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Review

Wearable Electrospun Nanofibrous Sensors for Health Monitoring

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Abstract: Various electrospinning techniques can be used to produce nanofiber mats with randomly oriented or aligned nanofibers made of different materials and material mixtures. Such nanofibers have a high specific surface area, making them sensitive as sensors for health monitoring. The entire nanofiber mats are very thin and lightweight and, therefore, can be easily integrated into wearables such as textile fabrics or even patches. Nanofibrous sensors can be used not only to analyze sweat but also to detect physical parameters such as ECG or heartbeat, movements, or environmental parameters such as temperature, humidity, etc., making them an interesting alternative to other wearables for continuous health monitoring. This paper provides an overview of various nanofibrous sensors made of different materials that are used in health monitoring. Both the advantages of electrospun nanofiber mats and their potential problems, such as inhomogeneities between different nanofiber mats or even within one electrospun specimen, are discussed.

Keywords: wearables; electrospinning; health monitoring; ECG; heartbeat; strain sensors; temperature sensors; light sensors

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1. Introduction

Electrospinning enables the manufacturing of nanofiber mats from various materials and material mixtures [1,2]. Such nanofiber mats have a large surface-to-volume ratio, can be lightweight and yet mechanically stable, and are, therefore, a good basis for many sensory applications [3–5].

Continuous monitoring of health status is becoming increasingly important nowadays as fewer and fewer doctors are available, especially in rural areas, and life expectancy is increasing, combined with the desire to live independently for as long as possible [6–8]. This requires wearable sensors that should ideally be lightweight, breathable, stretchable, either attached to the skin or integrated into garments, and highly sensitive [9]. Electrospun nanofibrous sensors are thus the optimal choice in many cases.

Different sensor principles can be used to record vital parameters, e.g., bioelectric, mechano-electric, opto-electric, magnetic, optical, or ultrasonic sensors [10–13]. Typical vital parameters to be continuously measured include ECG and heart rate, blood pressure and blood oxygen saturation, movements, or environmental parameters such as light, temperature or volatile organic compounds [14–16]. Depending on the polymer or material combination of the nanofiber mat, the potential inclusion of nanoparticles, the potential post-treatment to stabilize and carbonize the nanofibers, etc., nanofiber mats can be used in many of these wearable sensor applications [17–19].

Here, we provide an overview of the latest wearable electrospun nanofibrous sendsors that can be used for long-term monitoring of the vital signs of patients or elderly, as well as athletes. The paper is structured as follows: Section 2 gives a brief overview of electrospinning, describing different techniques and possibilities for manufacturing nanofiber mats with different fiber orientations and different fiber cross-sections and for spinning different materials and material combinations. Section 3 discusses the possibilities of making nanofiber mats wearable, e.g., by embedding them in smart textiles or by sticking them to the skin. Section 4 describes comprehensively electrospun sensors for health monitoring, e.g., ECG and heartbeat monitoring, movement and respiration rate sensors, and sensors to detect temperature, humidity, and other physical and chemical parameters. Section 5 concludes with recent challenges and future research prospects. By discussing the whole chain from electrospinning and spinnable materials to wearable nanofiber mats and their use as wearable sensors, the paper will contribute to the understanding of how electrospinning improves the development of wearable sensors and provide suggestions for necessary future research.

2. Brief Overview of Electrospinning

Electrospinning is generally based on electrostatic fiber formation in which electrical forces are used to produce polymeric nanofibers with diameters from around ten to several hundred nanometers [20]. Based on a patent by Formhals [21] and an initial investigation in more detail by Taylor [22], the electrospinning process has been further developed in recent decades, leading to dozens of further patents [23] and a growing number of research results and applications.

2.1. Different Electrospinning Techniques

In general, the electrospinning process requires a polymer solution or melt and a DC or, sometimes, AC voltage in the kV range that generates sufficiently strong mutual electric repulsive forces to overcome the weaker surface tension in the polymer solution or melt [24]. In the simplest case, the spinneret from which the polymer solution is released is a syringe with a needle. This needle-based electrospinning technique is depicted in Figure 1 [20]. The spinneret is connected to high voltage, while the collector is grounded. It is possible to increase the number of syringes in one electrospinning setup, i.e., to use multiple-jet spinning, either to produce a nanofiber mat with a larger area or to combine nanofibers from different spinning solutions on the substrate [25,26].

In addition to this needle-based technique, there are several needleless electrospinning techniques, such as bubble electrospinning, conical wire coil electrospinning, or edge plate electrospinning [27]. Figure 2a shows rotary roller electrospinning, while Figure 2b depicts wire electrospinning; both systems are commercially available [27]. Such needleless techniques enable the spinning of larger areas on the substrate due to the larger area in which the polymer solution is available to form nanofibers [27]; on the other hand, inhomogeneities can occur in large nanofiber mats, which have to be taken into account, especially in practical applications [28,29].

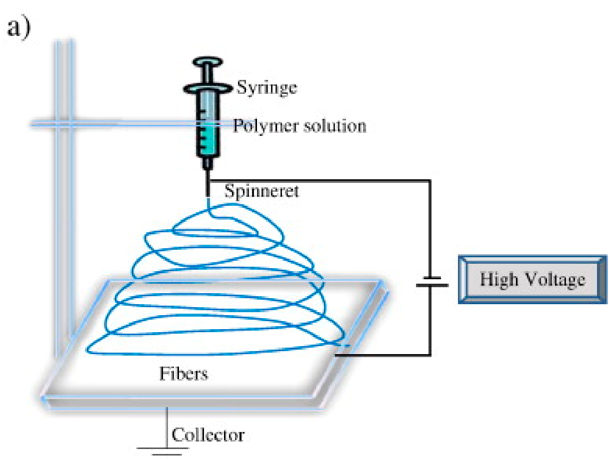

Figure 1. *Cont.*

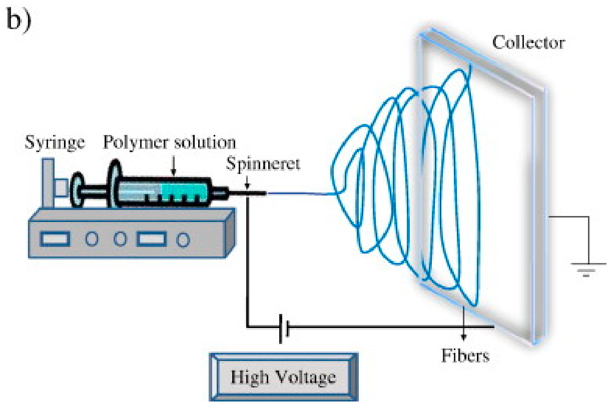

Figure 1. Needle-based electrospinning in a (**a**) vertical and (**b**) horizontal setup. Reprinted from [20], with permission from Elsevier.

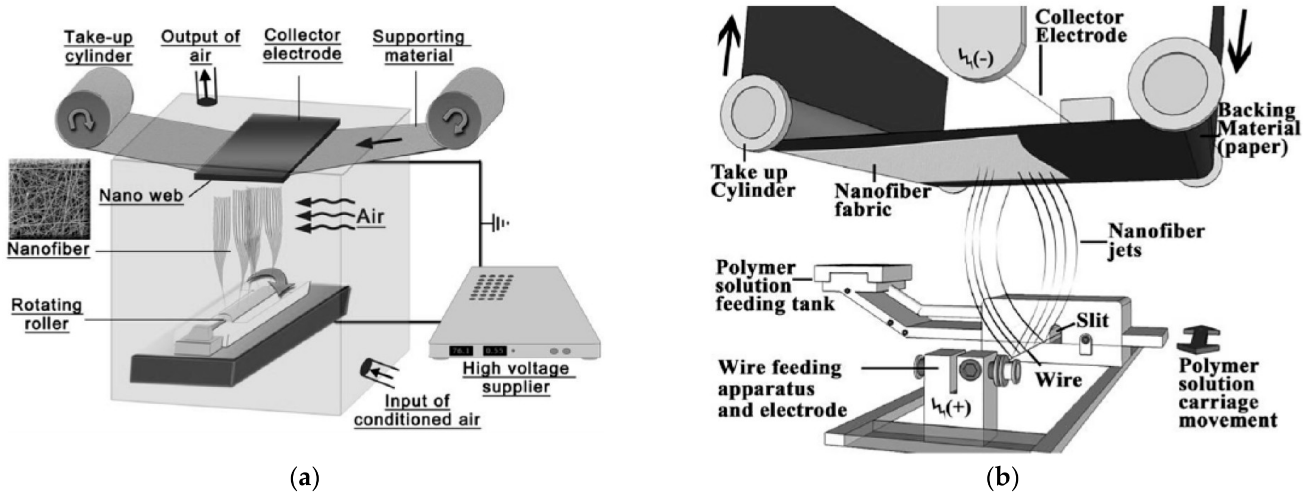

Figure 2. Diagrams of (**a**) a roller electrospinning machine; (**b**) a wire electrospinning machine. From [27], originally published under a CC BY license.

