Tikrit Journal of Engineering Sciences (2025); 32(3): 1768
DOI: http://doi.org/10.25130/tjes.32.3.8

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Smart Polymer Composites Strain Sensors in Biomedicine: State-of-the-Art Material De-Sign and Applications

Tabarak M.K. Al-Sharooi [a,b], *Wessam Al Azzawi* [*a], *Muzher Taha Mohamed* [c]
a Material Department, Engineering College, Diyala University, Diyala, Iraq.
b Biomedical Department, Engineering College, Karbala University, Karbala, Iraq.
c Blad Alrafidian University College, Diyala, Iraq.

Keywords:
Conductive polymer composite; Medical applications; Nanocomposite; Strain sensor; Smart material.

Highlights:
- *State-of-the-art strain sensors using smart materials.*
- *They offer high sensitivity, potentially revolutionizing the healthcare field.*
- *These sensors are used in medical applications.*
- *Smart materials in strain sensors are a healthcare innovation for bet-ter care and diagnostics.*

ARTICLE INFO
Article history:

Received	06 Oct. 2023
Received in revised form	08 Jan. 2024
Accepted	18 May 2024
Final Proofreading	02 July 2025
Available online	18 Aug. 2025

Citation: Al-Sharooi TMK, Al Azzawi W, Mohamed MT. **Smart Polymer Composites Strain Sensors in Biomedicine: State-of-the-Art Material De-Sign and Applications**. *Tikrit Journal of Engineering Sciences* 2025; **32**(3): 1768.
http://doi.org/10.25130/tjes.32.3.8

***Corresponding author:**
Wessam Al Azzawi
Material Department, Engineering College, Diyala University, Diyala, Iraq.

Abstract: Polymer composite strain sensors have garnered significant attention in recent years within the field of biomedical applications, primarily due to the remarkable advancements achieved in conductive polymer technology. This review discusses in detail the intricate design of these sensors, their various types and classifications, and their applications in biomedical contexts. The discussion begins with the evolution of conductive polymer composites and their aptitude to transform mechanical deformation into electrical responses. Sensors are then categorized based on their sensing mechanisms. Moving forward, the review examines sensor design and fabrication considerations, including the impact of filler materials, polymer matrices, and production methods on the sensor's sensitivity, linearity, and reliability. Lastly, the review highlights the potential applications of these sensors in the biomedical field, with a particular focus on wearable health monitoring systems, prosthetic devices, and biofeedback mechanisms. In conclusion, these sensors are promising, characterized by unmatched sensing precision, and expected to fuel significant advancements in the field of biomedical innovation. The analysis presented in this review provides a comprehensive set of tools for academics and industry professionals, enabling them to customize strain sensors for specific applications.

مستشعرات إجهاد مركبات البوليمر الذكية في الطب الحيوي: تصميم المواد الحديثة وتطبيقاتها

تبارك الشاروي [١،٢]، وسام العزاوي [٢]، مزهر طه محمد [٢]

[١] قسم هندسة المواد/ كلية الهندسة/ جامعة ديالى/ ديالى / العراق.

[٢] قسم الطب الحيوي/ كلية الهندسة/ جامعة كربلاء/ كربلاء / العراق.

[٣] كلية بلاد الرافدين الجامعة / ديالى – العراق.

الخلاصة

حظيت مستشعرات الانفعال المصنوعة من مركبات البوليمر باهتمام كبير في السنوات الأخيرة في مجال التطبيقات الطبية الحيوية، ويعود ذلك أساسًا إلى التطورات الملحوظة في تكنولوجيا البوليمرات الموصلة. تناقش هذه المراجعة بالتفصيل التصميم المعقد لهذه المستشعرات، وأنواعها وتصنيفاتها المختلفة، وتطبيقاتها في السياقات الطبية الحيوية. تبدأ المناقشة بتطور مركبات البوليمر الموصلة وقدرتها على تحويل التشوه الميكانيكي إلى استجابات كهربائية. ثم تُصنف المستشعرات بناءً على آليات استشعارها. وتتناول المراجعة لاحقًا اعتبارات تصميم المستشعر وتصنيعه، بما في ذلك تأثير مواد الحشو، ومصفوفات البوليمر، وطرق الإنتاج على حساسية المستشعر، وخطيته، وموثوقيته. وأخيرًا، تُسلط المراجعة الضوء على التطبيقات المحتملة لهذه المستشعرات في المجال الطبي الحيوي، مع التركيز بشكل خاص على أنظمة مراقبة الصحة القابلة للارتداء، والأجهزة التعويضية، وآليات التغذية الراجعة الحيوية. في الختام، تُعد هذه المستشعرات واعدة، وتتميز بدقة استشعار لا مثيل لها، ومن المتوقع أن تُسهم في إحداث تقدم كبير في مجال الابتكار الطبي الحيوي. يوفر التحليل المقدم في هذه المراجعة مجموعة شاملة من الأدوات للأكاديميين ومحترفي الصناعة، مما يمكنهم من تخصيص أجهزة استشعار الضغط لتطبيقات محددة.

الكلمات الدالة: مركب بوليمر موصل، التطبيقات الطبية، مركب نانوي، مستشعر الانفعال، مادة ذكية.

1.INTRODUCTION

Recent advancements in biomedical technologies have generated a significant demand for cutting-edge smart materials that can integrate smoothly with the human body. These materials are expected to exhibit intelligent properties that enable them to optimize specific performance aspects to the maximum level. The development of smart composite sensors for biomedical applications has presented a formidable challenge, capturing substantial interest within the field. Smart composites have emerged as an excellent competitive to conventional sensors, which may be incompatible with special biomedical applications, including implants, prosthetics, artificial skin, and wearable sensors. Additionally, a strain sensor utilizing cellulose composite materials possesses highly conductive networks that provide outstanding stretchability and sensitivity, durability, scalability, and biocompatibility, making them excellent for these applications. They hold immense promise for a wide range of applications across various domains, including human health monitoring, motion detection, and human-computer interaction [1]. Various smart composite sensors have been recently used in bendable strain gauges. Chen et al. [2] created Elastomeric Conductive Polymer Composites (ECPCs). Conductive nanocomposite film was employed by Khalid and Chang [3] to compose sensors that demonstrate alterations in the electrical resistance upon being subjected to stretching, bending, or twisting. Jin et al. [4] developed lightweight piezoelectric, resistive, capacitive, and triboelectric sensors for motion monitoring. Shen et al. [5] noted that the monitoring of various physiological signals is now possible through flexible sensors, thanks to recent advancements in nanomaterials technology. This article critically reviews the current research on polymer strain sensors. It focuses on the background of conductive polymer development, specifically the strain sensor fabrication techniques and their potential applications in biomedical fields. The present paper is organized into three main sections: First, the concept of conductive polymer composites is discussed, and the effect of using different polymers and nanomaterials on conductivity is deliberated. Second, the strain sensing concept is established, and the fabrication methods are deliberated. The last section discusses the latest applications that have been achieved in the biomedical field using these sensors.

2.CONDUCTIVE POLYMER COMPOSITES

Conductive Polymer Composites (CPCs) are composite substances comprising conductive charges that are embedded within an insulation matrix [6]. According to Alemour et al. [7], the particles form a continuous path, as shown in Fig. 1, which allows free electrons to travel easily.

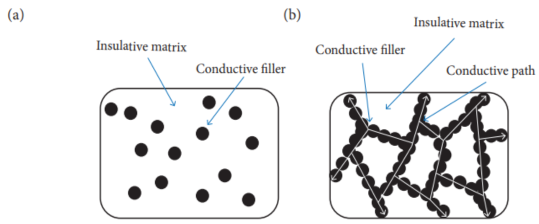

Fig. 1 Distributing Filler in a Polymer Composite (a) with a Low Content and (b) with a High Enough Conductive Path [7].

