Flexible Textile-Based Sweat Sensors for Wearable Applications

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The physical health care system has gradually evolved into a form of virtual hospitals communicating with sensors, which can not only save time but can also diagnose a patient's physical condition in real time. Textile-based wearable sensors have recently been identified as detection platforms with high potential. They are developed for the real-time noninvasive detection of human physiological information to comprehensively analyze the health status of the human body. Sweat comprises various chemical compositions, which can be used as biomarkers to reflect the relevant information of the human physiology, thus providing references for health conditions. Combined together, textile-based sweat sensors are more flexible and comfortable than other conventional sensors, making them easily integrated into the wearable field.

textile sweat sensors sensor communication

1. Introduction

Traditional diagnosis based on physical hospitals shows limitations in obtaining and monitoring a patient's physical condition in real-time. It is worth noting that the present physical health care system has gradually evolved into a virtual hospital form, which is not only time-efficient but also makes real-time diagnosis of a patient's physical condition possible. With the increasing attention paid to health monitoring and the rapid development of electronic device technology, the customization of personalized wearable devices combined with personal conditions has attracted intensive interest. At present, most wearable devices are mainly used for monitoring changes in the physical conditions of the human body, such as heart rate, movement and temperature, etc., which hold limitations in reflecting the whole health status of the human body. Thus, the real-time monitoring of biological fluids such as bodily fluids, blood and interstitial fluid for physiological health evaluation has become a new trend in wearable sensors. Compared with the invasive analysis of blood components, monitoring bodily fluids (e.g., tears, saliva, sweat and interstitial fluid) as a non-invasive method is a more convenient, simple and safe way of obtaining physiological signals [1][2].

Sweat is the liquid secreted by the sweat glands of the human body and is distributed in all parts of the body [3]. It can be continuously collected and has great potential in body fluid monitoring by wearable sensors. Sweat production is influenced by a variety of factors, such as ambient temperature, physical movement, mental state, etc. Therefore, it is possible to use the related biochemical information in sweat to identify the physical and mental health of the human body [4]. The main components of sweat are water and NaCl in addition to some ions (e.g., K^+ and Ca^{2+}), metabolites (e.g., lactic acid, glucose and alcohol), etc. [3][5], and is dramatically dependent on the region of generation over the body [6][7]. Monitoring sweat components is one of the most important ways to adapt the physiological index in real time, which move from the bloodstream to the skin's surface through sweat, carrying a lot of physiological information in the process [8]. For example, changes in the Na^+ concentration in sweat can be used as a biomarker to monitor dehydration during long-term exercise [9][10], which can be an important implication for the water intake of athletes. In this way, a water and electrolyte deficit [6] caused by a significant loss of perspiration from heat sickness can be prevented [11]. Similarly, glucose changes in sweat provide a convenient way to detect blood glucose changes for diabetic patients, which is due to the correlation between the glucose concentration in the blood and the glucose concentration in the sweat [12]. Lactate buildup can cause soreness and fatigue in the body, and over a long period it can lead to severe illnesses such as body acidification or lactic acidosis [13]. Cortisol is considered to be one of the biomarkers used to monitor human mental health [14][15]. As a result, for these biomarkers, various types of wearable sweat sensors in different forms have been developed in recent years, such as headbands, wristbands, underwear and electronic tattoos with improved wearing comfort and flexibility. These sweat sensors are mainly based on electrochemical, conductive and colorimetric detection. Electrochemical detection mainly includes potentiometric, amperometric and voltametric detection and has the advantages of a high detection accuracy and a fast response speed [16][17]. Sensors based on conductivity changes in sweat can detect changes in sweat quantity and ion concentration, which can measure the conductance value directly or by using the electrochemical impedance spectroscopy (EIS) method. Compared with the above two methods, colorimetric detection is usually carried out based on visual observation and is easier to operate.

