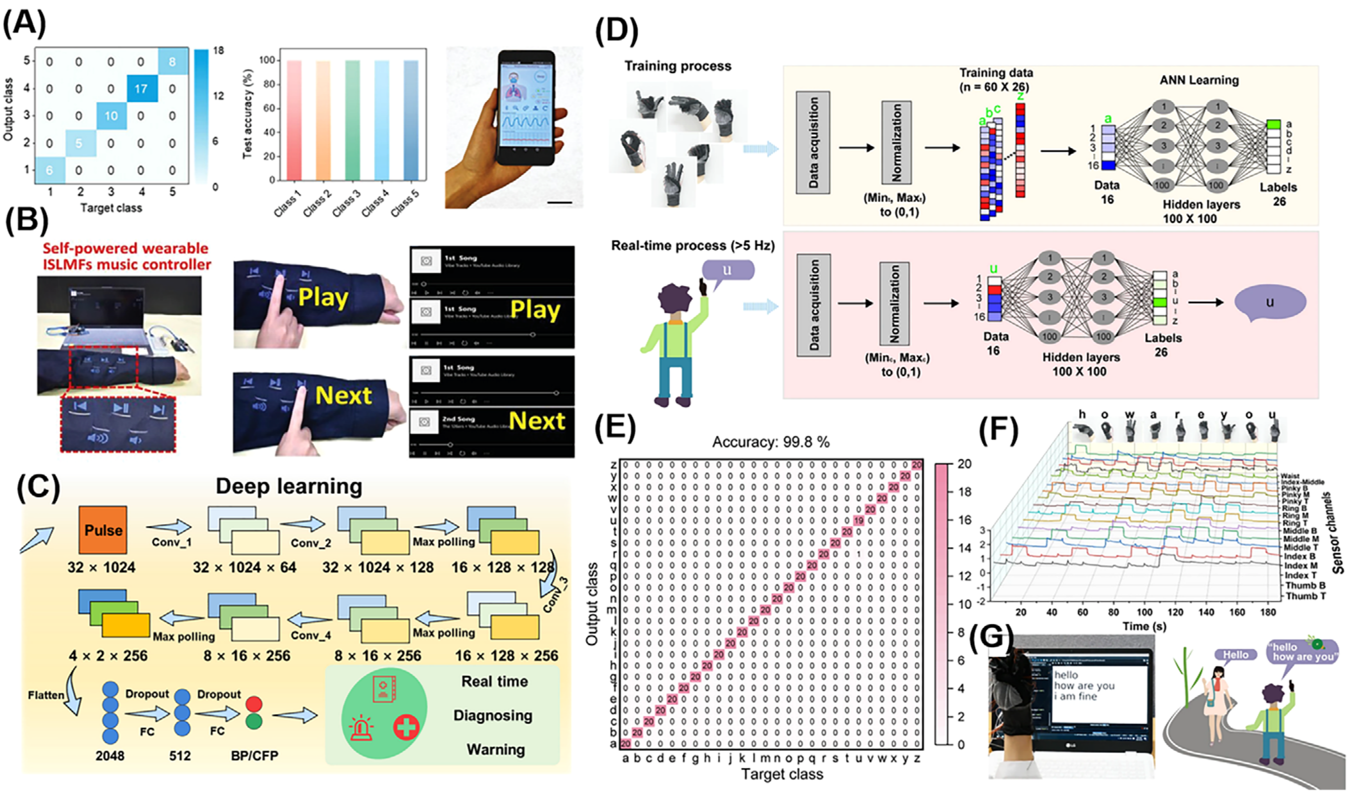


FIGURE 19 (A) Confusion matrix for identification of respiratory, real-time monitoring of respiratory pattern recognition, and real-time display of respiratory monitoring in cellphone APP. (B) Schematic illustration of a wearable music controller via machine learning-sensor. (C) Schematic scenario of a deep learning neural network. (D) Schematic illustration of a glove translation system and machine learning. (E) Confusion matrix of classification for 25 letters and recognition time. (F) Schematic diagram of a health monitoring system and photos of real-time signal monitoring. (G) Real-time input from signal language and signer communicating. *Source*: (A) Reproduced with permission: Copyright 2022, Wiley-VCH.[215] (B) Reproduced with permission: Copyright 2021, Wiley-VCH.[216] (C) Reproduced with permission: Copyright 2023, Science.[145] (D–G) Reproduced with permission: Copyright 2022, Springer Nature.[303]

