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A Literature Review on The Principles, Research Status, And Development Trend of Wearable Sensors

Hannah Owusu Ansah[1], **Daniel Karikari Frempong**[2], **Gabriel Oduro Asirifi**[3]
[1,2] School of Optoelectronic Engineering, Hubei University of Automotive Technology, Shiyan 442002, China
[3] School of Automotive Engineering, Hubei University of Automotive Technology, Shiyan 442002, China

Abstract- Wearable sensors have emerged as a transformative technology in healthcare, sports, and fitness, enabling continuous monitoring of physiological and environmental conditions. Advances in stretchable substrates, microfluidic channels, and skin-integrated electronics now facilitate real-time, high-fidelity information from the human body. Integration into textiles and garments has led to the development of smart e-textiles with sensing capabilities for motion, pressure, and sweat composition. These systems operate on principles such as piezoresistivity, piezoelectricity, electrochemistry, and triboelectricity, converting physical or chemical stimuli into quantifiable electrical signals. As self-powered platforms, they minimize reliance on conventional batteries, enabling energy-autonomous sensing. Consequently, extensive research efforts are ongoing to innovate and overcome current limitations in wearable sensor technologies. This literature review explores the fundamental principles, current research status, and development trends of wearable sensors, with a focus on their integration into smart textiles, flexible electronics, and real-time health monitoring systems. Despite remarkable progress, challenges remain in sensor durability, data accuracy, energy management, and large-scale manufacturing. Nonetheless, the integration of flexible electronics, artificial intelligence, and Internet of Things (IoT) infrastructure continues to propel wearable sensors toward broader applications in telemedicine, ageing care, industrial safety, and human–machine interfaces. Importantly, this work serves as a blueprint for researchers, engineers, and policymakers committed to advancing wearable sensor technologies toward practical, scalable, and human-centric applications.

Keywords – Wearable sensors, triboelectricity, piezoelectric, nanogenerators, e-textile.

I. INTRODUCTION

Over the past decade, wearable device technology has grown remarkably, driven by advances in materials science, electronics, data science, and the expanding need for non-invasive, continuous monitoring of human behavior and health [1-3]. One of the most transformative components of this field is the wearable sensors, which are compact, lightweight, and often flexible electronic devices capable of detecting a wide range of physical, chemical, and biological signals directly from the human body [4, 5]. These sensors have been widely used in medicine and health to measure various physiological parameters of the human body, such as body temperature [6], electromyography [7] heart rate and blood glucose [8]. Beyond healthcare, sensors can detect different states of motion of the human body, including acceleration, muscle extension, and foot pressure.

With the advent of smart living and precision medicine, wearable sensors are increasingly recognized as a cornerstone of modern digital health strategies. In the context of today's fast-paced clinical environment and growing demand for non-invasive point-of-care testing, wearable sensors offer an attractive solution for early diagnosis and treatment, remote monitoring, and personalized health management [9]. Their incorporation into everyday objects such as wristbands, clothing, spectacles, patches, and skin-like electronics are part of a larger Internet of Things (IoT) ecosystem [10, 11]. As low-power electronics, wireless communication standards (Bluetooth Low Energy, NFC, and 5G), and high-throughput data processing methods evolved, wearable sensors went from proof-of-concepts in the research space to commercially available products, notably in the field of personalized and preventive medicine [12].

As a result, both research activity and market momentum of wearable sensors have grown significantly over time. Over the past three decades, more than 62,181 research publications have focused on wearable sensors. For instance, from 2015 to 2017 (emerging phase) had 4,515 articles, the tempo phase (2018 to 2021) has 11,553 articles, whereas the rapid growth phase (2022 to 2026) has 14,960 articles and increasing (see Fig.1a). This is attested from figures extracted from Scopus database, where wearable sensors increased among Chinese scholars, the United States, India, the United Kingdom, South

Korea, Italy, Japan, Germany, Canada, and Australia (see Fig.1b). However, according to Grand View Research, the global wearable technology market was valued at USD 84.2 billion in 2024 and is projected to reach USD 186.14 billion by 2030, registering a CAGR of 13.6% during the forecast period of 2025 to 2030. This rise is attributed to the growing prevalence of chronic diseases like diabetes and hypertension, growing awareness among individuals towards personal health, and the need for continuous monitoring during pandemics like COVID-19 [13]. This indicates the huge market demand for wearable sensors with innovative functionality in academia and industries. Because of their wearability, multifunctionality, and capability to enhance real-time decision-making in performance and health, wearable sensors have become a flagship cross-disciplinary research area. Thus, this review addresses the operational principles, materials, and research progress of wearable sensors, as well as future development trends of wearable sensors across domains such as healthcare, fitness, and smart textiles.

Additionally, it also highlights remaining challenges such as scalability and cost, and proposes strategies for optimizing the design and performance of next-generation wearable sensors.

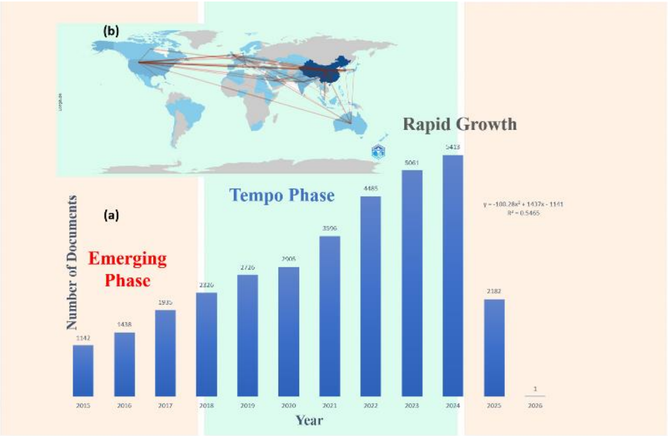

Fig. 1. Schematic example of a smart home.