Wearable sweat sensors have been developed based on textiles owing to their advantages in flexibility, light weight and low cost compared to traditional conductor materials. Textiles are composed of natural or manufactured fibers, which possess the intrinsic characteristics of breathability, durability, sustainability and flexibility, meaning that their integration into sweat sensors generates little interference with daily life. As for their role in the preparation of sweat sensors, the unique structure of textiles can be directly used for sweat transportation channels. Textiles as sensing elements support the full contact of sweat with the fabric, which helps to increase the sensitivity of the sensor. Therefore, textile-based sweat sensors have great appeal and potential for real-time medical health and fitness monitoring.

2. Materials and Preparation Processes of Textile-Based Sweat Sensors

2.1. Materials

Natural materials including cellulose, silk, chitosan (CS), etc. have been explored as sweat sensors. These natural materials have the similar characteristics of being comfortable, breathable, flexible, unharmful and sustainable. Cellulose, as the most abundant renewable resource in nature, has been widely adopted in various forms for use in textile sensors with different structures such as fabric, yarn, etc., which can be used to collect or transport sweat [11][18].

Functional materials are roughly divided into flexible and conductive materials. Among them, the selection of flexible materials for the base substrate of wearable sensors demands that the material is more suitable for human skin and can meet the requirements of human daily activities. Flexible materials such as polyurethane (PU), poly(styrene-ethylene-butadiene-styrene) (SEBS), polyethylene terephthalate (PET), polyimide (PI), ecoflex, etc., are frequently used as substrates for sweat sensor, whereas conventional conductive materials, including conductive polymers (e.g., poly(3,4-ethylenedioxythiophene) (PEDOT), polyaniline (PANI), polypyrrole (PPy)), metal (e.g., Au, Ag, Cu), metallic oxides (ZnO), carbon, etc., have high conductivity, which is ideal for use as the electrodes of sensors.

Further developing these materials into microstructural forms such as quantum dots (QDs), nanoparticles (NPs), nanowires (NWs), nanorods (NRs) and nanotubes (NTs) as the electrodes of sweat sensors can effectively improve the sensitivity of the sensors. This is because these microstructures have a larger specific surface area than traditional conductive materials, which can effectively improve the sensitivity of the sensor as a sensing element. For example, carbon QDs (CQDs) are zero-dimensional carbon-based nanoparticles (<10 nm), which have a uniquely large specific surface area, strong electrochemical responses and a high electron transfer rate. In addition, they can effectively transfer electrons to electrodes. The immobilized content of an enzyme can be significantly increased by preparing the metal material into a microstructural form [19]. In addition, graphene (Gr)-based materials provide binding sites for enzymes when they are used as electrodes [20][21], which can effectively improve the sensitivity of the sensor [22], and they have great potential to be used in the field of biosensors. Among them, GO, due to the more oxygen-related functional groups on its surface, has been explored and developed for humidity-driven electric generator [23].

2.2. Preparation Process

2.2.1. Direct Transformation

The preparation of functional materials directly transformed into fiber or yarns commonly adopts techniques such as dry spinning [24][25][26], wet spinning [27] and electrospinning (ES) [28][29], etc. The fibers or yarns are then incorporated into the fabric by weaving, embroidery or braiding [30]. With its simpler processing procedure compared to wet spinning, dry spinning prepares uniform and compact polymer fibers without using a coagulation bath [25]. Zhao et al. [26] successfully prepared SEBS/AuNWs fibers by dry spinning. In the preparation process, the SEBS/AuNWs were dissolved by a low-boiling-point solvent, and the AuNWs on the fiber surface effectively promoted the subsequent Au chemical deposition. For wet spinning, the polymer solution is injected into a non-solvent coagulation bath and solidifies to form continuous fibers. Zhou et al. [27] dispersed single-walled carbon NTs (SWCNTs) into sodium dodecyl sulfate (SDS)/poly(vinyl alcohol)(PVA) mixed solutions. Acetone was adopted as the coagulation solution in the wet spinning, which could remove the SDS surfactant. The SWCNTs were well aligned along the obtained filament axis, and the mechanical and electrical conductivity of the filament were also improved. Although these technologies have different preparation processes, they can be used to synthesize fibers by mixing different polymers.