CPCs exhibited exceptional physical and mechanical properties, including conductivity, specific strength, and modulus of elasticity. The electrical conductivity of CPCs is intentionally designed to be high. Nevertheless, the CPCs' mechanical qualities deteriorate due to the incompatibility between the matrix and filler materials. When CPCs are tested for tensile strength, flexural strength, hardness, and three-point probe electrical conductivity, the functionalized CPC outperforms the as-produced CPC in terms of strength and elongation. Eighty MPa is the maximum flexural strength, while 35 MPa is the maximum tensile strength. Compared to CPC in its raw form, functionalized CPC is harder and has superior electrical characteristics [8]. According to Green and Goding [6], there are two distinct CPC categories: inherently conductive polymers (ICPs) and conductive polymer composites. Inherently conductive polymers are a class of materials that exhibit electroconductivity due to their distinctive structure. Conductive polymer composites, on the other hand, are composed of a well-insulated matrix and conductive fillers. A wide range of ingredient combinations is available for creating CPCs. Figure 2 shows that the use of polymer matrices, whether thermoplastic or thermoset, allows for the incorporation of both metallic and carbon nanofillers. This figure illustrates the process of incorporating conductive fillers into insulating materials to produce conductive polymer composite materials. The morphologies and structures of the nanofillers and macromolecules are crucial factors in controlling the conductive architecture of the composites [9].

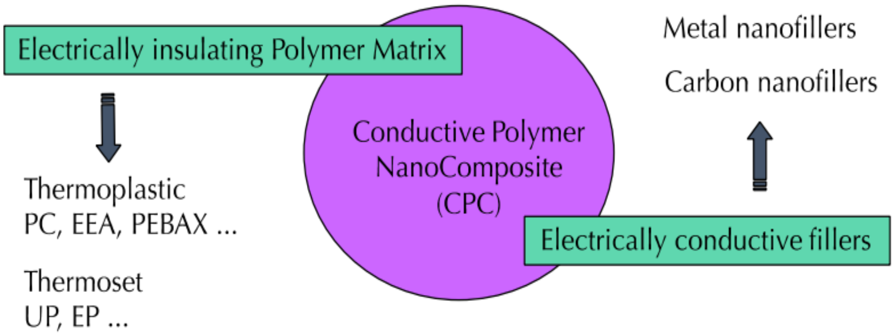

Fig. 2 Structuring of a Conductive Architecture from the Percolation of Nanofillers into an Insulating Polymer Matrix [9].

Carbon nanotubes are widely used as an additive due to their high electrical conductivity and distinctive high aspect ratio. When they are used inside a polymer, they create a well-connected conductive network, as depicted in Fig. 3 [10].

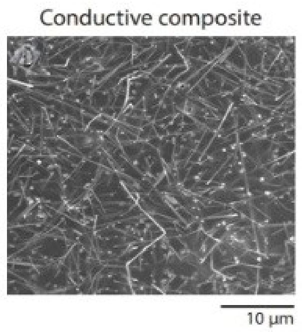

Fig. 3 SEM Image of the Conductive Network Inside Carbon Nanotube Composite [10].

In a study conducted by Xu et al. [11], a thermoplastic polyurethane (TPU) layer was employed using the dip-coating technique to encapsulate a core-sheath composite fiber consisting of single-walled carbon nanotubes (SWCNT) and reduced graphene oxide (RGO)/PU. The outcomes demonstrated a remarkable increase in the gauge factor (GF), reaching a value of 114.7, which suggests that the material holds significant potential for various applications.

3.POLYMER COMPOSITE STRAIN SENSOR

Traditional strain sensors typically consist of metals or inorganic semiconductors. These materials fall short of meeting the demand for high-strain sensing capabilities, as they are characterized by a limited detection range, typically only up to 5%. On the other hand, flexible conductive polymer composites (FCPCs) exhibit a high strain range, which makes them highly attractive for applications such as wearable strain sensors, disease diagnosis, human motion monitoring, and artificial skin [12]. Adding conductive fillers to a polymer is the primary step in making CPCs. Compounds commonly utilized as conductive fillers include carbon black, metal nanoparticles, carbon nanotubes (CNTs), nanowires, graphene, and nanosheets, among others. Flexible polymers, including Polydimethylsiloxane (PDMS), Eco-flex, silicone-based rubber, and Thermoplastic Polyurethane (TPU), are commonly employed as matrices [13]. Khalili et al. [14] developed a sensor using a cross-linked PLA and TPU polymer blend with a thin layer of SWCNTs on as-spun fibers. This sensor exhibited remarkable properties, including stretchability, flexibility, and sensitivity. The study showed that TPU/PLA (25:75 wt%) exhibited superior performance, outperforming in terms of ultimate stretchability, gauge factor, and mechanical/electrical recovery for large-strain flexible strain sensors. Sun et al. [15] developed a flexible, ultrathin (100 µm) and reversible strain sensor using multi-walled carbon nanotubes (MWCNTs), which improves conductivity, uniformity, and strain accuracy by up to 80% of the maximum. These epidermal sensors demonstrated real-time detection of human motion. Chen et al. [16] developed a flexible, transparent strain sensor using a PDMS composite, carbon nanotubes (CNTs), and PDMS (PDMS/CNTs/PDMS) with 0.16 mg/cm² CNTs. The sensors demonstrated exceptional strain detection up to 130% and optical transparency. Figure 4 shows that the CNT enhances electrical properties but reduces the optical transparency.

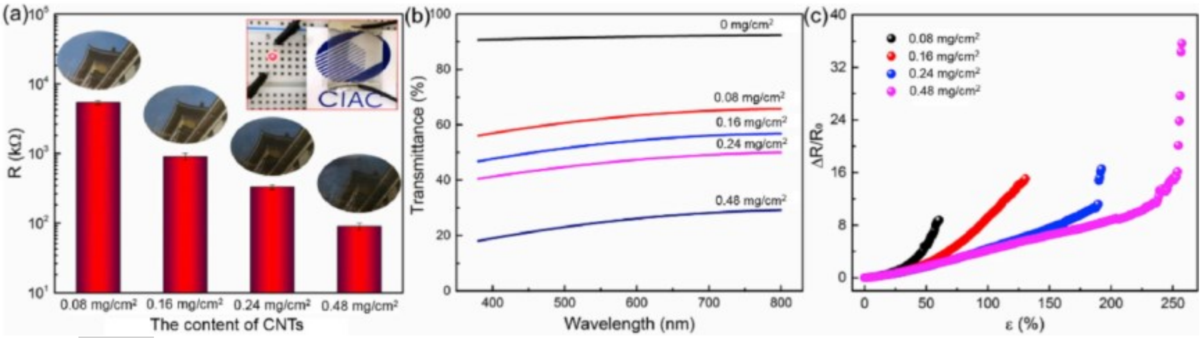

Fig. 4 (a) Electrical Resistance of PDMS/CNTs/PDMS Composites vs. CNT Content, (b) Transmittance Spectra of CNTs/PDMS Film, and (c) Relative Resistance Change of Composites vs. Strain. Fixed Strain Rate: 10 mm/min [16].

2.1.Classification of Composite Strain Sensors

Many types of stretchy strain sensors have been studied, including optical, piezoelectric, triboelectric, resistive, and capacitive sensors. Due to their high operating frequencies, piezoelectric and triboelectric sensors are often unable to detect static tension [17]. Recent research efforts have primarily focused on resistive and capacitive types for applications in wearable devices and skin-mounted devices. This preference is due to their flexibility, responsiveness, and ease of manufacturing processes.

2.1.1.Resistive-Type Strain Sensors

Resistive-type strain sensors typically employ metal elements and have been effectively used to detect strains up to 5% [18]. A change from brittle to stretchable resistive-type strain sensors has been brought about by the modern desire for wearable electronic gadgets. The conductive composite's active ingredients are nano- or micro-sized conducting materials [19]. The matrix of the composite can take various forms, including thin films, fabrics, or yarns [12]. When subjected to a voltage, the conductive structure of active materials acts as a resistor. In a mechanically stretched or compressed state, the resistance to electricity of the conducting network changes in direct proportion to the strain. A resistive-type composite strain sensor was developed by Qu et al. [20] for wearable and stretchable strain sensor applications. The sensor showed high sensitivity and tunable sensing ranges. They were able to convert various types of deformation into detectable electrical signal changes in a physical system.