II. PRINCIPLES AND MECHANISMS OF WEARABLE SENSORS

Wearable sensors are primarily designed for continuous, real-time sensing and transmitting of physiological, biomechanical, or environmental signals through non-invasive or minimally invasive devices that are attached on the body or integrated within clothing, accessories, or skin-like substrates (see Fig.2a). These sensors function by converting a physical or biological stimulus into an electrical signal that is processed, analysed, and transmitted wirelessly to external devices for interpretation and decision-making [5]. The principles and mechanisms of wearable sensors are diverse and specific to certain physiological signals and application contexts. Figure 2 (b-e) shows the four main sensing mechanisms: resistive, capacitive, piezoelectric, and triboelectric.

For instance, Ali et al. [14] categorize wearable sensors into piezoelectric, electrostatic, and thermoelectric, having various working principles. Piezoelectric sensors generate electrical signals in response to mechanical stress, electrostatic sensors to electrical field variation, and thermoelectric sensors to temperature gradients. These mechanisms are employed in detecting various health states, with emphasis placed on material properties and transduction techniques.

Hussain et al. [15] Investigated respiration sensors, which operate primarily on principles of sensing airflow or mechanical movement corresponding to breathing. The materials and fabrication processes are tailored to attain optimum flexibility and sensitivity for specific respiratory monitoring in wearable systems. Thanks to the incorporation of nanocomposite materials along with elastomers, the sensors can easily monitor small variations in strain or pressure during the process of inhaling and exhaling. The flexibility offered by these devices means that the sensors can adhere to the skin or be embedded into smart clothes without hampering any movement on the part of the user. In addition, the significance of signal transduction, including methods like piezoresistivity or capacitance, has been highlighted by the scientists in order to ensure that all kinds of respiration processes are registered.

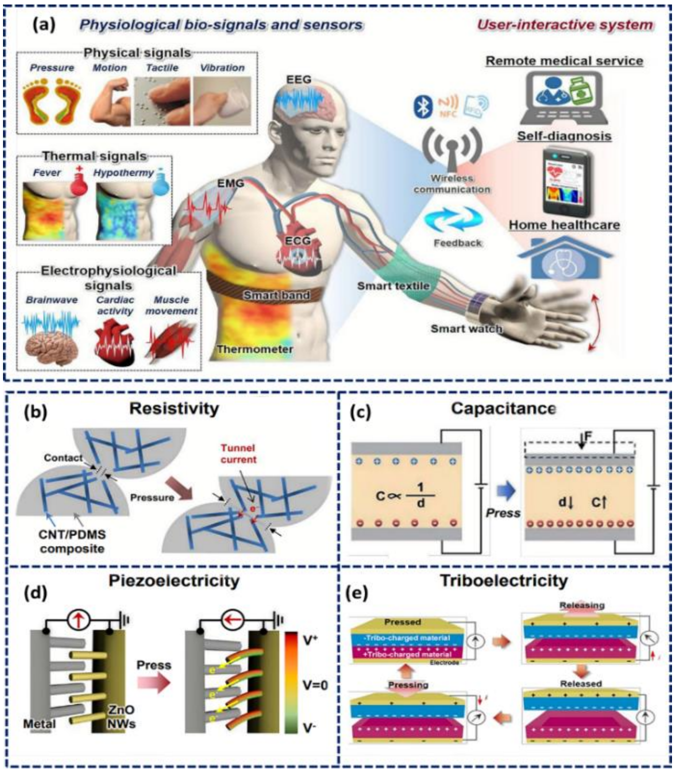

Fig. 2. (a) Physiological bio-signals in the human body and corresponding wearable sensors with user-interactive systems

[16]. (b) Principle of wearable mechanical signal sensors: (i) Piezoresistive sensor [17] (ii) Capacitive sensor [18] (iii) Piezoelectric sensor [19] , and (iv) Triboelectric sensor [20]

III. APP DEVELOPMENT TREND AND APPLICATION AREAS

In recent years, with the leading forces of material science, electronics, and microfabrication technologies, wearable sensors have evolved toward miniaturization, flexibility, low power, and intelligence [21]. Meanwhile, the limitations of single-signal monitoring have become increasingly apparent, and multi-channel wearable sensing systems are emerging as a future development trend. The Current research in wearable sensors focuses heavily on the development and exploration of novel flexible materials. In addition, material composite technologies allow the integration of multiple material properties, enabling the fabrication of flexible sensors with enhanced performance [22]. Historically, numerous materials, including metal materials, carbon materials [23], two-dimensional (2D) materials [24], and hydrogel materials [25], have been pivotal in the development of flexible sensors. This section addresses both the new development trends that are shaping the next generation of wearable technologies and the application domains where these new developments are making a significant impact. A thorough understanding of wearable sensor trends and applications provides a solid foundation for analyzing the field’s ongoing growth and future potential.