Different from above technologies, micro/nanofibers have the advantages of a high specific surface area and porosity [29][31], which can improve the sensitivity of sensors based on these materials [32]. Furthermore, micro/nanofibers with core–sheath, beaded, spherical and porous structures can be prepared through the ES technique, which can be utilized in sensing [33], wound healing [31], filtering and so on. The nanostructure and high porosity attributed to electrospun micro/nanofibers could provide good conformity to the skin and facilitate sweat uptake through capillary action [1]. In addition to fabricating micro/nanofibers into membrane structures, studies have shown that converting nanofibers into yarn structures contributes to a higher sensitivity and more sweat diffusion channels [34].

2.2.2. Textiles Post Treatment

The diameter distribution of directly prepared fibers is sensitive to the aggregation and agglomeration of functional materials in the solution, resulting in nonuniform diameters and distributions of fibers loaded with functional materials. This is because excessive functional materials may destroy the properties of the substrate itself when mixed with the substrate. Therefore, materials coated on various types of substrates by electrodeposition [26][35], polymerization [36], growth [37], sputtering [1][37], dip-coating [38][39] and printing [40][41], etc., can effectively solve the above problems. Electrodeposition, polymerization and the growth of functional materials on substrate materials belong to the category of chemical processes. The electrodeposition technique is used to construct a variety of electrode materials, in which thin and uniform coatings are deposited on a substrate by redox reactions in a short time. The morphology of the deposited film can be adjusted by controlling the temperature and the applied current density as well as the electrolyte composition [42].

Another approach to coating functional materials on substrates is to use physical processes such as sputtering and printing technologies, which are simpler than chemical processes. Sputtering technology can achieve the deposition of metals or complex oxides onto a substrate material, and the cost is relatively low. In addition, the most commonly used coating method is the inkjet printing or screen printing of various materials on a substrate surface, which can achieve low-cost large-batch electrode preparation with a specific pattern. Although inkjet printing is less efficient than screen printing, electrodes with two or three different materials can be fabricated simultaneously by applying the same voltage pair with a certain spacing of ink drops, which greatly saves preparation time [41].

3. Key Components of the Sweat Sensors

3.1. Sweat Transportation Channels and Collectors

The effective transportation of sweat is supposed to not only deliver sweat to the sensing area but also provide a comfortable skin environment. Then, a sweat collection device can quantify the sweat loss and sweat rate that affects the concentration of ions. In recent years, various types of microfluidic devices have been prepared to collect sweat, but their preparation processes are complex. Wearable microfluidic devices utilize biocompatible, low-modulus elastomeric (e.g., PMMA, PDMS and its derivatives) substrates to prepare sweat capture patches for the pristine capture and clean storage of sweat [43][44][45]. These type of sweat collection devices are fabricated using films and only collect the sweat produced by sweat glands in specific locations, which is less comfortable than textile-based sweat collection devices [46].

There are various strategies to fabricate sweat transportation channels and collectors based on textiles. For some textiles, the gaps between the fibers in the fabrics provide capillary channels where the liquid can be sucked along the thread [18]. Sweat transportation based on wetting gradients combined with the advantages of textiles and natural networks have been explored. Some Janus textiles, which imitate the asymmetric structure of a lotus leaf, have been used for sweat transportation, that is, a hydrophobic material is used on the side that touches the sweat to keep it dry, and a hydrophilic material is used on the other side to achieve the unidirectional transport of sweat to the collection device for substance detection [47].