It should be mentioned that especially inhomogeneity of nanofiber mats will lead to large variations of the physical properties of the nanofiber mats, which will reduce the ratio of usable parts of these nanofiber mats and, correspondingly, the costs of the nanofiber mats per area. In addition to increasing the throughput, it is highly important to improve the homogeneity of the produced nanofiber mats in order to reduce the production costs.

To overcome such problems regarding inhomogeneities and support the positioning of nanofibers at specific positions, robot-aided single- or multi-nozzle electrospinning has been suggested to enable precise position control of the needle(s) and even the production of three-dimensional nanofiber structures [30].

2.2. Different Fiber Orientations

Electrospun nanofiber mats normally contain randomly distributed fibers. For many applications, however, oriented nanofibers (mostly parallel, sometimes even perpendicular [31]) are advantageous. This has led to investigations of various methods to produce aligned nanofibers by electrospinning [32].

Usually, the collector is modified for this purpose, e.g., a fast-rotating collector, a structured collector, or a water bath is used [32]. Pan et al. suggested not only to use a fast-rotating cylindrical collector but also to modify the spinneret by using two opposite needles with opposite voltages, i.e., to use conjugate electrospinning, as shown in Figure 3a, to produce aligned poly(vinyl alcohol) (PVA) nanofibers [33]. The authors used stainless steel needles with an outer diameter of 0.9 mm in a distance of 14 cm and tested collectors made of Teflon, aluminum, and plastic with different diameters and different rotation speeds from hundreds to thousands of rounds per minute. The study concluded that long spinning times are possible since the fibers do not accumulate charges on the substrate on average [33].

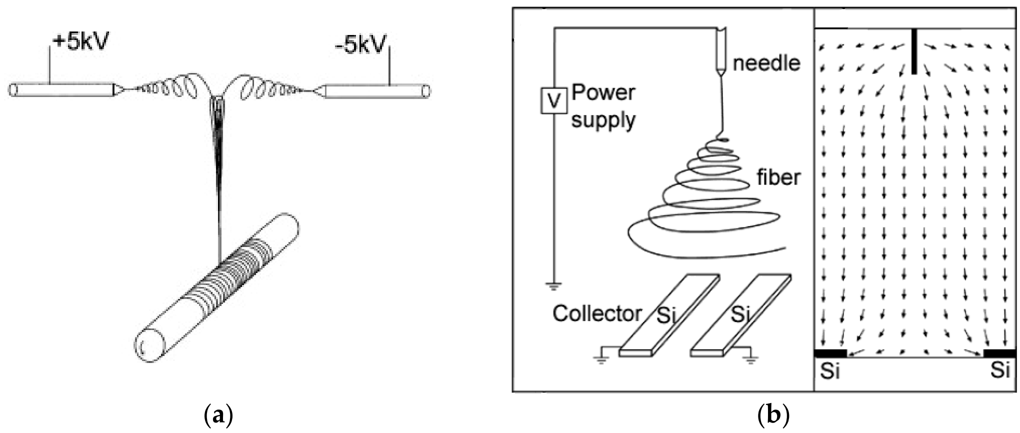

Figure 3. Schematic electrospinning setup for collecting continuous aligned fibers: (**a**) fast-rotating cylindrical collector (reprinted from [33], with permission from Elsevier); (**b**) collector from two conductive silicon (Si) stripes separated by a gap (reprinted (adapted) with permission from [34]). Copyright 2003 American Chemical Society.

While such fast-rotating collectors use mechanical stretching forces to parallelize the nanofibers, a structured collector, e.g., consisting of parallel conductive strips with gaps in between (Figure 3b), can also be used to produce parallelized nanofibers based on electrical forces [34]. Similarly, a wire-spring substrate can be used to produce aligned fibers [35], while a drum collector with conductive strips parallel to the cylinder axis combines principles of mechanical and electrical fiber orientation [36]. It should be mentioned that not only conductive patterns as a substrate can improve fiber orientation but also the addition of patterns with different dielectric properties on the substrate affects fiber positioning and orientation [37,38].

Finally, electrospinning in a water bath collector is another way of aligning the nanofibers. The technical setup and alignment principle are depicted in Figure 4 [39]. Here, the grounded collector water bath is prepared in a Petri dish with a metal plate at the bottom (Figure 4a). The alignment of fibers is achieved by pulling the nanofiber mat that forms on the water surface toward the take-up roller, first by hand and then using a constant take-up speed of the roller to produce nanofiber yarn [39].

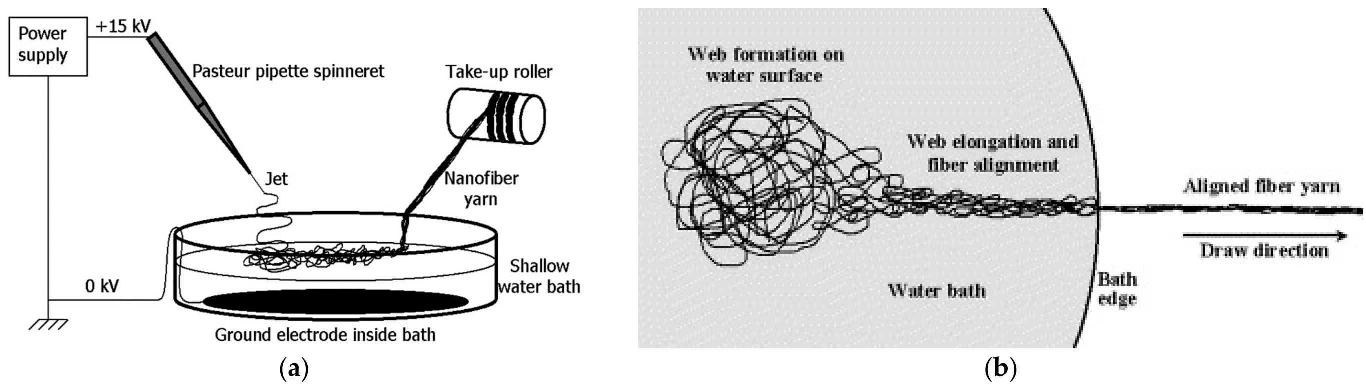

Figure 4. (**a**) Yarn-spinning setup with water bath-grounded collector electrode; (**b**) the top view of the yarn formation process. (**a**,**b**) Reprinted from [39], with permission from Elsevier.

Similarly, nanofiber mats can be post-processed by stretching at elevated temperatures with a stretching ratio of typically 200–300% [40,41].

In addition to these various ways of orienting the nanofibers by modifying the substrate, it is also possible to use magnetic forces to orient fibers containing magnetic material [42]. Similarly, a secondary electric field with suitable geometry can be used to guide the charged jet of the polymer solution [43]. In centrifugal electrospinning with a rotating spinneret, centripetal forces are used in combination with the usual electrostatic forces to produce aligned fibers [44,45]. Finally, near-field electrospinning and melt electrowriting should be mentioned, which use a smaller distance between the nozzle and the collector and enable defined "writing" of nanofibers [46].

2.3. Different Fiber Cross-Sections

In addition to the fiber orientation, the fiber cross-section also influences the sensing properties of nanofiber mats. In most cases, nanofibers are round and have a more or less homogeneous material distribution along their radius. However, it is also possible to produce ribbon-like fibrous structures instead of the usual round fibers to prepare core-shell fibers by coaxial or even tri-axial electrospinning or to integrate internal channels by multichannel electrospinning.

Several researchers reported ribbon-like or other fibers without round cross-sections. Koombhongse et al. showed that not only flat ribbons but also ribbons with other shapes, as well as branched and split fibers, can be produced by electrospinning, depending on the chosen polymers and solvents, which they attributed to the interaction between mechanical and electrical forces and solvent evaporation [47]. Amiraliyan et al. reported that ribbon-like structures were formed at higher electrospinning temperatures [48]. For gelatin fibers electrospun from concentrated formic acid, Topuz and Uyar found ribbon structures that could be obtained at high voltages and high gelatin concentrations, as shown in Figure 5 [49]. Here, the ribbon-like structures are clearly visible at higher voltage conditions (Figure 5e,f), while the flow rate does not significantly change the nanofiber cross-section [49]. Other special ribbon-like structures, such as the helical ribbon [50], and prerequisites for the occurrence of ribbon-like fibers, such as an average polyamide (PA) concentration for the electrospinning of PA from formic acid [51], can also be found in the literature.