2.1.2.Capacitive-Type Strain Sensors

A dielectric substance is sandwiched between two bendable electrodes to create capacitive-type strain sensors [21]. Here, the used dielectric material is a polymer composite containing conductive nanomaterials. Carbon nanotubes or graphene are typically used as conductive additives; however, the choice of nanomaterial or matrix polymer depends on the desired properties of the sensor and its application. The underlying concept of capacitive strain sensors is the change in capacitance that occurs as the material deforms [22]. When mechanical strain is applied to the sensor, it alters the distance between the electrodes, causing deformation of the dielectric polymer composite. When the electrodes move closer together due to strain, the capacitance increases, and when they move farther apart, the capacitance decreases. When no strain is applied, the sensor has an initial capacitance (*Co*) as provided by Eq. (1) [23].

$$C_o = \varepsilon_o \varepsilon_r G \quad (1)$$

where εo is the air's permittivity, εr is the material dielectric value, and G is a function related to the geometry of the capacitor. Various factors, including the surface area of the electrodes, the distance between them, and the dielectric properties of the composite material used, affect the capacitive sensor's performance [24]. A flexible and durable hydrogel was synthesized in situ by combining polyacrylamide, graphene oxide, and N-isopropyl diacrylamide. An extremely sensitive capacitive pressure sensor was made with this hydrogel. An insulated, ultra-thin polyethylene film was used as the primary dielectric layer, and two soft-plated, woven textiles were used as conductive layers to encapsulate the hydrogel. The nanocomposite hydrogel exhibits a breaking strength of 45 kPa and an elongation at a break of 2110% of the maximum. Capacitive pressure sensors have a 2.6 rating and can detect pressures ranging from 0 to 80% of the maximum value. These characteristics allow the sensor to detect low-pressure limb stresses and movements [25]. All kinds of wearable tech, including electronic skin, HMIs, and flexible pressure sensors (FPSs), rely on them. Due to their low power consumption, high resolution, and rapid response time, capacitive FPSs are ideal for portable and wearable electronic devices. Parasitic capacitance and electromagnetic interference restrict their sensitivity. Previously, improvements in sensitivity to microstructure or porous dielectric materials were only applicable to specific areas of interest. Using a 3D network electrode (3DNE) and a high-permittivity MXene nanocomposite dielectric, a new capacitive FPS sensing method was introduced [26]. Flexible strain sensors are crucial in biomedical devices, healthcare, and human-machine interfaces (HMIs). The innovative capacitive strain sensor is a nanocomposite composed of ionic hydrogels and silver nanofibers (AgNFs), which are exceptionally sensitive, biocompatible, and highly flexible. AgNFs induce an increased electrical double layer (EDL) area at the hydrogel/metal interface, enabling sensor capabilities such as 1000% stretchability and a maximum gauge factor (GF) of 165. It can detect and record a wide variety of physiological signals, such as those related to the heart, breathing, speech, and emotions, and operates steadily while responding quickly [27]. Ung-Hui et al. created highly stretchable and dependable elastic conductors by incorporating vertically aligned carbon nanotubes (vCNTs) into elastomers. These conductors retain their electrical activity even when subjected to various types of deformation, such as stretching up to 450%, bending, twisting, and folding. The authors proposed a technique for fabricating a piezocapacitive strain gauge capable of precisely measuring tensile strains of up to 150%. This strain gauge has excellent linearity, sustainability, and reversibility. The strain gauges have been demonstrated to efficiently track the real-time, large-scale static and dynamic movements of human body components [28]. Shanshan et al. developed delicate sensors that can be worn and simultaneously sense touch, pressure, and stretch. Electrodes made of silver nanowires and an Ecoflex dielectric with electrodes printed on them make up the capacitive sensors. Thanks to their high sensitivity, rapid response (40 ms), and accurate pressure mapping, they can detect strains of up to 50% and pressures of up to 1.2 MPa. With wearable technology, it is possible to track various aspects, including patellar reflex knee strain, thumb movement, and human behaviors such as jogging, jumping from a squat, and walking. Robotics, prosthetics, medicine, and bendable touchscreen displays are all potential applications for these sensors [29].

2.1.3.Optical Strain Sensors

A photodetector and light source are housed in the core-cladding structure of an optical strain sensor, which is stretched over a waveguide [30]. Deformation-induced changes in light transmission are the primary sensing mechanism. The resulting light power difference has recently garnered attention due to its encouraging dynamic performance and the advent of innovative electronic fabrication techniques, such as soft lithography and 3D printing [31]. A graphene-infused PDMS fiber with high light transmittance optical strain sensor was designed by Wang et al. [32] to detect human movement. The fiber maintains a constant graphene concentration as it stretches, utilizing optical loss through the fiber to sense tensile strain. The sensor boasts exceptional strain-sensing capability, with high sensitivity and the ability to withstand up to 150% tensile strain. Guo et al. [33] developed an optical strain sensor by incorporating plasmonic gold nanoparticles into flexible elastomer-based optical fibers with a core/cladding configuration. High linearity and negligible hysteresis were achieved through precise, reversible strain detection made possible by the sensor's highly localized surface plasmon resonance effects. At varying gold concentrations, the sensor's absorption spectra are displayed in Fig. 5. A solution of ice and water was used for bath sonication to slow down the ultrasonic polymerization process of PDMS. Absorption spectra of GNP-PDMS nanocomposites at different concentrations of gold are displayed in Fig. 5. As the concentration of GNPs grows linearly, the LSPR peaks at approximately 532 nm become more prominent.

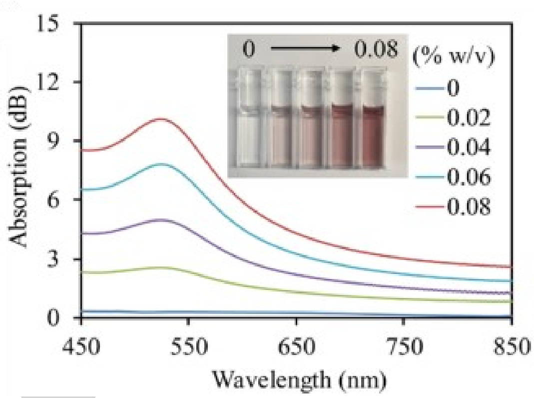

Fig. 5 The GNP-PDMS Nanocomposites' Absorption Spectra Measured at Different Concentrations of Gold [33].

Guo et al. [34] recommended a strain detector that utilizes a dye-doped polydimethylsiloxane optical fiber to measure variations in light absorption resulting from strain. The optical characteristics of PDMS materials were characterized using attenuation spectroscopy, as depicted in Fig. 6. The optical loss of undoped PDMS was less than 0.25 dB/cm between 450 and 850 nm, demonstrating its remarkable transparency.

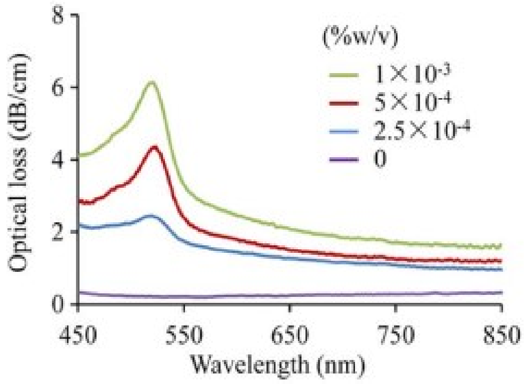

Fig. 6 Optical Attenuation Spectra of PDMS Doped with Different Concentrations of RB Dyes [34].

2.1.4.Other Types of Composite Strain Sensors

Recently, there has been an emergence of novel stretchable strain sensors designed to fulfill the demanding stretch-sensing needs within the field of biomedical applications. Among these sensors, piezoelectric and triboelectric sensors have garnered growing interest from researchers [35]. Piezoelectricity is a phenomenon in which piezoelectric materials generate an electrical voltage directly in response to external strain due to the presence of electrical dipole moments [36]. Piezoelectric sensors are capable of detecting strains with exceptional sensitivity and rapid response. To create piezoresistive sensors with stretch capability and sensitivity, Huang et al. [37] utilized conductive porous materials. They detected minute movements, such as breathing, coughing, and swallowing, since the sensor was very elastic, had elevated pressure sensitivities of 0.35 kPa-1, was durable and reproducible for 2000 cycles, and had a response time of 45 ms. A triboelectric strain sensor, on the other hand, is a sensor that utilizes the triboelectric effect to detect and measure strain. It functions by harnessing triboelectric interactions and electrostatic induction to transform external deformations into electrical signals. It has been introduced for wearable sensor applications. When materials with opposite tribopolarity come into contact, it results in a transfer of charges at their interface, subsequently producing an output potential. The magnitude of the created potential depends on the external load or deformation source [38].

