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# Textile-Based Mechanical Sensors: A Review

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**Abstract:** Innovations related to textiles–based sensors have drawn great interest due to their outstanding merits of flexibility, comfort, low cost, and wearability. Textile-based sensors are often tied to certain parts of the human body to collect mechanical, physical, and chemical stimuli to identify and record human health and exercise. Till now, many research and review work has been carried out to summarize and promote the development of textile-based sensors. As a feature, we focus on textile-based mechanical sensors (TMSs), especially on their advantages and the way they achieve performance optimizations in this review. We first discuss the sensing mechanism, active materials, structure design and novel fabricating strategies for implementing TMSs on the critical performance such as sensitivity, response range, response time, and stability. Next, we summarize their great advantages over other flexible sensors, and their potential applications in health monitoring, motion recognition, and human-machine interaction. Finally, we present the challenges and prospects to provide meaningful guidelines and directions for future research. The TMSs play an important role in promoting the development of emerging Internet of Things, which can make health monitoring and everyday objects connect more smartly, conveniently and comfortably efficiently in a wearable way in the coming years.

**Keywords:** textile-based mechanical sensors; mechanism; preparation; advantages; applications

## 1. Introduction

As measuring devices, mechanical sensors can obtain mechanical stimulus information and convert it into electrical signals to achieve functions such as stimulus acquisition, transmission, and storage. When mechanical stimuli, such as pressure, strain, motion, etc. is applied, the mechanical sensor can convert it into electrical signals such as resistance, voltage, capacitance, and based on the mechanical stimulus-electrical signal regression curve, we can infer the magnitude of the mechanical stimulus. In accordance to different mechanical stimulus, mechanical sensors can be substantially divided into strain sensors, pressure sensors, position sensors, velocity sensors, tactile sensors, etc. Traditional mechanical sensors made of metal, semiconductor or ceramic have stable performance, mature preparation technology, which have played a major role in traditional industries. However, their inherent shortcomings, such as rigidity, large size and weight, and small deformability, determine that they are not applicable fields of electronic skins, human physiological signals, intelligent robot, etc.[1] Flexible materials usually feature with softness, easy-to-deformation, and light weight[2, 3]. Some novel flexible materials exhibit unique properties such as self-healing, hydrophobicity, biocompatibility, and biodegradability[4-6] which make them more competitive when compared with rigid mechanical sensors[7-10]. Textile materials are considered as promising new version of silicon wafers in wearable electronics, not only because they have the properties of most flexible materials, but also because they hold the advantages of low cost, good conformality, comfortableness and wearability[11]. Therefore, textile materials have shown great application potential in wearable electronics, human-machine interaction, smart fabrics, etc.[12-14]

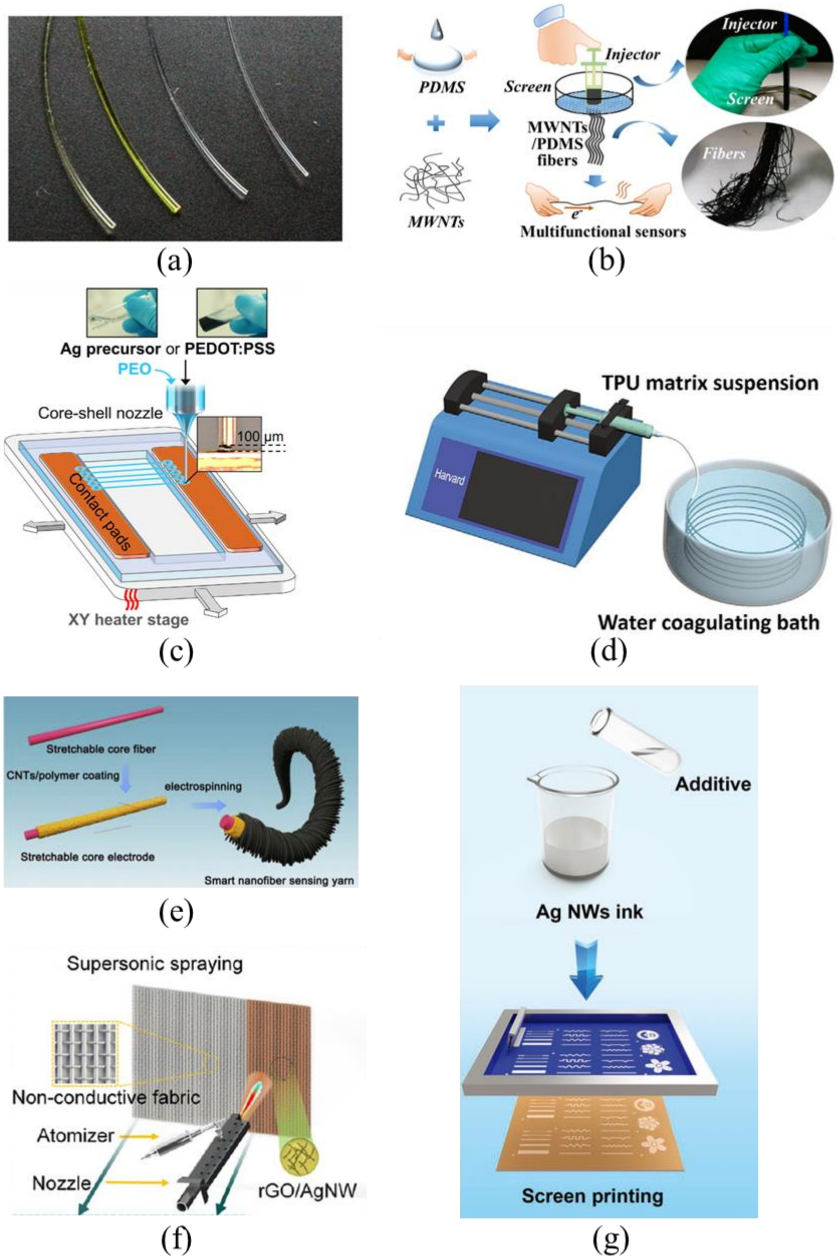


**Figure 1.** Illustration of the manufacturing process of various resistive TMSs. Fiber-based sensors prepared by (**a**) coating, reproduced with permission from [15], (**b**) extrusion, reproduced with permission from [16], (**c**) printing, reproduced with permission from [17], and (**d**) wet spinning, reproduced with permission from [18]; (**e**) Yarn-based sensors prepared by electrostatic spinning, reproduced with permission from [19]; Fabric-based sensors prepared by (**f**) spraying, reproduced with permission from [20] and (**g**) screen printing, reproduced with permission from [21].

Among them, the preparation of TMSs and their application in such as monitoring heartbeat, pulse and other health signals[22-24], in constructing of the robot's human-like tactile perception function [25-27], and in fabricating human-movement monitor smart clothing[28-30], have already been the research hotspot of wearable electronics, but these researches are still in the laboratory stage, and there are many scientific and technical problems to be solved, such as the inability to balance good electrical conductivity and air permeability, poor durability, and integration of active materials and fabrics needed to be improved, etc. Although many reviews have been reported on the principles, materials, preparation methods, and application areas of textile-based sensors[31-36], there are few reviews that systematically introduce TMSs. Here, we conduct a systematic review on TMSs, especially introducing the unique pros and cons of the TMSs, and summarizing methods to improve existing deficiencies.

