electronics

Review

Revolution in Flexible Wearable Electronics for Temperature and Pressure Monitoring—A Review

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Abstract: In the last few decades, technology innovation has had a huge influence on our lives and well-being. Various factors of observing our physiological characteristics are taken into account. Wearable sensing tools are one of the most imperative sectors that are now trending and are expected to grow significantly in the coming days. Externally utilized tools connected to any human to assess physiological characteristics of interest are known as wearable sensors. Wearable sensors range in size from tiny to large tools that are physically affixed to the user and operate on wired or wireless terms. With increasing technological capabilities and a greater grasp of current research procedures, the usage of wearable sensors has a brighter future. In this review paper, the recent developments of two important types of wearable electronics apparatuses have been discussed for temperature and pressure sensing ($P_{sensing}$) applications. Temperature sensing ($T_{sensing}$) is one of the most important physiological factors for determining human body temperature, with a focus on patients with long-term chronic conditions, normally healthy, unconscious, and injured patients receiving surgical treatment, as well as the health of medical personnel. Flexile $P_{sensing}$ devices are classified into three categories established on their transduction mechanisms: piezoresistive, capacitive, and piezoelectric. Many efforts have been made to enhance the characteristics of the flexible $P_{sensing}$ devices established on these mechanisms.

Keywords: wearable sensors; temperature sensor; pressure sensor; wearable electronics

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1. Introduction

Wearable sensing devices are incorporated into wearable products or directly with the body to assist health monitoring and/or offer clinically useful data for care, as the name indicates. Until roughly a decade ago, most research in this subject depended on stiff electrical devices made in the semiconductor electronics platforms [1]. The attention has recently switched to wearable sensing systems that make use of stretchy and flexile electronics [2]. These flexile sensing apparatuses, unlike stiff electronics, have a wide span of mechanical characteristics, making manufacturing more difficult. So far, the most common method for making soft sensing apparatuses has been to use transfer printing [3], screen printing [4], photolithography [5], microchannel molding [6], and lamination [7] to combine deformable conducting material patterns onto a stretchy substrate. These technologies, however, have some drawbacks, including high cost, multistep manufacturing processes, low durability, and prototyping and scaling issues. As a result, 3D printing is a realistic option that may be used in conjunction with other methods. Its key benefits are high-resolution fast prototyping and the ability to manufacture biomedical apparatuses directly [8].

Smart sensing devices, wearable materials, actuators, power sources, wireless communication modules and linkages, control and processing units, a user interface, soft-ware, and complex algorithms for extracting data and making decisions are all part of wearable electronic systems. As a result, the systems can track the patient's physiological data such as temperature; blood pressure; strain; and the concentration of gases, ions, and biomolecules in the blood circulation [9,10]. Smart sensing devices, which are made up of flexile substrates with implanted conducting electrodes, must be ultrathin, low modulus, lightweight, very flexile, and stretchy to be employed in wearable electronic systems.

The growth of Si-based semiconductor technology has substantially aided the progress of the information technology section since the 1950s, profoundly altering people's lives. Traditional Si-based electronics with high Young's modulus, in contrast, are confronting new issues as the world becomes more informationized and the Internet of Things (IoTs) develops. Flexile and wearable electronics have piqued scientists' curiosity over the last few decades and have become a prominent subject in the scientific community [11]. Flexile electronics, as opposed to rigid silicon-based electronic devices, have several distinct advantages, such as high elasticity, lightweight, and conformality, which allow flexile and wearable electronics to be employed in a broader span of applications [12,13]. Figure 1 shows the recently developed flexile electronics apparatuses for personal healthcare.

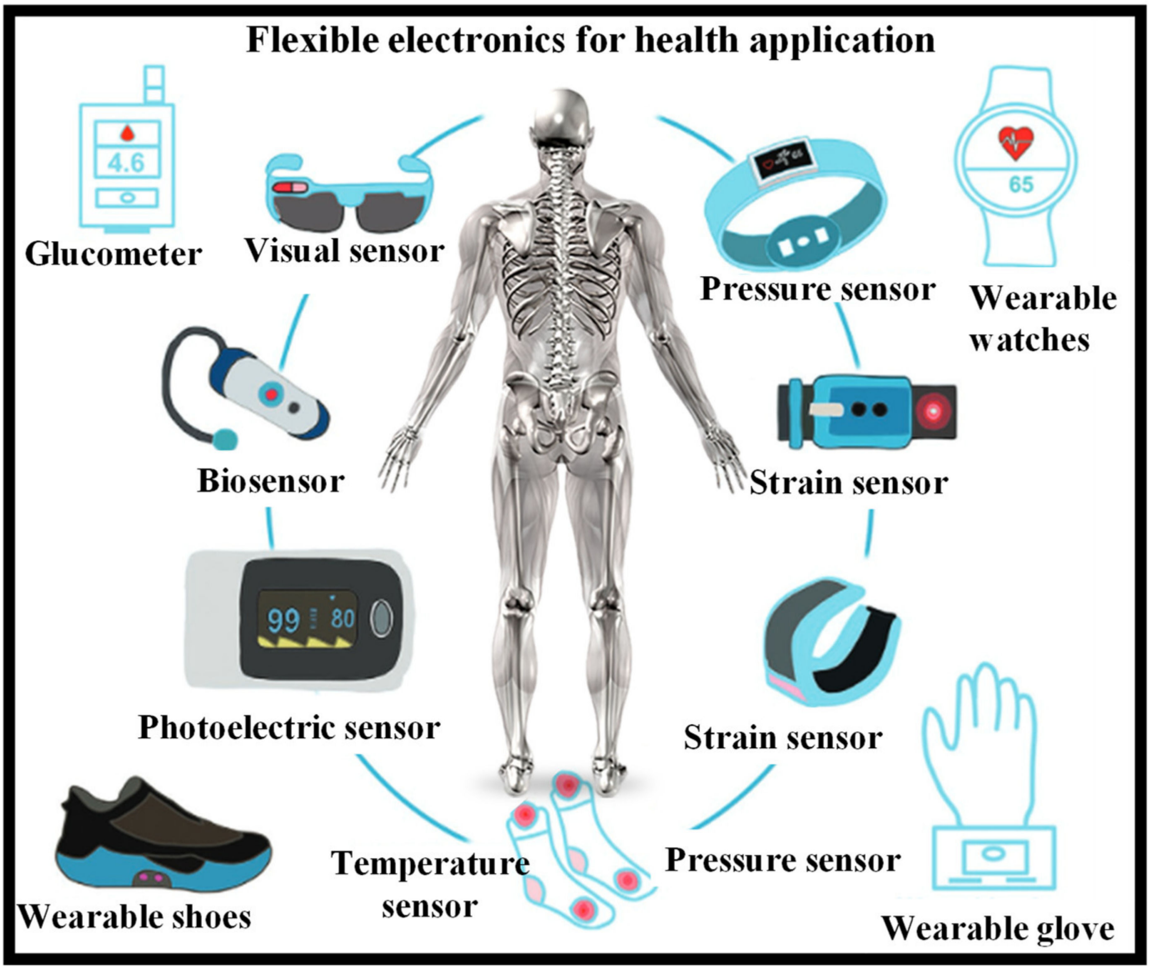

Figure 1. Schematic of flexile electronics for personal healthcare. Inspired by the work in [14].

An increasing curiosity in flexile and wearable medical devices for frequent and continuous checking of human health data has emerged [15]. Novel gadgets are being developed to provide for the most comfortable continuous monitoring of vital signs. By simply connecting these wearable medical electronic apparatuses to the human body surface, they can measure different health information, for instance, heart rate, pulse, body temperature, blood glucose, among others, noninvasively and in real-time [16–19].

When an individual's physical health indicators are unusual, real-time surveillance of crucial signs can inform users and health management professionals to seek additional medical attention, allowing optimal treatment. Flexile electronics can also be distorted at will and detect a wide span of signals with exceptional sensitivity, making them suitable for utilizations such as artificial electronic skin, motion detection, telemedicine, and in-home health management. There is no denying that next-generation flexile and wearable electronics will usher in a paradigm shift in human behavior. Wearable electronics have received much attention recently, and interesting advances have been achieved in novel materials, processes, and sensing mechanisms [20,21].

The paper is organized in the following manner. In Section 2, the worldwide wearable sensing demand has been presented which shows a tremendous increase in the market need for smart equipment for personal healthcare. Section 3 presents the current research on the materials for the realization of wearable sensing equipment. $T_{sensing}$ apparatuses should be flexile and elastic for long-term in situ monitoring, allowing for conformable integration onto human skin. The recent developments in wearable electronics temperature sensors are discussed in Section 4. Several novel, cost-effective, highly sensitive, and accurate body temperature monitoring apparatuses are discussed in detail. In Section 5, the advancement in wearable pressure sensors and their prospects are presented. Flexile $P_{sensing}$ apparatuses are classified into three categories established on their transduction mechanisms: piezoresistive, capacitive, and piezoelectric. Many efforts have been made to enhance the characteristics of the flexile $P_{sensing}$ device established on the three conversion concepts. The paper ends with a brief conclusion in Section 6.

