Temperature Sensors for Thermoregulation in Personal Protective Equipment

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The exposure to extreme temperatures in workplaces involves physical hazards for workers. A poorly acclimated worker may have lower performance and vigilance and therefore may be more exposed to accidents and injuries. Due to the incompatibility of the existing standards implemented in some workplaces and the lack of thermoregulation in many types of protective equipment, thermal stress remains one of the most frequent physical hazards in many work sectors. In order to provide a better protection of individuals against thermal aggressors, the scientific community has been interested in the development of the textile-based or flexible temperature sensors that can be integrated into personal protective equipment. These sensors can measure the skin temperature and monitor the microclimate temperature between the body and the clothing or the outside temperature during exposure to thermal aggressors.

Keywords: thermoregulation ; personal protective equipment ; smart textiles ; flexible electronics ; performance

1. Thermal Stress in the Workplace

Thermal stress is among the most common physical hazards in various work sectors. In fact, any worker exposed to a high heat load through a combination of his or her metabolic heat during work, environmental factors (air temperature, humidity, air movement, heat transfer by radiation), and the clothing requirements of his or her job can suffer health problems [1]. In addition, exposure to extreme temperatures in workplaces involves physical hazards for workers. Workers in firefighting, construction, mining, smelting and primary metal processing, metal product manufacturing, forestry, agricultural, food manufacturing, and police services are among the most exposed sectors to heat-related hazards. Workers in construction, agriculture, fishing, logging, forestry, and other outdoor activities are at risk of cold stress [2].

Indeed, the exposure to extreme temperatures can lead the worker to a state of heat stress, which occurs when the body is unable to maintain its temperature between 36 and 37 °C [3]. Heat syncope, heat exhaustion, heat stroke, dehydration, heat cramps, miliary eruptions, hyponatremia, and rhabdomyolysis are among the diseases or health disorders due to heat exposure. Hypothermia, immersion feet, and frostbite are the most significant injuries and illnesses caused by exposure to extreme cold [2]. Therefore, the prevention of thermal stress risks should be a priority in order to avoid any negative effects on workers' health and safety [4]. Adequate prevention of heat stress risks not only provides a sense of comfort for the worker toward his work environment, but it can also have a positive impact on the productivity rate and result in a decrease in the employer's number of injuries [5].

In addition to being a direct cause of serious injuries in the workplace, thermal stress can indirectly lead to accidents and other types of injuries. A poorly acclimated worker may have reduced performance and alertness and therefore may be at greater risk of accidents and injuries [6][7][8]. One of the main risks indirectly related to working in extreme cold is the decreased manual function, which can quickly impair task performance and increase the risk of accidents or intensify a hazardous situation [9]. Research has shown that manual dexterity is impaired during work in cold storage warehouses [10]. Cold can also reduce alertness and impair cognitive performance, increasing the risk of inappropriate mental actions leading to accidents. Indeed, one study was able to demonstrate that reaction time and signal detection decreased in workers exposed to a temperature of -20 °C for more than 45 min [11].

Exposure to extreme temperatures can also temporarily reduce work capacity and affect productivity [2]. As a result, thermal stress can directly alter operational capacity, both by decreasing work tolerance and by requiring changes in work schedules, such as longer rest and recovery breaks [2]. For some professions, such as firefighters, the interaction between high physical exertion and heat is the main cause of death [12]. According to studies conducted in the United States, thermal and physiological stress during interventions is associated with an increased risk of cardiovascular accidents, which are the most common cause of death among firefighters [13]. In addition to the impact of heat on cardiovascular behavior, the thermoregulatory mechanisms of the human body under thermal stress and the physiological changes they imply can alter the functions of several organs related to the absorption and chemical metabolism. Heat exposure has been shown to be associated with increased pulmonary and dermal absorption of xenobiotics [14].

The protection of workers against thermal risks becomes even more important since, according to experts, the current climate change context will contribute to emphasizing the impact of thermal constraints in the workplace [15][16][17]. Over the past few decades, many research studies related to thermal management have been witnessed, as shown in **Figure 1**.

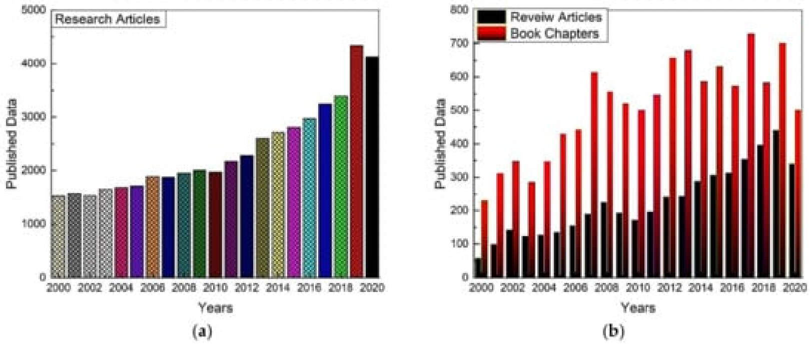

Figure 1. Published data for personal thermal management from 2000 to 20 June 2020. (**a**) Research articles published during the last two decades. (**b**) Review articles and book chapters published during the last two decades. Reproduced with permission [3]. Copyright 2020, Elsevier.

As a result of the importance of preventing the risks of thermal stress, recommendations and measures have been planned by the authorities. These regulations recommend redesigning the workstation, reducing the workload, and wearing appropriate personal protective equipment (PPE) to ensure that thermal stress thresholds are not exceeded. However, some studies have shown that despite compliance with these regulations, some workers may be subject to thermophysiological constraints depending on their age, sex, physical fitness, or state of health [12]. Moreover, these types of measures against thermal stress are sometimes far from being applicable in certain environments such as agriculture [18][19]. Regulations are sometimes very cautious and sometimes overestimate the level of thermal stress, while for heavy work in indoor workplaces, they may underestimate exposure [20]. Prevention measures remain unclear and sometimes unrealistic in the face of reality [21].

2. Personal Protective Equipment Design Challenges

In addition to several gaps in the established regulations to counter the risks of thermal stress in the workplace, PPE can accentuate the impact of thermal stress, as many of these items of equipment lack comfort [22]. PPE is designed primarily to protect workers against external hazards such as chemical, biological, thermal, and mechanical. Various polymeric materials are commonly used for the fabrication of PPE [23]. For instance, protective gloves can be made with polymers (nitrile, latex, neoprene, poly(vinylacetate), polyvinyl chloride (PVC)), with woven or knitted textiles materials (aramid fibers (Kevlar®), high-performance polyethylene (HPPE)), coated or not with polymers, in single or multiple layers [24][25][26][27]. Depending on the protection required, different synthetic materials can be used also in the fabrication of protective clothing, such as meta-aramide (Nomex®), para-aramide (Kevlar®), polybenzimidazole (PBI), melamine (Basofil®), polyphenylene benzobisoxazole (Zylon®), and polyimide for heat and flame hazard, polyurethane (PU), chlorinated polyethylene (CPE), polytetrafluoroethylene (PTFE), PVC, and polyvinylidene chloride (PVDC) as impermeable layers and moisture barriers [26][28], or activated carbon impregnated foam, fluoro-polymer coatings, polyurethane nonporous membrane, or elastomers for chemical protection [23][29][30][31]. Being a multidisciplinary field calling for several technological knowledge, the materials used in the design of protective equipment has been the subject of several technical reviews. While some of these studies have been devoted to a global state of the art of materials used and the evolution of associated needs [23][26][32][33], others analyzed specific developments and needs to counter a particular type of risk, for example, reviews specifically dedicated to advances and applications of materials for chemical protective clothing [25][30]. Some contemporary research studies have even evoked a potential application of nanofiber materials in protective clothing. These materials obtained from nanoparticles mixed with polymer solutions can offer greater breathability, a selective filtration potential along with an improved liquid chemical and aerosol particle retention capability compared with current commercially available membranes [25][34][35].