2.2.Composite Sensors Design

The process of developing composite sensors involves creating materials capable of detecting and quantifying changes in strain. The research results yield various approaches. Wang, Chiang and Loh [39] proposed a topological design-based methodology aimed at manipulating the piezoresistive effect of nanocomposites to enhance their strain-sensing capabilities. Electromechanical experiments were conducted to compare and characterize the strain-sensing characteristics of various topology nanocomposites. In another study by Kang et al. [40], a hybrid structure's topology was used to develop an intelligent conducting nanocomposite that features an extended strain sensing range through the conjugation of hybrid structures, including carbon nanotubes and polymers. The results can serve as a valuable reference for designing sensors for various applications. The developed conducting composites exhibited enhanced strain-sensing capabilities and reduced plastic deformation. Recently, Zhu et al. [41] employed an interface design strategy, utilizing modified nanocellulose to develop an elastomer by dispersing graphene, thereby enhancing both the stretchability and sensitivity of the material. This methodology potentially yields stretchable sensors that are tolerant to environmental factors. Sankar et al. [42] established a comprehensive design framework for flexible strain sensors considering factors such as design scalability and suitability for specific application requirements. Implementing this framework has the potential to streamline and enhance the flexible sensors optimization process for special application requirements. In general, designing flexible sensors involves incorporating various materials and structures to achieve the desired levels of sensitivity, stretchability, and detection range. The sensitivity of the sensor can be evaluated by measuring the normalized change in resistance (ΔRn) as a function of applied strains ($\Delta\varepsilon$) and calculating the gauge factor (GF) [39]. Stretchability, also known as strain range or maximum strain, refers to the sensor's ability to withstand large deformations without compromising its functionality [43]. Linearity indicates the degree to which the relationship between the sensor's electrical response and the mechanical strain is proportional. A linear response is desirable for accurate and consistent measurements [44].

2.2.1.Materials

For the polymer-based CPCs, several electrically conductive fillers are dispersed within the polymer matrix to develop an insulator-to-conductor transition composite. Zhao et al. [45] produced versatile conductive composites using poly (vinyl alcohol), sodium alginate, tannic acid, and borax as cross-linker.

The results exhibited remarkable flexible composites with an ability to stretch up to 780%. It also exhibited notable conductivity and maintained consistent resistance variations, demonstrating high sensitivity with a gauge factor (GF) of 15.98 at a strain of 780%. To make polymer composites that transmit electricity, Zhan et al. [46] combined CB with polyamide 6 (PA6) and poly (vinyl alcohol) (PVA). As shown in Fig. 7, this combination was achieved by combining a PVA matrix with a conducting CB/PA6 electrospun fiber mat.

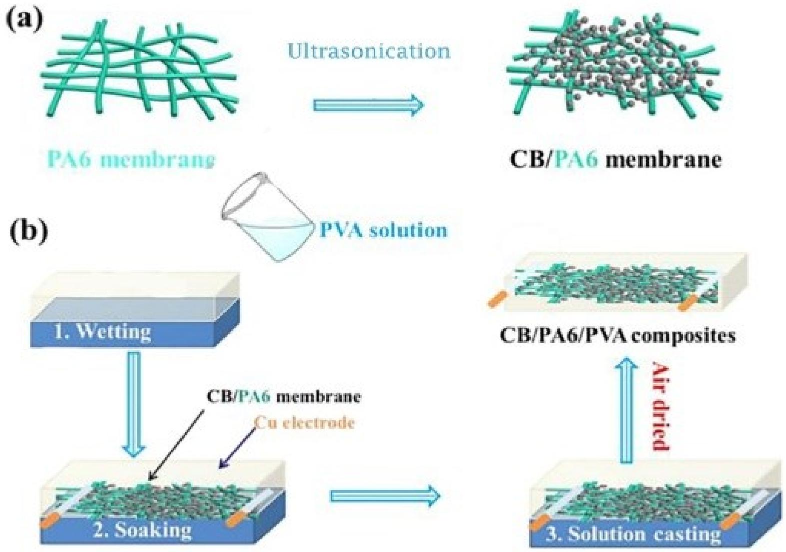

Fig. 7 (a) and (b) SCHEMATIC Illustration of the Fabrication of CB/PA6/PVA Composites [46].

Li et al. [47] developed strain sensors utilizing electrospun reduced graphene oxide (rGO) and silver nanowires (AgNWs) on thermoplastic polyurethane (TPU). The resultant hybrid sensors had a significantly high detection limit and extremely high sensitivities (GF = 4.4×10^7). Their performance over a thousand cycles proved that these sensors reliably responded to a range of frequencies, pressures, and strains applied over an extended period. Gao et al. [48] developed superhydrophobic conductive nanofiber composites (SCNCs) by first attaching graphene to polyurethane (PU) nanofibers using ultrasonic treatment. Subsequently, SiO2 nanoparticles were decorated onto the graphene shell through stretching-induced methods. One notable characteristic of the SCNCs is their ability to maintain superhydrophobicity and conductivity even after repeated stretching, which makes them highly durable and dependable for strain sensor applications. Additionally, the SCNCs exhibit excellent stretchability. Consequently, they are considered a promising option for wearable electronics. Novel conductive polymer films for microfabrication were developed by Huang et al. [49]. These films are produced by dispersing highly conductive nanoporous carbon blacks (n-CBs) in gelatin, PHOTONEECE® (CBPh), or polyvinyl alcohol (CBsPV) (CBsGel) solutions. The produced composites exhibited GFs up to 523. Gul et al. [50] developed a flexible electrically resistive-type strain sensor with a distinctive three-dimensional conducting network. The study combined conductive graphene pellets with flexible TPU pellets. The resultant strain sensor displays a blend of flexibility and electrical resistance characteristics. Zhou et al. [51] developed a stretchy strain sensor made by sandwiching conductive hybrids of silver nanowires and polystyrene pellets in an elastic PDMS matrix with rGO covering. The sensor has a high linear coefficient of 0.9594 and a big GF of 11 at 0-100% strain and 47 at 100%-230% strain. Sun et al. [52] created a flexible, waterproof, and highly sensitive strain sensor by integrating GE, CB, and PDMS into the 3D structure of a commercial nickel (Ni) sponge. With an elevated gage factor (>100 during 4-16% strain) and long-term endurance, the sensor demonstrated exceptional adaptability.

Wei et al. [53] applied a layer of AgNW onto a cotton thread using a direct dip coating method, obtaining complete coverage in four cycles. The researchers showed that there was a robust bond between AgNW and cotton fibers since the resistance only experienced a slight increase when subjected to washing conditions. By examining the reaction of the composite conductive fiber to pressure, researchers noticed that the resistance decreased as the contact area increased, indicating a greater potential for higher sensitivity in the sensor. Nevertheless, it was observed that there are limitations in detecting multiple forces simultaneously, emphasizing the importance of accurate sensor positioning on the human body. Aligned cellulose acetate (CA) nanofibers with a belt-like shape and decreased graphene oxide make up the sensor. CA Nano fibrous membranes' spatial alignment, microstructure, and wettability allow close interaction with GO colloids. GO on the CA membrane is easily reduced to a conductive RGO layer after a 700-second hot press at 150°C. This technique strengthens CA nanofiber connections and improves GO-CA substrate interaction, resulting in an outstanding mechanical strength of 1.3 GPa and a low sheet resistance of 10 kΩ. Thus, the conductive RGO/CA membrane is a versatile strain sensor that can detect several deformations. Moreover, mechanical resilience under varied stretch angles gives intriguing stress-direction sensitivity. This method is cost-effective, eco-friendly, and scalable for graphene-based flexible electronic fabrics [54]. By combining 2D MXene sheets with Aramid nanofibers (ANFs), MXene/ANFs aerogels are created using vacuum filtering and freeze-drying techniques. The unique three-dimensional structure of these aerogels enables them to withstand up to a thousand cycles of stress while maintaining a very low density (25 mg/cm^3), exceptional resilience, and outstanding sensing capabilities. They exhibit good flame resistance, sensitivity sensing (128 kPa−1), and ultralow detection limits (100 Pa) even when subjected to high pressures (~623 kPa) and temperatures up to 200 °C. Their detection ranges are very extensive, ranging from 2.0 to 80.0% compression strain. These characteristics suggest that there may be uses for monitoring and sensing human behavior in harsh environments [55]. Combining MXene with reduced graphene oxide (MX/rGO), two lightweight and superelastic materials, creates a new piezoresistive sensor. Due to the high conductivity of MXene and the combination of rGO's large specific surface area and a rich porous structure, this sensor provides outstanding performance. Specifically, it exhibits a sensitivity of 22.56 kPa−1, a response time of less than 200 ms, and outstanding stability over 10,000 cycles. Pressure distribution measurement, delicate strain detection, and health activity monitoring are just a few of the potential applications for this sensor, which can detect signals below 10 Pa and enable accurate tracking of adult pulses [56].