3.2. Signal Selection Unit

Signal selectivity, as an important factor that affects the accuracy of a sensor, is the ability to resist the interference and disturbance from other substances in the detection environment. One way to eliminate the unwanted disturbance is to select the target substances that need to be detected and exclude the interference of other ions. Polyvinyl chloride (PVC) and PU have been reported to be ion-selective membranes (ISMs) [40][48] or ion-sensitive field effect transistors (ISFET). The corresponding ionophore, ion exchanger, polymer matrix and plasticizer are dissolved in a specific solvent and are then dried to form an ISM [49]. The ISM is deposited or coated on conductive yarns or fabrics as the electrodes, which can achieve a signal response to target ions without interference from other ions [50]. Textiles as electrodes have a hierarchical and porous structure, which facilitates the rapid diffusion of electrolytes and the efficient transport of ions and electrons [51]. Another way is that certain components or structures can act to block interfering substances. The limitation of ion contamination can be eliminated by employing alkaline conditions on the electrode surface, as the OH^{-} ions suppress the adsorption of Cl^{-} ions to the electrode’s surface [52]. Nanoporous polyamide (PA) membranes used as a substrate material can act as a biomolecular sieve, allowing only desirable biomolecules to travel to the sensor surface, thereby preventing interference from other factors and improving the accuracy of the sensor [53].

3.3. Sensing Element

The selection of the material and structural design of sensing elements for sweat sensors are vital, since they have direct impacts on the sensor’s sensitivity and electrical performance. The electrodes in sweat sensors, as crucial elements, especially for sweat sensors based on electrochemical methods, are mainly composed of either two-electrode systems (a working electrode (WE) and a reference electrode (RE)) or three-electrode systems (WE, RE and counter electrodes (CE)). Most sweat sensors respond to metabolites in sweat, and the principle involves the anchoring of enzymes to the WE. Therefore, the selection of the materials and structural design of the electrode has a great impact on the sensitivity and selectivity of the sensor. Traditional sweat sensors consist of screen-printed electrodes on rigid substrates such as glass or plastic. The rigid substrates restrict the flow of the capillary tube and have poor flexibility, which requires further consideration for their integration into clothing [30].

Natural materials are not conductive by themselves, but they can be used as electrodes by simple treatment or the doping of conductive substances. For example, He et al. [51] transformed silk fabrics into highly conductive, intrinsically nitrogen-doped, flexible and structurally maintained carbon textiles with a graphitic nanocarbon structure through thermal treatment. The treated silk fabric was used as an electrode with abundant active sites, facilitating electron transfer, the quick diffusion of electrolytes and efficient ion and electron transmission. Growing or coating conductive materials on natural threads or yarns is also an effective approach for integrating them into textiles.

The structure of electrodes or the sensing area of the sensors is important for sensor performance as well. For instance, the porous structure of mesoporous carbon results in a high electron transfer rate, which interacts with the GOx enzyme with an increased surface area and enhances the sensitivity to glucose [52]. AuNP-modified electrodes can improve the charge transfer rate and glucose sensitivity compared to common Au electrodes [54]. Designed electrodes based on textile structures have larger contact areas than traditional electrodes, which effectively improves the sensitivity of these electrodes.

3.4. Integrating Sensing with Communication Technologies

In recent years, many related sweat biomarker detection methods have been proposed. In order to identify the multiple biomarkers in sweat using wearable sensors in real time and in a portable manner, it is necessary to integrate sensing technology with communication and analysis technology on flexible printed circuit boards (FPCB) to realize the transmission of signals to external receiving devices for users to obtain the information. The most commonly used communication technology includes near-field communication (NFC) [55] and Bluetooth modules [49], although they are only suitable for close-range signal transmission. The advantage of NFC is that it does not rely on battery power to transmit signals wirelessly, but it can only be used at very short distances [55]. Bluetooth communication usually demands a high power consumption and needs to be combined with low-power instruments for proper operations [16]. These communication technologies can realize the internet-of-things approach of transferring data to the cloud [56].

Therefore, batteries play a key role in the stable operation of sensor in terms of communication. Traditional batteries, such as Li-ion batteries, coin cells, etc., have been rigidly compared with flexible batteries and are difficult to integrate into miniaturized sensors, which limits their application in wearable sensors. By combining them with self-powered batteries such as triboelectric nanogenerators (TENGs) [57], piezoelectric generator [58], biofuel cells (BFCs) [59][60][61], etc., the monitoring of sweat information can be achieved without an external power supply.