Core-shell nanofibers are usually electrospun by coaxial needles with an inner and an outer outlet through which different polymers are delivered into the electric field [52,53]. Interestingly, it is also possible to produce core-shell fibers from a single-nozzle spinneret, e.g., by mixing poly(methyl methacrylate)/poly(acrylonitrile) (PMMA/PAN) solutions in dimethylformamide (DMF) [54]. Bazilevsky et al. showed that PMMA solution droplets were trapped on the outside of the Taylor cone so that the PAN flew around them and, consequently, formed a core-shell jet [54]. Core-shell fibers have even been prepared by free-surface electrospinning, using a rotating spindle with wires, from two immiscible fluids, as shown in Figure 6 [55]. Tri-axial electrospinning, on the other hand, is usually performed by a nozzle containing inner, outer, and middle solutions or solvents and can be used not only to form tri-layer nanofibers [56] but also to make core-shell fibers from certain materials spinnable, that cannot be electrospun from a common coaxial spinneret [57] or to spin composite fibers from combinations of materials of which only one material is spinnable alone [58]. Finally, multichannel microtubes can be electrospun by a multifluidic compound-jet electrospinning technique and have been suggested for the delivery of multiple drugs [59].

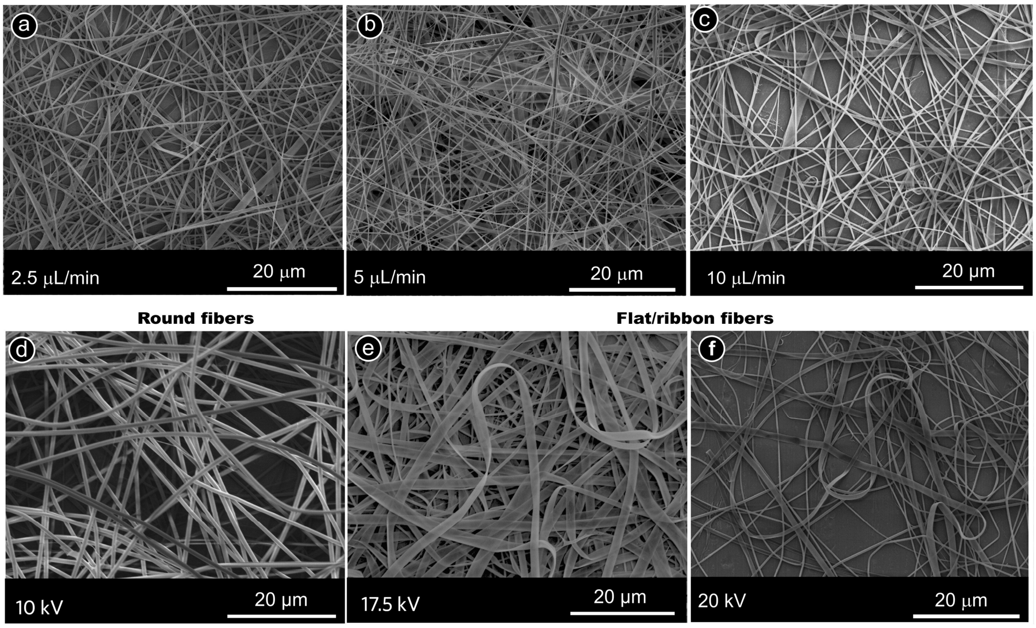

Figure 5. (**a**–**c**) Scanning electron microscopy (SEM) images of the gelatin fibers produced at 20% (w/v) in formic acid at various conditions. The distance between the tip and the metal collector was 15 cm, and the applied voltage was set to 15 kV. The flow rate varied between 2.5 and 10 μL per min. (**d**–**f**) The applied voltage varied from 10 to 20 kV, keeping the distance between the tip and metal plate at a constant value of 15 cm, along with a constant flow rate of 5 μL/min. Reprinted from [49], with permission from Elsevier.

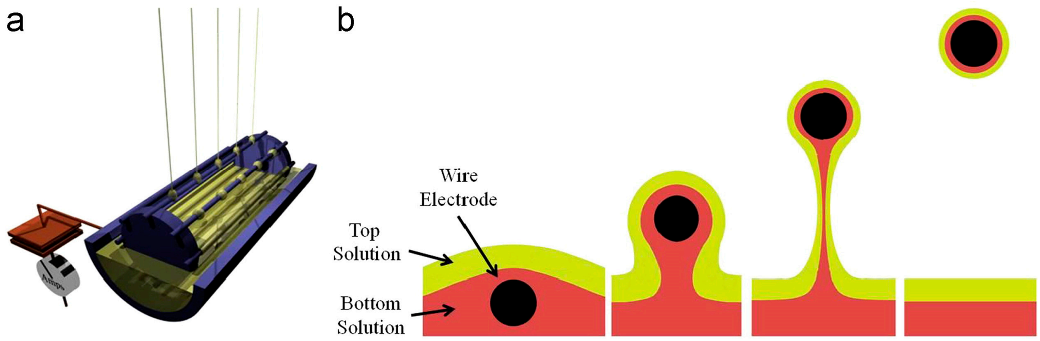

Figure 6. (**a**) Free-surface electrospinning from wire electrodes, illustrated for a single liquid. The liquid bath (gold) is charged to a high voltage. As the spindle of wires rotates counterclockwise (as viewed here), the entrained solution first forms a film, as shown on the first (leftmost) wire, which then breaks up into droplets, as shown on the second (middle) wire. As the spindle rotates, the electric field at the wire increases so that each droplet emits a fluid jet, as shown on the third (rightmost) wire. Evaporation of solvent results in the formation of dry fibers. (**b**) Evolution of the surface profiles of the two immiscible liquids as the wire (viewed end on) travels through the liquid interfaces. Reprinted from [55], with permission from Elsevier.

2.4. Different Materials

In general, a wide range of polymers, polymer blends, and polymers with embedded nanoparticles can be electrospun [60]. In addition, post-treatment of polymer/metal and other nanofibers by calcination enables the production of pure metal, metal oxide, ceramic, and similar nanofibers without organic compounds [61].

With regard to sensing applications, various electrospun nanoparticle-based materials have been investigated, including metallic nanoparticles such as Ag, Au, and Pt [62–64], metal oxide nanoparticles such as ZnO, NiO, or magnetite [65–67], other oxides such as silica (SiO_2) [68,69], or carbon materials such as carbon nanoparticles, graphene, graphene oxide, or carbon nanotubes [70–73].

Pure carbon nanofibers can be produced by stabilizing and, subsequently, carbonizing, e.g., PAN nanofiber mats. Here, not only the spinning process and the properties of the produced nanofiber mat but also the process parameters of stabilization and carbonization play an important role in the porosity, the degree of carbonization, and mechanical and other physicochemical properties of the final carbon nanofiber mat. In particular, the heating rates and temperatures during isothermal treatment [74–76], as well as a potential fixation of the nanofiber mat during these processes [77–79], significantly influence the properties of the carbon nanofiber mat.

Further post-treatments are, for example, the decoration of electrospun nanofiber mats with various nanoparticles [80–82] or other coatings [83–85].

Table 1 compares different electrospinning techniques, while Table 2 provides an overview of the effects of different spinning parameters and setup variations on the electrospun nanofiber mats. It should be mentioned that due to the large amount of influencing factors, the effect of one of them may be discussed contrarily in the literature.

Table 1. Comparison of different electrospinning techniques.

Parameter	Advantages	Disadvantages
Single-needle	Homogeneous nanofiber mat, well-controllable	Small area, low throughput
Multi-needle	Higher throughput → thicker or larger mats, alternatively combining different materials [25,26]	Risk of inhomogeneities, complicated electric field
Needleless electrospinning	Higher throughput → thicker or larger mats	Risk of inhomogeneities
Needle/fast rotating collector	Oriented fibers [32]	More complicated setup
Conjugate electrospinning/fast-rotating collector	Aligned fibers and long spinning durations since no charges are accumulated [33]	More complicated setup
Structured (drum) collector	Parallelized nanofibers [34–38]	More complicated setup
Water bath collector	Aligned nanofibers [39]	More complicated setup
Near-field electrospinning	Well-defined fiber positioning [46]	More complicated setup
Melt electrowriting	Well-defined fiber positioning [46]	More complicated setup
Coaxial electrospinning	Production of core-shell nanofibers [52,53]	More complicated process

Table 2. Influence of different parameters and setups on the resulting electrospun nanofiber mats.