2. Worldwide Wearable Sensing Demand

As a result of digitization, the electronic sector has risen tremendously. Therefore, the wearable technology industry, which is extensively employed for self-health monitoring utilizations, is exploding. People's health and safety awareness has risen because of rising consumer electronics spending, urbanization, and improved lifestyles of the growing population, which is fueling the expansion of wearable gadgets. Also driving the evolution of wearable gadgets such as Fitbit, ear wears, and smartwatches are the affordability and ergonomics provided by developments in miniaturized electronics; the proliferation of smartphones and connected equipment; and the rising demand for low power, compact, light sensors, and improved performance [22].

Smartwatch unit sales surged from 5 million in 2014 to 141 million in 2018, according to the Consumer Technology Association [23]. The main reason for this growth is that people are becoming more mindful of their health. Furthermore, in recent years, the number of wearable gadgets sold has expanded dramatically. As a result of this tendency, the usage of sensors in these wearable equipment has risen. As stated by Cisco Systems, the increase in connected wearable equipment from 325 million in 2016 to 593 million in 2018 offers a lot of potential, especially in healthcare utilizations. With numerous businesses investing extensively in IoT equipment and IoT sensor use dropping, wearable device demand is predicted to skyrocket across multiple industries [23].

14 December 2021, Jersey City, (Globe newswire)—"Wearable sensors market" by type (Accelerometer, gyroscope, optical, force and pressure), device (smart watch, fitness band, smart glasses), vertical (consumer, defense, healthcare, industrial), and Geography was just released by Verified Market Research. According to Verified Market Research, the global wearable sensors market was worth 660.89 million dollars in 2020 and is expected to reach 5208.05 million dollars by 2028, with a compound annual growth rate (CAGR) of 29.3% from 2021 to 2028 (See Figure 2) [24]. Over one-tenth of Americans now own a wearable sensing device, such as a specialized fitness monitoring device, up from a third in 2012 [25]. Using mobile phones and online connections, fitness trackers, and smartwatches may construct individualized health profiles by collecting data on the pulse, blood oxygen level, movement, speed, step count, and even eating and sleeping patterns [26]. Such equipment is particularly tempting for at-home health surveillance, especially for the growing number

of elderly who live alone. By allowing elder users, their families, carers, and healthcare professionals through remote health records, reduce hospital resource load and expedite response time in the case of an emergency. Wearable technologies for old health monitoring are now having an impact, with total device shipments related to elderly health scrutiny estimated to reach 44 million dollars in 2019. Wearables, with ergonomic displays and voice control capabilities for hands-free, computationally-assisted speedy diagnosis and other health decision-making, are also becoming the latest method for medical practitioners and healthcare employees. Wearables might be used to produce augmented reality for a diversity of purposes, comprising improving the visibility of important organs and tissue during surgery [27]. Even for environmental surveillance, wearable sensing device automation is being used. The ability to use crowdsourcing to easily monitor plant health, air quality, or contaminants across a large territory is intriguing, and specific novel wearable gadgets make it even simpler. Worldwide, wearable sensing instruments have been studied.

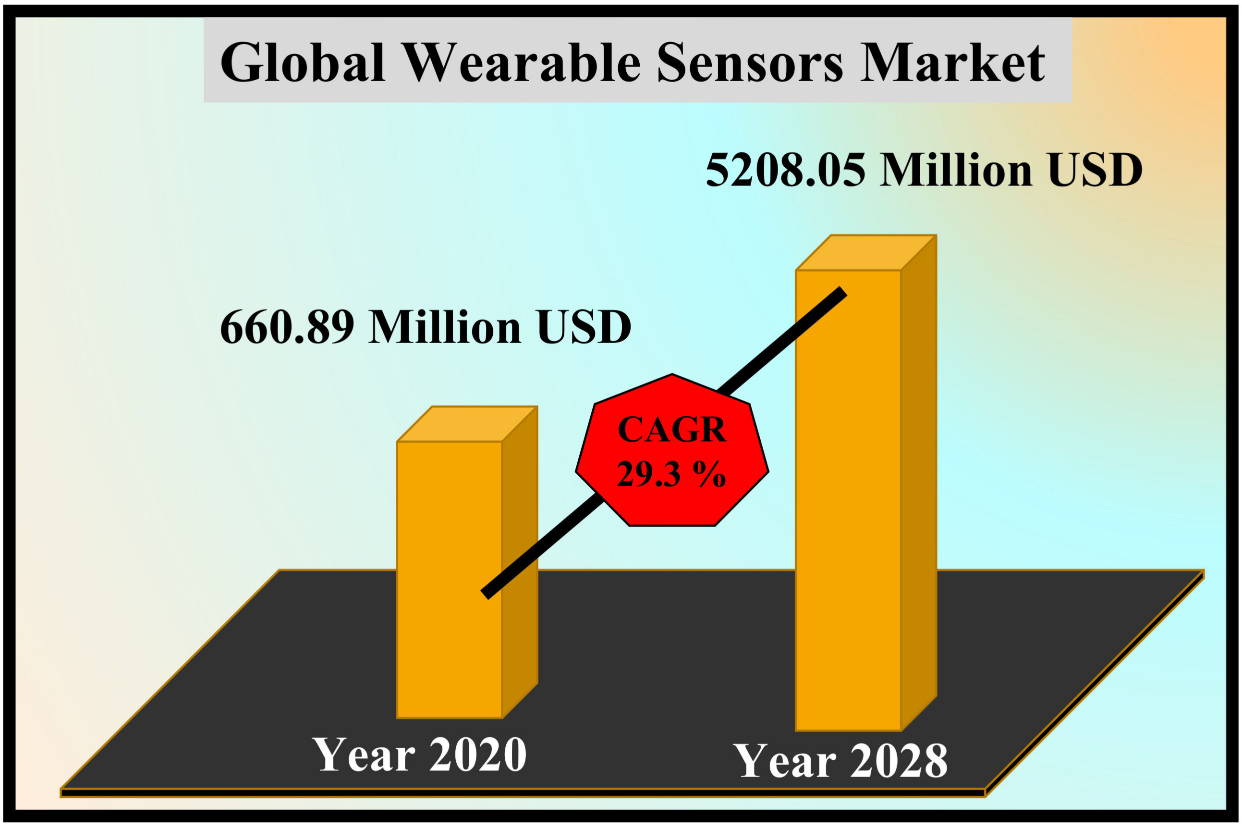

Figure 2. Global wearable sensors market. Inspired by the work in [24].

3. Materials Requirement of Wearable Sensing Apparatuses

Stretchy and wearable sensing apparatuses need stretchable substrates to function. In various studies of wearable sensing apparatuses, silicon-based elastomers, for example, polydimethylsiloxane (PDMS) and Ecoflex, which are created by polymerizing siloxane monomers with platinum catalysts, have been used as stretchable substrates [28]. Their Young's modulus is 4.8 MPa in PDMS and their elongation limit is 420%. The elongation maximum of Ecoflex is 900%. These elastomers have minimal intermolecular force and hence have high stretchability. Because of its strength and intermediate elasticity (Young's modulus 4 GPa), parylene is also employed as the substrate for thin-film wearable sensing systems. Furthermore, according to various sources, parylene is biocompatible [29,30]. Electrode elements are also crucial parts of wearable sensing systems. Substrates are often made of polymer-based materials, although metal-based electrodes are employed in electrodes because strong conductivity is necessary. To promote stretchability, thin-metal interconnects or serpentine structure metal is employed. Nanowire-based random network and liquid metal are two more techniques to create the stretchy connection [31,32]. At body temperature, liquid metal has metal-like conductivity, yet due to the nature of the liquid, it does not fail under strain, allowing for extremely flexile interconnects [33,34]. Depending on the type and purpose of the wearable sensing device, a variety of materials can be used as active materials [35]. A strain or P-sensing device uses a piezoelectric material or a strain-sensitive resistor that changes resistance in response to strain or pressure [36,37]. Chemical sensing systems also employ a variety of active materials, the most common of which are carbon nanotubes (CNT) or graphene [38]. Because numerous functional groups on CNT and graphene surfaces may be readily adjusted to provide a span of wearable sensing systems [39]. Polymers having conjugated groups that can easily con-jugate with CNT and graphene, such as pyrene, can be coated on the surface of CNT and graphene to display different sensing apparatuses, including ion, polymer, and gas sensing apparatuses.

In the active layer of flexible tactile sensors, template approaches are recognized as a significant way for micro-nanoprocessing. These template approaches introduce micro-nano structures on the active layer via physical/chemical procedures, which increases various aspects such as sensitivity, response/recovery time, and detection limit. However, because the template technique's processing and relevant circumstances have yet to be perfected, the development and commercialization of flexible tactile sensors based on the template approach are still in the early stages. Despite the aforementioned challenges, breakthroughs in microelectronics, materials science, nanoscience, and other fields have set the groundwork for a variety of template approaches, allowing for the further development of flexible tactile sensors [40].