However, the materials used in the design of several types of PPE tend to avoid the adequate dissipation of body heat [36]. Thus, workers such as firefighters or metal fabricators may be exposed to more thermal and physiological stresses due to their type of protective equipment [37]. As reported by occupational health and safety experts, workers often find protective equipment uncomfortable, too hot, or too bulky, which does not encourage them to wear it regularly, thus accentuating potential risk situations [38].

Given the existing shortcomings in the prevention of thermal stress in workplaces due to conventional conception in the design of protective equipment and the inefficiency of the established standards and recommendations, it is essential to develop new tools and equipment to ensure thermal risk management adapted to the individual situation of the worker and his or her work environment. In such a context, smart textile technologies integrated into personal protective equipment have a very great potential to respond to many issues related to thermal risks. Thus, using them in the development of PPE presents great potential for the field of occupational health and safety [22][39][40][41].

Being based on textronic (e-textiles), conductive textiles, functional textiles, and flexible and extensible electronics, smart textiles can contribute to the development of thermal regulation systems [42][43] to better protect workers against the risks of thermal stress while offering them greater comfort. They can also be used in the development of tools for measuring external and internal garment temperatures, as well as body temperature [39][40]. In addition to being the basic textile material, polymeric materials are also widely used in the production of smart textiles whether in the design of sensors or actuators, their methods of integration into textiles, conductive yarns fabrication, conductive polymers coating, functional coating, or embedding conductive fillers [44][45][46].

Recent technical reviews often report on knowledge in the area of smart textiles [44][45][47], including a number of studies that mention their potential use in PPE design [40][48][49]. Although some other studies have made reviews of the heat stress state in conventional PPE [50][51], to our knowledge, no reviews are specifically related to the analysis of smart textile technologies for the prevention of thermal stress risks while wearing PPE. In fact, despite the studies that have separately reviewed heating, cooling, or thermal sensor technologies integrated into clothing [44][45][48], no study exists on a complete analysis of all the technologies that facilitate intelligent thermal management in PPE. Furthermore, the continuous evolution of smart textile technologies in an increasingly connected world, both at the societal and industrial levels, requires an update of knowledge to better support the adaptation of such technologies to occupational health and safety applications.

In spite of the recent technological progress, a preliminary analysis has shown that most of the current commercial solutions are dedicated to the fields of sport and leisure, and very few are related to occupational protective equipment [52][53]. Indeed, heating systems integrated into different types of clothing and accessories have emerged in recent years [54]. However, these systems suffer from a lack of comfort and are difficult to use in a work context.

While some integrated systems have presented risks of overheating [55], others suffer from a lack of temperature control [56]. Integrated cooling systems are usually based on passive devices composed of multilayer structures or functional coatings, which limits their reactivity to temperature variations [57]. Moreover, active integrated cooling systems remain cumbersome and energy consuming [43] and sometimes not very efficient in extreme climatic conditions [58]. The development of self-regulating temperature systems using functional materials of phase change materials types [59][60] has attracted the attention of many research groups [59]. However, these materials in their current state remain limited by their overall enthalpy of phase change or thermal window. They are active during their phase change period but cease to function when the phase change is completed [61]. Despite the emergence of commercial products incorporating smart textile technologies, garments with integrated sensors capable of detecting thermal stressors in order to mitigate the risk of contact and prolonged exposure to extreme temperatures in workplaces are also rare. Although isolated cases have been developed for some trades in a few countries [62], most work remains limited to research [63].

Using the potential of advanced materials both in the design of conductive textiles and in the development of thermal sensors and actuators to be integrated in protective equipment can provide a reliable solution to fill current lacks in the design of intelligent thermal management tools in the context of occupational health and safety. Therefore, the present study aims to present a review of current knowledge of these technologies facilitating smart thermoregulation in personal protective equipment.

3. Temperature Sensor

This part of the study focuses on systems that provide data on the body temperature of an active person. It also discusses the sensors that can be integrated into PPE in order to facilitate the acquisition of the temperature of the microclimate under the clothing or the outside temperature with the objective of warning the worker in case of prolonged exposure to extreme temperatures.

Real-time monitoring of body temperature is very important in order to prevent in time the occurrence of disorder in many organs during exposure to high thermal stress [64]. The calculation of body temperature is commonly based on the measurements of the core body temperature (T_c) and the skin temperature (T_S). While T_c is adjusted by thermoregulatory mechanisms of the body, T_S is affected by blood circulation and is related to heart rate (HR) and metabolic rate [64]. Therefore, temperature sensors used for body temperatures (T_S and T_c) must operate efficiently over a temperature range of 35 to 40 °C and ideally offer a measurement accuracy of 0.1 °C [65].

3.1. Methods to Measure Body Temperature

Various types of analog electrical sensors have been deployed in recent years to measure body temperature (T_S and T_c). These sensors are generally based on thermistors, resistance temperature detectors (RTDs) [66] (**Figure 2**a–e), or thermocouples [64] (**Figure 2**f,g).

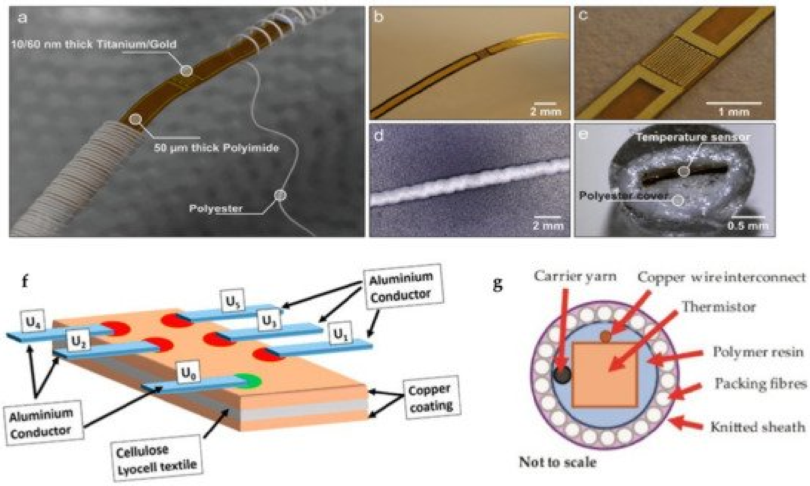

Figure 2. Temperature sensors: (**a**) Concept of the flexible temperature sensor embedded within the fibers of a textile yarn; (**b**) Bending of the uncovered flexible resistance temperature detectors RTD; (**c**) RTD Close-up sensing area. (**d**) Resistance temperature detectors embedded within a braided polyester yarn; (**e**) Cross-section of the braided temperature-sensing yarn ((**a**–**e**) [7]); (**f**) Lightweight and flexible conductor materials in a thermocouple array with copper-coated cellulose textiles [8]; (**g**) A cross-sectional schematic of encapsulation for a thermistor within a yarn. The standard encapsulation is composed of three layers: a polymer resin, packing fibers, and a knitted sheath [9].