In this review, we systematically introduce features and latest achievements in TMSs. Four types of sensing mechanisms of resistance, capacitance, piezoelectricity and triboelectricity of TMSs as well as the configuration features of each type devices and their corresponding preparation and integration methods are introduced. The commonly used substrate materials, sensor materials, and preparation methods of conductive fiber, yarn or fabric were also summarized. Next, the advantages and sensing performances of TMSs are analyzed, and the designs related to improving the performance and advantages of TMSs are discussed. Then, the advanced applications based on TMSs are described in detail. Finally, the challenges and development directions of the device are further discussed.

## 2. Sensing Mechanisms, Materials and Preparations

TMSs can introduce electrical conductivity in three structural forms: fiber, yarn, and fabric[32]. Among them, conductive fibers can be inherently conductive metal wires of silver, copper, and stainless steel, or they can be made by blending conductive materials of, such as polyaniline (PANI), polypyrrole (PPy) and graphite, carbon nanotubes (CNTs) into natural (e.g. cotton, silk, and bamboo fiber), synthetic fibers (e.g. nylon, vinylon and polypropylene), or by directly coating or plating these conductive materials onto polymer (polypropylene (PP), PET, PI, etc) fibers[37]. The obtained conductive fibers can be twisted to make conductive yarns, and subsequently weaving and knotting can be made into conductive fabrics. In addition, conductive fabrics can also be made by directly dip-coating, spin coating or printing conducting inks onto normal fabrics. TMSs in three structural forms of fiber, yarn, and fabric can be integrated into the textile or woven in the clothing. TMSs are mainly categorized as resistive, capacitive, piezoelectric and triboelectric[38] according to their sensing mechanism. The different sensing mechanisms and their implementation methods are described in detail below.

### *2.1. Resistive Sensor*

Resistive TMSs convert mechanical stimuli such as displacement, force to a resistance change using piezoresistive materials. As the resistance of a conductive material is defined as $R=\varrho L/S$, when a mechanical stimulus causes changes of the piezoresistive materials in resistivity ($\varrho$), length ($L$), and/or cross-sectional area ($S$), it will bring out a resistance changing. And, based on regression curve, the mechanical stimuli and its degree can be determined. Because resistive TMSs often have the advantages of high sensitivity, wide detection range, high precision, and simple measurement circuits, they have received the most extensive attention and study[39]. However, large signal drift, poor durability, and obvious hysteresis are the key issues that restrict their practical application[40].

Resistive TMSs are typically composed of a soft substrate and a sensing material[41]. The soft substrate needs to own the properties such as certain elasticity, good flexibility, and long-term stability. These properties, on the one hand, can provide a carrier for sensing materials, and endow the sensing materials and subsequent textiles with piezoresistive properties. On the other hand, they can reduce the stress concentration of TMSs when subjected to mechanical stimuli. Commonly used substrate materials for TMSs include silk, cotton, polydimethylsiloxane (PDMS), polyurethane (PU), etc. Correspondingly, commonly used sensing materials have carbon materials, metal materials, conductive polymer, etc. The sensing materials need to be both conductive and mechanically robust, which are typically prepared by coating, depositing, winding, or electroplating functional conductive layer on fibers, yarns or fabrics, and can also be prepared by progresses of wet spinning or 3D printing. Among them, functional fibers and yarns can be attached to complex surfaces or woven into fabrics, which makes the sensors adaptable to different application scenarios by changing its shape, and can be prepared on a sustainable and large-scale way. Neves et al.[30] produced conductive fibers by coating graphene onto polymer fibers that could be bent, stretched, compressed, twisted and deformed into complex shapes while still maintaining good performance and reliability (Figure 1a). These graphene-based conductive fibers can be utilized as a platform for constructing integrated electronics directly in textiles. Li et al.[31] used a syringe to extrude a mixture of conductive multiwalled carbon nanotubes (MWCNTs) and PDMS through a mesh with micron-sized holes to fabricate functional fibers (Figure 1b). The fibers as part of a wearable sensor were then integrated into a smart glove to recognize finger dexterity, gestures and temperature signals. This preparation method is simple and convenient, but it is not suitable for large scale preparation of functional fibers. Wang et al.[32] used a concentric nozzle to rapidly and precisely print nanofibers with a bilayer structure (Figure 1c). The inner layer of the nanofiber acts as a sensing layer composing of metal or conductive polymer materials, while the outer layer acts as a protective and supportive layer which consists of long-chain polymer materials. The smart mask made from the nanofibers by one-step progress can be used to detect whether the mask is worn properly and whether the breathing is abnormal. Additionally, traditional textile manufacturing technologies of wet spinning and electrostatic spinning are also applicable to fabricate functional fibers. Sheng et al.[33] prepared porous fiber-based strain sensors by wet-spinning method, wherein thermoplastic polyurethane was used as elastomer and carbon nanotubes (CNTs) and graphene as conductive fillers (Figure 1d). Before wet-spinning, dispersants and binders were introduced to improve the interaction between the elastomer and the conductive fillers to achieve the purpose of effectively withstanding external forces. Qi et al.[34] used a simple electrostatic spinning technique to prepare nanofiber sensing yarn, which was composed of a fibrous core electrode wrapped and wound by piezoresistive elastic nanofibers (Figure 1e). The yarn showed a fine layered structure, and could be woven into fabrics to achieve multi-mode sensing of various mechanical stimuli.

Fabric-based mechanical sensors can also be designed and prepared by the methods of coating, deposition, inkjet printing, screen printing, etc. Among them, directly coating sensing material onto common fabrics is the simplest and easiest method to achieve large-scale TMSs preparation. However, this method will bring about a poor bond between the sensing material and the flexible fabrics, so that the stability and durability of the prepared TMSs cannot be guaranteed. Thus, how to improve the adhesion between the two materials has become the first problem to be solved in the preparation of high-performance TMSs, wherein functionalized molecular grafting sensing materials is one of the preferred methods. Liu et al.[42] coated fluorinated MXene nanosheets onto 15 different fabrics, because the surface of the MXene is rich in a large amount of functional groups which interact with the fabric surface to improve adhesion between the two. It has been experimentally proven that the MXene formed a strongest bond with pure cotton and will not come off even after washing and ultrasonic processing. In addition, the adhesion can be enhanced by improving the preparation process of the TMSs. A multifunctional mechanical-sensitive fabric is prepared via ultrasonically spraying reduced graphene oxide (rGO) and silver nanowires (AgNWs) onto synthetic and 100% natural cotton fabrics (Figure 1f). The obtained fabrics has shown a good durability and can be washed repeatedly without performance degradation[35]. Luo et al.[36] used simple and efficient screen printing to transfer high-performance AgNWs inks onto stretchable fabrics (Figure 1g), which presented excellent tensile properties and sensing performances. Conveniently, sensing materials with different patterns can be printed by simply changing the screen with different shapes, and fabric-based mechanical sensors prepared by printing processes can be designed into desired patterns to improve the sensing range, sensitivity, and other properties of resistive sensors.