et al. adopted a 1D-CNN algorithm to realize masks with strain sensors can recognize accurately five kinds of respiratory patterns.[215] The confusion matrix verifies the system can recognize different respiratory signals with an average prediction accuracy of 100% (Figure 19A), showing enormous application of the sensor in big data-driven respiratory management. In addition, by using a microcontroller to program the signal from the fiber sensor, a wearable music controller was prepared.[216] Touching the "Play" key of the sensor to play remotely the music in the player and pressing the "Next" key of the sensor to play remotely the next song in the player (Figure 19B). The early monitoring, diagnosis, and intervention of cardiovascular diseases are paramount for the assessment of cardiovascular health, with the potential to substantially reduce the risk of cardiovascular-related mortality and enhance life quality. Li et al. developed a deep learning algorithm for automatically analyzing pulse signals into blood pressure and cardiac function by applying a supervised convolution neural network to sensors.[145] Figure 19C shows that

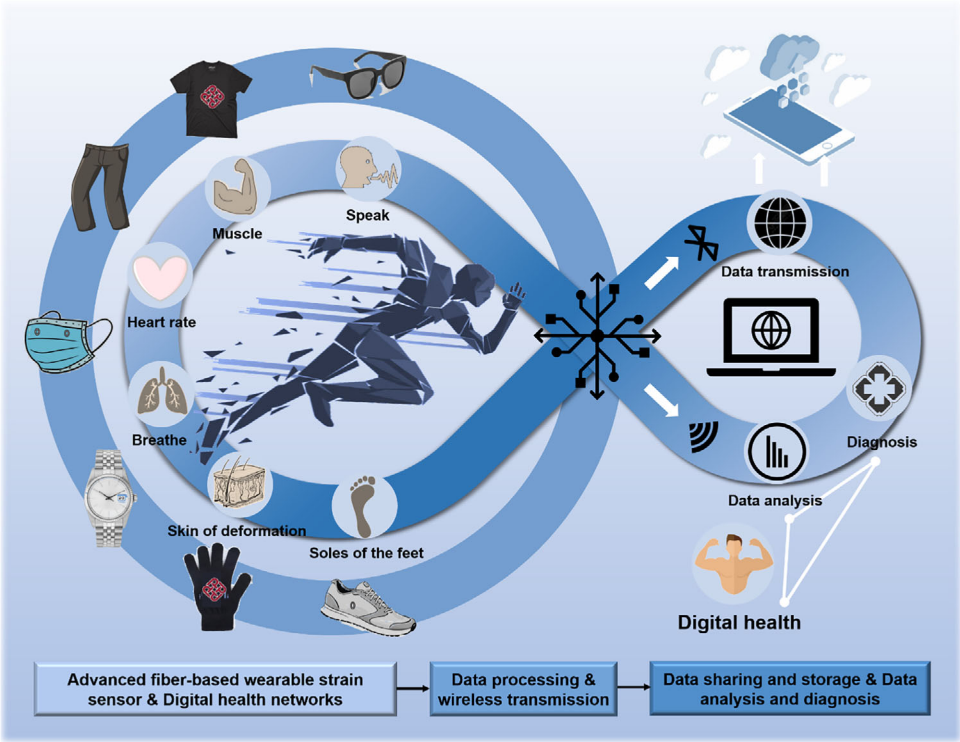


FIGURE 20 Perspectives of fiber-based strain sensors for digital healthcare.

high-quality pulse signals are processed by the deep learning module, which contains four convolutional layers, three max-pooling layers, and two fully connected layers. And then the blood pressure and cardiac function are calculated, showing potential in public healthcare and early diagnosis. Alternatively, a sign-language translation glove integrated with full-fiber sensors was fabricated by using an artificial neural network in Figure 19D.[303] The confusion matrix exhibits a high classification accuracy of 100% for 25 letters and a fast recognition time less than 0.25 s (Figure 19E). When volunteers put on smart gloves (Figure 19F), the corresponding sign-language gestures from "A" to "Z" can be translated into text by using the deep learning model. When they say "Hello," "How are you," and "I'm fine" (Figure 19G), they were converted into text without any obvious delay. These studies show the integration of machine learning and wearable fiber-based strain sensors has great prospects in completely changing digital health by realizing active monitoring, personalized intervention, and improving overall well-being.