Rectal thermometry is the most accurate method for measuring body temperature, and its value is recognized as the most representative of core body temperature [64]. It has been widely used as the standard measurement in many heat stress studies, including work on the development of heat stress indices [67][68][69][70]. However, rectal thermometry is an intrusive method that requires private arrangements and is therefore unsuitable for the continuous monitoring of workers with high physical activity [65]. Although heart rate can be used for indirect inference of T_c [71][72], some other studies have also proposed an estimation of T_c from T_S [73][74].

Thus, in order to contribute to the protection of individuals against thermal aggressors, the scientific community has been interested in the development of temperature sensors that can be integrated into personal protective equipment [75]. These sensors could measure T_S and monitor the microclimate temperature between the body and the clothing or the outside temperature during exposure to thermal aggressors. While much work has been dedicated to the development of temperature sensors based on smart textile technologies and flexible electronics, a very limited number of studies have been devoted to the systems integrated into clothing.

In fact, the main motivation for the development of textile or flexible sensors has been to overcome the obstacles that hinder portable temperature detection despite the progress made [76]. Most thermistors or thermocouples used in wearable technologies [77] are sensitive to deformation, which can impair temperature sensing with bending or twisting of the sensor [76]. To counter the strain dependence of this type of sensor, some researchers have proposed a hybrid approach based on the integration of a small rigid thermistor embedded in a flexible and extensible matrix [78]. In one of these selected works, an NTC-type thermistor (having a negative temperature coefficient) in association with conductive textile threads was integrated in a bamboo belt to monitor the body temperature of newborns. Despite an encouraging detection accuracy of 0.1 °C of the prototype tested in a hospital setting, the concept lacked mechanical strength due to the use of knots to ensure the connection between the sensor and the signal-transmitting conductive textile threads [79]. In more recent work, the aspect of mechanical strength could be improved by encapsulating a standard thermistor in a polymer resin microcapsule, then embedding it in the fibers of a yarn, and then incorporating it into a textile structure [78]

[80][81][82][83]. As part of this work, ongoing optimizations have been made, including encapsulating the commercial thermistor in a microcapsule of thermally conductive resin to improve the sensitivity of the sensor [82] or connecting the sensor leads to a microcontroller and a Bluetooth module for wireless transmission of the collected data [78][80]. However, the proposed concepts still require further optimization, particularly in terms of detection accuracy, as differences of 0.5 to 1 °C were observed between the reading and the actual temperature of the sample surfaces [80][82].

Temperature sensors can also be manufactured from textile materials composed of conductive fibers or yarns using conventional textile manufacturing technologies such as weaving, knitting, or embroidery [65]. Depending on their operating principles, these types of sensors can be classified as thermocouples or RTD-type detectors [84].

Textile thermocouples: They exploit the Seebeck effect, which is based on the development of a corresponding potential difference between the junctions of two different metal structures due to the temperature difference between the junctions [65]. Structures with textile electrode pairs consisting of graphite fiber/antistatic fibers, non-woven graphite/silver-coated yarns, or hybrid knitted steel/alloy constantan wire composition have been used to design textile thermocouples [85][86]. However, these thermocouples exhibit a non-linear relationship between potential change and temperature and are characterized by low accuracy and sensitivity compared to conventional wire thermocouples [65]. In addition, they are also sensitive to changes in environmental relative humidity [86].

Textile RTDs: They use the temperature dependence of materials with electrical resistivity to determine temperature. These sensors can be developed by incorporating wires or conductors with a high temperature resistance coefficient into the fabric [65].

Therefore, fibrous sensors of RTD types could be developed by inserting metal wires (copper, nickel, and tungsten) in a knitted structure [87], by integrating metallic filaments in the middle of a double-knitted structure with different densities of metallic wire incorporation [88], by using cotton yarns coated with a PEDOT-PSS conductive polymer solution and a polystyrene encapsulation layer embeddable in a textile structure by weaving or stitching [89], by embroidering chromium–nickel austenitic stainless steel threads on a textile substrate [90], or by embroidering a hybrid thread composed of polyester fibers and a stainless steel micro thread on a fabric [91], which could be inserted in the outer layer of firefighters' clothing [92]. This last work was able to demonstrate that textile RTDs offer increased accuracy and sensitivity, shorter response time, and better linearity with temperature compared to thermocouples [65]. However, these sensors could not provide localized temperature measurements, as the measurement is instead performed over the entire area of the textile [78][92].

Some studies, on the other hand, have reported an optical sensing approach for measuring body temperature by integrating optical fibers into the textile structure [93]. As a result, a distributed Bragg reflector with the ability to reflect light of specific wavelengths and transmit it to other wavelengths has been used [94]. The Bragg reflector was encapsulated with a polymeric substance and then woven into the fabric structure [95]. The authors have also analyzed mathematically the transmission of heat from the skin to the environment via the Bragg reflector and used a weighted coefficient model to estimate body temperature considering the wavelength shift as a function of temperature. They have also reported a high accuracy of ±0.18 °C in a range of 33 to 42 °C [95]. A new method of integrating optical fibers constituting a Bragg reflector into a hollow double-walled fabric structure has also been proposed in a recent study [96]. Despite the high accuracy provided by Bragg reflectors, the concept is far from being applicable to the design of a wearable device, as it requires connection to at least one amplified broad-spectrum light source and an optical spectrum analyzer [96]. The design of a textile heat flux sensor has also been proposed by investigating a method of inserting a constantan yarn into three different textile structures (polyamide-based knitted fabric, non-woven aramid, and aramid-based woven fabric), which is followed by several treatment and post-treatment steps including the electrochemical deposition of copper on the constantan yarn to obtain a thermoelectric yarn [97]. **Figure 3** shows some examples of integrated flexible sensors in textiles and yarns.

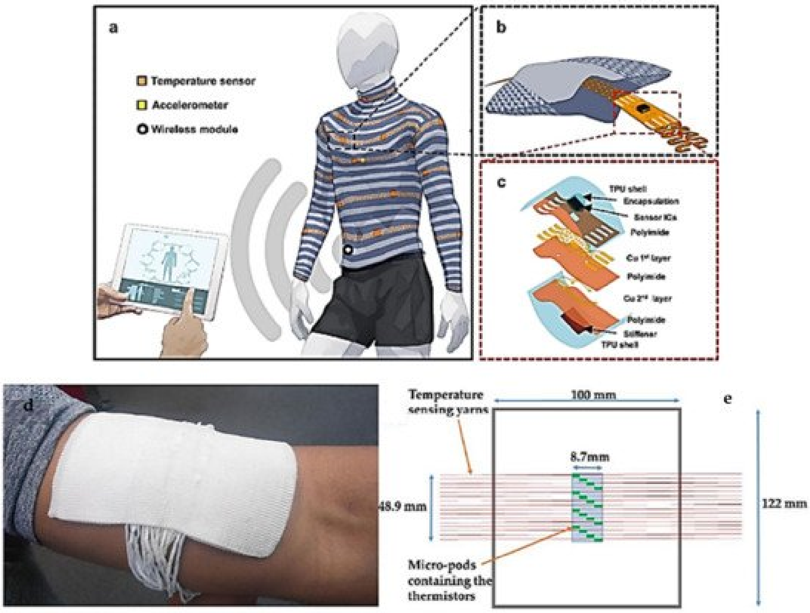

Figure 3. Thermal detection of smart textiles. (**a**) Illustration of spatiotemporal sensor mapping of the body with temperature and accelerometer (heart beat and respiration); (**b**) Wearable textile with embedding stretchable–flexible electronic strips; (**c**) Exploded view of a sensor island. Reproduced with permission [98]. Copyright © 2021, Wicaksono et al. (**d**) Health monitoring textile with temperature-sensing yarns; (**e**) A schematic of the textile thermograph (**d**,**e**) [78].