### *2.2. Capacitive Sensor*

Capacitive TMSs are realized based on the capacitance changes of the sensing devices induced by external mechanical stimuli. The capacitance of a sensing device is defined as $C=\varepsilon r \varepsilon o A/d$, where $\varepsilon r$ is the relative permittivity, $\varepsilon o$ is the vacuum permittivity, A is the effective area of the electrode, and d is the pole-plate spacing[43]. Therefore, the change of one or more parameters of the permittivity, spacing or effective area will cause the change of the devices in capacitance, and then the magnitude of the mechanical stimulus that causes the parameters change can be quantified. Capacitive TMSs feature with the properties of high sensitivity, high response repeatability, small signal drift and low energy consumption, but they are susceptible to external field interference[44].

Capacitive TMSs usually consist of two electrode layers and a dielectric layer[45], wherein, the electrodes require good electrical conductivity, and commonly used electrode materials include conductive fabrics, metal wires, carbon materials, etc. Meanwhile, the materials used as dielectric layer usually possess a large dielectric constant to reduce leakage current. Commonly used dielectric materials are elastic polymers, fabric gaskets, ionic gels, etc.

The preparation method of the capacitive TMSs is similar to that of the resistive ones, but the configuration of the two devices is different. The device configuration of a capacitive TMS can be roughly divided into two types, and the first one is constructed into a sandwich structure, which consists of two flat electrodes composed of conductive fabrics and a dielectric layer composed of such as common fiber membranes or ionic gel membranes sandwiched between electrodes. This type of structure is the most common one, which usually endows the device with a large sensing range. Keum et al. [46] prepared sandwich-structure ion-electron pressure TMSs using silver-plated compound silk fibers as electrodes and high-permittivity of ion gel membranes as the dielectric material. The composition and membrane thickness of the ionic gel were designed to maximize the change of the contact area between the conductive fabrics and the ionic gel under external forces, which in turn optimized the sensing performance of the devices. Fu et al.[47] prepared a flexible pressure TMS by using fabrics sprayed with AgNWs as the flexible electrodes and a ceramic nanofiber film fabricated via an electrostatic spinning process as the dielectric layer (Figure 2a). The obtained pressure sensor can be used to detect human health conditions and motion, such as pulse, vocal cord vibration, and body movement, etc. The second-type configuration of capacitive TMS is equipped with a core-sheath structure fabricated by the technology of coating and coaxial spinning. Compared with the capacitive TMSs with a sandwich structure, the TMSs with a core-sheath structure are smaller and easier to embed into clothes. Capacitive TMSs can be obtained by fiber crossing. Guan et al. [48] prepared silver nanowire-bacterial cellulose fibers with porous structures using a wet-spinning process, and then coaxially coated the fibers with PDMS to produce functional fibers with a core-sheath structure (Figure 2b). A capacitive multifunctional sensor was fabricated by arranged the functional fibers crosswise to form an interpenetrating network, in which the AgNWs-bacterial cellulose fibers served as electrode and the PDMS coating acted as the dielectric layer. By detecting changes in capacitance, the sensor could detect both the pressure and the position of objects. Besides, Zhang et al. [49] prepared a high-performance capacitive strain sensor by twisting two core-spun yarns into a fine double-ply yarn (Figure 2c). The core-spun yarns were fabricated by wrapping silver-coated nylon fibers with cotton fibers, and then fixed with polyurethane.

The sensor exhibits good linearity and tensile properties and can be blended into wearable fabrics to monitor athletes and patients without compromising lifestyle or comfort.

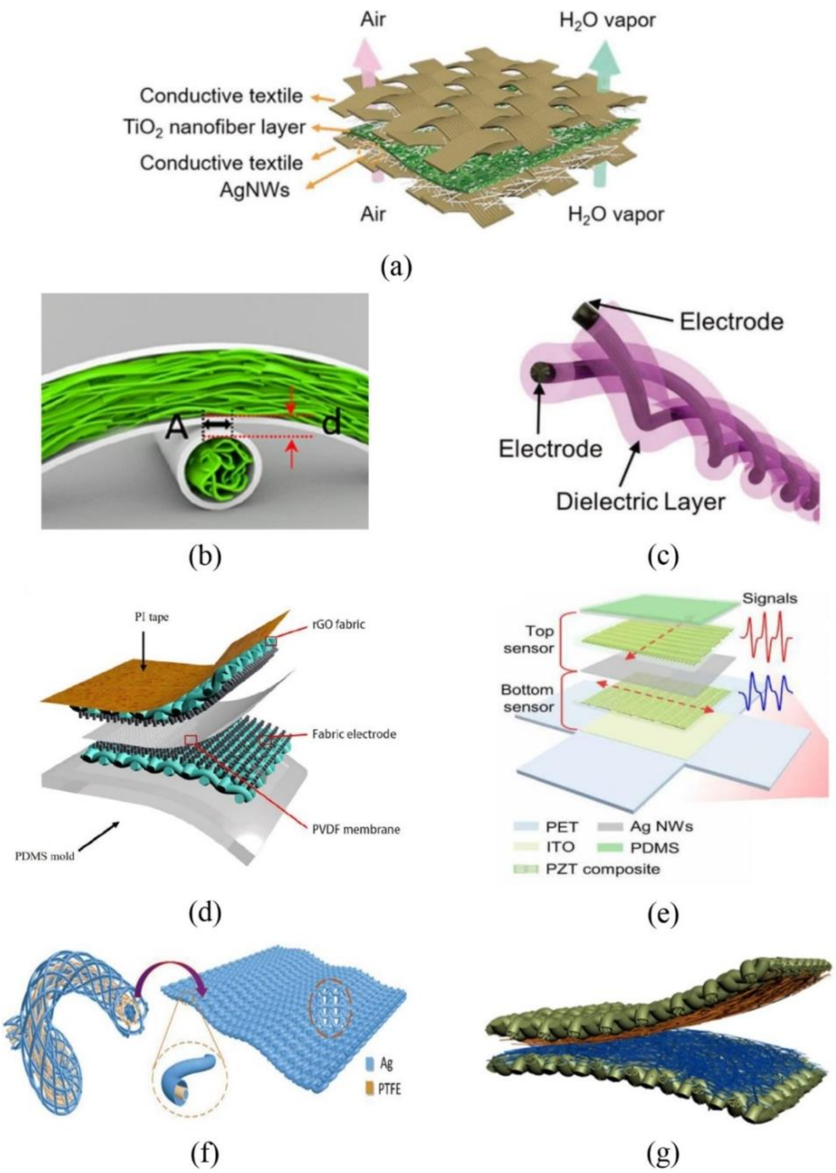


**Figure 2.** Schematic diagrams of TMSs configurations based on capacitive, piezoelectric and triboelectric sensing mechanisms. (**a**) Sandwich structure fabric capacitive sensors, reproduced with permission from [47]; (**b**) Crossed fiber capacitive sensors, reproduced with permission from [48]; (**c**) Helix fiber capacitive sensors, reproduced with permission from [49]; (**d**) Sandwich structure piezoelectric sensors, reproduced with permission from [53]; (**e**) Double-layer piezoelectric sensors with vertical arrangement, reproduced with permission from [54]; (**f**) Coaxial fiber triboelectric sensors, reproduced with permission from [55]; (**g**) Double-layer triboelectric sensors, reproduced with permission from [56].