Parameter	Influence on Electrospun Nanofiber Mat
Solid content in the solution	Reduces beads, only certain range spinnable [86,87]
Molecular weight of polymer	Reduces fiber diameter, only certain range spinnable [88]
Needle tip–collector distance	Decreases nanofiber diameter [86]
Wire–collector distance	Reduces nanofiber mat density [88]
Needle length (needle-based)	Increases nanofiber diameter [86]
Needle diameter (needle-based)	Increases nanofiber diameter [89]
Shape of the needle tip	Circular collection zone only for non-beveled needle [86]
Flow rate	Unstable spinning/no spinning at too low flow rates, defective fibers, and even electrospraying at too high flow rates [90,91]
Electric field strength	Increases or decreases fiber diameter, depending on needle–collector (wire–collector) distance [91–94]
Humidity	Reduces evaporation of solvent, eventually making spinning impossible or creating porous nanofibers [88,95]

3. Making Nanofiber Mats Wearable

Among the various methods of making nanofiber mats wearable for use as sensors, the most commonly used ones rely on integration into smart textiles and direct adhesion to the skin.

3.1. Embedding Nanofiber Mats in Smart Textiles

Various research groups have proposed strategies for integrating electrospun nanofibers or nanofiber mats into smart textiles. One of them is based on the production of nanofiber yarns [96,97] (cf. Figure 4). These nanofiber yarns can be used for many common textile production techniques, e.g., for weft knitting, braiding, or embroidery (Figure 7) [98].

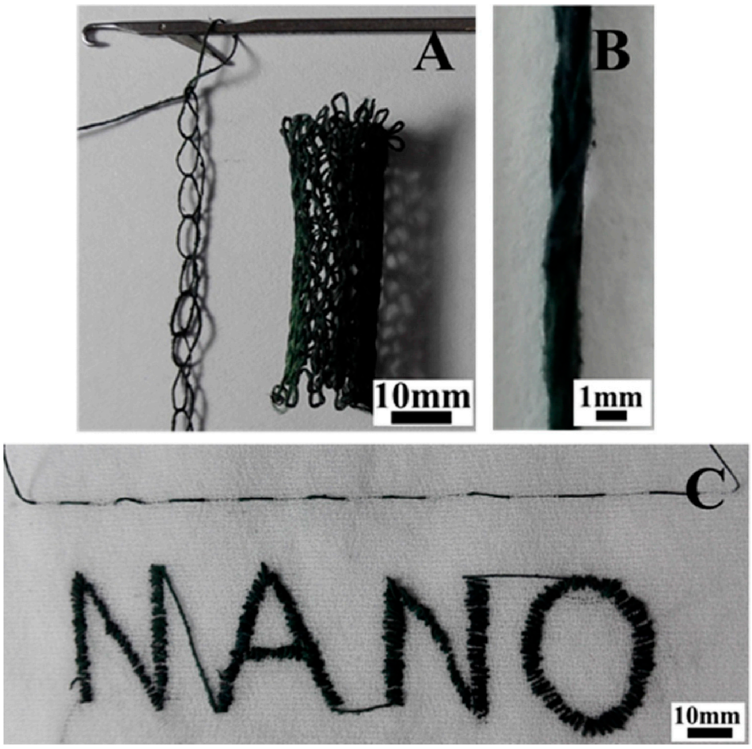

Figure 7. Nanofiber yarn-based fabrics manufactured by traditional textile-forming processes: (**A**) a simple closed chain stitch structure and a relatively complex weft plain stitch tubing structure by knitting technique; (**B**) three nanofiber yarn-based braided constructs; (**C**) "Nano" pattern formed on polyester plain woven fabric by embroidering. Reprinted from [98], with permission from Elsevier.

Nanofibrous yarns, produced by continuous electrospinning, can be used for various sensing applications. Yang et al. produced piezoelectric P(VDF-TrFE) (poly(vinylidene fluoride) copolymer with trifluoroethylene) nanofiber yarns that can be used not only for mechanical and thermal energy harvesting but also as pressure and force sensors and for motion detection [99]. Core-spun Cu/P(VDF-TrFE) yarns, woven into a plain weave fabric, could also be used for energy harvesting and motion detection [100]. By combining electrospinning and electrospraying, Dai et al. produced a polyurethane (PU)-based nanofibrous yarn for strain and pressure sensing with high stretchability and long-term stability [101]. Nanofiber yarns with similar applications have been reported by several other research groups [102–104].

Another method for integrating electrospun nanofibers into smart textiles is based on the integration of two-dimensional nanofiber mats into macroscopic textiles, e.g., by sandwiching the nanofibrous membrane between two woven fabrics or around a woven fabric to increase mechanical stability [105]. Alternatively, nanofibers can be electrospun directly onto a suitable macroscopic fabric for the same purpose [106,107]. The adhesion between the macroscopic substrate and electrospun nanofibers can be improved by hot-pressing and/or an adhesive layer between them [108].

3.2. Gluing Nanofiber Mats on the Skin

Nanofiber mats in direct contact with the skin can be used for drug delivery for pharmaceutical or cosmetic purposes on intact skin or as a wound dressing [109,110] and, also, as part of a stretchable "electronic skin" for sensing applications [111–113]. Such an "electronic skin" can consist of several layers based on polymer films containing not only the sensory part, e.g., in the form of a functionalized nanofiber yarn or nanofiber mat, but also electronic components and conductive connections between all parts, as depicted in Figure 8 [114]. Alternatively, nanofibers and electronic components can be integrated into hydrogels to produce wearable electronics [115]. By integrating a mechanical energy harvester, such an electronic skin can even be self-powered [116].

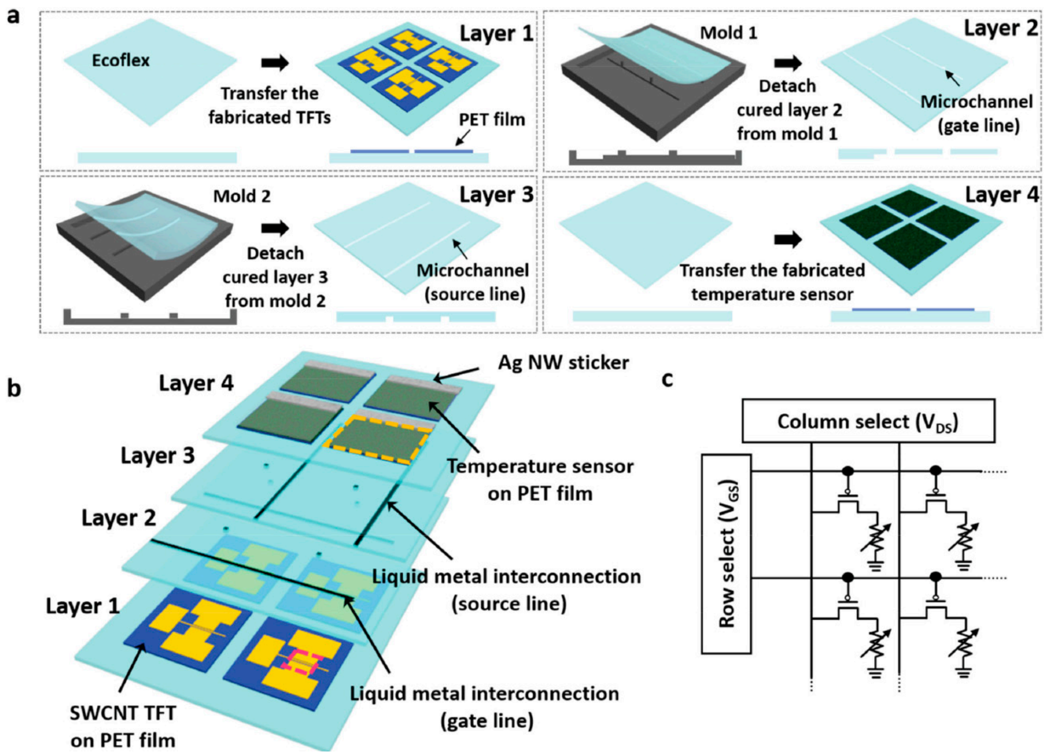

Figure 8. (**a**) Schematic of the fabrication process for the stretchable AM temperature sensor array. TFT: thin film transistor; PET: poly(ethylene terephthalate); (**b**) assembly of prepared layers, liquid metal injection, and formation of electrical contacts with the Ag NW sticker; SWCNT: walled carbon nanotube; Ag NW: silver nanowires; (**c**) circuit diagram of the stretchable active-matrix temperature sensor array. Reprinted from [114], with permission from Wiley.

This type of electronic skin can be used for various sensing activities, e.g., motion monitoring, gesture recognition, tactile sensing [117], pressure detection with spatial resolution [118], and physiological signals for health monitoring [119].