A. Health care

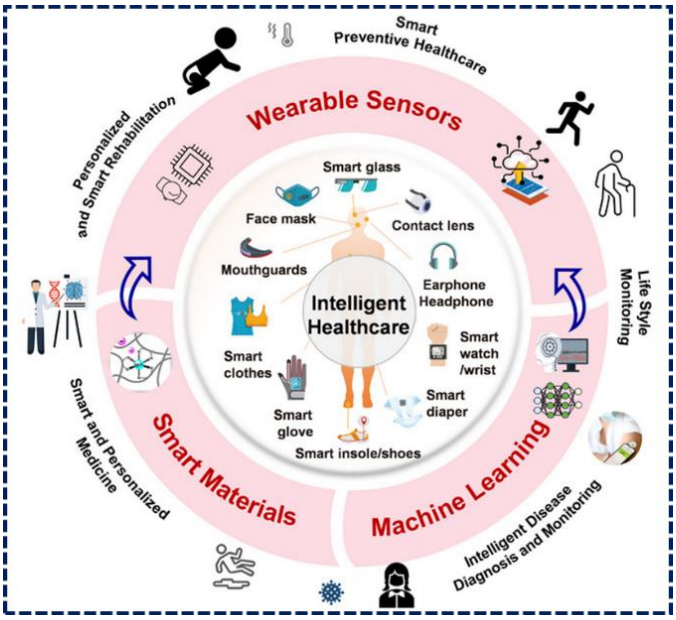

Fig.3. Smart materials and wearable sensors for intelligent healthcare [26]

In intelligent healthcare systems (see Fig.3), wearable sensors enable the continuous collection of real-time physiological data without disrupting daily lives [26]. Their continuous operation, minimal invasiveness, and ability to target a wide range of biomarkers make wearable sensors suitable for various biomedical applications, such as monitoring lifestyles for preventive healthcare, tracking drug metabolism for smart medicine, and assessing physiological parameters for disease diagnosis and treatment by quantifying signals from the skin [27, 28]. This enables early warning systems that alert both users and medical personnel to physiological anomalies, allowing timely intervention. Various nano-tech-based wearable devices have been developed for different purposes, including heart rate, perspiration, and blood pressure monitoring in advanced healthcare.

B. Heartbeat monitoring

The human heart is an essential organ, whose function observation is critical to help in the transmission of blood through the blood vessels. Effective observation and measurement of the heartbeat is achieved by the heart rate, which, according to Rajendra et al. [29], is the measure of the “number of contractions per minute (bpm)”. For this purpose, the human skin is fixed with an electrode such that the electrocardiogram (ECG) can be recorded from the heart rate [30]. The monitoring of these body vitals is considered to be a unique indicator of the body's health condition or wellness [31]. Hence, the discovery of carbon nanotubes (CNT) [32] and graphene has enhanced the capability to make use of nanostructures for sensing, primarily piezoresistive sensors [33].

Based on this premise, the invention, design, and integration of smart devices or sensors create a potent tool to facilitate real monitoring of the heartbeat in an effort to understand the psychological reaction, breathing, and heart condition of the individual. For example, they are critical indicators for observation in monitoring the training performance of an athlete [34]. The use of nano-fibers for wearables, according to [35, 36], efficiently records precise electrical signals of the heart that can be processed digitally. To measure the physiological signals of the athlete's human heart, a recent study by Tang et al. [36] prepared a nanoparticle-doped graphene film, which was incorporated into clothing in the form of a heart rate sensor module. Its preparation made heavy use of graphene due to the fact that it has unique mechanical characteristics, qualifying it as an apt material for strain sensors [37]. Results show that the porous graphene film (PGF-2), composed of 20 percent nanoparticles as its pore template, exhibited increased sensitivity towards low pressure and improved stability.

These characteristics render it effective in real-time recording of the signals. Pursuing the use of graphene, a past study by [38] reported on the fabrication of a graphene-based textile used for ECG monitoring (Fig. 4a,b). Here, vacuum filtration was used to reduce graphene oxide for the flexible graphene textile. The findings demonstrate high sensitivity, good impedance ranging from 116.2 KΩ to 24.7 KΩ, good electrical performance and excellent long-term monitoring even under wet conditions. In another work by Romero et al. [39], porous flexible nano-graphene was fabricated on a substrate using a low-power laser diode as an electrode for ECG monitoring. The use of porous graphene, according to [40], is largely attributed by their high electrical conductivity, which can be initiated via a photothermal process at the surface of carbon-concentrated materials.

During the experimental process, the flexible polyimide substrate comprises an electrophysical electrode, in which negative and positive terminal electrodes are respectively positioned at the right and left wrist. This was employed together with a clustering algorithm to probe for monitoring and recording the heart rate signals. The results show that the interface skin electrodes (Fig. 4c,d) have an unmistakable contact area that is due to the porosity of the material. Additionally, out of 70 R-peaks, the electrodes detected 66 R-peaks, with an accuracy of 94.3% in heart rate monitoring (Fig. 4e). Apart from the use of graphene as a material with high efficiency in fabricating electrodes, carbon nanotubes (CNT) are also some of the possible materials utilized for nanostructures for sensing applications. For effective electrocardiogram (EKG) monitoring on stretchable textiles (see Fig.4f), Taylor et al. [41] fabricated a carbon nanotube (CNT) fiber or threads by dip coating in CNT ink.

The fabricated CNT threads are non-toxic, have excellent contact impedance with skin, and it is relatively electrically conductive and strong [42, 43]. These CNT threads are sewn onto stretch clothing using zigzag stitches. Experimental tests revealed the ability of the threads to withstand greater flex fatigue, have high tensile strength, low interfacial impedance, and electrical conductivity, to detect and trans single from the human body. In a different approach, CNT (with excellent mechanical, thermal, and electrical properties), and polydimethylsiloxane PDMS due to its optical transparency, flexibility, and elastic properties, were combined for use as a dry electrode.

C. Sweat monitoring

Sweat is typically a biological fluid produced from the pores of the human body. These are typically managed in order to observe human health conditions and thus provide the electrolyte balance, hydration, and protein level, among others. The physical and mental well-being of an individual can be determined by the biochemical information of sweat produced by the human body [44]. For example, sweat from diabetic patients can be used to detect glucose levels [45].

The advancement of wearable devices with electrodes produced using nanoparticles has increased the sensitivity of sweat sensors. This is because the structures have a high specific surface area relative to traditional conductive materials [46]. The wearables can be used close to the skin for non-invasive, pain-free, non-destructive, and real-time sensing and monitoring [47]. Materials such as metal oxide and carbon-based nanomaterials are frequently used for sweat metabolite electrochemical sensors due to the fact that they possess good electrical and chemical properties, good sensitivity, and conductivity [48].