### 2.3. Piezoelectric Sensor

Piezoelectric TMSs are produced from flexible materials with piezoelectric effect, which work by converting mechanical stimuli into voltage signals[50]. The piezoelectric constant of the piezoelectric material determines the performance of a piezoelectric sensor in converting mechanical energy into electrical energy. Commonly used piezoelectric materials include composites, polymers, ceramics, single crystals, etc.[51]

Piezoelectric TMSs can generate internal voltage when subjected to external pressure, which makes them self-powered while achieving pressure sensing. In addition, such

TMSs often present the advantages of fast response time and high sensitivity[52], making them have great application prospects in wearable devices. Tan et al.[53] prepared piezoelectric TMSs using the piezoelectric effect of the single-crystalline ZnO nanorods grown on conductive rGO-PET fabric (Figure 2d). The piezoelectric TMS is constructed with three layers consisting of PVDF membrane, the top and bottom electrode layers of conductive rGO-PET fabrics with self-orientation ZnO nanorods. When subjected to an external force, the piezoelectric configuration deformed, leading to a potential difference between the two electrode layers, so the magnitude of external force can be obtained by detecting the voltage change. Hong et al.[54] provided a new solution of designing anisotropic kirigami structure and manufacturing functional piezoceramic network to monitor joint motions and distinguish between different motion modes, in which the piezoelectric composite is the core sensory element for the sensors, formed by a lead zirconate titanate (PZT) ceramic network with nylon textile with kirigami-structured honeycomb grids and a PDMS matrix (Figure 2e). The piezoelectric sensor shows obvious advantages in measurement range, piezoelectric anisotropy, multifunctional measurement, and long-term monitoring, which greatly enhance their practical application range.

### *2.4. Triboelectric Sensor*

The combining of the electrification effect/triboelectric effect and electrostatic induction is the principles of triboelectric TMSs that occur between a broad range of materials, including synthetic polymers and natural silk[57], wool[58], and cotton[59]. Similar to piezoelectric sensors, the triboelectric TMSs can convert mechanical motion into electrical signals, and in turn, by analyzing the obtained signals, dynamic mechanical motions can be interpreted. By correlating the mechanical input with the corresponding parameters, a series of triboelectric TMSs have been fabricated, including pressure sensors, strain sensor, and vibration sensors. Triboelectric TMSs are generally composed of a couple of electrodes with different tribo-polarities; the greater the difference in tribo-polarities between the two electrode materials, the better the electrical performance of the sensors[60]. Commonly used positively charged materials include nylon, cotton, silver, copper, etc, while commonly used negatively charged materials include PDMS, PVDF, polytetrafluoroethylene (PTFE), etc[61]. The advantages of triboelectric TMSs, such as low cost, simple preparation process, high output voltage, and self-powered, will strongly promote the construction of the Internet of Things[62].

Triboelectric TMSs can be divided into two kinds,and one kind is the single yarn device with two frictional electrical sequences and then woven into fabrics or textiles. Zhang et al.[55] prepared a coaxial triboelectric yarn by sequentially wrapping PTFE and Ag yarns around the axial metallized silver yarn via winding machine (Figure 2f). And then, the fabricated triboelectric yarn was woven into wearable, multifunctional textile by needles to harvest the mechanical energy from human body motions. Since the tribo-polarities between PTFE and Ag materials differ greatly, charge transfer was easily achieved in repeated contact–separation processes. The other kind of triboelectric TMSs is obtained by directly waving two types of yarns or fibers with inherently different tribo-polarities. Fan et al.[63] wove terylene wrapped stainless steel conductive yarns and nylon yarns into an all-textile triboelectric sensing array. Guo et al.[56] fabricated a textile based wearable hybrid triboelectric-piezoelectric TMS composing of silk fibroin nanofibers and PVDF nanofibers which were electrospun onto conductive fabrics as the triboelectric pair. Before fabricating a cloth-shape smart device, the two triboelectric fabrics were attached to separate substrates to realize effective contact and separation (Figure 2g). The hybrid TMS is capable to generate both triboelectricity and piezoelectricity at the same time to realize high power generation which enables its use as a sensor to identify various types of body motion without other power supply.

## 3. Advantages and Performances

### *3.1. Advantages*

To identify and quantify mechanical stimuli in space, the method of arranging sensing units in membranes or blocks on a flexible substrate is usually adopted. This method is indeed very simple and practical in the application situation where the precision of mechanical stimuli is not high. However, the large area of each sensing unit, as well as the messy electrode port (generally, n sensing units need n+1 electrode ports) and complex circuit layout make the sensing unit is not close enough[71], hence the integrated devices often show a low spatial resolution in detecting mechanical stimuli. By contrast, TMSs offer great advantages over other flexible mechanical sensors in terms of large area manufacturing. The TMSs, using fine fibers, yarns or fabrics as distributed sensing network, greatly reduce the number of electrode port (generally, m×n sensing points can be arranged with m+n electrodes.) and achieve a high-resolution spatial recognition of mechanical stimuli. Sundaram et al.[64] assembled a sensor array on a knitted glove to detect tactile information (Figure 3a). The sensing array consists of a piezoresistive membrane connected by a network of conductive wire electrodes. This approach allows the detection of mechanical stimuli with very high spatial resolution. In addition to the use of piezoresistive membranes, sensing arrays can also be prepared directly using piezoresistive fibers. Luo et al.[65] proposed a strategy to prepare fibers by coating conductive stainless steel wires with piezoresistive nanocomposites using an automated coating technique (Figure 3b). Taking advantage of this strategy, the fibers can be fabricated into a sensing unit by a simply vertically overlapping progress, and can be future woven into a large-scale sensing textile with arbitrary 3D shape for spatially accurate detection of mechanical stimuli. In addition to preparing an array sensor, fibers are also able to detect mechanical stimuli in space by using an electrical time-domain reflectometer to send pulses to a separate transmission line, and the amplitude of the step indicates the magnitude of the pressure and the occurrence time of the step indicates the distance. For example, Leber et al.[66] prepared an elastic fiber which integrated dozens of liquid metal conductors with a uniform, complex cross-sectional structure. The fiber was arranged in a snake shape onto a stretchable fabric, which was connected to an electrical time-domain reflectometer via a single contact (Figure 3c). An electrical time-domain reflectometer could detect the location and magnitude of mechanical stimuli by transmitting high-frequency pulses to a transmission line and then reflecting them at discontinuities. This approach makes the structure of the sensing fabric simpler, only with one electrode port. However, it is difficult to integrate the sensing fabric into a wearable device due to the need of an electrical time-domain reflectometer.