2.2.2.Composite Sensor Fabrication Techniques

Producing composite strain sensors necessitates cost-effective, simple, dependable, and scalable manufacturing techniques. Laser micromachining, printing, coating and sputtering, electrospinning, printing, and transfer patterning, Ref. [57] suggested for creating polymer composite strain sensors.

Liu et al. [57] proposed using one-step chemical vapor deposition to fabricate highly sensitive strain sensors. The purpose here is to cultivate GWFs that can stand on their own and then transplant them onto a PDMS base. The GWF/PDMS composites' manufacturing processes are illustrated in Fig. 8. The PDMS solution was stirred for 1 hour and then degassed in a vacuum oven for 30 minutes before being spin-coated onto a PET film.

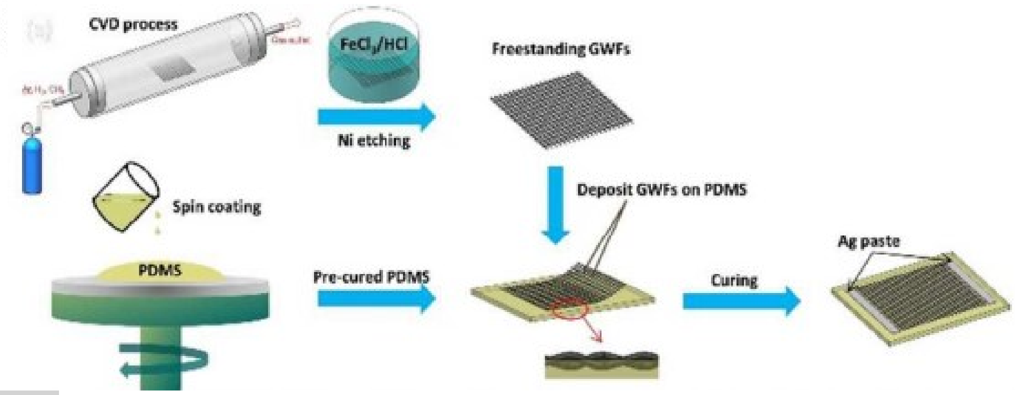

Fig. 8 Schematic Flowchart of the Fabrication Processes of GWF/PDMS Composites [57].

Wearable strain sensors were developed by Huang et al. [58] using PDMS composite and parallel-aligned vertical graphene (PAVG) sheets. After being deposited onto a PDMS layer, the PAVG sheets were produced using inductively coupled plasma chemical vaporization (ICPCVD). The sensor was made by moving the poly (arylene vinylene) graft copolymer (PAVG) from a steel substrate to a flexible, fully cured polydimethylsiloxane (PDMS) substrate. The PAVG@Steel was positioned in an upward orientation within a plastic culture plate, and the prepared PDMS was gradually poured into the dish. The PDMS, together with the embedded PAVG@Steel, was detached from the dish, and the steel substrate was removed, leaving the PAVG embedded in the PDMS matrix. Guo et al. [59] developed strain sensors with exceptional elastic properties using CNTs and CBs spin-coated on a PDMS substrate. The sensors were fabricated via 3D printing with chemically prepared

CNTs/GO composite dough, featuring a cross-sectional design with a conducting composite layer on a flexible substrate. Lee et al. [60] fabricated a stretchy strain sensor by employing a line-patterning process to pattern vertically aligned carbon nanotube (CNT) bundles, which were subsequently rolled and transferred over silicone elastomeric substrates. This innovative structure minimizes stretching disturbances within the plane, enabling the customization of stretchable strain sensors. Figure 9 illustrates the fabrication process of this strain sensor. The sensor utilizes the separation of overlapped CNTs embedded in the silicone elastomer, resulting in a highly sensitive and stretchable strain sensor. This fabrication process is highly suitable for mass production, as both the implemented processes can be applied to large areas, enabling industry-level production.

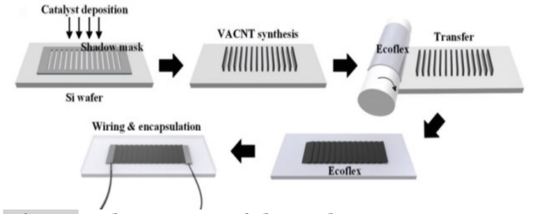

Fig. 9 Schematics of the Fabrication Process of the Strain Sensor [60].

Sun et al. [52] used a straightforward two-step procedure to create a G/CB/Ni strain sensor. The 3D Ni sponge was first electrocuted with two Cu wires joined with silver paste. The G/CB/Ni sensor was then created by applying the G/CB/PDMS suspension to the surface of the Ni sponge. A G/CB/PDMS suspension can penetrate the Ni sponge's framework due to the sponge's porosity structure. A dip-coating technique was employed by Xu et al. [11] to encapsulate a core-sheath composite fiber comprising SWCNT and rGO in a TPU layer. A highly sensitive and conductive layer is formed on the elastic PU core, while the outer TPU layer serves as a protective shield, preventing abrasion or delamination of the conductive layer. The temperature-controlled dipping coating technique was adopted by Choi et al. [61] to incorporate aligned silver nanowires to develop stretchy strain sensors. The study emphasized that the alignment orientation significantly impacted the sensitivities and strain range. The longitudinally aligned sensor exhibited an excellent sensitivity, 89.99 times higher GF compared to the laterally oriented sensor. However, its strain range was relatively small, limited to 25%. On the other hand, the laterally aligned sensor had a modest sensitivity of 22.10 GF but offered a high strain range of 60%. The flexible strain sensor was created by Chen, Zhu and Jiang [16] utilizing a sandwich-like PDMS/carbon nanotubes (CNTs)/PDMS composite with a homogeneous and ultrathin conducting layer. The method used was a straightforward spray deposition and transfer process. Excellent stretchability and sensing characteristics were demonstrated by the proposed strain sensors. Applications in human motion detection, wearable electronics, and e-skin were demonstrated by its wide sensing range of more than 130%, good optical transmittance of 53.1% at 550 nm, and capacity to perceive both the small movements of human joints and the more elaborate expressions on people's faces. Xu et al. [62] created a strain sensor using graphene that was treated with a laser. The sensor was placed on a polyimide sheet, and its backbone architecture consisted of kirigami structures. Eco flex encased the sensor to shield it from damage and boost its sensitivity. Even after 60000 cycles of testing, the suggested strain sensors maintained their excellent sensing capability and stability. Furthermore, multiple applications for monitoring human respiration and movement validated their performances. One potential approach for creating tailored therapies, especially for biomonitoring purposes, is the use of flexible piezoresistive composite sensors that have been 3D printed. Research was conducted to determine the compatibility of milled carbon fiber (MCF) concentrations with silicone rubber (SR). For the composite ink to be printed successfully while keeping its conductivity and printability, including ink deposition and curing, The range of 25 to 30 weight percent was found to be the ideal MCF concentration, ensuring a suitable compromise between electrical performance and printing quality [63]. Continuous fiber-reinforced polymer (CFRP) composites have been revolutionized by the advent of additive manufacturing (AM), which enables creating elaborately designed products with improved material properties. However, instead of exploring the new design options made possible by CFRP-AM, most existing research focuses on the production process. This study provided a design framework for CFRP composite additive manufacturing, improving product performance and encouraging innovation to meet future needs. It identifies design opportunities in the material, process, and structural domains while reviewing current CFRP-AM methodologies with functional demands in mind [64]. For electrochemical sensors that are printed via 3D printing, a novel thermoplastic material called graphite/acrylonitrile butadiene styrene (G/ABS) has been developed, which is more conductive than the traditional carbon black/polylactic acid (CB/PLA) combination. Due to their increased sensitivity, larger electroactive area, reduced charge transfer resistance, and 69% higher peak currents, G/ABS electrodes are the preferred choice. Due to an enhanced fabrication technique that allows for higher inclusion of conductive material, they also exhibit superior repeatability, reproducibility, and stability. In comparison to CB/PLA electrodes, G/ABS electrodes have an activation process that is both faster and easier to understand. The ability of G/ABS sensors to measure paracetamol in pharmaceutical products is just one example of the numerous potential applications of this technology [65].