3.3. Other Approaches to Integrating Nanofiber Mats into Wearable Textiles

In addition to the aforementioned methods to make nanofiber mats wearable, there are some reports in the literature that propose slightly different techniques. For example, Wang et al. demonstrated an all-nanofiber tactile sensor array that could adhere to the skin without an additional polymer film or macroscopic fabric [120]. Similarly, Ding et al. prepared an all-nanofiber humidity sensor that could also be used to monitor respiration [121]. A PAN nanofiber mat was used as reinforcement for a graphene film, brought together by annealing the PAN nanofibers on the graphene film, thus making this composite transferable to the skin where it could be used for pulse detection [122].

A very specific way of applying electrospun nanofiber mats to the skin was described by Chen et al. who used a hand-held electrospinning device to spin directly onto the skin, as depicted in Figure 9 [123]. Other research groups have also reported electrospinning directly on human skin with hand-held needle-based electrospinning devices [124–126].

Figure 9. Schematic diagram of the handheld electrospinning device for skin in situ coating with a nanofiber mat. Reprinted from [123], with permission from Elsevier.

4. Electrospun Wearable Sensors for Health Monitoring

After describing the technological base for electrospun wearable sensors, this section provides an overview of recent developments in different applications of such nanofibrous sensors.

4.1. ECG and Heartbeat

ECG measurements are usually performed by measuring electric signals on the skin, which requires conductive electrodes. Conductive nanofiber mats can be prepared by carbonization of polymeric nanofiber mats, usually electrospun from PAN, or by direct electrospinning of conductive nanofiber mats, as described above.

Huang and Chiu combined these approaches by making a carbon electrode from carbon black, reduced graphene oxide (rGO), and polyurethane, which they used as a substrate for electrospinning nanofibers made of polyvinylidene difluoride (PVDF) and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) nanofibers, thus achieving a low sheet resistance of 25 Ω and improved skin contact due to the nanofibrous coating [127].

Using a flexible nanofibrous composite made of a graphite nanosheet and polyamide 66 (PA 66), Li et al. were able to measure not only the ECG of a test subject with similar quality as with commercially available electrodes but also the temperature; in addition, this composite proved to be sensitive to polar chemical vapors [128].

Thermoplastic polyurethane (PU) was used as a base material for electrospinning nanofiber mats, which were then coated with silver nanoparticles, rGO, and PEDOT:PSS to produce highly flexible conductive electrodes [129]. Li et al. showed not only measurements of a test subject's ECG but also EMG measurements on different muscles. In addition, they found that Triton X-100 incorporated into the Ag/rGO/PEDOT:PSS coating supported self-healing and, generally, low sheet resistance of 13 Ω as well as high tensile strength of 15 MPa [129].

By combining near-field and far-field electrospinning of a PU grid spacer and a highly polarized porous PVDF mesh, Li et al. produced a heart sound sensor as an alternative to the usual voltage-detecting sensors, which could also be used to detect the heartbeat [130]. Figure 10 depicts heart sound measurements at different locations of the thorax in comparison with typical ECG measurements.

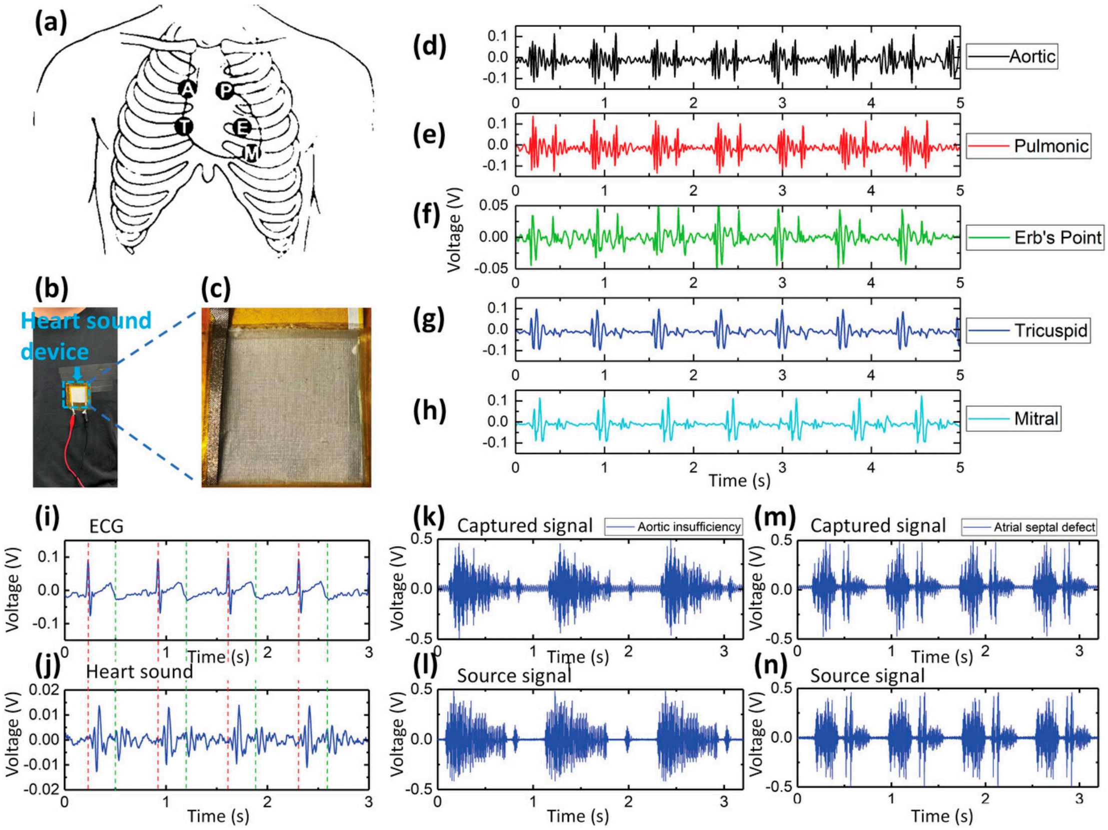

Figure 10. (**a**) The figure of five auscultation points on the human skeleton. A: aortic; P: pulmonic; E: Erb's point; T: tricuspid; M: mitral. (**b**) The image of the experimental setup for heart sound; (**c**) the image of the heart sound device worn by the subject on (**b**); the heart sound waveform measured on-site in five auscultation points including (**d**) aortic point, (**e**) pulmonic point, (**f**) Erb's point, (**g**) tricuspid point, and (**h**) mitral valve point; comparison between (**i**) ECG signal and (**j**) heart sound signal; (**k**) captured signal and (**l**) source signal of aortic insufficiency heart sound recording; (**m**) captured signal and (**n**) source signal of atrial septal defect heart sound recording. Reprinted from [130], originally published under a CC BY-NC-ND license.

Several other research groups reported on electrospun nanofiber mats for ECG measurements, e.g., based on electroless plating of chlorinated polyisoprene (CPI) and poly (styrene-b-butadiene-b-styrene) (SBS) rubber nanofiber mat with silver to make it conductive [131], on the coating of PU and PVDF nanofiber mats with Ag and carbon-based nanoparticles [132], or the surface printing of an Ag interdigital electrode on hydroxypropyl methylcellulose (HPMC) nanofibrous membranes, which resulted in conductivity of 121 S/m [133].

Despite these different approaches to fabricating highly conductive, flexible ECG electrodes that allow for good skin contact, there are still challenges to overcome in future research, such as biocompatibility, reliable electrical connections [134], integration of multiple functions into one electrode [128], adaptability, and flexibility of these electrodes [135].

4.2. Respiration Rate

Respiration rate can be measured in different ways, e.g., by strain or pressure sensors along the chest or by detecting water vapor in the exhaled air [136]. Li et al. used the latter method to detect respiration by electrospun sulfonated poly(ether ether ketone)/polyvinyl butyral (SPEEK/PVB) composite nanofiber mats [137]. They found a short response time of less than 1 s and stable sensing properties for a SPEEK:PVB ratio of 1:3 and showed that their sensor could be used not only to measure skin hydration but also to measure respiratory rate [137]. The use of humidity sensors as respiration sensors has also been proposed by other research groups [138–140] and is exemplified in Figure 11 [140]. Similarly, partially electrospun hot-film flow sensors have been investigated as potential respiratory sensors for monitoring sleep quality and other medical parameters [141]. For this application, highly oriented carbon nanotube films were sandwiched between electrospun PAN nanofiber mats, resulting in high airflow sensitivity combined with flexible and mechanically robust properties [142].