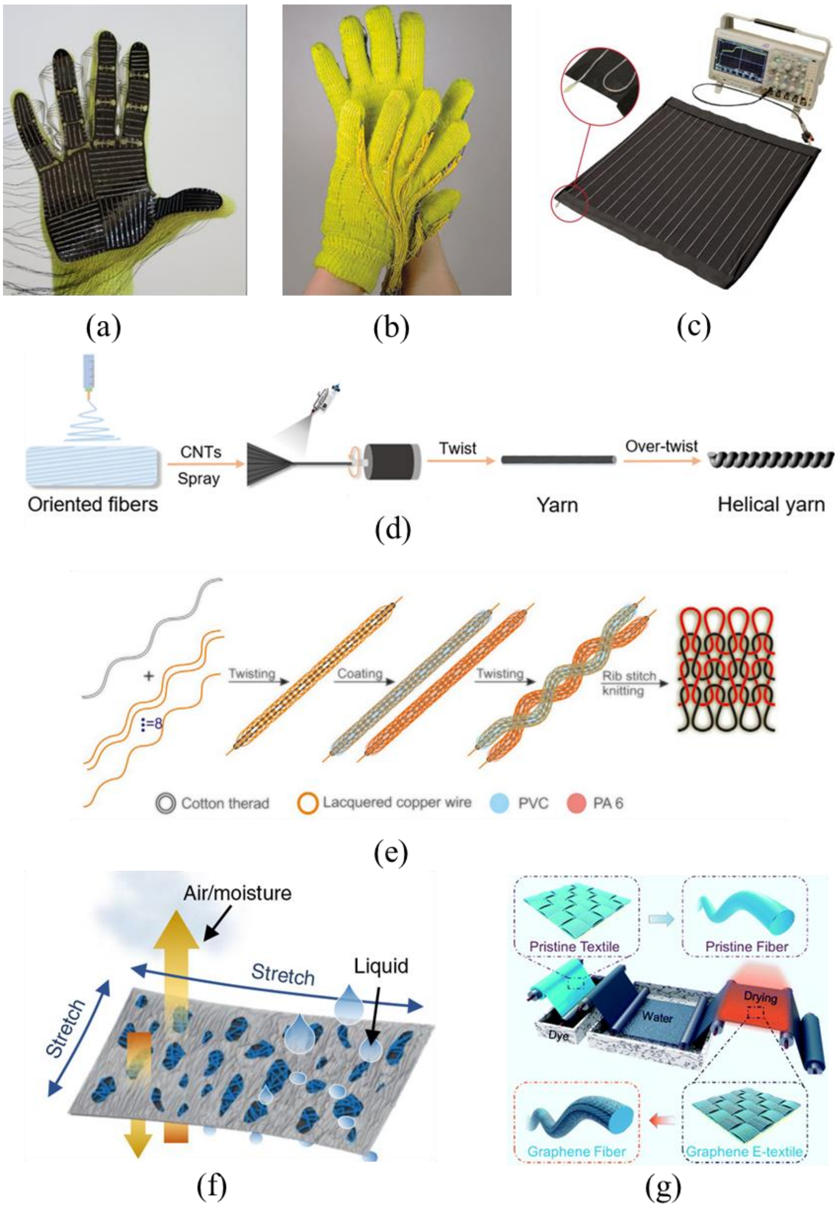


**Figure 3.** Advantages (**a**) Large area array sensors based on piezoresistive film, reproduced with permission from [64]; (**b**) Large area array sensors based on fibers, reproduced with permission from [65]; (**c**) Large area detection mechanical stimulation using electrical time domain reflectometer, reproduced with permission from [66]; (**d**) Large deformation sensors based on spiral structure, reproduced with permission from [67]; (**e**) Large deformation sensors based on ribbed weave, reproduced with permission from [68]; (**f**) Fabric sensors breathability based on pre-stretching, reproduced with permission from [69]; (**g**) Fabric sensors breathability based on coating shrinkage, reproduced with permission from [70].

During practical applications, mechanical sensors are subject to various mechanical stimuli such as stretching, squeezing, bending, etc., which require a good deformability of the electrodes and sensing elements in mechanical sensors, a stable sensing function in a large deformation state, and a structural and electrical performance reversibility after the release of deformation. TMSs have unique advantages in terms of deformability which is generally obtained by optimal structural and material design. Gao et al.[67] uniformly sprayed CNTs dispersion onto PU nanofiber substrate and then obtained CNTs/PU fibers with helical structure by twisting to over-twisting state. The CNTs/PU fibers could reach 900% deformation range (Figure 3d), because helical structure has the advantage in tensile strain and strength compared to fiber film and fiber bundle structures, which underwent unscrewing during a stretching process. Importantly, the spiral fibers could recover their original structure after stress release due to the PU elastic substrate, and the cracks in the conductive network of CNTs were rebuilt. Therefore, sensors are highly reversible in terms of structural and electrical properties. In addition to improving the deformation performance by designing the fiber structure, the deformation capacity of the fabric can also be improved by studying the weaving process and weaving structure. Rezaei et al.[68] twisted cotton threads with eight copper wires and then coated them with reactive triboelectric materials poly vinyl chloride (PVC) and Polyamide (PA 6), respectively. The two types of fibers were twisted and prepared into a double twisted thread as a triboelectric sensor. By studying the weaving process, the ribbed weave was chosen to endow the fabric with excellent tensile properties and flexibility (Figure 3e). Another key to improving the deformability of TMSs is material optimization through the development of materials with inherent deformation characteristics or the integration of deformable materials. Commonly used materials are hydrogels, PDMS, etc. Ye et al.[72] prepared a conductive hydrogel by integrating polymer, silk protein, and carbon materials, which had a strain range of 600% and showed a rapid recovery ability during large deformations.

When sensors are worn or fitted to the body, they should not cause any discomfort to the body, which requires good biocompatibility, skin friendliness, and comfort. Mechanical sensors that use textile materials as substrates usually possess these characteristics[73]. In addition, breathability is also a major focus of the sensors. Fabrics woven with fiber-based TMSs usually present good air breathability due to the voids between the fibers, while TMSs with a coated sensing layer usually needs to be designed as a porous or mesh structure to provide it with breathability. For instance, Ma et al.[69] fabricated a breathable liquid metal-fiber layer by coating liquid metal on an elastic fiber layer (Figure 3f). During the fabricating process, pre-stretching was applied to make the liquid metal suspended between the elastic fibers self-organize into a transverse mesh and a vertically curved structure, thus providing the liquid metal-fiber layer a good breathability. Besides, the combination of hydrophobicity and washability makes TMSs more attractive, which is not available in other types of flexible mechanical sensors. The combined characteristics can be possessed by material design without affecting breathability. Hu et al.[70] obtained graphene coated e-textiles through dipping, water treatment and subsequent drying step (Figure 3g). After dipping, the fabric is immersed in a water bath where the rapid separation of solvent and water causes the coating to shrink, allowing the fabric structure to remain breathable. At the same time methyltrichlorosilan reacts with water to form methyl-trihydroxysilane precursor, which undergo condensation to form a highly hydrophobic and sticky polymethylsiloxane structure in a high temperature drying step. Even when textiles are immersed in detergent under ultrasonic washing conditions, the coating remains stable and does not peel off, demonstrating excellent washability. The microstructure design also allows the fabric to be hydrophobic. Inspired by the "papillae structure" on the surface of lotus leaf., Song et al.[74] successfully prepared a waterproof multimode sensor by constructing two-dimensional MXene nanosheets and zero-dimensional silicon nanoparticles on a cotton fiber substrate. The conductivity can be maintained even under wet and corrosive conditions.

### *3.2. Performances*

So far, a lot of work has been carried out on the developing and research of TMSs to improve the sensing performance of the devices, such as sensitivity, response range, response time, stability, etc, because these properties determine the practical application capabilities of sensors[75]. Sensing performance can be improved by introducing special geometric structures, such as microarrays[76, 77], microcracks[78], micropatterns[79, 80], pleated structures[81, 82], porous structures[83, 84], spiral structures[85, 86], etc. Besides, the innovation of materials is also a major key point to improve the sensing performance. For example, new materials such as graphene[87, 88] and MXene[89, 90] have good electrical conductivity and mechanical properties and are widely used in sensors.