2.3. Biomedical Applications

Polymer composite strain sensors find application in a wide range of areas within the biomedical field. They play a crucial role in vital sign monitoring, rehabilitation aids, and detecting human body motions, such as respiration, heartbeat, and joint motion. Additionally, it offers significant potential in enhancing healthcare and patient care technologies. These applications required the sensors to be comfortable, efficient, and reliable. For instance, wearable strain sensors must exhibit a high level of adaptability to ensure skin protection and enhance wearable comfort through features like breathability and self-cooling capabilities [66, 67]. According to Zhou et al. [12], incorporating piezoresistive strain sensors in conjunction with FCPCs can effectively meet the application's specific demands while maintaining user comfort and sensor performance. FCPCs offer promising sensor solutions for biomedical implants. They exhibited self-adaptive characteristics and multifunctional capabilities, enabling them to effectively monitor loads and detect potential damage within the implant. Notably, by incorporating strain gauges into smart spinal implants, real-time feedback from the implant was obtained [68]. Figure 10 shows various applications where wearable and flexible strain sensors are utilized. On the other hand, resistive- and capacitive-type strain sensors have been extensively studied in recent years for wearable and skin-mountable strain sensing applications, given their relatively simple readout, high stretchability, acceptable dynamic performance, and facile fabrication process. Recently, soft and stretchable optical strain sensors have also received considerable interest in wearable and soft robotic applications due to their merits, including resistance to environmental factors, e.g., temperature and humidity, as well as minimized sensitivity to electromagnetic interference [69].

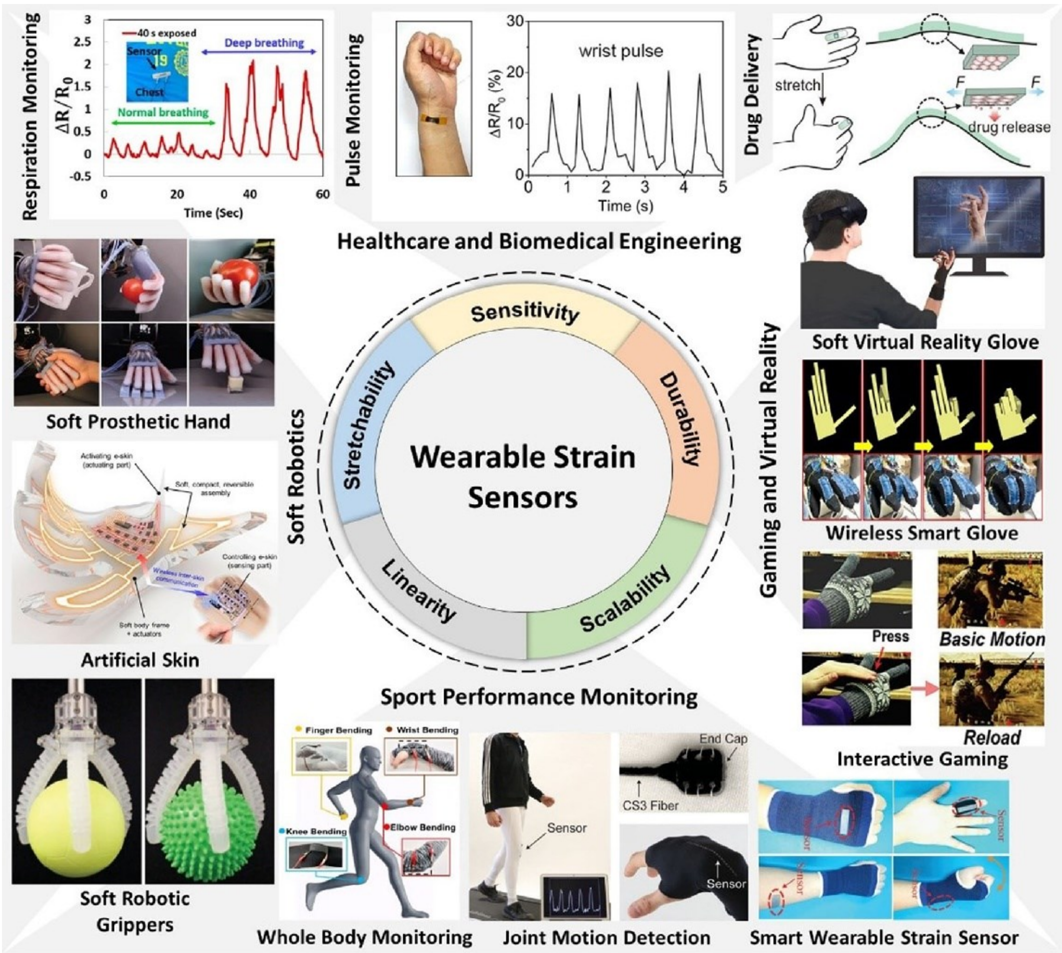

Fig. 10 Strain Sensors that are Both Flexible and Wearable for Use in Medicine, Biomedical Engineering, Sports Performance Tracking, Soft Robots, Video Games, and VR [69].

2.3.1.Artificial Skin

Smart conductive composites have been proposed as a promising sensor for wearable electronics used in artificial skin applications [51]. These sensors demonstrate outstanding potential in the fields of electronic skin, human-machine interactions, and health status monitoring [70]. Moheimani et al. [71] investigated various composites, including TPU combined with CNTs, as well as composites incorporating metal nanowires and nanoparticles for wearable sensor applications. Capacitive-type strain sensors, due to their exceptional sensitivity and stretchability, these sensors are well-suited for integration into skin-integrated electronics. By using an elastic substrate of graphene oxide-doped polyurethane nanofiber coated with an ultrathin layer of conductive poly(3,4-ethylenedioxythiophene) (PEDOT), Qi et al. [72] created highly sensitive and flexible electronic skin. This cutting-edge electronic skin demonstrates the ability to sense static and dynamic strain, bending, and pressure. The novel material's structure allowed for extremely sensitive and broadly applicable multimodal mechanical sensing. Chen et al. [73] fabricated a flexible dendritic-lamellar MXene/carbon nanotube/polyvinylpyrrolidone (PVP) electrode for a tactile sensor. Its performance was evaluated in speech recognition and pulse measurement, demonstrating a detection range of 0.69 Pa and a response time of 48 ms. Figure 11 shows a successfully printed artificial skin using the fabricated material.

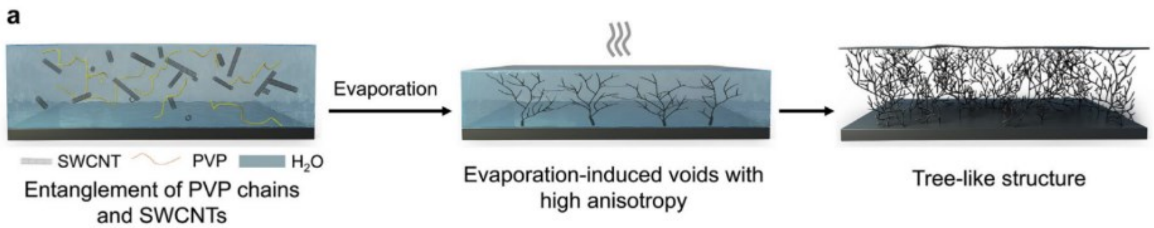

Fig. 11 Schematic Illustration of the Formation Process of Self-Assembly of the Dendritic SWCNT/PVP Film by Water Evaporation [73].

Zhao et al. [74] reported that electronic skin, which is both biocompatible and permeable, could be produced by a layered dipping-drying process using graphene Nanoplatelets (GNPs) and a GNPs/polyaniline (PANI) synergetic conductive network. Yin et al. [75] utilized an interlocking fabric composed of graphene and polyamide to develop a flexible sensor that mimics the skin's characteristics. Due to the interlocking fabric's unique microstructure, the sensors remained very stable after more than 10,000 cycles of loading and unloading. They also had a wide sensing range (up to 80 kPa), a low detection limit (1.38 Pa), and great sensitivity (2.34 kPa-1). These sensors offer a multitude of sensing functions, including vibration, bending, and stretching, as well as spatially map pressure stimuli and monitor subtle human physiological signals. A novel type of flexible sensor was developed by Zhou et al. [51], showcasing remarkable sensitivity, stretchability, and excellent dynamic response characteristics. A 3D hybrid conductive network and a serpentine-shaped sensing layer composed of graphene nanoplatelets, carboxyl-functionalized multiwall carbon nanotubes, and silicone rubber (GNPs, MWCNTs, and SR) collaborated to develop these sensors.