3.2. Flexible Temperature Sensors

Although these studies are still at a very preliminary stage, some research groups have attempted to develop shape memory textile sensors. The concept is based on the use of shape memory polymers sensitive to external stimuli such as light or temperature. Recently, the innovation of sol gels, conductive polymers, and copolymers as biomaterials enabled the miniaturization of biological analyses in an integrated chip with new generation sensors using a Si light source with a wide visible wavelength range as an optical biosensor [99].

Temperature sensing functionality can be obtained by spinning shape memory polymer fibers, such as polyurethane fibers, with other types of fibers to make textile fabrics, or by coating shape memory polymer emulsions on a woven or knitted fabric [100]. Other configurations of shape memory materials applicable to fabrics include silicon [101], nanofibers, and shape memory foams. In order to facilitate the characterization of the thermal sensitivity of textile shape memory sensors, a shape memory coefficient based on the change of deformation angle with temperature variation was suggested [102].

Many researchers have also worked on the development of flexible temperature sensors with the deposition of materials that facilitate temperature detection on flexible polymeric substrates using printing, coating, and lamination techniques [65] (**Figure 4**).

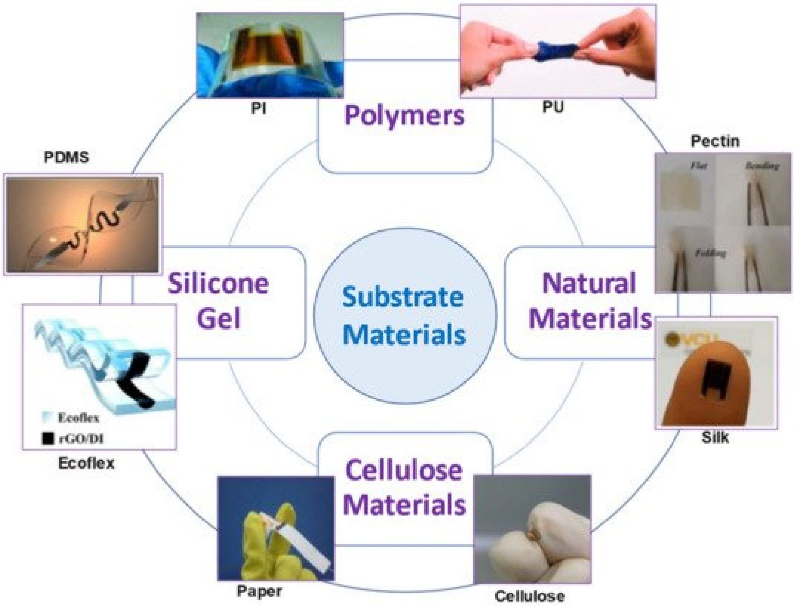

Figure 4. Schematic illustration of flexible sensors materials. Clockwise from the right top: polyimide (PI) [103], polyurethane (PU) [104], pectin [105], silk [106], cellulose [107], paper [108], ecoflex [109], polydimethylsiloxane (PDMS) [110].

If they maintain their mechanical strength, these types of sensors can then be attached to fabrics or integrated into textile structures [100]. In this context, several studies investigated the development of flexible temperature sensors based on graphene as a highly conductive material from an electrical and thermal point of view [111][112]. Therefore, electrical resistance temperature-sensing layers have been developed by printing a graphene oxide formulation on polyimide and polyethylene terephthalate substrates, which is followed by infrared firing to obtain a material with a negative temperature coefficient [113]. A layer with an RTD property having a positive temperature coefficient (PTC) was also developed by deploying the plasma-assisted chemical vapor deposition method of graphene nanosheets on a polydimethylsiloxane (PDMS) substrate [114]. In addition, a stretchable thermistor was designed by integrating a graphene-based dispersion in a PDMS-based matrix as a detection channel, which was associated with electrodes formed from silver nanofilaments in polycarbonate membranes [111]. Thanks to the use of graphene, temperature sensitivities very close to those of metal oxide materials used in classical sensors have been obtained in a flexible structure [113]. However, the stretchable structure based on graphene has shown strong variations in its thermal behavior as a function of mechanical deformation [114], which may constitute a limitation for their integration in textile structures.

Printing techniques were also used to design flexible temperature sensors [115]. The most notable works include the screen printing of a carbon-based ink on a polyimide sheet to obtain a PTC thermistor-type structure [43], the screen printing of various resistive inks on polyethylene naphthalene being protected by a passivation layer of dielectric ink and plasma post-treatment to improve the temperature resistance coefficient of the printed layer [116], the ink-jet printing of a dispersion based on nanoparticles of nickel oxide in the space between two silver-printed electrodes using a polyimide substrate to develop an NTC thermistor [117], a 100 × 100 pixel array all-CMOS (Complementary metal–oxide–semiconductor) monolithic microdisplay system has proven possible to create a high-optical power efficiency all-CMOS microdisplay [118], and the ink-jet printing of a silver complex dispersion on a polyimide substrate to obtain a layer with PTC thermistor behavior [119]. Overall, the printed thermosensitive structures were able to offer high temperature sensitivity, while having very low hysteresis during heating and cooling cycles [116][117][119]. Screen printing of PEDOT-PSS conductive polymer and carbon nanotubes dispersion on polyimide substrates and the use of silver-based printed electrodes has also allowed the development of RTD layers. Then, the printed RTD layers were combined with radio signal transmittances to design a label [120] or bandage [121] to be placed on an individual's skin to communicate with an external reader device [120]. Printed temperature sensors have also been developed on paper substrates [122][123]. In their current state, these types of development are rather intended for the packaging field and require work to reformulate the inks used to make them compatible with non-porous polymeric substrates with surface properties different from those of paper [64].

The formation of composite layers on flexible substrates has also been another method for the design of flexible temperature sensors. In this register, a composite film with RTD properties could be obtained by coating a mixture of poly o-methylaniline and manganese oxide (Mn_3O_4) on a solid substrate [124]. In addition, a composite film based on tellurium nanofilaments in a poly-3-hexylthiophene matrix deposited on a flexible substrate was used to obtain RTD behavior [125]. The deposition of graphite particles dispersed in a PDMS matrix on inter-digitalized copper electrodes prefabricated on a polyimide substrate was also deployed to obtain a composite film demonstrating RTD properties [126]. The dispersion of multiwall carbon nanotubes in a toluene solution of polystyrene–ethylene–butylene–styrene (SEBS) deposited on gold electrodes fabricated on a polyimide substrate resulted in a composite film showing NTC-type thermoelectric characteristic of a sensitivity comparable to the highest values for metals [127]. In a similar study, a mixture of multiwall carbon nanotubes and a polyvinyl benzyl derivative with trimethylamine coated on a pair of gold electrodes fabricated on a polyimide film led to the formation of a composite film with RTD behavior and a sensitivity comparable to that of metals [128]. The combination of a binary composite film of polyethylene and polyethylene oxide loaded with nickel microparticles with a passive RFID antenna has led to the design of a portable RTD temperature sensor. Despite the portability of this prototype sensor, it had three times the sensitivity of similar commercial sensors and a significant measurement error of ±2.7 °C [85]. In this framework, an array of 16 RTD-type temperature sensors was also fabricated with narrow serpentine gold traces using a microlithography technique on thin layers of polyimide to design an electronic skin to be fixed to the skin by the action of Van der Waals forces [129].