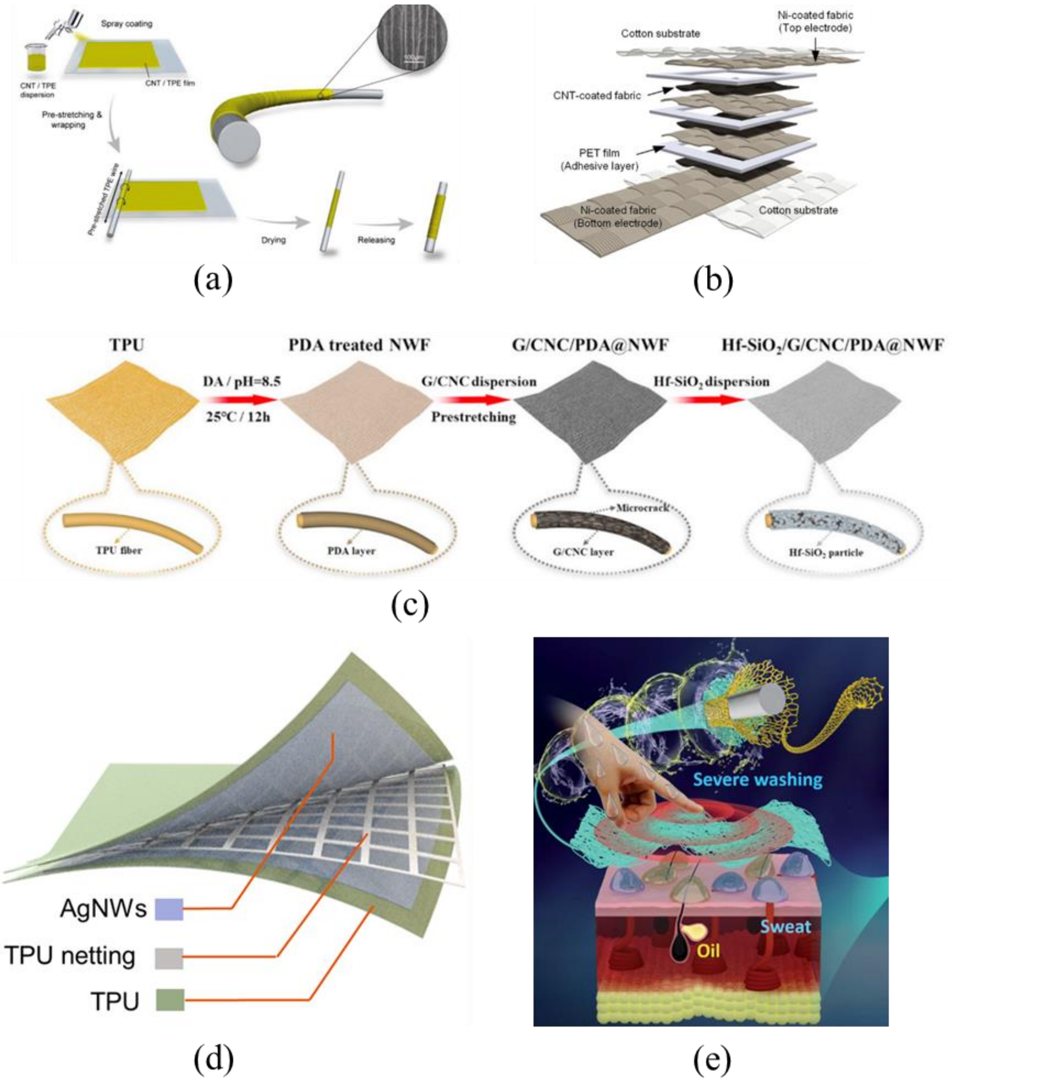


**Figure 4.** Performance (**a**) High sensitivity based on folded structure, reproduced with permission from [92]; (**b**) Large response range based on hierarchical and multilayer structure, reproduced with permission from [91]; (**c**) Weighing sensitivity and response range based on microcrack density, reproduced with permission from [93]; (**d**) Short response time based on micropatterned dielectric layer, reproduced with permission from [94]; (**e**) Excellent stability based on layered protection structure, reproduced with permission from [95].

Sensitivity is a key factor in evaluating the performance of various sensors. Therefore, many scholars focus on pursuing high sensitivity. The formula for sensitivity is $S=(\Delta X/X0)/Y$, where S represents the sensitivity, X0 represents the initial value of the electrical signal, resistance, capacitance, voltage, etc., ΔX represents the amount of change in the electrical signal, and Y represents the mechanical stimulus applied to the sensor, such as pressure, strain, etc. The usual methods to improve sensitivity include the introduction of microstructures[78], the use of new sensing materials[80], and the employment of multilayer structures[91]. Li et al.[92] prepared a folded core-sheath structure fiber strain sensor by pre-stretching and releasing ultra-light MWCNTs/themoplasticelastomer (TPE) composite film wrapped TPE fiber core. After releasing the pre-stretched TPE fiber core, a periodic bending structure was formed along the fiber axial direction (Figure 4a), which combined with the super-elasticity of the TPE core and provided this fiber high strain sensitivity.

Detection range of a sensor determines its application field. So, maintaining a high sensitivity over a wide detection range is one of the properties pursued by scientists.

Using multi-layer structure and increasing the contact area are the main method to improve detection range at present. Pyo et al.[91] developed a resistive tactile sensor by alternately stacking CNTs and Ni fabrics (Figure 4b). The graded structure of the fabric provides a large surface area and microscopic roughness, thereby significantly increasing contact area in response to pressure. The design of multi-layer structure can further increase the contact area and effectively distribute stress to each layer, consequently dramatically increasing the pressure detection range as well as device's sensitivity. The sensor shows a sensitivity of 26.13 kPa-1 over a wide pressure range of 0.2~982 kPa. Liu et al.[93] successfully fabricated a microcracked nonwoven strain sensor with a wide operating range and a high sensitivity (Figure 4c). Taking advantage of the difference in modulus between the electrically conductive cellulose nanocrystal/graphene coating and the nonwoven fabric, microcrack structure was constructed by simple dip-coating and pre-strain technique, which determined the sensor's detecting range and sensitivity, making it possible to prepare sensors with designed sensing capability by adjusting the density of the microcrack structure.

Response time of a mechanical sensor is defined as the time to achieve a steady-state response upon mechanical stimulating, and it is usually described as 90% time to reach stability. The response time of a sensor is especially important in applications that require real-time data processing and the shorter the response time, the better the real-time performance of the results. The response time of TMSs is typically in the millisecond range level, which can of course be effectively reduced by structural design and material optimization. Yu et al.[94] prepared an ultrathin all-fabric capacitive sensor with two AgNWs electrodes and a breathable micropatterned nanofiber dielectric layer sandwiched between them (Figure 4d). Due to the unique structure of the micropatterned nanofiber dielectric layer, the sensor shows a response time of 27.3 ms. Xu et al.[96] prepared fabric sensors using laser engraved silver-plated fabric as electrode and graphite flake modified nonwoven fabric as sensing material. Due to the unique structure of the electrodes and the random rough surface of the sensing material, the sensor has a fast response time of 4 ms.