2.3.2.Human Body Monitoring

Sensors fabricated using materials, such as liquid natural rubber, silver nanowires, poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate), natural rubber, PEDOT, and PSS, have demonstrated remarkable effectiveness in detecting physiological and medical signals, as well as monitoring physical activities [12].

2.3.2.1.Human Motion Monitoring

Ma et al. [76] successfully developed wearable sensors using carbon nanotubes embedded in an epoxy matrix. These wearable sensors showed high sensitivity and comfortable use, with possible applications in identifying microexpressions on the face, as well as movements of the fingers and elbows. A carbon-kapton-carbon (CKE) band was employed to monitor finger, wrist, and elbow movements. To enhance the band's sensing capabilities, a low-cost, custom-made graphite-polyurethane nanocomposite (G-PU) paste was dip-coated onto it. The sensor accurately identified and tracked changes in resistance over time, allowing motion and angle measurements to be taken in the wrist, finger, and elbow joints. Therefore, it can be used to track joint angles in real-time through a human-machine link [77]. Ben Atitallah et al. [66] focused on the utilization of polymer carbon nanotube composites for monitoring finger movements and facilitating hand muscle rehabilitation. By integrating the carbon nanotubes within polymer matrices, the resulting composite materials exhibited unique electrical and mechanical properties that make them suitable for sensing and monitoring applications. Moreover, they can be used in rehabilitation programs to assist individuals recover hand muscle functionality. Tao et al.

[78] developed novel strain sensors made of graphene printed using lasers. Laser-patterned graphene (LPG), which provides flexible performance. These single-step-fabricated sensors are perfect for various human motion detection applications due to their high gauge factors or large strain ranges. They have the ability to be adjusted using graphene patterns. Figure 12 shows LPG strain sensors controlling LED brightness. The LPG strain sensor was securely attached to a finger to detect large motions. Figure 12(a-d) shows the LED darkening with finger bending. In addition, Fig. 12(e) shows the relative resistance change at various bending degrees, topping out at 24. According to the ESI, LPG strain sensors demonstrated excellent reproducibility and a rapid reaction speed.

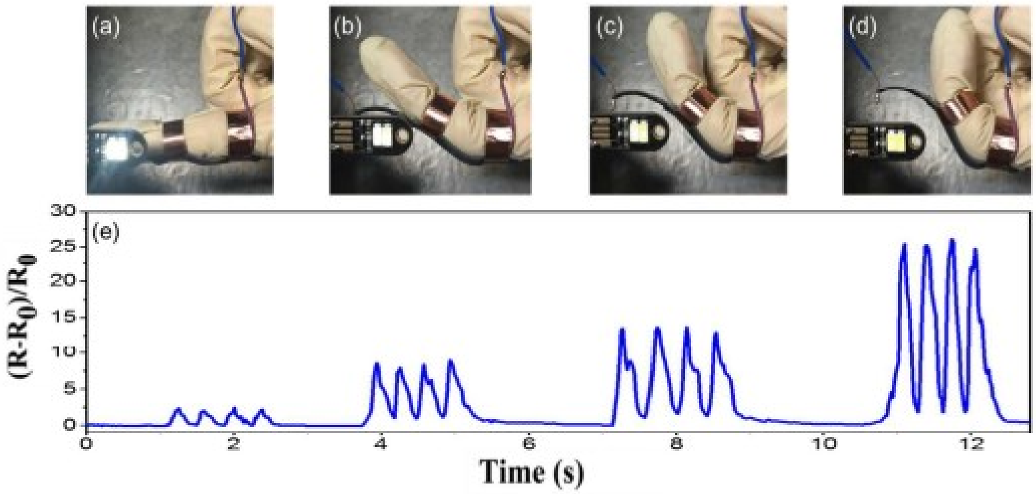

Fig. 12 The No-Mesh LPG Strain Sensor Controls Brightness and Detects Finger Bending. (a-d) Reduced LED Brightness with Increased Finger Bending. Different Finger Bending Degrees Affect Relative Resistance [78].

Zeqing et al. presented a serpentine-connected, inherently flexible Ecoflex acceleration sensor that can measure three angular velocities and accelerations in real-time, allowing for precise motion detection and monitoring. Mechanical analysis and experimental results confirm that the flexible acceleration sensors are fully functional under typical operating circumstances, even when subjected to bending, stretching, and twisting motions. Furthermore, the flexible acceleration sensor's monitoring capability under vibrational conditions is comparable to that of a commercial accelerometer. Movement-specific acceleration and angular velocity patterns are shown in Fig. 13. Thumb and finger directions match positive X and Y-axis acceleration, whereas the upward hand aligns with positive Z. Sutting boosts Z-axis acceleration, arm twisting Y, and jumping Y. Continuous X, Y, and Z-axis acceleration is visible when running. Patterns let the flexible acceleration sensor identify movements [79].

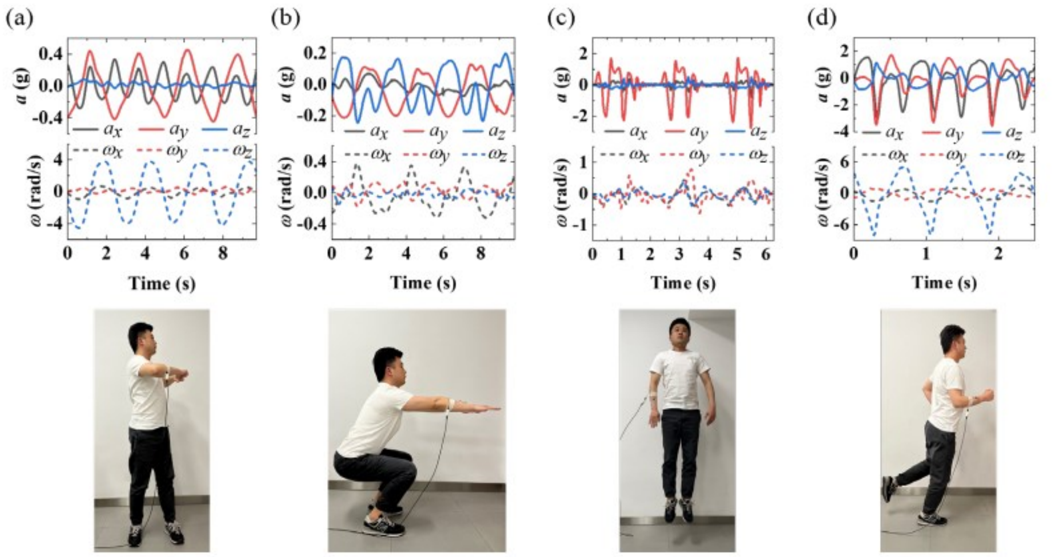

Fig. 13 (a) Arm Twisting, (b) Squatting, (c) Jumping, and (d) Running—Real-Time Acceleration and Axial Angular of/Around the X-Axis, Y-Axis, and Z-Axis Direction [79].

To create flexible and electrically conductive hydrogels, carboxylic multiwall carbon nanotubes (c-MWCNTs) were electrostatically self-assembled onto bacterial cellulose (BC) membranes using bovine serum albumin (BSA). The piezoresistive strain sensor, composed of c-MWCNTs/BSA/BC hydrogel, showed 70% stretchability and excellent cycle stability. Large-scale human motions, such as finger knuckles, wrist bending, knee joints, and elbow joints, were accurately detected. For flexible strain sensors, eco-friendly BC provided a cost-effective and renewable substrate. Figure 14 displays the real-time monitoring of various human motions and illustrates how the relative resistance changes over time as the index finger bends and releases. The inset shows pictures from a single bending cycle of the hand, Fig. 14(b). The inset displays pictures of a single bending cycle, showing the change in relative resistance for c-MWCNTs/BSA/BC strain sensors as a function of bending motion. The sensor that tracks the arm's bending motion at 45, 90, and 135 degrees is shown in the inset. It is directly attached to the elbow joint [80].