4. Applications in Wearable Sensors

4.1. Sweat-Quantity-Sensing Devices

Sweating is one way in which the body temperature is regulated [62]. The real-time monitoring of sweat volume or the sweat rate helps to evaluate the dehydration or abnormal sweating of athletes in high-intensity exercise and workers in extreme conditions. To achieve this, the sweat volume or rate can be directly measured by sweat transportation or collection. Li et al. [46] conducted plasma treatment on cotton thread to effectively improve its hydrophilicity and wicking ability, achieving a sweat delivery rate of 0.27 ± 0.03 cm/s. In addition, the effective combination of hydrophilic and hydrophobic materials to form a certain pattern can evaluate the sweat volume or rate. Zhao et al. [63] adopted hydrophilic cotton thread embroidered on a substrate of hydrophobic cotton fabric in the form of color blocks as microchannels and micro-reservoirs for sweat collection and detection.

4.2. Ion-Sensing Devices

Sweat contains a large number of micronutrients such as Na^+, Cl^-, K^+, Ca^{2+}, etc., which endow sweat with natural, safe and reliable electrolyte properties. These ions have a tight connection to the heart rate, blood pressure, cardiovascular function, muscle contraction, enzyme activation and bone development in humans [34][38]. The concentration of Na^+ is the highest among all the ions, with a typical value of 38 mmol/L [64]. Therefore, changes in the Na^+ concentration in sweat can enable the monitoring of heat stress and the detection of various diseases such as hyponatremia and cystic fibrosis, which can provide important information for clinical diagnosis [65].

The most-used detection method for detecting the change in ion concentration in sweat is the electrochemical method, which uses ion-selective electrodes (ISE) to detect the target ions. Kil et al. [66] printed serpentine-patterned Gr/ecoflex electrodes onto socks, which showed a high conductivity and stable resistance under a strain of 150%. A Na^+-ISM was drop-cast onto this Gr/ecoflex electrode, which could exhibit an excellent response to the Na^+ concentration under different motion states. Similar toISMs, binding ion-specific receptors is a way to detect target ions. Ghoorchian et al. [65] used $Na_{0.44}MnO_2$ as the sensing material to monitor Na^+ in sweat, which enabled the observation of a stable potentiometric response for Na^+. Combined with a microcontroller-based circuit integrated into a headband, a wireless transceiver could be used to real-time monitor the Na^+ during exercise activity. Ag/AgCl can also be used as an electrode to measure sweat Cl^- levels directly [67][68]. Possanzini et al. [67] coated PEDOT: PSS onto four different types of threads to enable the threads to exhibit a semiconductor behavior and then deposited Ag/AgCl onto these threads with semiconductor behaviors as specific receptors, which could respond the current of the threads with the change in the Cl^- concentration without performing output signal processing or correction. In addition, AgCl exhibits a reproducible and well-defined electrochemical potential with respect to a RE, which depends on the concentration of Cl^-. Mo et al. [34] prepared core–sheath yarns using nylon yarns as the core layer and PAN/PVP/valinomycin nanofibers as the sheath (PPVN yarns). The hydrophilic PPVN yarns were woven with hydrophobic polyester yarns to form a plain fabric so that the sweat was completely confined in the PPVN yarns, which helped to obtain a stable and accurate signal. Among them, the PPVN yarns as a specific receptor for K^+, the valinomycin was highly selective for K^+ and generated the corresponding potential.

4.3. pH-Value-Sensing Devices

The pH value of sweat in a healthy human usually varies from 4 to 7, which has become one of the biomarkers for monitoring exercise intensity [1]. It has been reported that there is a relationship that exists between the pH value and the concentration of Na^+ [69]. The higher the pH, the greater the concentration of Na^+. A colorimetric approach is always used for sweat pH measurement. Screening this color change by the naked eye or via a spectrometer can enable the monitoring of sweat status in real-time during exercise. It is often valuable to use color-changing materials blended into a textile to monitor the acidity of sweat. This method involves a pH-sensitive dye and halochromic materials, which change color depending on the pH of the sweat. These materials are polyelectrolytes possessing acidic or basic groups in their structure, which will either accept or release protons depending on the environmental pH [70][71].