3.3. Radio-Frequency Identification (RFID)

As part of the development of flexible temperature sensors, other work has opted for radio-frequency identification (RFID) tags to be placed on the skin to measure T_s. For example, these studies have contributed to the development of a passive ultra-high frequency (UHF) RFID tag, which is based on the temperature dependence of the ring oscillator frequency and allows data to be sent to a reader at 868 MHz with a range of 2 m [130]. Similar work has developed a flexible RFID tag comprising a commercial microchip providing direct thermal reading and an antenna designed with copper adhesive transferred onto a polycaprolactone membrane to be attached to the individual's arm or abdomen with hypoallergenic cosmetic glue. The label allowed the data collected to be sent in a band of 780–950 MHz and a range of 30–80 cm to a nearby reading device [131]. According to the analyses of this study, the label placed on the skin requires that the label itself does not alter the locally measured T_S and must allow the natural perspiration of the skin to be preserved [131]. In a similar work, a modular patch with two detachable components, including a reusable inner part housing electronic element (the antenna, the integrated circuit, and the battery) and a disposable cover encapsulating the sensor associated with a medical-grade adhesive ensuring adhesion to the skin surface, made it possible to develop a real-time epidermal temperature sensor using UHF-type RFID communication [132]. In addition to a deviation of 0.6 °C from reference measurement methods, the influence of human variability and environmental conditions on the sensitivity of this sensor remains to be clarified [132].

Advanced materials have also been applied to the optimization of certain types of portable devices such as portable in-ear devices, which is a new technological trend in recent years to measure body temperature and other physiological parameters through sensors that hold. A dispersion based on graphene, as a highly conductive material known for its strong optical absorption in the infrared range, has been coated on the silicon substrate of the lens of IR thermopiles used in portable in-ear devices with the aim of increasing the accuracy of measurements in such a thermopile [133].

3.4. Textile Prototypes with Flexible Temperature Sensors

The overall analysis of the research on temperature sensors integrated in textile structures, textile sensors, and flexible temperature sensors has shown that the vast majority of these studies remain at the level of proof-of-concept of components that are still to be integrated in clothing, although some work is dedicated to temperature sensors integrated in work clothing. In one of these studies, the ambient temperature and heat flux through the garment could be measured by a modified PTC grade sensor network integrated in the outer and inner side of the firefighters' protective clothing with the transmission of the collected data to an external reader device using the Zigbee communication protocol. The prototype, tested on a thermal manikin in the laboratory, had yet to be validated in an operational environment [134]. A work jacket for oil workers operating in extreme cold was also developed using an embedded IR temperature sensor and two combined humidity/temperature sensors. The jacket consisted of one humidity/temperature sensor on the outside of the jacket, a second pair of sensors placed on the opposite side of the jacket on the inner side, and the IR sensor, which was integrated on the inside of the sleeve for non-contact measurements of T_S at the wrist [135]. This jacket equipped with temperature sensors could be optimized by, among other things, placing a layer of heat-reflecting film in the lining of the jacket on the inside to reduce the influence of the person's heat on the outside temperature measurements and adding a layer of elastomeric material around the outside sensor to reduce the heat flow through the jacket in the vicinity of the sensor [136].

A smart glove and an armband each comprising two electrodes made of conductive textiles to measure the galvanic skin response and a sensor from a commercial digital thermometer detecting T_S were developed to assess the conditions of soldiers in real time. Both were tested on about 40 subjects, but the assembly remained cumbersome, and the main signal transmission lines were fabricated with electrical wires that could be damaged during use or maintenance [137]. A thermistor microencapsulated in a wire [78][82] has been integrated into a cuff, glove, and sock for measuring T_S [138]. The cuff contained four wires each with a thermistor, while the glove and sock were based on a set of five wires each containing a thermistor. The contact pressure on the hands was found to influence the measurements due to the deformation of the sensor wire structure in the glove. In addition, the fit of the sock can also affect the measurements, as can the wearing of a shoe or walking, which appear to strongly influence the temperature measurements. These measurement errors seem to show that monitoring the foot skin temperature by sensors integrated in the textiles could be challenging for applications where accurate measurements are required. According to this study, fabrics containing sensor yarns should be manufactured according to the contact pressure exerted at the temperature measurement emplacement [138].

3.5. Commercial Textile with Temperature Sensors

Due to the need to monitor patient health or athlete performance, more and more portable products with temperature sensors have appeared on the market in recent years. Some integrate temperature sensors into their structure and others are based on the deployment of advanced materials. Among the commercial devices for biometric sign detection in the form of portable accessories in recent years, Biofusion (by Biopeak, Ottawa, Canada) and QardioCore (by Qardio, San Francisco, US) offer integrated systems that use contact RTD-type temperature sensors to measure T_S from the chest.

Based on printable electronics techniques, flexible temperature sensors have also been produced and have entered the market to serve areas such as transportation, logistics, food supply chain, and home appliances. Thanks to their flexibility, their integration into textile structures seems conceivable. However, their adaptation to textile structures still requires a certain number of technical challenges to be taken up, especially in terms of durability in wear or maintenance, especially in washing [139]. These types of flexible sensors such as those proposed by the company PST sensors (Cape Town, South Africa) are mainly printed thermistors associated with an electronic chip. The conductive ink used in these types of development is based on a composition that, once printed, demonstrates RTD properties [113][120].

Then, circuits containing these types of printed thermistors can be combined in a hybrid system with wireless data transmission protocols [140]. According to the manufacturers of these types of flexible thermistors, the sensors developed provide measurement accuracy ranging from ±0.1 to ±0.25 °C. While providing a very low response time of 100 to 250 ms, these flexible temperature sensors have the advantage of operating with low working powers in the nano or micro watt range. Graphene conductive layers with RTD characteristics, demonstrating a very high sensitivity to temperature changes [111], have recently been successfully used in the design of a connected insole based on an integrated thermistor to continuously monitor temperature changes in patients' feet and detect early signals of foot ulcers in diabetics (Smart Insole by Flextrapower, New York City, NY, USA). These types of products for the medical field may be of interest for knowledge transfer toward an occupational health and safety application.

Regarding products marketed in the form of temperature sensors integrated into clothing, a very limited number of products exist on the market. These products were mainly developed to help protect firefighters [39]. In this context, the companies Ohmatex (Aarhus, Denmark) and Viking (Esbjerg, Denmark) jointly presented a firefighter suit containing thermal sensors integrated inside and outside the firefighter's clothing to monitor environmental and near-body heat, respectively. The sensors are connected to LED displays on the sleeve and shoulder of the jacket. Above a certain temperature threshold detected on the outside or inside the jacket, the flashing of the display alerts the user. Despite the presence of an integrated electronic device, this garment had the advantage of withstanding at least 25 wash cycles.