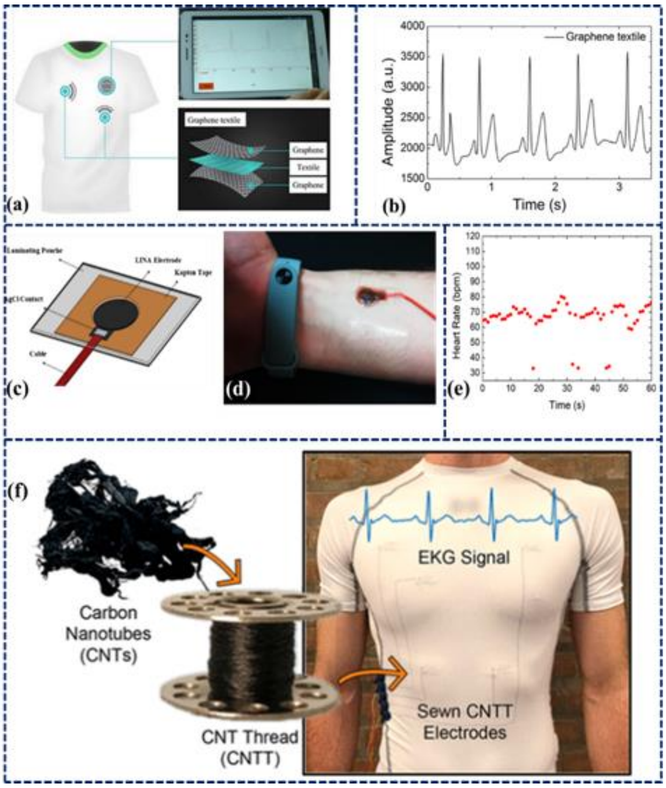

Fig. 4. (a) Design and application of the graphene textile. (b) ECG signals of the graphene textile [38]. (c) Flexible electrode schematic. (d) Image of a forearm attached with a flexible electrode (e), RS-peaks frequency shows the heart rate over time [39] (f) Stretchable clothing for effective monitoring of electrocardiograms [41]

Studies have been conducted using different nanomaterials for wearables that have direct interfacing with the skin surface in sweat monitoring. Glucose was detected in sweat using a stretchable biosensor prepared from reduced graphene oxide nanocomposites [49]. During the experimental process, electrostatic assembly was employed to fabricate graphene oxide onto silicon dioxide (SiO2) nanospheres, which were reduced to electroactive rGO/SiO2 nanocomposites with the assistance of tannic acid. The sensor possessed a sensitivity of 60.8 µA mM–1 cm–2 and a linear detection range from 0.1 to

9 mM towards glucose in sweat. In another study, CNT electrodes were used in the fabrication of a wearable sweat sensor as shown in Fig.5a [50]. Here, a solid-state ion-selective electrode responsive to Na+ ions was fabricated using CNT electrodes by depositing a plasticized poly(vinyl chloride) doped with ionophore and ion exchanger coating over it. The sensor is 58 mV/decade sensitive and shows a response of 57s due to its reliability, stability, and flexibility. Guan et al. [51] reported a very sensitive biosensor for the measurement of the concentration of ethanol in sweat, because an irregular quantity of ethanol in someone's biofluids can be linked to health issues from internal illness.

Here, gold nanowire aerogel was employed in fabricating the sensor through a substrate-assisted growth process. Using a 0.01 and 0.5 M range of ethanol concentration, the bioelectrode developed exhibited rapid and efficient linear current responses. In 2017, Munje et al. [52] demonstrated a functionalized antibody wearable sweat sensor. Fig.5c depicts that sensing arrays are constructed with nanoporous polyamide membranes as substrates and capture probes (antibodies) immobilized in room temperature ionic liquid (RTIL) for improving the stability of antibodies. The sensing platform enables the first-ever simultaneous detection of IL-6 and cortisol in human sweat. Although competitive immunosensing is highly sensitive, its complex sensing protocols make it difficult to comply with wearability requirements.