In addition to conventional pH indicators, pH-sensitive dyes have been reported recently, including bromocresol purple (BCP), nitrazine yellow (NY), anthocyanins [28][72], tricyanofuran hydrazones [73], a mixture of bromocresol green (BCG) and methyl orange (MO) [74] and so on. Most synthetic dyes are halochromic dyes, which have adverse effects on the environment and are also allergenic to humans [71]. Adding hydrophilic materials such as CS, cellulose, GO or porous structures of materials can boost their sensitivity and shorten their response time dramatically. Prophet et al. [74] deposited CS, sodium carboxymethyl cellulose (NaCMC) and dye (a mixture of MO and BCG) on cotton fabric in sequence and added CTAB to fix the dye to prevent fading caused by the interaction between the positively charged amino group of CS and the negatively charged indicator dye. The L* a* b* space model was used to quantify the color change, where the value of L* represented the brightness, while the values of a* and b* represented the distance along the red–green and blue–yellow axis, respectively.

4.4. Glucose- and Lactate-Sensing Devices

It has been found that sweat glucose can directly reflect the blood glucose level [75]. Especially for diabetes patients who need to monitor their blood glucose level frequently and need targeted treatment, non-invasive monitoring is very important. Glucose is found in the concentration range of 0.02–0.6 mM in human sweat [52]. Monitoring lactate can prevent muscle soreness, pain and cramp during exercise [74][76]. Lactate and glucose sensors are usually enzyme-based (glucose oxidase (GOx), glucose dehydrogenase (GDH) and lactate oxidase (LOx)) sensors that respond to lactate and glucose concentrations by electrochemical measurements [51][77]. Therefore, a fabricated electrode is essential for lactate and glucose sensors, which can be integrated into yarns or fabric.

Therefore, non-enzymatic sensors have been explored to overcome these problems during the detection of the glucose or lactate level. Several noble metals (e. g. Pt, Au) have been developed for the preparation of non-enzymatic sensors. Au structures exhibits excellent poison resistivity for the electrooxidation of glucose due to its large specific surface area and highly active binding sites on the particle surface [12][78]. Cu-based glucose sensors have attracted much attention due to their low cost and easy implementation, making them suitable as non-enzymatic alternative materials for glucose sensing [79][80]. This is due to the obvious redox reaction between Cu materials and glucose.

4.5. Other Sweat-Biomarker-Sensing Devices

Cortisol is recognized as a stress hormone [81][82]. The concentration of cortisol in sweat changes during human daily activities [81], so it is necessary to monitor the change in cortisol concentrations in real time. The textile-based sweat sensor detection of cortisol includes enzymatic and non-enzymatic methods. Some inorganic compounds such as ZnO, TiO_2, SnO_2, Fe_2O_3, MoS_2, etc., have been reported as enzyme-based cortisol sensors [15][37][83][84]. For example, Sekar and co-workers proposed cortisol sensors by coating Fe_2O_3 [83] and ZnO NRs [37] on the surface of flexible conductive carbon yarns (CCY), which exhibited a wide linear detection range and mechanical stability. In addition, ZnO NRs/CCY used as electrodes showed good biocompatibility, which could be more safely used in wearable sensors. Kinnamon et al. [15] used MoS_2 nanosheets functionalized with cortisol antibodies as recognizable receptors. When cortisol was bound to the surface of the MoS_2 nanosheets, the surface charge changed, and the change in the cortisol concentration could be obtained from the change in the impedance. Non-enzymatic sensors are mainly based on molecular imprinted polymers (MIPs) or recognizable receptors interacting with cortisol. As a kind of MIP, poly (glycidylmethacrylate-co ethylene glycol dimethacrylate) (poly (GMA-co-EGDMA)) can be used for the stable detection of cortisol [14][81].