The Balsan fire jacket (by TeckniSolar Seni, Saint-Malo, France) was also equipped with temperature and humidity sensors. A temperature sensor on the outside of the jacket measures the environmental temperature and a pair of temperature/humidity sensors on the inside of the jacket measures microclimatic conditions close to the body. When parameters exceed a certain level, an audible and visual alarm alerts the firefighter [62][141].

3.6. Apparels Measuring Thermal Stress

The review of research literature for measuring body temperature tools and sensors that can be integrated into protective equipment to assess the microclimate under the clothing or the environmental temperature in order to develop warnings in case of very high thermal stress are presented in **Table 1**.

Table 1. Temperature sensors to be integrated into textile apparels.

Technology Used	Integration Method	Operating Temperature Range	Reference
Temperature-sensing yarns incorporated in a knitted fabric	**An off-the-shelf thermistor encapsulated into a polymer resin Multi-Cure® 9-20801 (Dymax Inc.) micro-pod embedded within the fibers of a polyester yarn**	**Physiologically relevant temperature range of 25–38 °C**	[78]
Electronic temperature sensing yarn	**Knitted polyester-based armband demonstrator using a polyester yarn with embedded thermistor encapsulated into a polymer resin Multi-Cure® 9-20801 (Dymax Inc.) and connected to an Arduino Pro Min Hardware**	**Tested to measure the temperature of a hot object of 65 °C**	[83]
Yarn with embedded thermistor	**NTC thermistor soldered to copper interconnects and encapsulated with a cylindrical micro-pod made of conductive resin (Multi-Cure® 9-20801 by Dymax Inc.), then embedded in a polyester yarn**	**Tested in a range of 0 to 40 °C**	[82]
Yarn with embedded thermistor	**A commercial temperature-sensing element within a polymeric resin micro-pod embedded in the fibers of a polyester yarn**	**Tested in a range of heating-cooling cycle of 25–38 °C**	[81]
Yarn with embedded thermistor	**Commercially available NTC thermistor encapsulated in a polymer micro-pod made of UV curable resin (Multi-Cure® 9001-E-V-3.5 by Dymax Inc.) embedded into the fibers of a thermoplastic monofilament yarn spun from liquid crystal polymer (Vectran™)**	**NTC sensitive to 25–38 °C**	[80]

Technology Used	Integration Method	Operating Temperature Range	Reference
Thermistor integrated into textiles	Embedded NTC thermistor and conductive textile yarns (Shieldex® silver plated polyamide) in a belt made of soft bamboo yarns	25 to 43 °C	[79]
Embroidered hybrid resistive thread (RTD)	(1) Hybrid thread composed of three strands. Each strand contains 33 polyester fibers; only one includes one resistive stainless steel microwire, (2) The surface of the hybrid thread is covered by a silicone lubricant, (3) The sensor is embroidered in a helical meander-shaped structure into the carrier fabric made of KERMEL®, Lenzing™ FR, Technora, and antistatic fibers	Temperature calibration (40 to 120 °C); rapid temperature cycling (−40 to 125 °C)	[92]
Embroidered resistance temperature detector (RTD)	Conductive silver R.STAT® yarn as humidity and chromium–nickel austenitic stainless steel yarn as thermal sensors embroidered on a cotton substrate	Validated for 20 °C to 100 °C and 50 to 98% of RH	[90]
Temperature-sensing knitted resistance temperature detector (RTD)	Metal wire inlaid in the middle of a rib knitted structure of polyester fabric	Validated at 20–50 °C	[87]
Dip dyed yarn by PEDOT-PSS as RTD	RTD yarns fabricated by: (1) Dip dyeing cotton yarns in PEDOT-PSS solution, (2) Applying a silver paste applied at the two ends of the dyed threads to form electrical pads, (3) Creating encapsulation layer by dip dyeing the yarns in polystyrene to better protect against dust and moisture	Validated for −50 to 80 °C	[89]
Metal wires incorporated in a knitted fabric (RTD)	Knitted temperature-sensing fabric developed with two different wire inlay densities and a fine metallic filament embedded within the courses of a double-layer knitted structure made of poly acrylic/wool yarns	Validated at 20–60 °C	[88]
Flexible platinum-based resistance temperature detector (RTD) integrated into textile	Sensors manufactured by electron beam evaporation followed by photolithography on Kapton® polyimide foils, then cutting the foil into stripes each containing an individual sensor and connecting lines, which are then inserted into a fabric during the weaving process	Validated for 25 to 90 °C	[142]
Optical fiber Bragg grating (FBG) based sensor integrated into textile	Encapsulating the optical fiber with polymeric (copolymerization of unsaturated methyl ethyl ketone peroxide (MEKP) and cobalt naphthenate) filled strips, then embedding it into the fabric by combining large and small pipes together in fabrication	Validated for body temperature ranging from 33 to 42 °C	[95]
Optical fiber Bragg grating (FBG)-based sensor integrated into textile	A textile structure of hollow double-wall fabric was adopted as a base, and quasi-distributed FBG sensors were embedded by the methods of cross-walls and between-walls for smart fabric sensor development	Validated in a T_{env} range of 20 to 130 °C with 10 °C steps and then decrease back to 20 °C with the same procedure	[96]
Textile thermocouple	Four different textile thermocouples: (1) Flat textile composed of pairs of textile electrodes: graphite non-woven—woven fabric with nirtil static fibers, (2) Linear textiles composed of pairs of textile electrodes: thread of Nitinol—static fibers—thread of steel fibers, (3) Flat linear thermocouple manufactured from pairs of electrodes: graphite nonwoven—silver-covered polyamide yarn, (4) Hybrid thermocouple composed of pairs of electrodes: steel knitted fabric—constantan wire	Validated for temperatures up to 70 °C and 90 °C	[86]
Thermocouple	(1) T_s measured by a thermocouple placed at the armpit with an elastic belt made of spandex, (2) T_{env} and the heat flux through the garment measured by modified platinum sensor array integrated into the outer garment of firefighters, (3) Sensors associated to a planar textile-based antenna made of conductive yarns	Heat flux sensor is able to operate in the range of −70 to +500 °C	[62]
Textile heat flow sensor	Insertion of a constantan wire within three different textile structures (polyamide-based knit, aramid non-woven, woven aramid-based), followed by a local treatment with polymeric resin to allow the partial copper deposition, then an electrochemical deposition of copper on the constantan wire to obtain a thermo-electrical wire and finally a post-treatment for polymer removal	Tested in a range of 30 and 80 °C and 0 to 150% moisture content	[97]