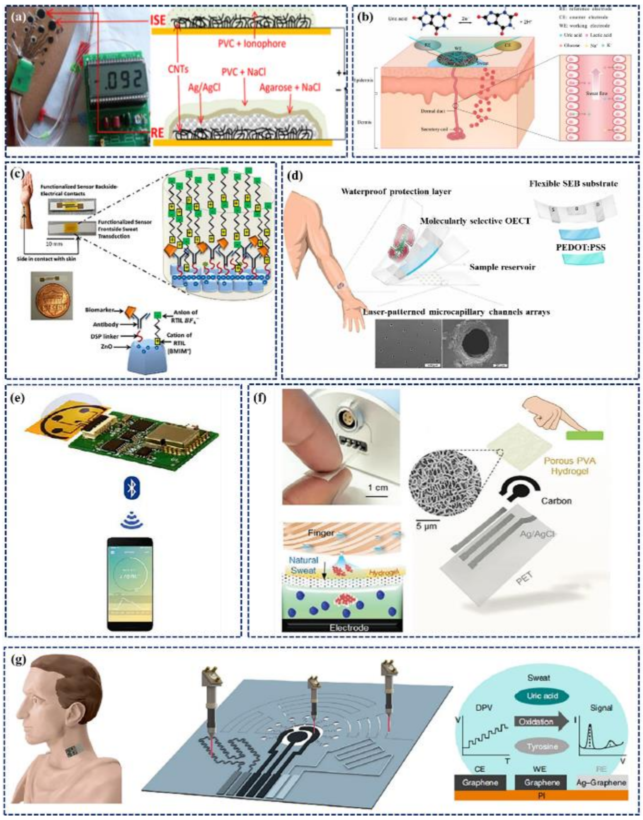

Fig. 5. (a) CNT-based solid-state ISE and RE for sweat analysis [50] (b) Schematic illustrations of sweat gland structure, biomarker secretion, and wearable biosensor for uric acid detection in sweat [54] (c) A wearable sweat sensor based on room-temperature ionic liquids, enabling the detection of interleukin 6 and cortisol in sweat [52] (d) A wearable organic electrochemical noninvasive cortisol-sensing device based on molecularly selective nanoporous membranes [53] (e) A graphene-based wearable sweat sensor for sweat cortisol detection [55] (f) A fast, stress-free MIP-based cortisol sensing sensor [56] (g) A wearable laser-engraved sensor for the sensitive detection of uric acid and tyrosine in sweat [57]

As shown in Fig.5d, Parlak et al. [53] fabricate an organic electrochemical transistor (OECT), which uses an artificial recognition membrane of molecularly imprinted polymers (MIPs) as a specific recognition element. The limitations of OECTs, which are not suitable for the detection of cortisol since they are uncharged at physiological pH, were overcome. Stable and selective molecular recognition of cortisol in sweat is facilitated on this sensing platform. Yet, such MIP-based sensing will normally entail lengthy physical exertion or other iontophoretic sweating gland stimulation for sweat collection, which can increase users' psychological stress and thus alter cortisol levels, leading to stress assessment inaccuracy.

As such, Tang et al. [56] designed a wearable touch-activated cortisol sensor (see Fig.5f) with a porous perspiration-wicking permeable polyvinyl alcohol (PVA) hydrogel, which allows efficient and fast sweat collection. Molecularly imprinted polymer (MIP) electrochemical sensor technology was utilized to achieve fast, simple, and stable detection of sweat cortisol through highly selective conjugation with a cortisol-imprinted electropolymerized polypyrrole coating. The sensing platform was experimentally proven to have significant advantages over standard cortisol measurement in capturing sudden changes.

Similarly, graphene, due to its very large surface area and high mobility of electrons, shows improved performance in electrochemical sensing. In this regard, [55] created a wireless sensing device founded on laser-induced graphene integration and a competitive immunosensing strategy for the rapid, dependable, sensitive, and noninvasive monitoring of the stress hormone cortisol (Fig.5e). As a result of the study, the first circadian cycle of cortisol and dynamic stress response curves constructed from human sweat were introduced, and a considerable empirical relationship between serum and sweat cortisol was established. To measure uric acid and tyrosine in sweat at low concentrations, Yang et al. [57] fabricated a laser etched sensor composed of graphene with high accuracy and rapid response under differential pulse voltammetry (DPV) to assess ultralow uric acid and tyrosine concentrations from the peak oxidation current amplitude as demonstrated in Fig.5g.

D. Blood pressure monitoring

Monitoring of one's blood pressure (BP) is important since it allows for early detection of hypertension and is a causative agent for deadly cardiovascular diseases worldwide. Consequently, wearable electrochemical nanosensors have been developed for hypertension biomarkers that, according to Madhurantakam et al. [58], have exhibited a high surface area to volume ratio, high sensitivity, and fast response rate. These properties help in the identification of hypertension biomarkers such as uric acid, cortisol, nitric oxide, galectin-3, ghrelin, leptin, adiponectin, and nitric oxide, amongst many others. Around 1.4 billion people are afflicted with arterial hypertension; hence, technological progress is urgently needed for timely and effective detection. According to Ismail et al. [59], arterial catheterization, being the most effective technique for monitoring blood pressure continuously, is, however, invasive and typically reserved for patients who are critically ill. Besides that, sphygmomanometers offer a lesser invasive technique of blood pressure measurement, albeit there are some limitations there such as being non-portable and giving intermittent readings [59]. Due to the properties of nanomaterials, studies have emerged regarding the production of wearable sensors, which are portable, non-invasive, and provide real-time data on measuring blood pressure in the human body.

For instance, Ai et al. [60] fabricated a highly shaped and sensitive flexible pressure sensor based on reduced graphene oxide, which is inserted between two thin flexible polydimethylsiloxane (PDMS) sheets. The results show that, following 20,000 cycles of loading and unloading, the sensors displayed excellent stability. They also displayed a high sensitivity of 50.9 per kilopascal between 3 to 1000 Pascals and a fast response rate of 50 milliseconds for effective monitoring of blood pressure. The electrocardiogram (ECG)-derived pulse arrival time and the blood pulse wave can be applied for continuous blood pressure monitoring. As such, Kim et al. [61] printed a paired stretchable sensor with an accelerometer and ECG electrodes to monitor the blood pressure (see Fig.6a). Silver nanoparticle ink was fabricated here by aerosol spraying and direct printing methods.

The accelerometer and the ECG electrodes were attached to the right wrist and the chest, respectively. Results show that the accelerometer was used to capture the pulse waves, and the blood pressure and ECG signals were captured using the electrode. In another study, Kireev et al. [62] reported a wearable graphene bioimpedance electronic tattoo for real-time and effective arterial blood pressure monitoring in another experiment. Results showed that with an accuracy of 0.2 ± 5.8 mm Hg and 0.2 ± 4.5 mm Hg for systolic and diastolic pressure, respectively, the designed bioimpedance platform is able to track blood pressure non-invasively and in real-time. Triboelectric, piezoresistive, capacitive, and piezoelectric transduction mechanisms can be made for use as flexible sensors to capture electrical signals from the skin of humans for monitoring BP [59]. For example, piezoresistive sensors operate under an activation-induced resistance change. A flexible piezoresistive sensor (FPS) patch system, as illustrated in Fig.6b, was designed for cuffless blood pressure monitoring by employing epidermal electrocardiogram and piezoresistive sensors (refer to Fig.6c) [63].