Urea is an important marker of the status of the human kidney. Clinical studies have shown that the uric acid concentration in sweat is highly correlated with that in the blood [85]. The direct carbonization of PAN nanofibers can produce carbon nanofibers with an oriented graphitized layer structure, which can be directly used as a working electrode for uric acid detection and contribute to the rapid transmission of electrons [85]. Different carbonation temperatures will affect the accuracy of uric acid content detection. When the carbonation temperature is 1000 ℃, the uric acid molecules in sweat can be detected sensitively. A certain concentration of urease and phenol red were successively coated on a cotton thread coated with CNF and CS-GO [18]. When the urea in sweat came into contact with the cotton thread, it changed the PH value of the cotton thread, resulting in a significant color chan

4.6. Sweat Self-Powered Batteries

Wearable electronic devices generally require a power supply to work, while the development of self-powered batteries using sweat enables signal detection without an external power supply. Recently, textile-based batteries powered by sweat, including BFCs derived from the electrochemical reactions in sweat, liquid–solid contactTENG and humidity driven electric generator, have been developed. The acquisition and conversion of these energies are environmentally friendly and sustainable, and they are promising for powering miniature electronics. The metabolites in sweat, such as glucose, lactate and alcohol, react electrocatalytically with enzymes or microbes to produce energy and are used as BFCs to sense biomarkers and power electronic devices [59][60][61].

Solid–solid contact TENG systems for wearable sensors have been widely developed, which are only suitable for converting mechanical energy to electrical energy [86][87]. On other occasions, liquid–solid contact TENG systems have been established according to the change in ion concentration or sweat evaporation. Sweat-activated batteries based on the electrolytes in sweat have been developed in recent years and have the potential to be used in self-powered wearable textiles [88].

5. Conclusions

Massive developments in textile-based sweat sensors have shown the great potential for traditional textiles in the field of wearable electronics. As shown, textile-based sweat sensors have unique structures, a high flexibility and good air permeability, thus giving users a better wearing experience. The main components of textile-based sweat sensors and their roles in the sensors were investigated. Several mechanisms and functions of sweat sensors in detecting biomarkers were also briefed. The flexible combination of functional materials and textiles has made great progress in the development of sweat sensors.

Human sweating depends on race, body parts, environmental temperature, physical activity and other factors. Sweat sensors are challenging for the long-term monitoring of users who have dry skin and do not sweat easily. This means that a sweat sensor with a lower detection limit is in demand. Next, the effective combination of physical and sweat sensors helps to comprehensively reflect the human body’s condition. Furthermore, the preparation of most sweat sensors is still in the laboratory testing stage, and efforts are still required to turn them into reliable commercial products. Therefore, the combination of sensing with communication and analysis technology demands more attention. The improved wireless communication range facilitates real-time and continuous signal acquisition during events such as competitions. At the same time, the integration of communication and analysis components should not affect the sensing performance and flexibility.

At present, there are several problems blocking wearable sweat sensors from being transformed into reliable commercial products. Firstly, the preparation process and material selection of the sensors lacks consideration of sustainability and environmental friendliness. In most cases, the substrate materials are synthetic materials, which can produce uncomfortable reactions and poor degradation when in long-term contact with skin. It has become a trend to develop natural materials for the preparation of wearable textile-based sweat sensors. Apart from the comfort of wearing a sweat sensor and the sensitivity of sweat detection, it is also necessary to consider whether human movement and environmental changes in the wearing process will affect the detection performance and sensitivity. Secondly, electrochemical sensors need to be calibrated repeatedly and frequently due to individual differences, making it inconvenient for public users. Next, for the preparation of non-enzymatic sensors based on electrochemical detection methods, the preparation of electrode materials with low cost, good stability and good performance is yet to be explored. Lastly, the long-term stability and durable performance of sweat sensors needs to be emphasized, since it is common that sweat sensors become unstable and inaccurate after prolonged use or being contaminated by sweat. This leads to a followed issue of the improper disposal of colorimetric sensors, showing poor environmental protection and sustainability consideration.

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