Technology Used	Integration Method	Operating Temperature Range	Reference
Sensorized glove/upper-arm strap	(1) A glove with two textile electrodes integrated inside in the proximal phalanx of the index and middle fingers on the inside of the glove and a temperature sensor placed in the tip of the ring finger of the glove, (2) Upper arm strap confectioned with two integrated textile electrodes and a temperature sensor placed in the inner lining of the strap	Validated for T_s measurements averaging 34 °C	[137]
Platinum sensor integrated into a jacket	Modified platinum sensor array (welded on Kapton® polyimide foil) integrated into the outer firefighting garment (composed of external impermeable, thermal insulation Gore-Tex® PTFE membrane, and internal comfort layers) to measure T_{env} and the heat flux through the jacket	Able to operate in the range of −70 to +500 °C	[134]
Working jacket with integrated sensors	Sensors and wireless communication integrated into a commercialized Wenaas® working jacket, while packing sensors on the textile by vacuum molding using biocompatible silicon, and wiring external sensors to the main sensor module by conductive yarns also coated with silicon after vacuum molding	Verified in a climatic chamber −20 to 25 °C with RH 0% to 50%	[136]
Working jacket with integrated sensors	Infrared temperature sensor and two combined humidity–temperature sensors integrated into the jacket in three different areas, using two different packages: (1) sensor enclosed into a pouch made from Gore-Tex Paclite® PTFE membrane, and (2) only the opening of the sensor covered with membrane made form Gore-Tex Paclite®	Validated at 22 °C and −5 °C	[135]
Firefighting clothing with integrated sensors	A firefighting garment with three main integrated components: physiological sensors (including the body temperature), fire-related sensors (including field temperature), and the computing node	N/A	[63]
Sailing garment with integrated sensors	The electronic system is consisted of a master system and a slave system placed inside a waterproof pocket above the cuff of a waterproof sailing top garment made of coated and laminated woven fabrics	N/A	[143]
Thermosensing armband, glove, and sock based on yarn with embedded thermistor	Temperature-sensing garments (armband and glove made of polyamide/spandex, sock made of cotton) containing thermistor soldered to copper interconnects and encapsulated with a cylindrical micro-pod made of conductive resin (Multi-Cure® 9-20801 by Dymax Inc.)	Tested at 23 °C and validated for T_s ranging from 28 to 33 °C	[138]
Printed polymeric PTC and NTC thermistors	Carbon-based paste screen printed on Kapton® polyimide foil	Validated at a range of 30 to 42 °C	[43]
Printed polymeric PTC and NTC thermistors	Resistive inks screen printed on polyethylene naphthalate and protected by a dielectric ink (CYTOP-like fluro-polymer) as a passivation layer, followed by a plasma post-treatment	Validated at a range of 20 to 90 °C	[116]
Printed polymeric NiO based NTC thermistor	Stable NiO ink (suspended in ethylene glycol aqueous solution) inkjet-printed in between two silver conductive electrodes on a polyimide substrate, then thermally cured at 200 °C for an hour	Validated at a range of 25 to 250 °C	[117]
Printed resistance temperature detector (RTD)	Silver complex ink inkjet printed on Kapton® polyimide foil	Validated at a range of 20 to 60 °C	[119]
Printed smart bandage	Temperature sensor fabricated by PEDOT-PSS/CNT paste screen-printed on a nm-thick-SiO 2-coated Kapton® polyimide, then cured at 100 °C for 10 min	Validated for 22 to 48 °C (normal T_s ≈ 29 to 31 °C)	[121]
Printed wearable resistance temperature detector (RTD)	Shadow mask printing of PEDOT-PSS/CNT suspension on SiO_2-coated Kapton® polyimide substrate and silver electrodes by screen printing	Validated at a range of 22 to 50 °C	[120]
Printed paper-based thermal sensor	(1) Ionic liquid, 1-ethyl-3-methyl imidazolium bis (trifluoromethylsulfonyl) imide ([EMIm][Tf2N]), inkjet printed on a regular paper, (2) Two gold electrodes deposited on the paper substrate through magnetic sputtering evaporation setup	Thermal responses validated at 25 and 45 °C	[123]

Technology Used	Integration Method	Operating Temperature Range	Reference
Printed resistance temperature detector (RTD) on paper	Silver nanoparticle ink inkjet printed on specific coated paper substrate	Validated at a range of −20 to 60 °C	[103]
Stretchable graphene-based resistance temperature detector (RTD)	(1) Silver nanowire first filtered as electrodes using polycarbonate filter membranes, (2) Graphene/nanocellulose dispersion then filtered as the detection channel to connect electrodes, (3) PDMS base and curer poured on top of the filtered films, then degassed and cured, (4) Solidified PDMS with embedded silver electrodes and graphene detection channels peeled off from the polycarbonate membrane to obtain a stretchable device	Validated at a range of 30–100 °C	[111]
Graphene-based wearable resistance temperature detector (RTD)	Graphene nanowalls deposited on a polydimethylsiloxane substrate with plasma-enhanced chemical vapor deposition technique and polymer-assisted transfer method, associated to silver paste electrodes	Validated at 35 to 45 °C	[114]
Flexible graphene-based resistance temperature detector (RTD)	Graphene oxide-based formulation printed on Kapton® polyimide and polyethylene terephthalate substrates reduced by infrared heat lamp and then annealed at 200 °C	Validated in a range of 30 to 180 °C	[113]
Flexible composite-based resistance temperature detector (RTD)	Ni microparticle-filled binary polymer of polyethylene and polyethylene oxide composites with copper tape strips-based RFID antenna	Validated at a range of 35 to 42 °C	[85]
Flexible composite-based resistance temperature detector (RTD)	HCl doped poly-o-methyl aniline/Mn_3O_4 nanocomposite spin coated on glass substrate	RT characteristics in the temperature range of 35–185 °C with repeatability in the range of 75–185 °C	[124]
Flexible composite-based resistance temperature detector (RTD)	Dispersions of multiwall CNT drop casted onto gold electrodes fabricated on a polyimide substrate	Validated in a range of 20 to 60 °C	[127]
Flexible composite-based resistance temperature detector (RTD)	Graphite/PDMS composite dispensed on flexible polyimide films, associated to copper electrodes	Validated at 30 to 110 °C	[126]
Flexible CNT-based composite	Multiwall CNT/polyvinyl benzyl chloride derivative with trimethylamine (PVBC_Et3N) dispersions drop casted onto a gold electrode pair supported on a polyimide film	Validated for 20–40 °C	[128]
Flexible composite-based thermoelectric nanogenerator	A composite of the tellurium nanowires/poly (3-hexylthiophene) (P3HT) dropped onto a Kapton® polyimide flexible substrate associated to two silver electrodes	A heat source of 24.8 °C	[125]
E-patch	A modular patch with electronics elements: (1) The thermometer prototyped by attaching a flexible adhesive-backed copper foil on a polyethylene terephthalate substrate, (2) The loop enclosed between two layers of a medical-grade adhesive dressings to attach the tag over the skin	Validated for T_S ranging from 32.7 to 34.7 °C	[132]
E-skin sensor	Two main technologies compared: (1) Arrays of 16 temperature sensors relying on thin serpentine traces of gold, fabricated using microlithographic techniques with thin layers of polyimide, (2) Multiplexed arrays of 64 sensors based on PIN diodes formed by patterned doping of nanoscale membranes of silicon	T ranging from 27 to 31 °C and 30.7 to 32 °C (during mental and physical stimulus tests)	[129]
Dual-heat-flux associated with two double-sensors	Two double-sensors with dual-heat-flux embedded in the neck pillow, while using rubber sheets to simulate the subcutaneous tissue layer of the neck during experiments	Tested at 32–38 °C	[144]
Heater-less deep body temperature probe	Dual-heat-flux method wired sensors placed on the skin, each probe containing the two insulators on a rubber sheet	Validated at 36.5–37.5 °C	[145]
Double-sensor thermometer	The sensor consists of two temperature probes on each side of a standardized insulator placed in a plastic shell	Validated at 36–37.8 °C	[146]