It is suggested to manufacture an active-matrix, pressure-sensitive graphene field-effect transistor (FET) array with air–dielectric layers produced by folding an origami substrate made up of two plastic panels and a foldable elastic junction [28]. By patterning source/drain/interconnects on one plastic panel and gate/interconnects on the other panel at the same time, all electrodes of the integrated FET array may be created concurrently, reducing total processing steps (see Figure 3a,b). The elastic link that joins these two plastic elements permits the substrate to be folded entirely deprived of causing any harm. By folding this substrate to pile these two panels (one with source/drain and the other with gate), integrated arrays of top-gated transistors with local air gaps as dielectrics may be easily created. Because of the clean interface between the graphene channel and the air, these air–dielectric graphene FETs have excellent electric characteristics and good reliability under ambient circumstances. The depth of elastomeric partition spacers between the graphene and top-gate determines the height of air gaps, which may be reduced by applying pressure when the capacitance of the metal–air–graphene system increases. This pressure-sensitive capacitance shift allows each FET to function independently as a tactile $P_{sensing}$ device with a detection span of 250 Pa to 3 MPa. As a result, the direct integration of these FETs, which requires no extra element of layer, results in active-matrix $P_{sensing}$ device arrays with minimal manufacturing costs and densifications. In addition, the construction of a translucent $P_{sensing}$ device using silver nanowire (AgNW)-graphene hybrid translucent electrodes is demonstrated for utilizations such as translucent e-skin and an analogue touch screen panel [28]. E-skin is propelling substantial advancements in flexible elec-tronics, with applications in health monitoring, human–machine interfaces, soft robotics, and other areas. In e-skin, flexible sensors that can detect a variety of stimuli or have diverse qualities are essential. Despite significant research efforts devoted to flexible sensors with good performance in a specific detecting mode or attribute, growing e-skin requires multifunctional flexible sensors with skin-like capabilities and beyond. Carbon materials are used to develop multifunctional flexible sensors because of their great electrical conductivity, chemical stability, and simplicity of functionalization [41].

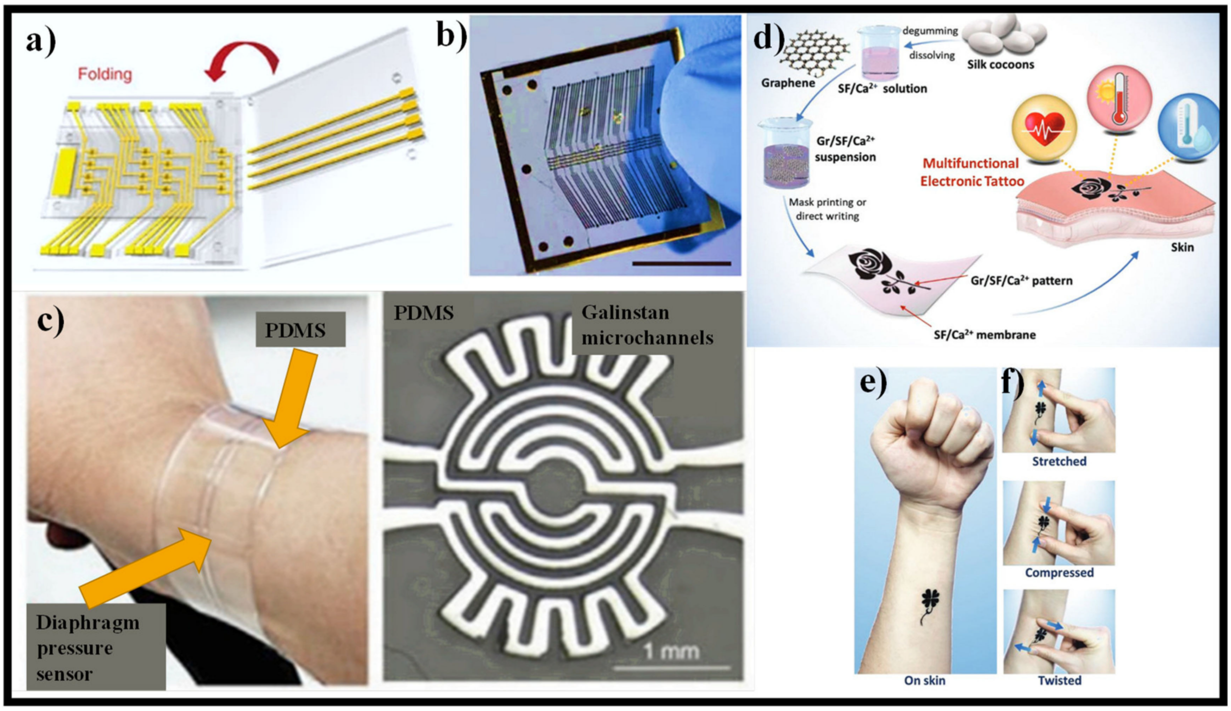

Figure 3. (**a**) Schematic image of pressure-sensitive graphene FETs with air–dielectric layers [28]. (**b**) Photograph of the manufactured pressure-sensitive graphene FETs, Scale bar, 1 cm [28]. (**c**) Microfluidic elastomers [42]. (**d**) Manufacturing process of the Gr/SF/Ca^{2+} E-tattoo and its stable adhesion on human skin [43]. (**e**) Photographs showing a four-leaf clover E-tattoo attached to the forearm [43]. (**f**) Photographs of the tattoo on skin in different states: stretched (**top**), compressed (**middle**), and twisted (**bottom**) [43].

With several other ways like injection, direct writing, and contact printing, microfluidic elastomers have been the most common technology for employing liquid metal (LM) alloy for electronic sensing apparatuses and circuit elements [44,45]. Unlike other solid materials, LM may be injected into silicones in a restricted manner to generate microfluid-ic elastomers while remaining in a liquid state deprived of affecting directly written traces. The electromechanical characteristics of microfluidic elastomers with no LM leakage are often quite constant [44]. However, regardless of how LM is placed on the substratum, all these apparatuses require an encapsulating layer to passivate the wire arrangement. This also results in a poor vapor diffusion rate at the skin–electronics contact, which can induce itching and other negative effects. As a result, there are currently ongoing efforts to im-prove patterning resolutions by creating high-resolution traces using a high-vacuum-assisted filling or micro-nanostructure stamping for microfluidic elastomers [42] (see Figure 3c). Furthermore, very permeable fiber mats with printed LM traces are being created to reduce inflammation and discomfort in the future of LM wearable electronics.

Researchers in the field of wearable electronics are interested in E-tattoos which may be intimately installed on human skin for noninvasive and high-fidelity sensing. Fabricating E-tattoos capable of self-healing and multi-stimuli sensing, like the innate characteristics of human skin, remains a challenge. A multifunctional and healable E-tattoo based on a graphene/silk fibroin/Ca^{2+} (Gr/SF/Ca^{2+}) combination is described in [43]. E-tattoos with great flexibility is created by printing or writing using Gr/SF/Ca^{2+} suspension. The graphene flakes dispersed in the matrix produce an electrically conductive channel that responds to environmental changes such as strain, humidity, and temperature fluctuations, giving the E-tattoo great multi-stimuli sensitivity. The E-tattoos creation method is depicted in Figure 3d. To make the Gr/SF/Ca^{2+} suspensions, silkworm cocoons were utilized to make the SF/Ca^{2+} solution, and graphene was added to a portion of the SF/Ca^{2+} solution.

To create the intended E-tattoos, the Gr/SF/Ca^{2+} suspensions can be patterned on SF/Ca^{2+} membranes via screen printing or direct writing. To attach the Gr/SF/Ca^{2+} E-tattoo to human skin, all that is necessary is a droplet of water poured over the desired spot. Because of the modest breakdown of SF/Ca^{2+} membrane caused by water, the Gr/SF/Ca^{2+} E-tattoo can be effectively affixed to the skin. The E-tattoo adheres to human skin in a stable and conformal manner, as seen in Figure 3d,e. Even when subjected to external pressures such as stretching, compression, and twisting, the E-tattoo can maintain its place without dislocation, delamination, or fracture. As a result, it demonstrates its appropriateness for usage as a dependable E-tattoo (Figure 3f).

4. Flexile Wearable $T_{sensing}$ Apparatuses

$T_{sensing}$ is one of the most important physiological factors for determining the human body temperature, with a focus on patients with long-term chronic conditions, normally healthy, unconscious, and injured patients receiving surgical treatment, as well as the health of medical personnel. Wearable $T_{sensing}$ is appealing not just in the medical area, but it may also be used to track and monitor the body temperature of healthy persons engaging in strenuous outdoor activities [46]. Aside from athletes' and sportsmen's intense workouts for fitness, wearable $T_{sensing}$ apparatuses are quite beneficial for workers working in extreme environments [47,48]. The growing levels of climatic circumstances, notably temperature and humidity, create dehydration in people, as well as exhaustion and other major health consequences. Consequently, creating wearable $T_{sensing}$ apparatuses is important not only for monitoring human health, but also for evaluating the local ambient environment.