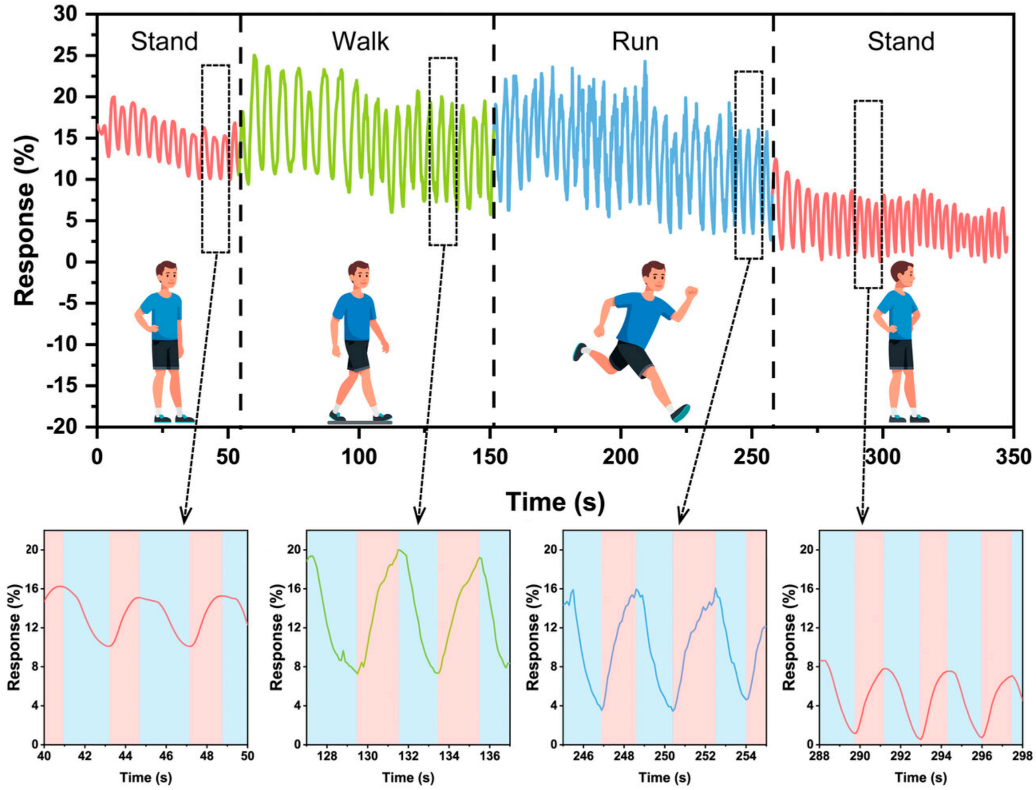

Figure 11. Respiration response curves during continuous different motion states and magnified response curves in the black frame regions. Reprinted from [140], originally published under a CC BY license.

An interesting idea for the fabrication of self-powered respiration sensors is based on a triboelectric nanogenerator (TENG). Hu et al. produced a TENG from electrospun silk fibroin (SF)/poly(ethylene oxide) (PEO) and poly(vinylidene fluoride-*co*-hexafluoropropylene) (PVDF-HFP) nanofiber mats, separated by an elastic silicone ring [143]. By attaching this sensor to the abdomen of a proband, the authors were able to measure respiration with this sensor, with the sensor signal varying with respiratory rate and depth [143]. The use of a TENG as a respiratory sensor has also been suggested by several other research groups [144–146].

4.3. Movement Detection

In addition to the aforementioned vital parameters, the movement of fingers, arms, legs, or other body parts is often measured, e.g., for regeneration or to transfer a certain movement to a robot [147].

Finger movements are most easily measured with a glove that contains a strain sensor produced, e.g., by electrospinning [148]. While far-field electrospinning is mostly used for this task, Huang et al. described near-field electrospinning to get a strong anisotropic response of the fabricated strain sensor based on a grid-like pattern of the sensing layer [149]. The orientation of the nanofibers was also improved by Shao et al. who embedded piezoelectric $BaTi_2O_5$ nanorods into piezoelectric PVDF nanofibers to enable differentiation between different bending directions [150]. Based on piezoresistive carbon nanofiber bundles derived from electrospun PAN nanofibers, Sengupta et al. designed flexible strain sensors to detect human movements, such as wrist bending, walking, or breathing, as discussed in Section 4.2 [151]. Some results of these experiments are shown in Figure 12 [151].

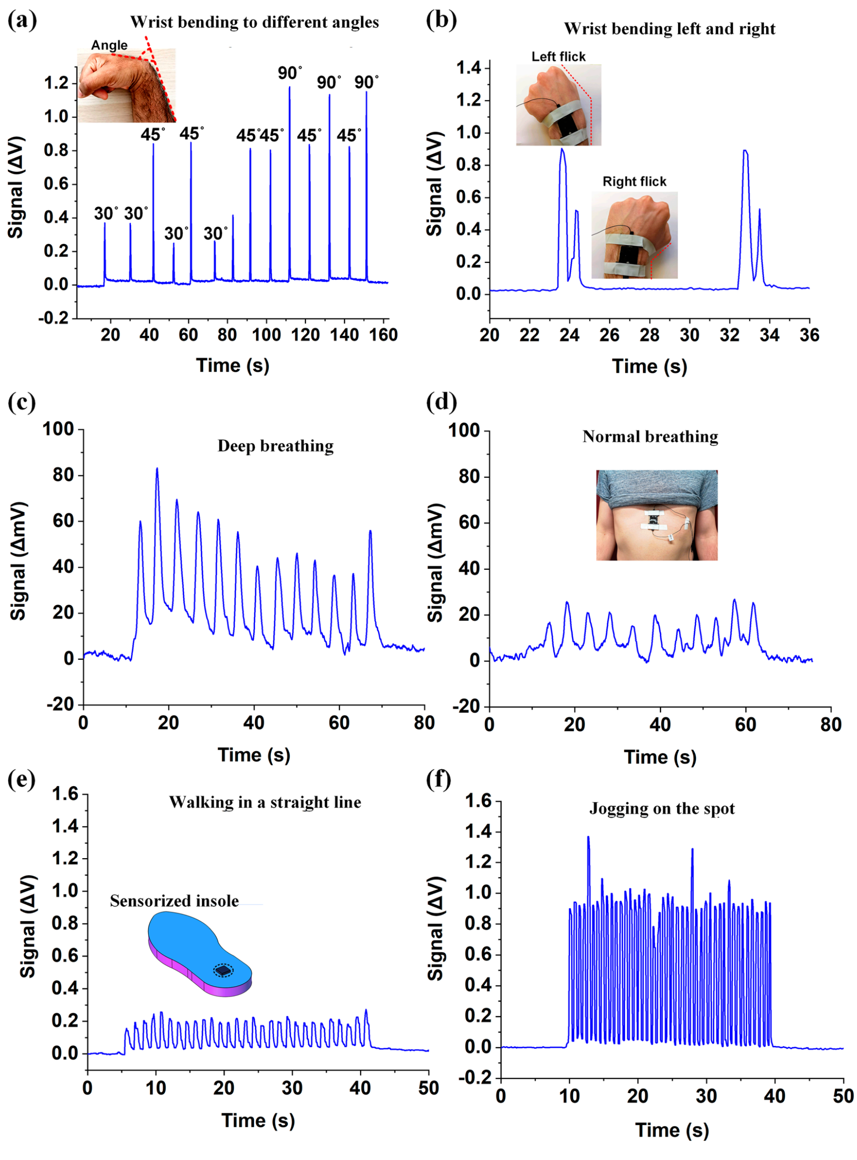

Figure 12. (**a**) Response of the sensor to various wrist bending angles; (**b**) response of the sensor to sideways wrist flicking; (**c**,**d**) response of the sensor to deep and normal breathing, respectively; (**e**,**f**) response of the sensor to walking in a straight line and spot jogging, respectively. Reprinted from [151], originally published under a CC BY license.

Similarly, many research groups have proposed to produce conductive nanofiber mats, e.g., by dip-coating TPU nanofibers with carbon nanotube/MXene [152], to design highly flexible, elastic, and durable strain sensors [153–155].

4.4. Pressure Sensors

Pressure sensors can be used for tactile sensing of robotic or prosthetic arms, as well as for monitoring blood pressure and measuring other human body parameters.