In the present work, three epidermal ECG electrodes were embedded with the FPS consisting of a carbon black ornamented fabric. Results show that the proposed sensor is capable of tracking the minute variation of physiological signals at an ultralow power consumption level of 3 nW. The FPS can capture precise pulse waveforms due to its high response rate, sensitivity, and 0-35 Kpa linearity range. Park et al. [64] designed a highly flexible piezoresistive pressure sensor with robust conductive electrodes made of highly elastic and structured CNT thin films. The sensor demonstrated a response time of < 20 ms and 12,800-fold pressure sensitivity when employed as a wearable sensor on human skin (see Fig.6d).

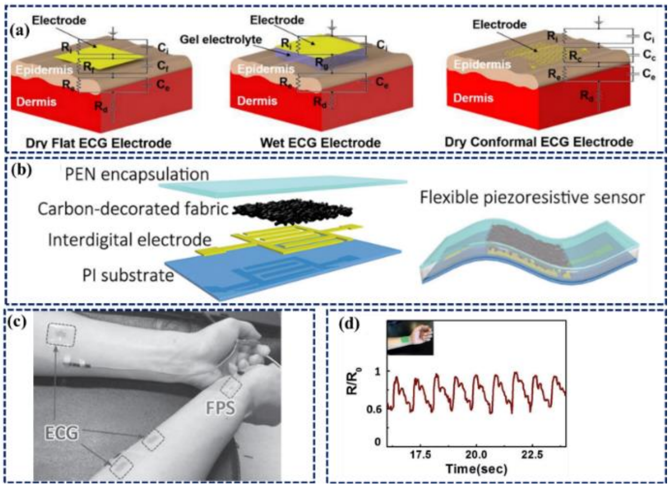

Fig.6. (a) Schematic models of electrode-to-skin interface of three different electrode types for ECG measurement [61] (b) Schematic structure of the FPS (c) Sensor patch system containing FPS and epidermal electrocardiogram (ECG) sensors [63] (d) Pressure sensor was placed on the radial artery of the wrist demonstrating pulsatile blood flow detection [64]

E. Textiles and Clothing

Wearable textiles are electronic textiles or smart textiles that combine and integrate electronic technology into clothing for effective sensing, tracking, and monitoring [65]. These new materials integrate electronic components like microcontrollers, actuators, and sensors into textiles, enhancing their applications. Kan et al. [66] assert that such fabric can sense, react, and adapt to external stimuli. This enables wearable textiles to perform key functions like energy generation, feedback, and monitoring the vitals or signals of the human body, among others. The working principle of wearable textiles is that electronic feedback process is received from stimuli, with or without sensing (concerning light, sound, heat, and touch) from the physical environment, where this sensed stimulation is processed and transformed into quantitative data for efficient analysis [67, 68]. Based on these unique principles and components, wearable textiles have several advantages that are significant for users to fully explore their functionality for various applications. Continuous monitoring of physiological changes and vital signals is a significant advantage of wearable textiles, which finds applications in healthcare.

This approach has greatly transformed the disease management and patient care, since these wearable textiles equipped with electronic components monitor, track, and record data in real-time on critical vital signs from the human body. These data are then transmitted to their respective healthcare provider for quick detection and timely interventions to save the lives of users. Key examples include an integrated belt sensor system developed to measure the respiratory cycle for easy detection of hypopnea/apnea, and a textile-based humidity and temperature sensor was developed [69] and a smart glove system with a transcutaneous electrical nerve stimulator was proposed to stimulate the meridian point on the palm for treating hypertensive disease

F. Sports and Fitness

The integration of wearable sensors into fitness and sports applications has garnered extensive interest throughout the past few years, driven by advancements in sensor technology, wireless communication, and low-power circuit design [70, 71]. They have made it possible to create small, low-power devices such as smartwatches, chest straps, or clothing, and can offer continuous physiological and motion sensing (such as heart rate, oxygen consumption, body temperature, acceleration, joint angle, and muscle activity) that are crucial to enhance sport performance and preserve health and fitness [72]. Thus, the collected data aids in the optimization of training intensity, improvement of sport performance, and prevention of injuries by enabling the early identification of fatigue or aberrant biomechanics [73], for example, can capture 3D motion for running gait or extremity movement analysis in real time, providing athletes and coaches with valuable information on form and technique [74]. A variety of materials, such as polymers (polyaniline and polyvinylidene fluoride), layered structures, carbon nanotubes, and silicon nanowires, have been utilized to develop wearable strain sensors [75, 76].

For instance, mimicking overlapped tiles on roofs, Chao et al. [77] introduced a stacked hierarchical microstructure to the piezoresistive film by the overlap of Ti3C2 nanosheet and polyaniline fiber. The overlap of Ti3C2 and polyaniline fiber generates additional conductive paths to guarantee the continuity of the conductive pathway. As a result, the strain sensor exhibited high sensitivity with a gauge factor of 2369.1, an ultralow detection limit of 0.153% strain, and good reproducibility.