4.1. Types of $T_{sensing}$ Apparatuses

$T_{sensing}$ apparatuses are traditionally designed in a variety of geometric shapes based on the application, material processability, and manufacturability in the required shape. The $T_{sensing}$ system distinguishes these diverse structures through modifications and physical interaction with hot surfaces [49]. The two main types of $T_{sensing}$ systems are those that use contact or non-contact sensing technique. Sensing systems of the contact kind are used to monitor a variety of surfaces, including solids, liquids, and gaseous phases. Non-contact-based sensing systems, in contrast, can detect the heat irradiations released by hot surfaces from afar. Thermostats, thermistors, resistive temperature detectors (RTDs), thermocouples, negative temperature coefficient thermistors (NTCs), and silicon-based sensing systems are some of the most common $T_{sensing}$ apparatuses [50]. The operating mechanism of these sensing apparatuses is described in detail in [51,52]. Among the most prevalent types of $T_{sensing}$ apparatuses are RTD, thermally sensitive resistors (thermistors), mercury-based thermometers, optical and portable infrared surveillance sensing apparatuses, and so on.

Each form of sensing device has benefits over the other, but certain limits for wearable-related utilizations limit the types of sensing apparatuses that may be used. RTDs and thermistors are commonly used in a variety of utilizations because of their consistent and quick reaction, structural stability, high precision, and ease of manufacture, which makes them excellent for batch production at low prices [53]. Thermal infrared, and optical sensing apparatuses, in contrast, are widely used in indoor medical facilities, but they are developed on wafer-based substrates, with signal conditioning circuits embedded on rigid printed circuit boards (PCBs), making lightweight, portable, and wearable utilizations difficult [54]. All contributing materials must be flexile or elastic enough to absorb the stresses induced by deformations caused by human physical activity for the sensing apparatuses to adhere to human skin in a conformal manner. The vast area coverage of the sensing apparatuses plays an important role in this scenario, which is made possible by the RTD and thermistor geometric methods.

Sensitivity, precision, detection at lower temperature spans, reliability, and repeatability are the key performance parameters for wearable sensing apparatuses when worn on non-planar surfaces. Increased accuracy is achieved via a linear response in the sensitivity, which is especially important for human body temperature detection. $T_{sensing}$ spans are an important parameter, as is choosing a suitable material that is sensitive to minor variations in the human body [55]. Another important element to consider is the sensing device's response time, which plays an important role in detecting thermal fluctuations. The early recognition of symptoms aids in the prompt diagnosis and treatment of the condition. The sensing device's reaction time, stability, and hysteresis, among other critical factors, are all crucial in real-time surveillance. When it comes to wearable $T_{sensing}$ apparatuses, resolution denotes the measurement of the lowest number of variations observed by the sensing device and so becomes an essential characteristic. Finally, sensing apparatuses must be created on biocompatible substrates, be lightweight, and comfortable onto non-planar surfaces deprived of considerable loss of sensing device response to be wearable [56].

4.2. Developments in Wearable $T_{sensing}$ Apparatuses

The biomedical research community has recently shown a lot of interest in printed wearable sensing apparatuses for surveillance key bio-signals such as body temperature, respiration rate, blood pressure, glucose, and electrophysiology [56–58]. These sensing apparatuses are built on biocompatible substrates and adhere to the target surfaces in a conformable manner. These sensing apparatuses are often printed as electronic tattoos that are applied straight to the human skin, or they are incorporated into fabrics that are more prone to deformation [59]. Human body temperature measurement is given special attention among the numerous vital indicators, and it is used as an early indicator for a span of disorders. $T_{sensing}$ apparatuses should be flexile and elastic for long-term in situ monitoring, allowing for conformable integration onto human skin. Commercially accessible sensing apparatuses are built on hard planar substrates that cannot be used on non-planar surfaces for wearable sensing utilizations. The lower glass transition temperature of polymeric substrates, in contrast, prevents standard cleanroom procedures from being used to manufacture these sensing apparatuses. As a result, the novel printed electronics technology allows for the manufacture of electronic devices, circuits, and systems on a variety of substrates under ambient circumstances [60].

Several printing approaches to produce flexile electronics and sensing devices on polymeric substrates have recently been published. For the development of printing systems, two basic techniques are used: contact [61] and non-contact [62]. The patterned inked surfaces are brought into physical contact with the target substrate in the contact printing process. Gravure printing [63], flexographic printing [64], micro-contact printing [65], nanoimprint [66], and screen printing [67] are examples of contact-based printing processes. In non-contact printing, fluid is placed on the target substrate using nozzles in a preprogrammed pattern. Slot-die coating [68], aerosol [69], electrohydrodynamic and inkjet printing [70] are examples of non-contact printing processes. Due to appealing features such as simplicity, affordability, speed, adaptability to the fabrication process, reduced material wastage, high pattern resolution, and easy control by adjusting a few printing parameters, non-contact printing techniques have attracted more attention for flexile electronics manufacturing. Inkjet printing is the most widely used contactless method for fabricating electrical devices on a wide span of substrates in ambient settings and is highly resourceful in material usage [71]. Inkjet printers can print patterns with a resolution of up to 50 μm and film thicknesses of a few nanometers. A wide span of materials and shapes have been used in the creation of $T_{sensing}$ devices. Resistive $T_{sensing}$ devices on paper substrates [72], silver meander patterns on plastic substrates [73], and graph-ite-polydimethylsiloxane composites [74], among others, have been used. All these sensing devices such as temperature spans, sensitivity, and manufacturing procedures, to name a few. One of the most important concerns with printed $T_{sensing}$ devices is resistance drift over time. Sensing devices for wearable electronics must be robust and produced at ambient temperature on a span of alternative substrates such as plastic, paper, and clothing. Ali et al. propose a two-step deposition approach for fabricating a human body $T_{sensing}$ device using an inkjet material printer at room temperature [75]. The sensing device is made up of a silver-based interdigital electrode and a carbon black sheet that is sensitive to human body temperature. The gadget contains two terminals that measure changes in resistance in response to temperature. A positive temperature coefficient means that the change in resistance is proportional to the change in temperature. The spacing of the interdigital electrodes was tuned for high sensitivity (0.00375/°C), and linear resistance behavior was obtained at a temperature ranging from 28 to 50 °C. On human body temperature readings, the response is highly linear.

The most common approach for temperature measurement in skin-like electronics apparatuses is to detect temperature through changes in the resistance of sensitive materials. The temperature coefficient of resistance (TCR) is a key measure of resistive $T_{sensing}$ device sensitivity. It is defined as the change in resistance when the temperature changes by 1 °C. Pure metal elements (Pt, Au, Cu) [76–78], metal oxide particles [79], carbon nanotube (CNT) polymer composites [80], and graphene [81] have all been used as sensitive materials in resistive $T_{sensing}$ apparatuses. Due to their temperature sensitivity, metals have been employed for $T_{sensing}$ for a long time. The detecting process is explained by the fact that when the temperature rises, the thermal vibration of the lattice increases, resulting in more intense scattering of the electron wave and hence an increase in resistivity. Traditional $T_{sensing}$ apparatuses made of metal have limited stretchability and bendability. Wrinkle buckling, in-line horseshoe-like structures, and rigid-island design have all been proven to be viable ways to circumvent the restrictions. Yu and colleagues created a stretchy $T_{sensing}$ device with corrugated thin-film sensing elements on an elastic substrate [77]. Sputtering a thin Cr/Au layer on a pre-stretched 30% flexile substrate was used to make the sensing device. The sensing device can stretch up 30% mechanical strain deprived of losing performance because of the periodical wavy shape created by releasing pre-strain. Webb et al. presented an ultrathin, skin-like $T_{sensing}$ device array made from a thin, narrow, gold thin film in the shape of serpentine, which was created using microlithographic processes [82]. Stretchable electronic apparatuses were proficient in unintrusive mapping of shell temperature in millikelvin precision when combined with advanced modeling and analytic techniques.

The simplicity with which graphene nanowalls (GNWs) and PDMS may be combined to create an ultrasensitive wearable $T_{sensing}$ device is illustrated in [83]. Fabrication of the sensing device allows for a polymer-assisted transfer method making it considerably facile, biocompatible, and cost-effective (see Figure 4a). The elasticity of the sensing device can be seen in the inset in Figure 4a. The resistance fluctuation of the $T_{sensing}$ device is measured across a wide temperature span, from room 25 °C to 120 °C, to study its responsiveness. To ensure a thermal equilibrium between the testing sample and the hotplate, the temperature was first adjusted to the appropriate value and then kept constant for 10 min for each measurement. In Figure 4b, a typical response curve is displayed on a logarithmic scale [83]. The resulting device has a positive TCR of 0.214/°C, which is three times higher than its standard counterparts. This is due to GNW's exceptional stretchability and temperature sensitivity, as well as PDMS's huge expansion coefficient. Furthermore, the sensing device can monitor body temperature in real-time and has a relatively fast response/recovery speed as well as long-term stability. Yan et al. used a lithographic filtration process to create stretchable graphene thermistors with intrinsic high stretchability as shown in Figure 4c–e [84]. The heat detection channels were made of 3D crumpled graphene, and the electrodes were silver nanowires. To achieve great stretchability, the detecting channel and electrodes were entirely incorporated in an elastomer matrix. At varying strains of up to 50%, detailed $T_{sensing}$ characteristics were recorded. It is clear that the sensing apparatuses can continue to work even when stretched to extremes. The apparatuses showed strain-dependent thermal indices, and strain may be used to efficiently modify the thermistors' sensitivity. For various and adaptable utilizations in wearable electronics, the unique variable thermal index outperforms standard ceramic thermistors.