Stability is a key factor to ensure that a sensor can effectively acquire mechanical stimuli and respond accordingly. The stability of TMSs includes mechanical stability, chemical stability, and cyclic stability, etc, which can also be improved by optimizing structure and materials. To address the vulnerability of textile-based sensors to external mechanical and chemical and environmental interference, especially human sweat, grease, and wear and tear, Zhang et al.[95] combined carbon nanotube networks, polymer layers, and textile substrates to form self-protected and reproducible e-textiles with a layered structure (Figure 4e). The sensor exhibits excellent characteristics of superhydrophobicity, wear resistance, mechanical and chemical stability, and its response resistance does not change significantly during 3,000 compression cycles. Resistive TMSs usually rely on large deformation to change the resistance to play the role of sensing. Due to irreversible deformation, they are less cyclically stable compared to other types of sensors. Thus, improved cycling stability can also be done by changing the sensing mechanism. Wu et al.[97] transferred water-soluble poly(vinyl alcohol) template-assisted silver nanofibers onto fabric surface to serve as sensor electrodes, and used a highly elastic three-dimensional penetration fabric as a dielectric layer. The integrated capacitive TMS were prepared with good dimensional stability and excellent cycling stability (≥20,000).

In addition to some of the properties discussed in detail above, the reply ability[98], crosstalk problems[99], linearity[100], and anti-interference[101] of TMSs are also key factors that determine the overall performance and practical applicability of the sensor. Therefore, high-performance TMSs are a research hotspot in the past or in the future.

## 4. Applications

TMSs have great advantages of easy large-scale preparation, flexibility, and biocompatibility. Combined with integrated circuits, they can obtain real-time data for machine learning and artificial intelligence[102], and thus receiving increasing attention from academia and industry. Although TMSs have not yet been marketed on a large scale like most other flexible electronic devices, a great number of studies have shown that TMSs have promising application prospects in wearable electronics, smart fabrics, robots and other fields. It is foreseeable that such devices will change people's lives and improve people's quality of life in the near future.

### *4.1. Health Monitoring*

Health issues are the most important concern for human beings. Traditional medical services usually require professional physicians and large testing equipment and rehabilitation equipment, which leads patients have to go to hospitals for testing and treatment on each occasion. On the one hand, it increases the burden of patients and physicians, and on the other hand, it reduces the real-time of disease detection and treatment. TMSs are very suitable for being applied in the field of health monitoring[103]. Utilizing the inherent flexibility and comfort of fabric-based sensors, TMSs can not only be used to detect the wearer's blood pressure, heart rate, electroencephalography signals and certain diseases, but also can be used to monitor the wearer's disease progression or motor symptoms for a long time, will provide an objective basis for doctors to guide the wearer in medication or rehabilitation training, and will even greatly influence the reform of medical industry and home care industry.

Wicaksono et al.[104] reported a large-scale e-textile-based smart clothing (Figure 5a), which is able to perform multi-modal physiological (temperature, heart rate and respiration) monitoring. Moreover, customized clothing with various forms, sizes and functions could be made using standard, adjustable and high-yield textile manufacturing processes and garment patterning techniques. Similar to corsets, the soft and stretchable features of the customized smart clothing allow for close contact between the electronic device and the human skin, providing physical comfort and meanwhile improving the anti-interference of sensor. These make it suitable not only in hospitals and laboratories, but also in home care for mobile, comfortable and continuous physical activity monitoring, which has huge potential in healthcare, rehabilitation and scientific training.

Most users are very sensitive to the monitoring tools placed on the face or head, and are even caused by psychological fluctuations that affect the measurement results. The combination of fabric sensor and clothes can be designed into a wearable device that is not easy to detect or even senseless, so that when it is used as a health detection device, it increases the comfort of the wearer and the accuracy of the test data. For example, when a reusable hydrogel wet electrode and a full-fabric ionic pressure sensor were integrated into an eye mask, the eye mask could track and monitor eye movements and intraocular pressure in daily use [105] (Figure 5b). The technology is virtually non-irritating and non-invasive to the wearer, coupled with its aesthetics and washing stability, when combined with artificial intelligence algorithms, it can be used to accurately monitor the ophthalmology and heart signals required for sleep quality and mental health research.

### *4.2. Motion Recognition for Analysis*

Collecting information about human movement and analyzing it to extract useful information can be used to scientifically correct training modes and intensity, monitor sitting posture, guide ergonomic design, sign language recognition, etc. Those have become major applications of TMSs.. The realization of motion analysis through TMSs firstly lies in high-precision detection and quantification of various motion variables, such as position, angle, and pressure, and converting them into visualized electrical signals in real time. And subsequently comprehensively analyzing and establishing the relationship between these electrical signals and human body posture is the key to realize the high-precision recognition of human spatial motion characteristics.

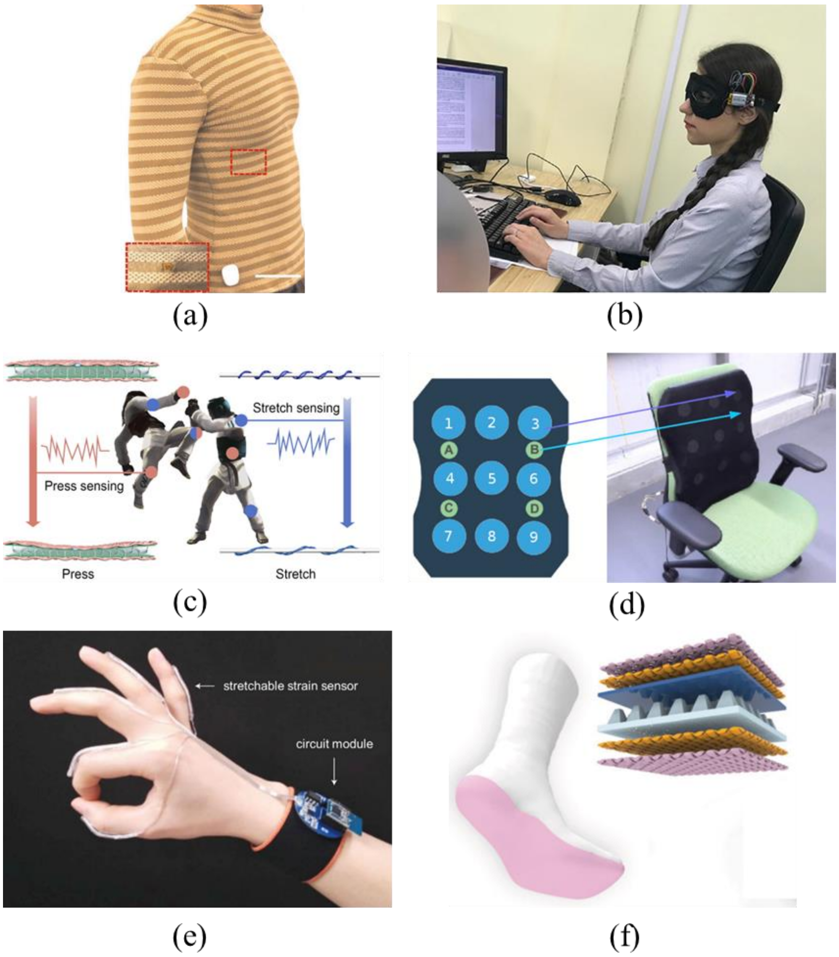


**Figure 5.** Applications (**a**) Smart clothing applied to health monitoring, reproduced with permission from [104]; (**b**) Smart eye mask applied to health monitoring, reproduced with permission from [105]; (**c**) Smart clothing applied to motion analysis, reproduced with permission from [106]; (**d**) Smart cushion applied to sitting analysis, reproduced with permission from [107]; (**e**) Smart glove applied to sign language recognition, reproduced with permission from [108]; (**f**) Smart socks applied to human-machine interaction, reproduced with permission from [109].