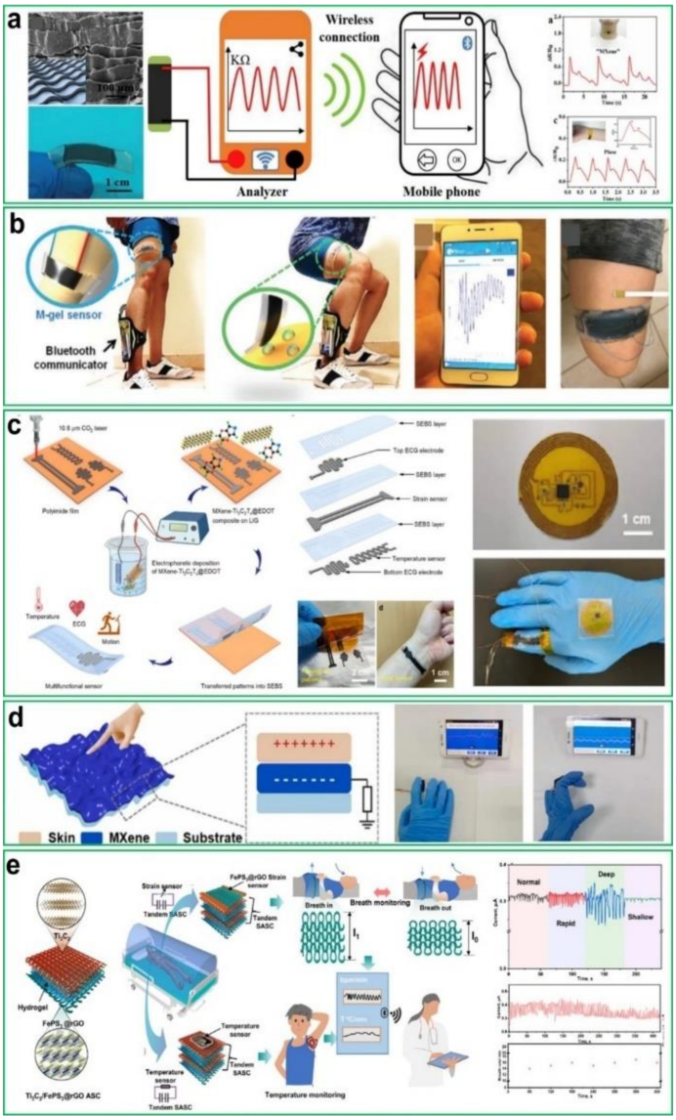

Fig. 7. (a) Polyaniline@Ti3C2-based flexible strain sensor with a tile-like stacked structure for wireless detection of artery pulse and phonation [77] (b) Wearable wristband based on a Ti3C2 hydrogel strain sensor and Bluetooth module wrapped around a human thigh during a workout to measure the degree of muscle tiredness [78] (c) Ti3C2@3,4-ethylenedioxythiophene/graphene composite-based wireless multifunctional sensors for strain, temperature, and heartbeat monitoring [79].

As a proof-of-concept demonstration, the wearable strain sensor was integrated with a wireless transmitter for wireless detection of human activity-like finger and elbow joint bending and even sound and human wrist pulse detection (see Fig.7a).

In another study, Lee et al. [78] reported a Ti3C2-polyacrylic acid@ polyvinyl alcohol composite hydrogel attached to a wearable wristband sensor. The wearable hydrogel sensor is pH-dependent and resistant to strain. Based on the pH of sweat, the cation selectivity of the Ti3C2 surface can be weak or strong. In this case, the wearable Ti3C2 hydrogel sensor was attached to the skin during exercise and was able to sense the pH levels (ranging from 4 to 6) of the human sweat based on the electrochemical response of the hydrogel for remote medical care. The sensor can also be integrated with a Bluetooth communicator to transfer recorded electrochemical responses to the mobile phone directly, as shown in Fig.7b. In another example, Zhang et al. [79] demonstrates a Ti3C2/graphene@EDOT composite (as shown in Fig.7c) with a superior temperature coefficient of resistance (0.86%), high strain sensitivity, and lowered skin contact impedance, making it an outstanding wearable sensor for real-time tracking of various fitness bio signals.

IV. EMERGING INNOVATIONS IN WEARABLE SENSORS

Emerging innovations in wearable sensors are revolutionizing healthcare and other fields, offering real-time monitoring of various biomarkers and physiological data. Key advancements include chemical and optical sensors, integration with AI and machine learning, and the development of flexible and stretchable materials [80]. These technological advancements can process vast amounts of data, recognize patterns, and generate accurate predictions of a person’s health status. The AI techniques learn from previous and real-time wearable biosensor data to conclude trend analysis in the outcomes of health and predict future states [81]. For instance, given some heart rate variability, AI may predict possible cardiac events and thus enable timely interventions [82].

Similarly, continuous glucose monitoring systems use machine learning to predict blood sugar fluctuation, under some diet or exercise regimen, to provide personalized information for diabetic patients. Machine-learning algorithms improve in understanding biologically complex data by reducing noise and extracting useful patterns [83]. A study by Gu et al. [84] emphasizes that flexible and skin-friendly materials form the foundation of wearable devices, enabling snug attachment to the skin surface for continuous health monitoring, including vital signs such as pulse, temperature, and blood glucose. These devices are enabled by the mechanical compliance of soft elastic materials to ensure comfort and high-quality signal acquisition.

Furthermore, Kim et al. [85] and Chen et al. [86] focus on the development of stretchable and flexible electronics for wrapping on the skin to offer sophisticated human–machine interfaces and cardiovascular health monitoring. Sensors from these devices operate by using mechanisms that transduce mechanical deformation into electrical signals, i.e., piezoresistive or capacitive changes, to track real-time dynamic physiological parameters. A recent study designed a tactile sensor (Fig. 8) consisting of optical fibers with a 92.41 % identification rate in a 0–3.5 N contact force [84]. A successful coaxial piezoelectric fiber-based electronic skin was fabricated for tactile sensing [85]. Findings revealed the high sensitivity rate of the fiber for 80–230 kPa pressure range [87].