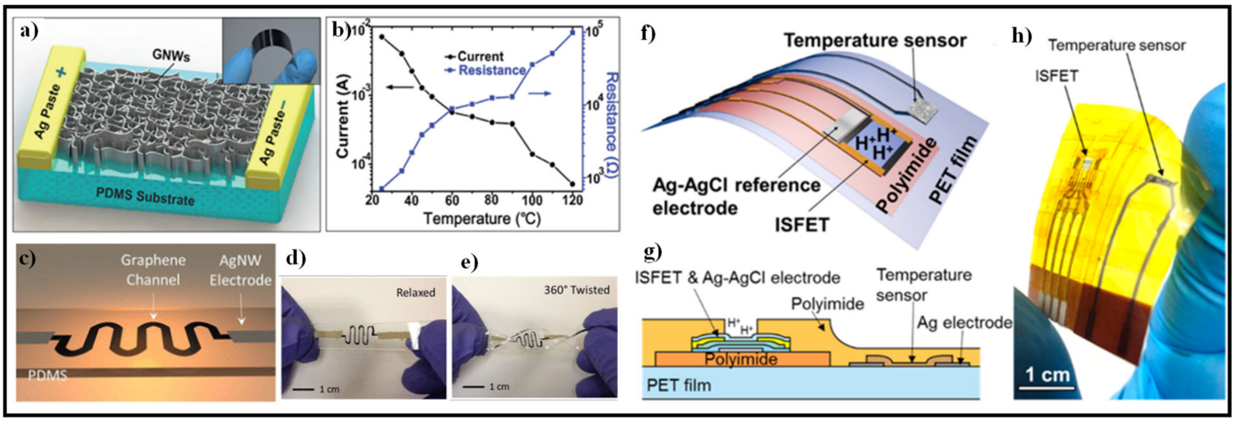

Figure 4. Flexile $T_{sensing}$ apparatuses: (**a**) Schematic of flexile GNWs/PDMS $T_{sensing}$ device. The inset shows the optical image of manufactured flexile sensing device prototype [83]. (**b**) Current and resistance versus temperature curves that span from 25 °C to 120 °C by applying a constant voltage of 5 V at the two terminals of the sensing device [83]. (**c**) Schematic diagram of the stretchable graphene thermistor [84], (**d**) manufactured sensing device in a relaxed state [84], and (**e**) manufactured sensing device in 360° twisted state. (**f**) Schematic of a wearable apparatus integrating flexible pH and temperature sensors [85], (**g**) cross-sectional diagram of the apparatus [85], and (**h**) photograph of the manufactured device [85].

Noninvasive healthcare technologies of the future, such as flexible multipurpose sensor sheets that may be worn on the skin, are thought to be ideal candidates for continuous real-time health monitoring. Obtaining data on the chemical status of the body, as well as physical parameters like body temperature and activity, is critical for forecasting and recognizing probable health issues in healthcare applications. A wearable, flexible sweat sensor sheet for pH measurement is being developed, consisting of an ion-sensitive field-effect transistor (ISFET) coupled with a flexible temperature sensor (see Figure 4f) [85]. Figure 4g,h shows the entire device construction, with general handling indicating that the device is mechanically flexible and not impaired when bent. An amorphous thin-film of InGaZnO and an Al_2O_3 were employed for the FET channel and pH reactive membrane material, respectively. A detailed study of the multipurpose sensor device can be found in [85].

5. Flexile Wearable $P_{sensing}$ Apparatuses

The goal of modern society is to make the world smarter and more pleasant. To achieve these aims, several electrical apparatuses have been actively explored and created. Flexile and wearable electronics that revolutionize the way we work and play on the horizon, thanks to a variety of well-developed products. Electronic apparatuses, such as smartphones and smartwatches, make it possible to access an unprecedented quantity of data with ease. Many academics are working on making apparatuses and systems that are lighter and more compact. Many investigations have been carried out to develop a small system capable of facilitating human–machine interaction. The sensing device plays a key role in human–machine interaction, and $P_{sensing}$ apparatuses can collect a lot of data from individuals, thus most research is focused on the human-sensing device interface [86,87].

The development of flexile $P_{sensing}$ apparatuses is the subject of several investigations. There are two key elements to realizing flexile $P_{sensing}$ apparatuses: the first is to employ intrinsically flexile materials, and the second is to achieve elasticity by building specifically engineered structures. Flexile $P_{sensing}$ apparatuses made of functional polymers like silicone rubber have drawn a lot of interest. Silicone rubber, especially polydimethylsiloxane (PDMS), is extremely flexile and, because of its biocompatibility, is particularly well suited to wearable electronics [88]. To increase the electrical performance of silicone rubber, composite materials were recently created by combining $BaTiO_3$, carbon nanotubes

(CNTs), reduced graphene oxide (rGO), carbon black (CB), silver nanowires (Ag NWs), and silver nanoparticles (Ag NPs) [89,90]. These composite materials have superior electrical characteristics to bulk materials, which can increase the electrical performance of the sensing apparatuses greatly. Another key technique to provide the sensing device elasticity is to manufacture the sensing layer with a porous structure or to manufacture it in NW shape. Even though the materials are intrinsically brittle, the nano- or micro-scale structural shape of the materials can give great elasticity. The elasticity of a naturally flexile material, for example, may be dramatically altered if it is created with diverse structures. A flexile material and a sensing layer with a specific structure not only provide exceptional mechanical endurance but also increase electrical performance [91].

Flexile $P_{sensing}$ apparatuses can provide vital information about particular demands within the human body as well as during contact with the external environment [92,93]. Silicon-based $P_{sensing}$ apparatuses have been in use for about 50 years. The piezoresistive or capacitive sensing principle is used in most silicon-based $P_{sensing}$ apparatuses, which are produced using well-established silicon micromachining techniques [94–96]. Even if the sensing apparatuses' lateral dimensions and functionality have improved, the primary drawbacks of silicon-based $P_{sensing}$, especially the minimum height and brittleness, have yet to be addressed. There have been a few attempts to make thin silicon-based $P_{sensing}$ apparatuses, but they all need a significant shift in manufacturing processes [97]. Several utilizations, for example, material integrated sensing and surface functionalization, require low-cost, thin, and flexile $P_{sensing}$ apparatuses that can operate over a wide pressure span.

Rigidity, fragility, poor sensitivity, small sensing span, limited tensile capacity, and low-resolution limit traditional semiconductor and metal-based $P_{sensing}$ apparatuses, making them challenging to use in utilizations requiring flexile contact or wearable apparatuses [98]. As a result, flexile $P_{sensing}$ apparatuses appropriate for arbitrarily curved surfaces have been investigated, and they have significant implications in the sectors of human-machine interface, wearable electronics, electronic skin, and therapy [99]. Flexile $P_{sensing}$ apparatuses, in contrast, have problems in terms of high sensitivity, high resolution, rapid response, good stability, and strong durability to successfully adapt to these developing applications.

5.1. Types of $P_{sensing}$ Apparatuses

Flexile $P_{sensing}$ apparatuses are classified into three categories established on their transduction mechanisms: piezoresistive, capacitive, and piezoelectric. Many efforts have been made to enhance the characteristics of the flexile $P_{sensing}$ device established on the three conversion concepts mentioned above. Table 1 compares the benefits and drawbacks of the three different types of $P_{sensing}$ apparatuses. Because each sensing device has benefits and limitations, we must select the appropriate sensing device established in the application field. Medical examination, sealing inspections, physical activity, and other utilizations can all benefit from piezoresistive $P_{sensing}$ apparatuses. There are several commercial items on the market, such as the fantastic smart bra, that can monitor the heartbeat through resistance fluctuation to prevent illnesses from occurring [100]. Because of its simple designs, easy signal processing, high sensitivity, low power consumption, and excellent operating stability, the flexile piezoresistive $P_{sensing}$ device is extensively employed [101].