Smart clothing is often used to monitor human health or exercise analysis. To detect athletes' movement in high-intensity physical exercises similar to Taekwondo, the smart sportswear is required to withstand large-scale deformation (strain>50%) and heavy blows (> 100 kPa) action while maintaining good performance stability. Ma et al.[106] used a composite fabric of core-sheath yarn and spacer fabric to prepare an "all-in-one" electronic fabric with a dual tactile and tension stimulus response (Figure 5c). In general, retractable strain sensors with a core-sheath yarn structure can easily perform large, yet with a "double solution phenomenon", that is, a non-monotonic electrical signal response to tensile deformation. To solve this problem, an insulating PU layer was pre-coated on the core-sheath yarns before twisting. This allows the TMS to accurately monitor the exercise action and intensity, thereby implementing its potential application in taekwondo and high-intensity physical exercise analysis.

Long-term incorrect sitting posture is not good for people, especially teenagers, because it can cause bone deformation, hunchback, curvature of the spine, myopia and other health problems. Ishac et al.[107] designed a smart cushion, which is flexible, adaptable, and portable (Figure 5d). The cushion consists primarily of a new conductive-fabric pressure sensing array designed and arranged based on human biomechanics, which was used to sense and classify sitting posture (98.1% in accuracy) and adjust upright posture of the user through vibrotactile feedback.

By collecting and analyzing human movement information, TMSs can not only be used to monitor human movement status, assist in training and guide ergonomic design, but also assist in communication between people. Sign language is a basic communication method for a considerable portion of the population, but it can only be used by trained individuals. To overcome this limitation, Han et al.[108] developed a wearable system that integrates yarn-based stretchable sensors on five fingers (Figure 5e). With this wearable system, sign language gestures can be converted into analog electrical signals and transmitted wirelessly to a portable electronic device. Then, real-time speech translation can be achieved using machine learning algorithms and a graphical user interface with recognition rates >98% and recognition times <1 s. An automated sign language recognition system can obviously strengthen the communication function of sign language, making it easier, smoother and more effective for deaf-mute people to communicate with the outside world.

### *4.3. Human-Machine Interaction*

Human-machine interaction is a study of the interaction between a system and its users. In the past, the the realization of human-machine interaction usually required bulky, large and hard devices. Due to the characteristics of E-textile itself, TMSs, as the core of electronic fabrics or wearable devices, provide a more convenient and comfort channel than other flexible electronics for human-machine interaction. It is possible to control machines or VR games using TMSs without affecting human physical activity, which has huge impact on industries such as entertainment and leisure, and robotics. And so, more and more work is carried out to study and improve the TMSs performance for high-effective Human-machine interaction.

TMSs have great potential for human-machine interaction scenarios such as smart furniture, VR games, and robot control etc. Shuai et al.[110] prepared stretchable, conductive and self-healing hydrogel sensing fibers by continuous spinning. When the fiber sensors were fixed on five fingers separately, it could monitor and distinguish the movement of each finger by monitoring the electrical signal changes caused by fingers bent, and then judge the gestures such as "OK", "Victory" and "claw". The strain sensing capability of this fiber sensor shows its great potential in human-computer interaction. Zhang et al.[109] simulate a virtual reality (VR) fitness game by mapping gait information collected by smart socks to virtual space (Figure 5f). The smart socks were developed by embedding textile-based triboelectric pressure sensors into commercial socks, by combined with deep learning, five different gaits can be recognized with an accuracy of 96.67%, ensuring the feasibility of the gait control interfaces and promoting the practical application of flexible electronics in the field of smart home. Chen et al.[111] obtained flexible hierarchical helical yarns was via coiling the conductive electrodes around a highly stretchable PU (the first helix layer) and super flexible silicon rubber (the second helix layer), respectively. The yarn can work in a strain range of up to 120% and obtain bioenergy to convert into electrical signals that are used to control household devices without amplifying the signal. Interactive electronic pianos and robotic arms can be precisely controlled using the sensors with little noticeable delay, which makes them promising as portable self-powered wearable electronics.

## 5. Challenges and Prospects

Ingenious structures, perfect processes, and outstanding materials endow TMSs with excellent performance and more prominent advantages over other flexible sensors. And it is the great advantages of TMSs in terms of cost, large-area array, deformation, conformability, wearability, and comfort that make TMSs attract extensive research in academia.

However, like most flexible electronics, TMSs suffer from a short lifetime compared to rigid sensors. Besides, their roll-to-roll production technology is immature and most TMSs are fabricated in the laboratory or research stage. Many of the reported TMSs are manufactured using manual techniques rather than mechanical engineering. Besides, the large-scale manufacturability and reproducibility of e-textile are uncertain. There are many challenges in moving TMSs to market commercialization: (1) The complex manufacturing methods and expensive materials of some sensors greatly increase cost and reduced practicality; (2) It is difficult to prepare sensors with uniform performance on a large scale; (3) They lack excellent repeatability and robustness, and are often accompanied by poor reliability and lifetime; (4) The lack of standards makes it difficult for them to be accepted by the general public; (5) The development of flexible integrated circuits and flexible battery has limited the practical application of TMSs. In addition, most of the current TMSs are still used to detect a single or dual mode of mechanical stimuli, mostly pressure or strain, but the mechanical stimuli associated with the human body are much complex than these. Therefore, how to collect more mechanical stimulus information, how to decouple different types of signals, and how to quantify and spatially resolve multiple mechanical stimuli are the current difficulties faced by TMSs to be solved. In the future, textile-based mechanical sensors will move in the direction of high integration, which not only refers to the high integration of sensor fabrication technology and functions, but also refers to the integration of flexible electronic technology with other technologies such as flexible circuits, machine learning, and drive control. What is more, the smart fabric has the functions of responding to environmental stimuli, sensing and driving, and can even adapt to the environment. To address these challenges, with the joint efforts of scientists and engineers from many different disciplines, we believe that TMSs have a bright future and will contribute to the next generation of health monitoring, motion recognition, and human-computer interaction.

## 6. Conclusion

In this work, we have given a comprehensive review of TMSs. Various types of TMSs including resistive, capacitive, piezoelectric and triboelectric have been introduced. In addition, we have also made a detailed discussion on the materials, structures, and processes of different types of TMSs. In particular, the advantages and performance of TMSs and their improvement methods are described in detail. Then, we summarize the latest applications of TMSs in different fields. Furthermore, challenges and perspectives in TMSs are also presented.

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