In a demonstrative validation of fiber-based wearable strain sensors for the realm of digital health, Figure 20 portrays an integrated and sustainable ecosystem embodying intelligent health tracking and diagnostic capabilities. This system comprises body-area wearable sensors that seamlessly facilitate the collection, transmission, storage, analysis, and diagnostic interpretation of health-related data. These sensors, adroitly affixed to human bodies, function as mobile remote devices, capturing real-time activity and health metrics encompassing parameters such as foot movements, skin elasticity, muscle deformation, respiratory patterns, heart rate, speech patterns, and more. Remarkably versatile, these sensors exhibit a superior sensing range and detection threshold, enabling the discernment of an array of bodily mechanical deformations ranging from minute to substantial scales. The amassed data can be wirelessly transmitted to a central repository for analysis and storage using communication protocols, such as Bluetooth, NFC, or radiofrequency identification. Subsequently, a data identification system, proficiently trained in deep learning algorithms, meticulously scrutinizes the holistic health dataset. In instances of aberrant data patterns, the system promptly triggers emergency medical services, ensuring timely intervention. Furthermore, this innovative framework not only revolutionizes healthcare delivery for patients but also orchestrates a paradigm shift in the broader healthcare landscape. Facilitating sustainable healthcare, low impact on the environment from medical consumables, and more affordable medical care has become an accessible reality. Notably, its potency is magnified during pandemics, enabling non-intrusive monitoring of infected individuals on an economically viable scale. The ubiquity of this transformative system diminishes the dependence on costly traditional hospitals, heralding an unprecedented transformation in the realms of health management and hygiene.

6 | CONCLUSION AND PERSPECTIVES

In recent years, fiber-based strain sensors have gained substantial traction in the realm of digital health, offering real-time physical perception capabilities. They facilitate various applications such as real-time detection within body area sensing networks, seamless integration of human health data, remote and efficient treatment expansion, intelligent health management, and medical rehabilitation. These sensors are prized for their exceptional flexibility, extended lifespan, serviceability, comfort during wear, and adaptability to diverse body structures. This paper provides a comprehensive review of advanced fiber-based strain sensors, offering a meticulous investigation and in-depth discourse. It covers the preparation of conductive fibers for strain sensor fabrication, encompassing spinning technology, surface functionalization, and in situ carbonization methods. The advantages and drawbacks of these techniques are thoroughly discussed with illustrative examples. The strain sensors have been categorized into three distinct types based on their varied sensing mechanisms: resistive strain sensors, capacitive strain sensors, piezoelectric sensors, and triboelectric sensors. A comprehensive elucidation of the sensing mechanisms inherent to each sensor type has been provided. The potential of fiber-based strain sensors in the applications of digital health, including intelligent health management, medical rehabilitation, and multifunctional healthcare systems, was carefully summarized and evaluated. The data collection and machine learning of wearable fiber-based strain sensors for the construction of a more complete digital health network were also systematically expounded.

Recent decades have witnessed remarkable achievements in the advanced fiber field, with much research on significant strides in the preparation method and performance optimization of conductive fiber for wearable strain sensors. However, there are still some fields worth exploring for the long-term development of strain sensors. A formidable challenge lies in enhancing the electrical conductivity and mechanical properties of fibers. Although numerous reported conductive fibers have possessed high electrical conductivity, they still face great obstacles to reaching the level of electrical properties similar to metal fibers. This could be realized through a superior amalgamation of active materials and fibers, coupled with innovative design of sensor structure. Meanwhile, the fiber faces the dilemma of deterioration of mechanical properties such as breaking strength and tensile strain in the process of conductive functionalization. It is vital to endow the fiber with exceptional electrical conductivity while preserving its robust mechanical properties. Although some elastic fibers have possessed excellent stretchability that can meet the requirement of preparing wearable strain sensors, highly stretchable conductive fibers with the ability to resist bending and twisting could be further improved. In addition, as digital health devices, fiber-based devices have to undergo constant deformations and hence are subjected to mechanical failures and the leakage of encapsulated materials in practical applications. In any circumstances, the safety of individuals is the primary consideration, and the toxicity from these materials toward humans is unequivocally unacceptable.