Wearable respiratory surveillance, health surveillance, human–computer interaction, and other utilizations can all benefit from capacitive $P_{sensing}$ apparatuses. Because of the capacitive $P_{sensing}$ device's features, it can not only be used in temperature-insensitive environments, but can also be used to achieve wireless transmission using induction capacitor technology [102]. Although $P_{sensing}$ apparatuses have come a long way in recent years, there are still numerous obstacles to overcome when it comes to the manufacture of extremely sensitive sensing apparatuses. Flexile capacitive $P_{sensing}$ apparatuses, in particular, are notorious for their poor sensitivity [103,104].

Table 1. Pros and cons of the three types of $P_{sensing}$ apparatuses. Inspired by the work in [99].

Transduction Principles	Pros	Cons
Capacitance	Extraordinary sensitivity, simple structure, big dynamic span, good temperature constancy, fast response, appropriate for small force test.	Poor linearity, vulnerable to EM interference, prone to parasitic capacitance.
Piezoresistivity	Simple fabrication process, cost-effective, large deformation, strong anti-interference ability, easy to attain small size.	Poor stability, low sensitivity, poor temperature stability.
Piezoelectricity	High sensitivity, fast response, low power utilization	Poor stretchability, low spatial resolution, only applicable to dynamic testing.

Some experiments included a $P_{sensing}$ device to accomplish continuous blood pressure surveillance to deploy a wearable device with a one-channel physiological measurement. A $P_{sensing}$ device, such as a capacitive $P_{sensing}$ device or piezoelectric sensing device, may detect pulsation changes in the artery, the capacitive $P_{sensing}$ device employs the process of distance variation between two parallel plates. Due to the modest stress from vascular compression, capacitive $P_{sensing}$ apparatuses are often characterized by poor pressure sensitivity. A PDMS spacer and wrinkling gold foil dielectric layer modification has been proposed to increase the sensitivity of a capacitive $P_{sensing}$ device for blood pressure surveillance [105]. In comparison to a capacitive pressor, a piezoelectric sensing device immediately translates pressure signals into electrical signals due to the piezoelectric sensing device's pressure sensitivity. A piezoelectric sensing device is commonly used to monitor continuous pressure wave signals in the radial artery of the wrist. Liu et al., for example, used a PPW-based blood pressure estimation model using a piezoelectric sensing device and a linear regression approach to show that blood pressure measurement has a low mean absolute error (MAE) when compared to the cuff method [106]. Kaisti et al. have created a wearable microelectromechanical system (MEMS) that provided a strong correlation of mean artery pressure (MAP) between non-invasive and invasive pulse waveforms [107]. Table 2 summarizes some reported results of the performances of flexible pressure sensors.

Table 2. A summary of the reported performance of flexible pressure sensors [100].

Transduction Principle	Active Materials	Sensitivity	Minimum Detection	Maximum Detection	Reference
Capacitance	PDMS microstructure organic field-effect transistor	0.55 kPa^{-1}	3 Pa	20 kPa	[108]
Capacitance	Graphene-paper	17.2 kPa^{-1}	2 kPa	20 kPa	[109]
Piezoresistivity	Vertically aligned CNT/PDMS	0.3 kPa^{-1}	2 Pa	10 kPa	[110]
Piezoresistivity	ACNT/G/PDMS	19.8 kPa^{-1}	0.6 Pa	0.3 kPa	[111]
Piezoresistivity	CNTs/PDMS interlocked microdome	15.1 kPa^{-1}	0.2 Pa	59 kPa	[112]
Piezoelectricity	ZnO nanorod	-	3.5 kPa	31.5 kPa	[113]
Piezoelectricity	Perfluoroalkoxy alkane	15 V kPa^{-1}	-	2.5 kPa	[114]
Piezoelectricity	Polyvinylidene difluoride	-	1 kPa	30 kPa	[115]

5.2. Other Types of $P_{sensing}$ Apparatuses

To sense external pressure, other transduction techniques have been used. The transistor-type $P_{sensing}$ device is an excellent choice for a sensitive $P_{sensing}$ device. Organic FETs are primarily explored, and their sensitivity is determined by the deformability of the gate dielectric layer under applied pressure, comparable to capacitive-type $P_{sensing}$ apparatuses [116,117]. Similarly, several ways have been devised to increase the dielectric layer's deformability. A photolithography-based silicon mold is used to produce a pyramidal PDMS dielectric layer, and the sensing device had an unusually high sensitivity of 514 k/Pa [118]. Furthermore, materials with high deformability, such as PDMS and Ecoflex, have been frequently employed [119]. It is exhibited a microfluidic tactile diaphragm $P_{sensing}$ device established on embedded Galinstan microchannels proficient in resolving sub-50 Pa pressure fluctuations with sub-100 Pa detection limits and a response time of 90 ms [42]. The use of tangential and radial strain fields in an implanted equivalent Wheatstone bridge circuit results in high sensitivity of 0.0835 k/Pa change in output voltage. Temperature self-compensation is also a feature of the Wheatstone bridge, allowing it to operate in the 20–50 °C span [42].

Another potential self-powered $P_{sensing}$ device is the triboelectric sensing device. Triboelectric nanogenerators (TENGs) are used in triboelectric $P_{sensing}$ apparatuses, and their mechanism is established on the triboelectrification and electrostatic induction coupling effect. TENGs are generally made in the contact/separation mode, with two dielectric layers. Dielectric materials at opposing ends of the triboelectric series are required to optimize the triboelectric effect. Furthermore, a bigger dielectric layer surface area is desirable to generate more charges on its surface. To enhance the surface area of the dielectric layers, silicon molds with pyramidal shapes are commonly employed [120]. A silicon mold, in contrast, is normally made through a lengthy and complicated procedure. Rasel et al. used a sandpaper mold to adjust the surface of the layer as a low-cost alternative to a silicon mold, resulting in a sensitivity of 0.51 V/kPa [121]. The pressure-sensing device's sensitivity was increased 14-fold when compared to a flat surface using a *C. zebrine* leaf as a mold. Electrospun nanofibers (NFs) are also commonly used because of their quick and easy construction technique, as well as their large surface area [122]. A novel method for constructing completely integrated active-matrix arrays of pressure-sensitive graphene transistors with air–dielectric layers is described, which involves merely folding two opposite panels [28]. Furthermore, a tactile $P_{sensing}$ span of 250 Pa to 3 MPa is achieved. Fabrication of $P_{sensing}$ device arrays and translucent $P_{sensing}$ apparatuses is also shown, implying that they have a lot of potential as next-generation electronics.

5.3. Development in Wearable $P_{sensing}$ Apparatuses

A capacitive pressure sensor with nanopillars on both sides is exhibited using a poly (vinylidenefluoride-co-trifluoroethylene) [P(VDF-TrFE)] dielectric film. Unlike the prior complex and expensive procedures, pattern transfer of anodized aluminium oxide templates allows for large-scale regular and consistent nanopillars to be made quickly and cheaply. The pressure sensor has a high sensitivity (0.35 kPa^{-1}), a wide operating range (4 Pa to 25 kPa), a low reaction time (48 ms), and exceptional durability because of the double-sided nanopillars that make up the P(VDF-TrFFE) dielectric layer. In addition to these distinguishing characteristics, this sensor performs well in bending states, ensuring that it can be used to detect a wide range of practical stimuli, as demonstrated experimentally by perceiving real-time and in situ human physiological signals and body motions that correspond to the low- and high-frequency ranges, respectively [123]. A flexile $P_{sensing}$ device with a polydimethylsiloxane (PDMS) layer integrated between indium tin oxide (ITO) coated flexile polyethylene terephthalate (PET) electrodes have been created using a capacitive transduction mechanism [124]. The dielectric layer's porosity was increased by injecting deionized water (DIW) into it, which enhanced the sensing device's essential characteristics. For the applied pressure span of 1 Pa to 100 kPa, the sensing device with a porous dielectric layer (PDMSDIW) shows a 0.07% to 15% relative variation in capacitance.

In comparison to an unstructured PDMS layer, the device has better sensitivity over the whole external pressure span. The fabrication process of a porous PDMS dielectric layer is shown in Figure 5a. The device with the porous PDMS layer has a wide operating pressure span, great working stability, fast response, and ultra-low-pressure detection. Furthermore, blood pressure surveillance was investigated, and the apparatuses produced an oscillometric waveform signature for various blood pressure (BP) values. Due to its outstanding functional features, the constructed flexile $P_{sensing}$ device may be employed for wearable BP apparatuses and biological utilizations [124]. As shown in Figure 5b, a sensing device with a porous PDMS dielectric layer detects ultra-low pressure of 1 Pa and produces a 0.07% relative change in capacitance.