Pressure sensors for robotics are often based on the piezoelectric effect [156], in addition to capacitive [157], resistive [158], and triboelectric sensors [159]. Piezoelectric nanofibers for pressure sensors can be prepared from conductive fabrics sandwiching a dielectric layer of P(VDF-TrFE) nanofibers [160]. Lin et al. combined microstructured electrodes with electrospinning to produce a capacitive pressure sensor, as depicted in Figure 13 [161]. They showed that the dual-layer dielectric structure, which consists of a microcylinder array and an electrospun nanofiber mat, had a high sensitivity as a pressure sensor of 0.6/kPa and a low detection limit of 0.065 Pa, as well as high reproducibility even after several thousands of loading/unloading or bending/unbending cycles. The authors also showed that this pressure sensor could be used for various measurements of body parameters, such as pulse measurement, arm or foot movement, breathing through a mask with an embedded capacitive sensor, or tactile perception in a robotic hand [161].

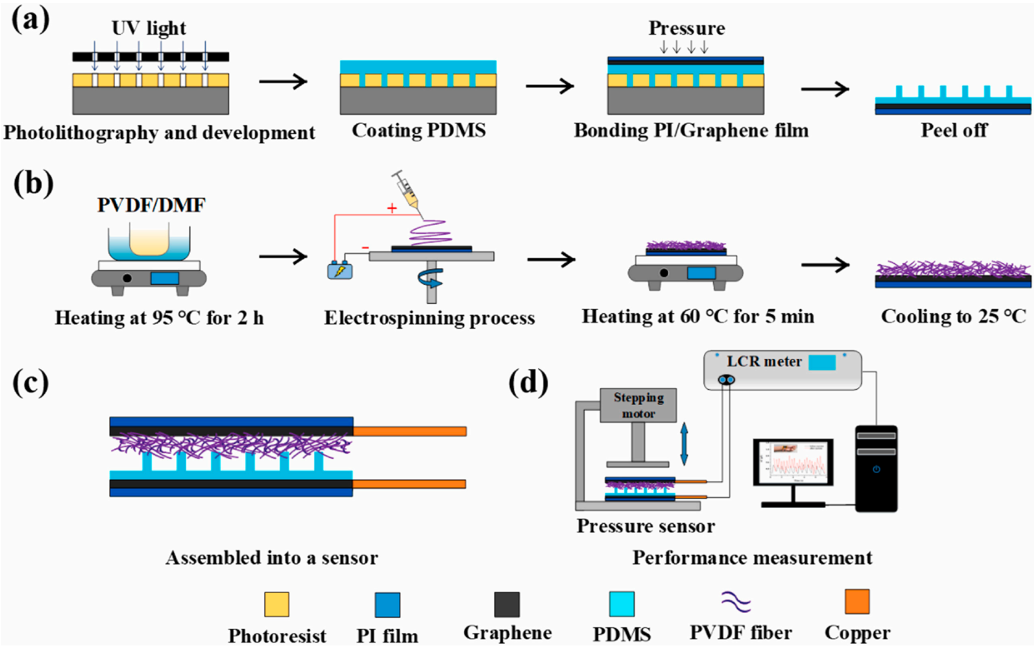

Figure 13. Schematics of (**a**,**b**) the fabrication process of microstructured electrodes, (**c**) the assembled array as a capacitive pressure sensor, and (**d**) the performance measurement setup of the sensor. PI: polyimide, PDMS: polydimethylsiloxane, DMF: dimethylformamide, PVDF: polyvinylidene difluoride. Reprinted from [161], with permission from Elsevier.

In general, such multi-level micro-/nanostructures are often reported to be advantageous for pressure sensors. To reduce their production to only one step, Yang et al. proposed template-assisted electrospinning, i.e., electrospinning a nanofiber mat on a microstructured substrate to combine a regular microstructure with the randomly distributed nanofibers in the mat, and found a high sensitivity value of 64/kPa and a low detection limit of 0.7 Pa [162]. Similar values were found for electrospun Halloysite@Ag_3PO_4/TPU nanofiber mats, in which Wang et al. reported a sensitivity of 6.7/kPa and a low detection limit of 4.8 Pa [163], while a lower sensitivity of 0.02/kPa was found for a PVA-CNT coated electrospun PVDF nanofiber mat [164].

As mentioned in Section 4.2, other researchers suggested the use of TENGs as self-powered pressure sensors [165–167] or different variations of the electrospinning process as well as various post-treatments of the nanofiber mats to improve sensitivity and detection limit [168–170].

4.5. Temperature Sensors

Temperature sensors can be made from various materials that change a physical parameter when the temperature changes. These can be resistive temperature sensors, thermocouples, thermistors, and other electrical [171] and optical fiber sensors [172].

Among the conductive materials used as electrospun temperature sensors, there are carbon nanofibers with or without a coating or doping, which exhibit high sensitivity, accuracy, and linearity as well as long-term durability [173,174]. Conductive coatings, such as graphite nanosheets on a PA66 nanofiber mat, also show a strong temperature-dependent resistance and are, therefore, suitable as temperature sensors for different situations with varying temperatures, as depicted in Figure 14 [128]. In addition, conductive polymers such as PEDOT:PSS were decorated with conductive nanoparticles, e.g., graphene nanoflakes and Co_3O_4 nanoparticles, resulting in a high-temperature sensitivity in the range of 0.002–0.04/K [175]. Alternatively, non-conductive nanofiber mats, e.g., made of TPU, were filled with an ionic liquid to enable temperature measurements with an accuracy of 0.05 K [176].

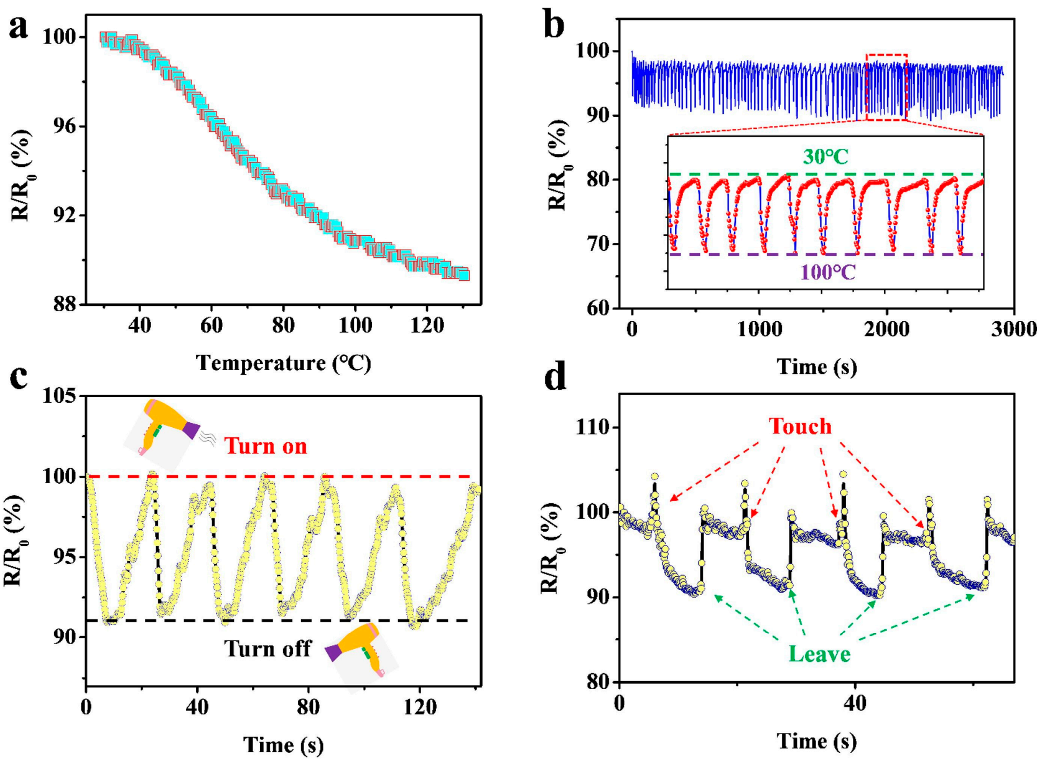

Figure 14. Temperature sensing behavior and application of a graphite nanosheet/PA66 nanofiber mat: (**a**) resistance–temperature curve from 30 °C to 130 °C; (**b**) resistance response vs. temperature under repeated heating/cooling cycles (between 30 °C and 100 °C); (**c**) sensing behavior of monitoring the hot wind blown out by a commercial blower and (**d**) touching a cup filled with hot water. Reprinted from [128], with permission from Elsevier.

An optical temperature measurement based on nanofiber mats was proposed by Ge et al. who prepared $Bi_2Ti_2O_7{:}Tm^{3+}/Yb^{3+}$ nanofiber mats with highly temperature-sensitive luminescence spectra, enabling a sensitivity of 0.024/K near room temperature [177].

Unexpectedly, the number of temperature-sensing nanofiber mats is smaller than that of other nanofiber-based sensors; nevertheless, these examples show the general feasibility of conductive or semiconductive nanofiber mats for this purpose.