Traditional electronic devices have a broader market and more popular consumers' demands, but they have a high cost, complicated preparation process, poor air permeability and flexibility, and difficulties in mounting on nonplanar human body surfaces. In contrast, fiber-based strain sensors break the technical barriers of electronic devices resulting from the merits of their excellent flexibility, outstanding lifetime and serviceability, brilliant wearability, and adaptability to various body structures. In previous studies, fiber-based strain sensors could monitor and identify various tiny physiological signals, such as pulse, and respiratory signals, as well as large physical deformations, such as finger, elbow, and knee bending. However, more efforts should be contributed to develop a strain sensor with both excellent durability and a wide sensing range due to the requirement of the large-scale movement of the human body (such as finger bending, walking, and running). Considering that human joints are frequently in motion, wearable strain sensors should ideally undergo at least 100 000 stretch-release cycles for wearable deployments. Moreover, the establishment of a linear correlation between mechanical deformation and electrical signal outputs is imperative for strain sensors. Linear detecting of human deformation under a certain degree of elongation range can easily distinguish human movement, realizing human health management and stable monitoring. However, the linearity across a wide sensing range, alongside the elucidation of the underlying mechanisms, needs to be investigated in the future. In addition, the human body is a complex physiological environment that continuously releases heat and produces sweat to the external environment. These metabolites lead to an increase in humidity and temperature between the human body and the sensor, deteriorating the sensing performance of the sensor. It is a challenge to develop fiber-based strain sensors that are independent of the increase in temperature and humidity, which can create a comfortable microenvironment and better monitor human health. Otherwise, the design and research of most reported fiber-based strain sensors were evaluated in laboratories, which lacks commercial value. There are still many challenges for strain sensors to be standardized in practical applications in the future.

Despite significant advancements in skin-mounted and fiber-based strain sensors, there remains considerable potential to explore in the context of strain sensors for digital health. Given the continuous respiratory activity of the human body, the monitoring of harmful gases has gained increasing attention. The instantaneous and expedited detection of harmful gases is of paramount importance for digital health, safeguarding the wellbeing of individuals. Hence, the ongoing development of fiber-based strain sensors capable of swiftly detecting life-threatening gases in the environment is crucial. Furthermore, human soft tissues, including muscles, tendons, and ligaments, are prone to injury during strenuous outdoor activities. Inadequate monitoring of such injuries can impede the healing process. Implanting strain sensors within the body offers precise tracking of injury recovery and timely intervention. However, contemporary implantable strain sensors necessitate surgical implantation and removal, disrupting quality of life and increasing costs. The pursuit of implantable fiber-based strain sensors with complete degradability holds significance for facilitating early rehabilitation and repair. The biodegradable strain sensor can decompose naturally over time, thereby reducing superfluous medical consumption and multiple surgical operations. The durability and stability of biodegradable strain sensors necessitate further enhancement to ensure the sensor does not degrade prematurely; thus, the selection of materials and structural design require meticulous consideration. The sensitivity and accuracy of biodegradable strain sensors need to be improved because the materials used in biodegradable sensors may not have the same sensitivity level as those employed in common sensors. Moreover, most strain sensors require external power sources, adding to equipment costs and weight, as well as necessitating frequent battery replacements during human motion monitoring. The amalgamation of fiber-based strain sensors with batteries enables continuous real-time monitoring of human activity without external power, facilitating health management and hazard alerts in the digital health context. The incorporation of biocompatible and self-powering strain sensors into the human body is pivotal for practical applications. It circumvents the risks associated with immune rejection, a crucial factor for long-term detection. Although the majority of reported fiber-based strain sensor designs remain in the laboratory stage, a shift toward transitioning these innovations from the laboratory to industrial production and practical usage is evident. Anticipating this trend, we envisage the continuous discovery of novel fiber-based strain sensors. We firmly believe that strain sensors with the aforementioned capabilities will soon become an integral part of our daily lives, addressing existing challenges by enhancing performance and safety, extending lifespan and sensing range, and integrating multifunctionality aligned with digital health requirements.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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