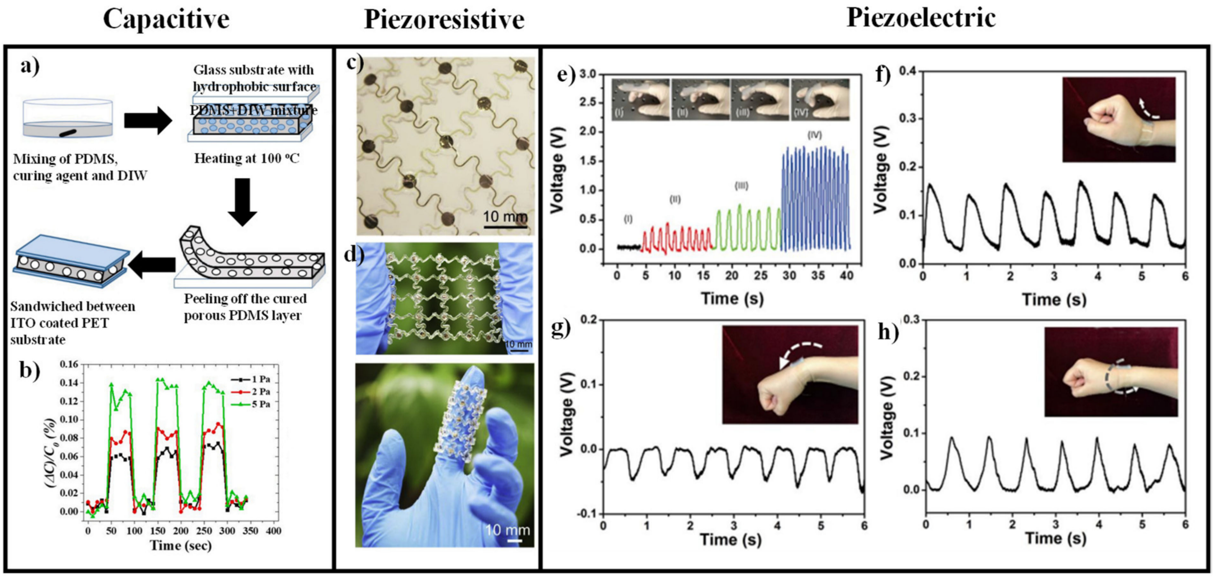

Figure 5. The fabrication process of PDMS-DIW: (**a**) Outline of the procedure to manufacture the sensing instrument with a porous dielectric layer (PDMS-DIW) [124], (**b**) sensing performance of the instrument in terms of capacitance change at 1–5 Pa pressure span [124]. (**c**) An optical image of the Au electrode made by MEMS [125], (**d**) stretchable sensing instrument adjusts to pressure detection under complex deformation settings such as stretching and bending [125]; Piezoelectric $P_{sensing}$ instrument used for detecting joint motion states (**e**) finger motion states [126], (**f**) change in produced voltage under upward bending wrist movement [126], (**g**) change in generated voltage under downward bending wrist movement [126], (**h**) change in generated voltage under torsion wrist movement [126].

Due to its unique qualities such as lightweight, huge surface area, strong electrical conductivity, and great compressibility, graphene aerogels have lately become one of the most appealing carbon metamaterials. However, fabricating extremely elastic graphene aerogels using simple and cost-effective techniques and assembling them into a well-designed unity for wider utilizations remain hurdles. Wet-spinning technology is used to create extremely elastic grouped graphene/carbon nanotube (CNT) aerogel spheres (GCSs) for intelligent piezoresistive sensing apparatuses as shown in [125]. Such clustered GCSs with core–shell structure annealed at 1000 °C demonstrate exceptional elasticity and fatigue resistance, which are equivalent to graphene spheres annealed at 2500 °C, thanks to the synergistic action of graphene and CNTs. Even after 1000 cycles at 70% strain, the clustered GCSs can fully recover after compression at 95% strain and preserve 70% of maximum stress with no plastic deformation and structural degradation. Each sensing unit coupled by Au electrodes operated as a pressure pixel to produce the pressure signal when pressure was applied to the sensing device. In comparison to $P_{sensing}$ apparatuses established on monolithic sensing materials, sensing units are connected by serpentine frameworks with exceptional stretchability, and the resistance of the sensing unit is scarcely influenced by stretching or bending as shown in Figure 5c [125]. As a result, the sensing device may be modified to detect pressure under complicated deformation settings, allowing it to address the rising need for stretchy electronics and wearable gadgets as shown in Figure 5d [125]. Significantly, the GCSs are suited for $P_{sensing}$ apparatuses because of their robustness, superelasticity, and conductivity, as well as their exceptional cycle stability and long working life. Small-scale GCSs with high sensitivity may be readily constructed into stretchy piezoresistive sensing apparatuses with pixel arrays for spatial pressure distribution measurement and object form identification thanks to intact and robust shells.

$P_{sensing}$ apparatuses in human health surveillance and anthropomorphic robotic systems are widely wanted for their self-powered operation, elasticity, good mechanical qualities, and extremely high sensitivity. Piezoelectric $P_{sensing}$ apparatuses, which have improved electromechanical performance and can efficiently discriminate numerous mechanical stimuli (such as pressing, bending, stretching, and twisting), have piqued interest in capturing the faint signals of the human body. An electrospinning procedure is used to create a poly (vinylidene fluoride-trifluoroethylene)/multi-walled carbon nanotube (P(VDF-TrFE)/MWCNT) composite, which is then stretched to align the polymer chains. Excellent piezoelectricity, mechanical strength, and sensitivity were all exhibited by the composite membrane. The sensitivity was 540 mV/N, and the piezoelectric coefficient d33 was around 50 pm/V. The composite membrane that resulted was used as a piezoelectric $P_{sensing}$ device to detect minor physiological signals such as pulse, breath, and minor muscle and joint actions including eating, chewing, and finger and wrist movements. The development of the phase of the piezoelectric device was aided by moderate doping with carbon nanotubes, and the piezoelectric $P_{sensing}$ device has the potential to be used in health management systems and smart wearable apparatuses.

The performance of the piezoelectric $P_{sensing}$ instrument was tested through a series of joint motion tests. As illustrated in Figure 5e, the sensing instrument was positioned on the knuckle, and the output voltage response was proportional to the degree of bending of the finger, reaching a maximum of 1.8 V [126]. As illustrated in Figure 5f–h, the sensor was attached to the wrist to discriminate between distinct types of wrist movements, such as upward bending, downward bending, and torsion [126]. The sensor bent as the wrist went up and down, and the maximum and minimum output voltages were 0.15 V and 0.05 V, respectively, as the wrist traveled up and down. The discrepancy in output voltage might be related to sensing instrument deformation differences. The sensing instrument was subjected to a mixture of upward, shear, and downward pressures when the wrist was twisted; therefore, the output voltage was the constructive or destructive combination of relevant reaction.

$P_{sensing}$ instruments established on pressure-sensitive organic transistors have recently been reported as thin, foil-based screen-printed $P_{sensing}$ instruments [127]. They do, however, need a time-consuming printing process as well as appropriate electronics for stimulation and reading. Force-sensitive resistors (FSRs) are resistive foil-based $P_{sensing}$ instruments that have been examined; however, they typically need a two-foil manufacturing method, with electrodes on one foil and a conducting material on the other [128]. A cross-sectional view of an FSR sensing instrument is shown in Figure 6a. Simple printed resistive $P_{sensing}$ instruments have also been produced, although only for low-pressure utilizations. Subject to the bodily part, the pressure spans are vastly diverse. Wearable $P_{sensing}$ instruments are classified into three pressure spans: low-pressure (less than 10 kPa), medium pressure (10 to 100 kPa), and high-pressure (more than 100 kPa). Because it comprises the intra-body pressure, the low-pressure span, which corresponds to both intraocular and intracranial pressures, is crucial. Blood pressure, heart rate, radial artery wave, phonation vibration, and skin modulus are all examples of body pressure in the medium pressure span [129]. The weight of a human or atmospheric pressure at high altitudes is included in the high-pressure span [130]. We can observe eye problems, heart disease, injured vocal cords, and exercise by surveillance these different sorts of pressure. Wearable $P_{sensing}$ instruments have therefore been thoroughly investigated for use in health management and medical diagnosis instruments. Physical inputs are converted into electrical signals via a variety of sensing techniques, including piezoelectric, piezoresistive, and capacitance systems.

In [131], a low-cost, thin, and flexile screen-printed resistive $P_{sensing}$ instrument for high-pressure application is proposed. Figure 6b shows a rendered image of the sensing instrument. The pressure sensitivity is established on the pressure-sensitive layer's percolation action. The applied pressure reduces the spacing between conductive particles in a polymer matrix, lowering the resistance of the layer. When tunneling effects are primarily responsible for charge transmission, this can be accomplished by lowering the tunneling distance or simply decreasing the contact resistance between the particles. Manual screen printing is done using a mesh size of 180 meshes/cm. During the mesh creating process, you may simply change the electrode shape, ink layer thickness, and thus the final sensing instrument size. Because just the resistance between the electrodes must be measured, the sensing instrument's excitation and readout are straightforward. The proposed sensing instrument (bottom left) is compared to a commercially accessible FSR from Interlink in Figure 6c (top left) [131]. Table 3 shows the list of a few recently proposed wearable electronic sensing instruments for different utilizations.

Table 3. Summary of wearable electronic sensing instruments for different utilizations.