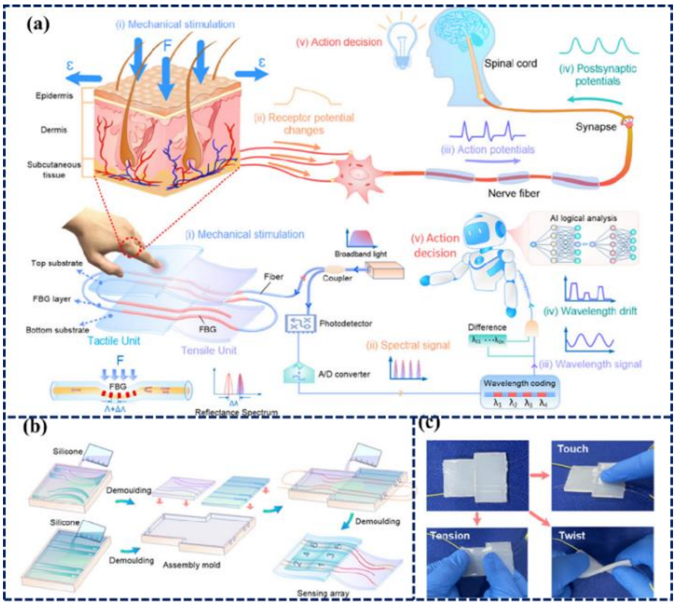

Fig.8. The fabrication process of the sensor (a) Design inspiration and structure of the sensor, and artificial tactile cognitive systems that mimic biological systems (b) Fabrication process of the sensor (c) Physical properties of the Sensor [87].

V. CHALLENGES AND FUTURE PERSPECTIVE

Wearable sensor technology has seen rapid advancements and increasing adoption across healthcare, fitness, and personal well-being sectors. However, several critical challenges continue to hinder its broader application and long-term reliability (refer to Fig.9). A primary challenge is ensuring material durability and mechanical resilience. Most wearable sensors depend on stretchable conductors, electrodes, and encapsulation materials that are susceptible to wear and fatigue from constant movement, bending, washing, and environmental conditions. Maintaining stable conductivity, biocompatibility, and low-noise signal acquisition over extended periods of use continues to pose significant technical challenges. Moreover, the commercialization of these materials in the form of lab prototypes to mass production by techniques like roll-to-roll or additive printing is still economically and technologically unfeasible, particularly in the case of products that integrate multiple functionalities like sensors, displays, and communications modules.

Energy and power management present another significant limitation. The majority of wearable devices today employ rigid lithium-ion batteries that constrain form factors and require high-frequency recharging or replacement. Autonomous, zero-maintenance functionality will require breakthroughs in flexible energy storage, hybrid supercapacitors, and energy-harvesting devices like thermoelectric, photovoltaic, and piezoelectric technologies. While promising, the aforementioned energy technologies are presently too expensive or inefficient for widespread commercial adoption. However, data management and privacy are increasingly critical problems. This is because the wearables collect extremely sensitive and personally identifiable physiological data, such as heartbeats, glucose levels, and behavioural information. Unauthorized use, secondary use, and poor data consent practices generate ethical and legal issues, especially considering that data is often shared with insurers, advertisers, or cloud services. Existing opt-in frameworks and privacy policies are not effective enough to offer protection, making it important to implement tighter data protection legislation and clear ethical principles.

Furthermore, long-term user studies have shown that initial enthusiasm for wearable devices often fades, especially when data becomes overwhelming or when users experience discomfort, misinformation, or a lack of tangible health benefits. In some cases, wearables may even contribute to anxiety, compulsive tracking, or dependence on algorithmic feedback, reducing overall user satisfaction and adherence. Despite these issues, the future of wearable sensors looks good. Much effort is being expended to develop self-sustaining and biodegradable electronics with minimal environmental impact and battery reliance. Similarly, the integration of artificial intelligence and machine learning is also reshaping the functionality of wearables. Devices will increasingly analyse data locally, using machine learning algorithms to interpret health signals in real-time.

This minimizes the need for continuous data transmission, lowers power, and increases user privacy. Furthermore, the evolution of intelligent fabrics capable of sensing, interpreting, and reacting to environmental and physiological changes opens the door to wearables that are more interactive, comfortable, and responsive. These smart textiles are able to alter compression, temperature, or visual feedback independently for improved user experience and therapy. For this future to be made possible, wearable sensors need to be designed with regulatory and ethical guidelines. Open consent mechanisms, data security protocols, and human-centred design will be necessary to allow trust and mass adoption. Notably, if these challenges are addressed, wearable technologies could become an indispensable tool that not only monitors but also enhances daily life and healthcare delivery.

Fig.9. Schematic overview of the recent development of multimodal sensors, highlighting strategies, challenges, and future outlooks

VII. CONCLUSION

Wearable sensors represent a rapidly evolving technology at the intersection of electronics, materials science, and biomedical engineering. The review has established the main principles that govern how they function, summarized research, and outlined trends that are influencing the future of wearable sensors. From stretchable electronics and flexible substrates to personal feedback systems and real-time health monitoring, wearable sensors have been monolithic in their potential to revolutionize healthcare, fitness, and day-to-day human-computer interaction. Despite all this development, the field remains beset by foundational challenges ranging from material longevity and energy efficiency to user compliance, privacy of data, and scalability of manufacturing. These limitations must be overcome through multidisciplinary research and innovation in materials science, artificial intelligence, low-power electronics, and data stewardship. Soon, self-sustaining, biodegradable, and autonomous systems may render wearable devices unobtrusive companions seamlessly integrated with the body and environment. As the technology advances, future wearable sensors will not only monitor vital signs but will also predict health risks, inform lifestyle choices in a more intelligent way, and support preventive medicine in real-time. It will all finally hinge on the coming together of engineering acumen, human-centred design, and ethical stewardship to determine how well wearable sensors can assist in moving toward a more connected, health-conscious, and data-driven world.

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