4.6. Humidity Sensors

Humidity not only has a strong influence on the electrospinning process [178], but can also alter the physical properties of the resulting nanofiber mats, such as resistance, capacitance, voltage generation, etc., which can be used to produce electrospun humidity sensors to detect sweating or, in contrast, very dry skin. The high porosity and large surface-to-volume area of nanofiber mats are advantageous for this application [138].

As an example, Wang et al. designed a flexible piezoelectric nanogenerator (PENG) made of PET with a single-layer $MoSe_2$ decoration and combined it with a flexible PVA/MXene-based electrospun humidity sensor to create a self-powered sensor [179]. These films not only exhibited low hysteresis and high response but also a good recovery, as shown in Figure 15 [179]. Such piezoelectric nanogenerators have also been suggested by other researchers [180].

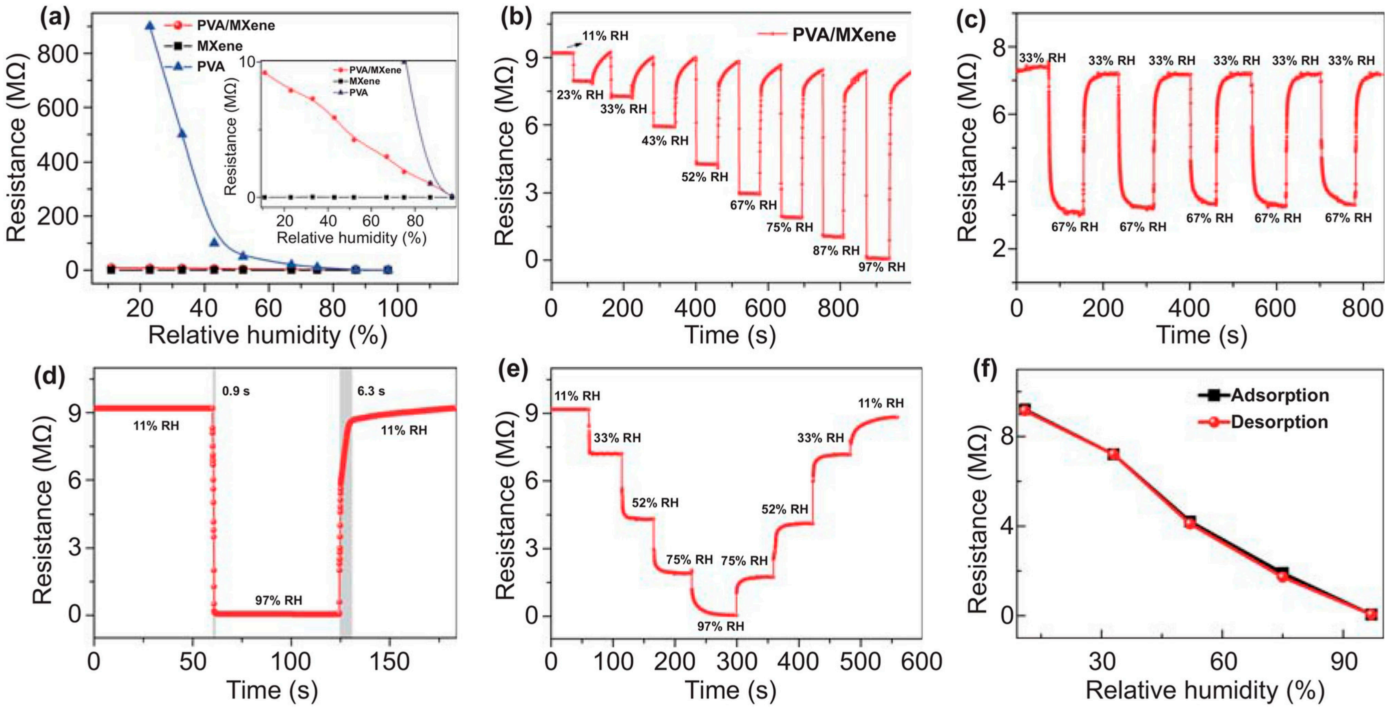

Figure 15. (**a**) Resistance of the MXene, poly(vinyl alcohol) (PVA), and PVA/MXene film sensor exposed to various relative humidities; (**b**) dynamic resistance changes of PVA/MXene film sensor exposed to various relative humidities; (**c**) repeatability of PVA/MXene film sensor; (**d**) time-dependent resistance response and recovery curves of the PVA/MXene sensor between 11 and 97% rH; (**e**) resistance of sensor with increasing and decreasing humidity; (**f**) humidity hysteresis curves of the PVA/MXene nanofibers film sensor. Reprinted from [179], originally published under a CC BY license.

Similarly, Sardana et al. proposed an electrospun TENG based on electrospun PVA/MXene nanofibers to produce a humidity sensor with high sensitivity due to the hydrophilic functional groups of PVA and MXene in addition to the high surface-to-volume ratio [181]. Hydrophilic polypyrrole/polystyrene nanofiber mats were also found suitable as electrospun humidity sensors [182]. Another approach, described by Choi et al., is based on SPEEK nanofibers, which show proton conduction and allow humidity measurements with higher sensitivity and linearity than continuous SPEEK films [183].

In addition to skin humidity, the moisture in the exhaled air can also be measured using electrospun nanofiber mats, e.g., from SPEEK/poly(vinyl butyral), whereby, as mentioned before, a fast response time is required for this application [137].

Finally, it should be mentioned that the humidity dependence of many nanofibrous materials can also be problematic if the nanofiber mat is used as a gas sensor or to detect other chemical or physical properties, which leads to the development of humidity-independent nanofibrous sensors for many applications [184–186].

5. Challenges and Prospects

In spite of the steady progress in the development of wearable electrospun nanofibrous sensors, there are still challenges that necessitate future research.

The electrospinning process itself causes several limitations, such as problems with upscaling and homogeneity on a large scale as well as reliability and reproducibility, caused by environmental factors that cannot often be fully controlled. These problems are most important to solve before the commercialization of the respective sensors.

Not all polymers are spinnable alone; conductive and other functional polymers usually need co-electrospinning or coaxial electrospinning to make them spinnable. Developing new polymers and polymer blends that are spinnable, ideally from low-toxic solvents, and adding new functionalities to electrospun sensors is, thus, one of the main aims for future research.

In addition to functionality, the mechanical properties of nanofiber mats, including flexibility, stretchability, and durability, are often lower than necessary, making sandwiching of the nanofiber mats or similar techniques necessary to improve their robustness against mechanical impacts. For this challenge, it would be supportive to either increase the nanofiber mat thickness significantly by speeding up the nanofiber deposition process or to develop simple possibilities to directly spin on a substrate in order to create rigidly fixed sandwiches.

Creating nanofiber yarns or, more generally, oriented nanofibers is an additional challenge that necessitates more sophisticated electrospinning techniques. Developing them further and making them easier to use and more reproducible belongs to the necessary future research areas. It should be mentioned that post-processing, such as stretching under defined conditions, may also support the production of oriented nanofibers.

Finally, many sensor applications necessitate the integration of many functions, electronics, etc., which again necessitates research on the one-step production of multifunctional nanofiber mats and their connectivity to miniaturized electronic components.

6. Conclusions

Electrospun nanofiber mats made of various materials can be used as sensors for health monitoring, e.g., for measuring ECG and heartbeat, respiration, movement, pressure, temperature, or humidity. For this purpose, the nanofiber mats are usually either stuck to the skin or embedded in smart textiles. Important prerequisites for a suitable sensitivity to the required parameter include the material or material combination of the nanofiber mats and potential decorations with nanoparticles or other post-treatments, as well as fiber cross-sections and fiber orientations within the nanofibrous membrane.

This paper provides a brief overview of recent research on electrospun sensors for health monitoring as well as a broad technological basis for the production of these sensors and can, thus, serve as a stimulus for researchers working in similar fields. Finally, it should be mentioned that there are still several challenges that are often not explicitly mentioned in papers, such as the cross-sensitivity of these sensors, i.e., sensitivity to substances other than the desired ones, the multifunctionality that is often required, potential inhomogeneities in the electrospun nanofiber mats, problems in calcination of the polymeric parts of mixed nanofibers, lack of mechanical stability, upscaling of needle-based or even near-field electrospinning, etc. These challenges are found along the entire chain from the material to the nanofiber mat and to the sensor application, including electrical contacts and data transmission, which underlines the importance of conducting further research in this interesting field.

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draft preparation, A.E.; writing—review and editing, all authors; visualization, N.S.M. and G.E. All authors have read and agreed to the published version of the manuscript.

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