Technology Used	Integration Method	Operating Temperature Range	Reference
Double-sensor thermometer	Combined heat and skin sensors specially sealed in a polycaprolactone-based enclosing cover	Validated at 10, 25 and 40 °C	[147]
Double-sensor thermometer	Combined skin and heat flux sensors specially sealed in a polycaprolactone-based enclosing cover	Validated for a body temperature of 36–38 °C	[148]
Wearable thermistor	T_s measured by a textile strip wristband containing a NTC thermistor	16–42 °C	[149]
Wearable thermometer	Array of 4 × 4 Silicon Kelvin precise sensor thermometers integrated into a textile-based affixation aid to the arm, associated with a signal processing chain	25–41 °C	[150]
Wireless connected temperature sensor	T_s of the hand measured by a connected temperature sensor	0–100 °C	[151]
Wireless connected temperature sensor	The system consists of a transceiver, a microcontroller, and a digital temperature sensor enclosed in a polycarbonate covering to be placed under the subject's arm	Validated for T_s (36.7 to 37.3 °C) in an ambient environment	[152]
Long-range RFID tag	RFID rigid tag based on temperature dependence of the frequency of the ring oscillator integrated in a ceramic package and assembled to a matched impedance dipole antenna designed on high-dielectric constant ceramic substrates	35 to 45 °C	[130]
Epidermal RFID-UHF tag	Tag and antenna layout with adhesive copper transferred on a polycaprolactone membrane attached on a skin with a hypoallergenic cosmetic glue	Validated at 30 to 42.5 °C	[131]
Remote HR and body temperature monitoring	A temperature sensor integrated into a polyurethane flexible substrate wearied on the left thumb, while being connected to a programmed microcontroller	Validated for body temperature range of 36.6 to 37.2 °C	[153]
Remote HR and body temperature monitoring	A portable temperature sensor connected to an analogue microcontroller measuring the body temperature, with the final product being packaged in a small lightweight polymeric package	Validated for body temperature range of 36.6 to 39.4 °C	[154]
Wireless humidity and temperature sensor	A semiconductor temperature and RH sensor affixed to the internal surface of an N95 filtering face-piece respirator made of highly hydrophobic nature of polypropylene	Validated for 30–36 °C and 60–89% RH	[155]
Wearable in-ear thermometer	(1) Thermal sensors integrated into a textile based earbag in order to measure the tympanic temperature inside the ear, T_s, and T_{env}, (2) The earbag added to a resizable headset shielding the outer ear	Validated for the body temperature range of 34.5 and 37 °C	[156]
Graphene-coated lens of IR thermopile sensors for an ear-based device	(1) Graphene/isopropyl solution drop casted over the silicon substrate of the lens of commercial IR thermopile being associated to a microcontroller collecting the temperature measured, (2) The ear hook-type enclosure 3D printed using Accura Xtreme polymeric resin, while covering the thermopile with a silicone cushion	Validated at T env of 21 °C and a body temperature range of 36.5 to 37.5 °C	[133]

3.7. Temperature Sensors Challenges

Concerning the studies dedicated to temperature sensors that can be integrated in textiles, the present state of the art has found that a lot of work is dedicated to the design of temperature sensors based on smart textiles and flexible electronics [53][93][157], and a very limited number of studies on sensors integrated in clothing has been identified. A hybrid approach has been proposed to integrate rigid thermistors in a flexible matrix in the textile structure. Despite several works related to integrated thermistors, some prototypes lack mechanical strength, while others require optimizations regarding detection accuracy. Another method has been to design fibrous sensors such as RTDs or thermocouples. According to the studies analyzed, fibrous thermocouples require significant optimization effort, because in addition to low sensitivity and low measurement accuracy, they have proven to be sensitive to environmental humidity. Although the textile RTDs developed in analyzed studies have provided better accuracy, higher sensitivity, and shorter response time compared to textile thermocouples, these sensors were not able to provide localized temperature measurements. Therefore, the use of textile RTDs to measure temperatures in micro or macro environments remains to be validated. The integration of Bragg reflector-type optical fibers to measure body temperature, which has provided high accuracy, is far from being applicable to a portable device, as such concepts require connection to fixed optical systems. The same observation is valid for concepts that have integrated heat flow sensors in textile structures. Being intended to be eventually integrated in clothing, textile temperature sensors need to be validated for mechanical or wash resistance in future work.

In addition, experts in flexible electronics have shown great interest in the development of temperature sensors on flexible polymeric substrates. Graphene layers deposited on flexible substrates have demonstrated RTD properties of very high temperature sensitivity. However, in an extensible configuration, the RTD graphene layers have shown thermal properties sensitive to mechanical deformations. Layers with RTD properties have also been developed on flexible substrates by depositing different types of dispersion (based on carbon, nickel oxide, silver complex, and mixing PEDOT-PSS with carbon nanotubes) using printing techniques. These heat-sensitive printed layers were able to ensure high temperature sensitivity while demonstrating low hysteresis in the heat–cooling cycles. The formation of composite layers on flexible substrates also allowed the fabrication of flexible temperature sensors. Among the various developments, composite layers based on carbon nanotubes have made it possible to obtain thermal sensitivities comparable to those of metals. However, in many studies on composite layers, electrodes based on precious metals such as gold have been used. Despite the advantages of some concepts for flexible temperature sensors, significant efforts are required to integrate them into clothing. From a general point of view, work on textile-integrated temperature sensors, textile sensors, and flexible temperature sensors seems to remain at the level of proof of concept with very few connected device demonstrators and even fewer prototypes of garments equipped with temperature sensors. In addition, the influence of various environmental parameters on the performance of these types of sensors remains unknown. Among the few studies on the design of garments with integrated temperature sensors, very few were dedicated to protective equipment, and almost all the work was carried out in the laboratory with tests on very few subjects. The effectiveness of these concepts has yet to be validated in operational environments. In addition, in most of these studies, conventional electrical wires were used for electrical connections or to ensure the transmission of collected signals. These types of structures containing electronics can be vulnerable to mechanical constraints during use and maintenance. The use of structures based on conductive textiles is to be expected in order to ensure a better mechanical resistance in use. Clothing equipped with temperature sensors that incorporate rigid thermistors embedded in textile fibers also require optimization efforts in order to reduce the impact of mechanical stresses on the quality of the sensor reading. The literature also mentions the influence of the fibrous structure surrounding the sensor on the reading [78]. Not only have few studies been carried out in this area, but an in-depth knowledge of the influence of the multilayer structures of various types of protective equipment on the performance of integrated sensors remains to be developed.

Among the commercially available products, flexible temperature sensors seem to be able to ensure high measurement accuracy and very short response times. Being mainly based on a very thin printed structure, this type of sensor requires relatively low power supplies of the order of microwatts. These products, which are currently manufactured on flexible polymeric substrates, are mainly dedicated to the fields of warehousing and logistics. In order to extend their application to clothing, research is still needed to ensure their reliability and durability in use. Very few products including garments with integrated temperature sensors currently exist on the market. These products are mainly dedicated to the protection of firefighting workers. These types of protective equipment, which include temperature sensors incorporated into their structure, can warn the firefighter when predefined temperature thresholds inside or outside the garment are exceeded.

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