Reference	Sensor Type	Sensing Element	Substrate	Electrode Material	Active Material
[133]	Bio	Lactate	Temporary transfer tattoo paper, GORETEX	silver/AgCl, conductive carbon	Lactate oxidase
[134]	Bio	Glucose	PDMS, Polyimide, Parylene	Graphene/AgNW	Graphene, glucose oxidase
[135]	Bio	Glucose, Lactate	polydimethylsiloxane	-	Enzyme and chromogenic reagent
[136]	Bio	Salivary Uric acid	polyethylene terephthalate	silver/AgCl	Prussian-blue-graphite
[137]	Strain	Facial expressions	polydimethylsiloxane	Polyurethane-PEDOT:PSS	Single-walled carbon nanotubes
[138]	Strain	Heartbeats	polydimethylsiloxane	Graphene woven fabrics	Graphene woven fabrics
[130]	Strain	Stretch and pressure	polydimethylsiloxane	Eutectic Gallium Indium	Single-walled CNT-Ecoflex
[139]	Strain	Strain	polyethylene terephthalate textile	CNT/reduced Graphene oxide	ZnO Nanowire
[75]	Temperature	Resistive	Plastic	Silver interdigital electrodes	-
[84]	Temperature	Temperature	polydimethylsiloxane	AgNW	Graphene
[76]	Temperature	Endothelial layer	Polyester fabric strip coated with polydimethylsiloxane	gold	Platimum
[134]	Pressure	Intraocular Pressure	Parylene	Graphene-AgNW	Ecoflex
[140]	Pressure	Cutaneous pressure	Ecoflex	gold	Lead zirconate titanate
[28]	Pressure	Pressure	polydimethylsiloxane and Epoxy	gold or AgNW/graphene	Graphene

Table 3. *Cont.*

Reference	Sensor Type	Sensing Element	Substrate	Electrode Material	Active Material
[141]	Gas	Nitrogen dioxide	PES	chromium/gold	Graphene
[142]	Gas	Nirogen dioxide	Paper	Gold	$NaNO_2$ treated PbS CQD
[143]	Gas	Oxygen	Porous PTFE	Gold	High-purity 1-buty-1-methylpyrrolidinium bis (trifluoro-methylsulfonyl)imide

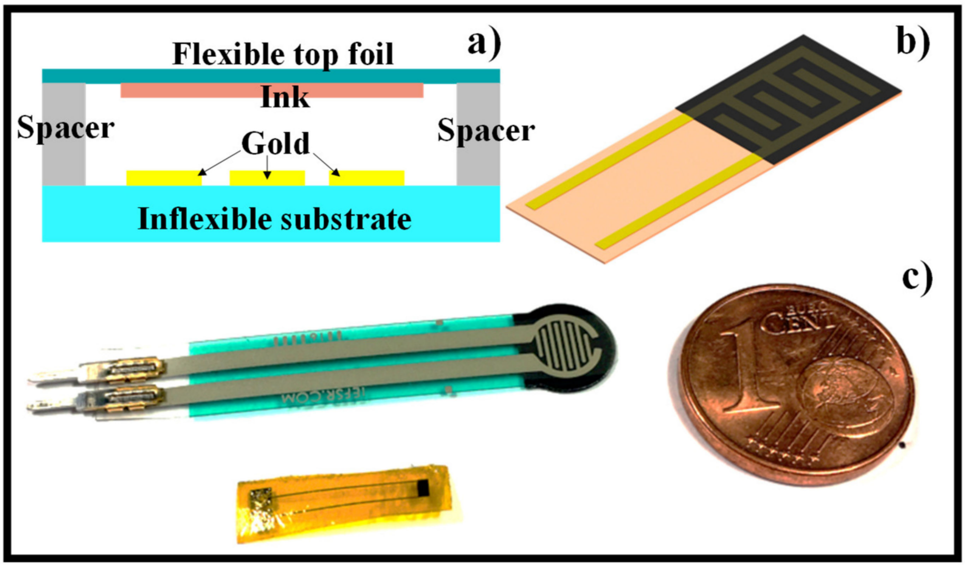

Figure 6. (**a**) Cross-sectional view of a force-sensing resistor. Inspired by the work in [132], (**b**) render image of a sensing instrument design proposed in [131]. (**c**) Photography of the sensing instrument design proposed in [131] (**bottom left**), and an FSR by Interlink (**top left**).

5.4. Prospects of the $P_{sensing}$ Instruments

The future development trend of sensing instruments is mostly in the following areas.

(1) Ultra-sensitivity is a required trend in $P_{sensing}$ instrument development in the future. Even though several high-sensitivity $P_{sensing}$ instruments have been produced, the sensitivity of the $P_{sensing}$ instruments developed is insufficient for some high-demand utilizations.

(2) The manufacturing of $P_{sensing}$ instruments will invariably result in the release of some environmentally hazardous compounds. It is critical to developing a low-cost, easy-to-use preparation process as well as high-performance, environmentally friendly functional materials.

(3) To keep up with the forthcoming development trend, $P_{sensing}$ instruments must relate to other flexile instruments and can be merged with big data from the Internet of Things. As a result, another significant difficulty is to connect the flexile wearable $P_{sensing}$ instrument with highly maneuverable signal transmission, data processing unit, power supply, and performance optimization method.

(4) It is critical to build $P_{sensing}$ instrument arrays that can detect many physical qualities concurrently to fulfill the application requirements of electronic skin, wearable electronic instruments, and other utilizations. Currently, most $P_{sensing}$ instrument arrays that detect two or more physical qualities do not rule out the possibility of physical quantities interacting. Temperature, for example, has a significant impact

on all other physical quantities; yet monitoring temperature is an essential capability of electronic skin. To meet this application need, novel active materials, structural designs, and transduction principles are being developed. As a result, despite the numerous research studies on wearable $P_{sensing}$ instruments, there are still many problems and solutions to be discovered.

6. Need for Multifunctional Sensing Apparatuses

Due to its deformability, lightness, mobility, and flexibility, flexile skin-like sensing devices have achieved several functions previously unavailable to ordinary sensing devices. The four basic types of flexile skin-like sensing devices are physical, chemical, physiological, and multifunctional, depending on the quantities they detect. The physical features of the substances that are responsive to the measured quantities are used to develop physical sensing devices [144]. Chemical sensing tools are made up of sensitive components that convert chemical quantities, such as composition and concentration of chemical compounds, into electrical quantities. Physiological sensing devices are devices that use diverse biological and physiological traits or characteristics of biological substances to detect and recognize biological and physiological quantities in humans. The three most common physical variables that can be sensed by flexile skin-like physical sensing devices are pressure, strain, and temperature. These devices can convert external physical stimulus signals into electrical impulses, completing the skin's sensing function [130]. Multifunctional sensing devices integrate many different types of sensing devices into a single unit that can instantly discover and test various variables [145]. For example, it has been claimed that the multifunctional electronic skin can simultaneously detect pressure, tension, and temperature [146]. Due to the vast range of categories and applications of flexile sensing devices, worldwide research on multifunctional sensors has accelerated in recent years [130].

In [147], a hydrogen bond cross-linked network based on carboxylic styrene-butadiene rubber (XSBR) and non-covalently modified carbon nanotubes (CNTs) with hydrophilic sericin (SS) is rationally developed and then built into multifunctional sensors. The resulting adaptable sensors have a low detection limit of 1% strain, great stretchability of up to 217%, a superior strength of 12.58 MPa, high sensitivity of up to 25.98, high conductivity of 0.071 S/m, and a decreased percolation threshold of 0.504 wt%. Furthermore, the produced sensors have an outstanding thermal response and may be used to assess the temperature of a human body. The XSBR/SSCNT sensor is a multipurpose and scalable sensor that has real-time and in situ physiological signal monitoring capabilities, offers a potential path to developing wearable artificial intelligence in human health and athletic applications.

7. Conclusions

In this paper, we have reviewed the recent developments in the field of flexible wearable electronics temperature and pressure sensors. Wearable $T_{sensing}$ is appealing not just in the medical field, but also for tracking and monitoring the body temperature of healthy people participating in vigorous outdoor activities. Flexile pressure sensors can provide valuable information about precise demands within the human body as well as during contact with the external environment. Rigidity, fragility, poor sensitivity, small sensing range, limited tensile capacity, and low-resolution limit standard semiconductor and metal-based pressure sensors, making them challenging to use in utilizations requiring flexible contact or wearable tools. As a result, researchers have looked at flexible pressure sensors that may be used on any curved surfaces and have significant implications in the domains of human–machine interfaces, wearable electronics, and medicine. Flexible pressure sensors, in contrast, have problems in terms of high sensitivity, high resolution, quick response, good stability, and strong durability to successfully adapt to these growing utilizations. Various conversion strategies are commonly employed to manufacture flexible pressure sensors because of the investigation of elastic and functional materials. Much research has also used various microstructures to create flexile pressure sensors. Furthermore, many papers have concentrated on enhancing the sensitivity of flexile pressure sensors to fulfill the demands of industrial production and practical utilizations.

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