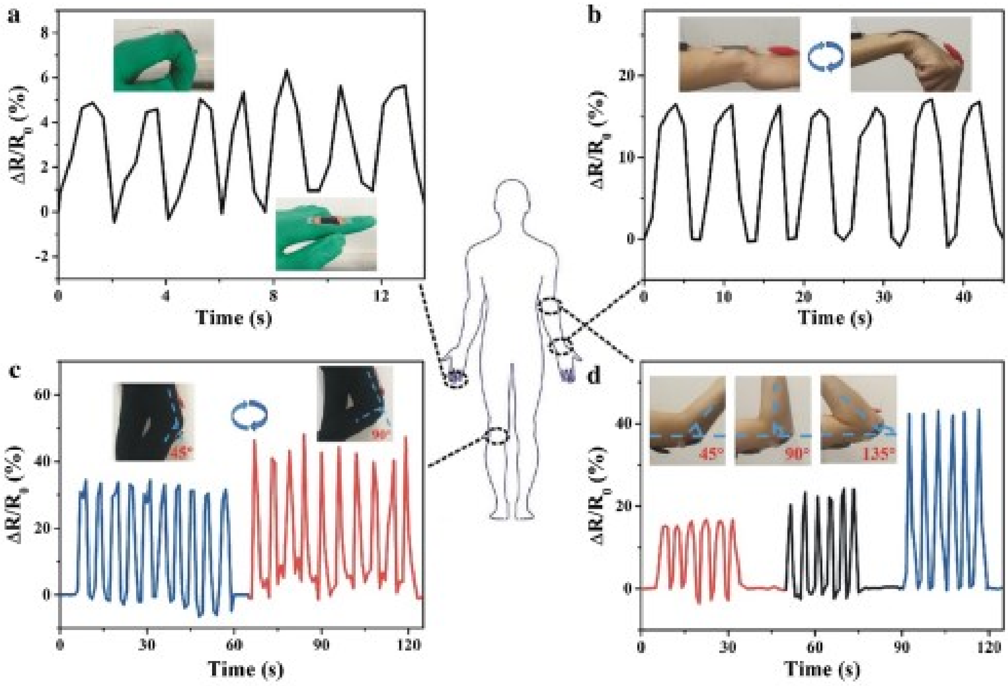

Fig. 14 Illustrates the Relationship between Relative Resistance and Bending with Release Times (a) Bending the Fingers, (b) Bending the Wrist, (c) Bending the Knees, and (d) Monitoring the Arm's Bending Action at 45, 90, and 135 Degrees.

2.3.2.2.Human Health Monitoring

These sensors were highly adaptable and capable of protecting both the skin and the sensor, which gave them great potential in sports monitoring and human-machine interface applications. A polymer/AgNWs composite sensor developed by Zhang et al. [81] showed a wide strain range (up to 500%), excellent durability (over 1,000 cycles), resilience to fatigue, a low sensing limit (1%), and significant strain linearity (50 to 500%). The monitoring of broken joints was found to benefit significantly from these characteristics. Figure 15 displays the ECG signals recorded by the AgNWs and polymer composite electrodes. The resulting signal is clearly similar to that of the commercial electrode. A novel stretchy conductive polypyrrole/polyurethane (PPy/PU) elastomer was developed through surface diffusion and in situ polymerization of PPy on porous PU substrates. The mechanism of reversible conductivity in PPy/PU elastomer was proposed. Using this characteristic, a waistband-like human breath detector was created. The results indicated a potential ability as a strain sensor for human healthcare, exhibiting reversible resistance changes during repeated stretching and contracting motions associated with breathing [82]. Figure 16 shows how stretchable and conductive PPy/PU elastomers are used to make a waistband-like strain sensor for breath detection. A PPy/PU elastomer in the waistband connects two rigid belt ends to form the sensor. Rigid belts reduce sensor efficiency effects of elasticity. The waistline lengthens and contracts as the wearer breathes, changing its electrical resistance. Exhalation stretches the substrate, increasing resistance; inhalation relaxes it. These changeable length and resistance variations allow breath cycle tracking [82].

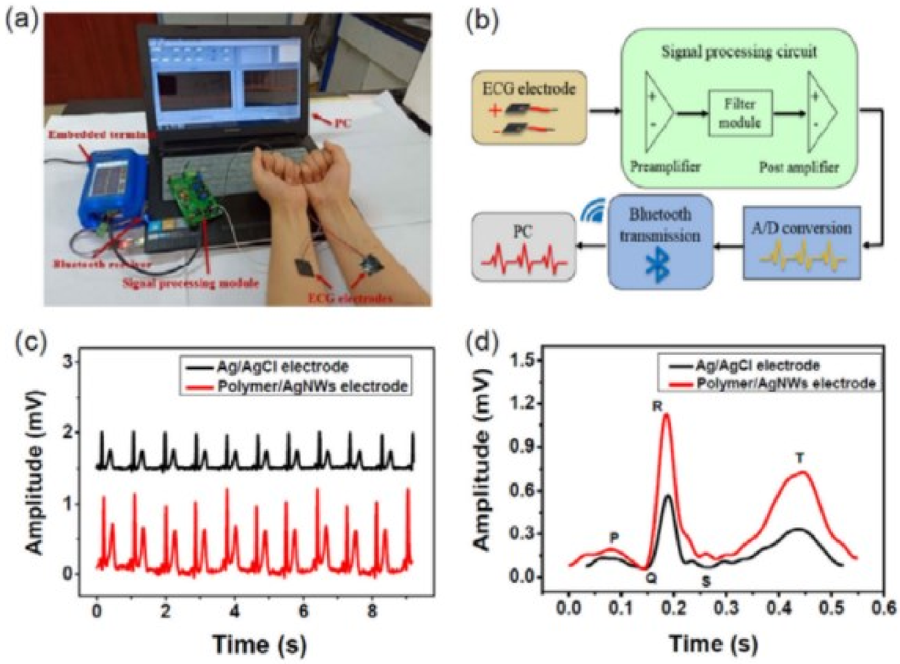

Fig. 15 (a) A Picture of the Setup for Watching the ECG Signal, (b) A Diagram of the Circuit System for Tracking ECG Signals, (c) ECG Readings from Composite Electrodes Made of Ag/AgCl and Polymer/AgNWs, and (d) P-QRS-T Waves in ECG Data from Mixtures of Ag/AgCl and Polymer/AgNWs [81].

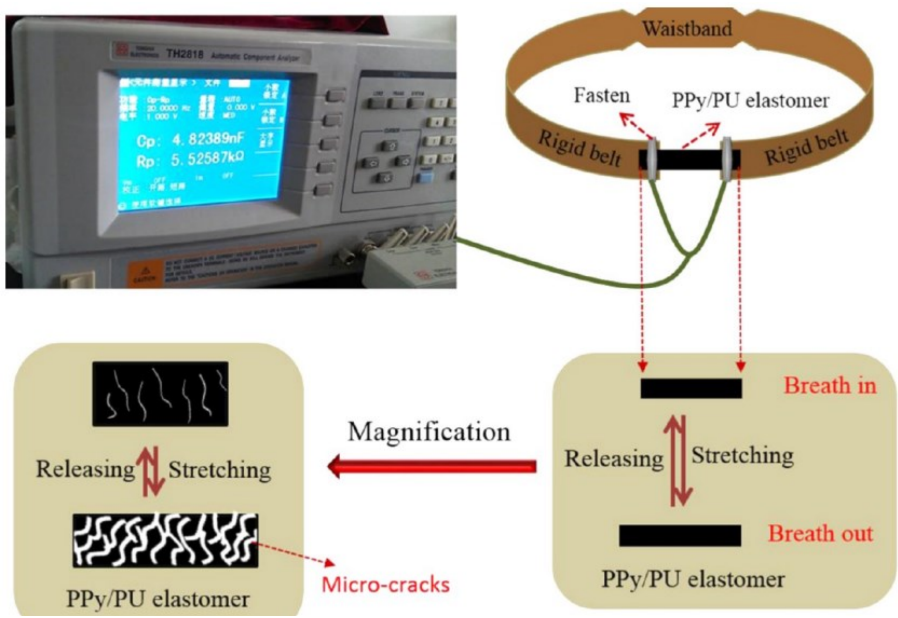

Fig. 16 Schematic Diagram of the Waistband-Like Human Breath Detection Sensor Built from the PPy/PU Elastomer [82].

According to Liu et al. [83], the integration of skin-like sensors plays a crucial role in monitoring physiological parameters, such as blood pressure detection. These sensors contribute to improved healthcare monitoring, diagnosis, and treatment by providing real-time data. By sandwiching indium-tin-oxide (ITO) between two layers of polydimethylsiloxane (PDMS), Kumar created a capacitive blood pressure sensor. It was encased in a mandrel, which simulated a human hand, and a cuff, all of which were linked to an OMRON blood pressure machine and the Fluke NIBP analyzer. Figure 17 shows the human pulse waveform retrieved from the deflation curve, which was derived from the sensor's output in terms of capacitance value using an LCR meter [84].

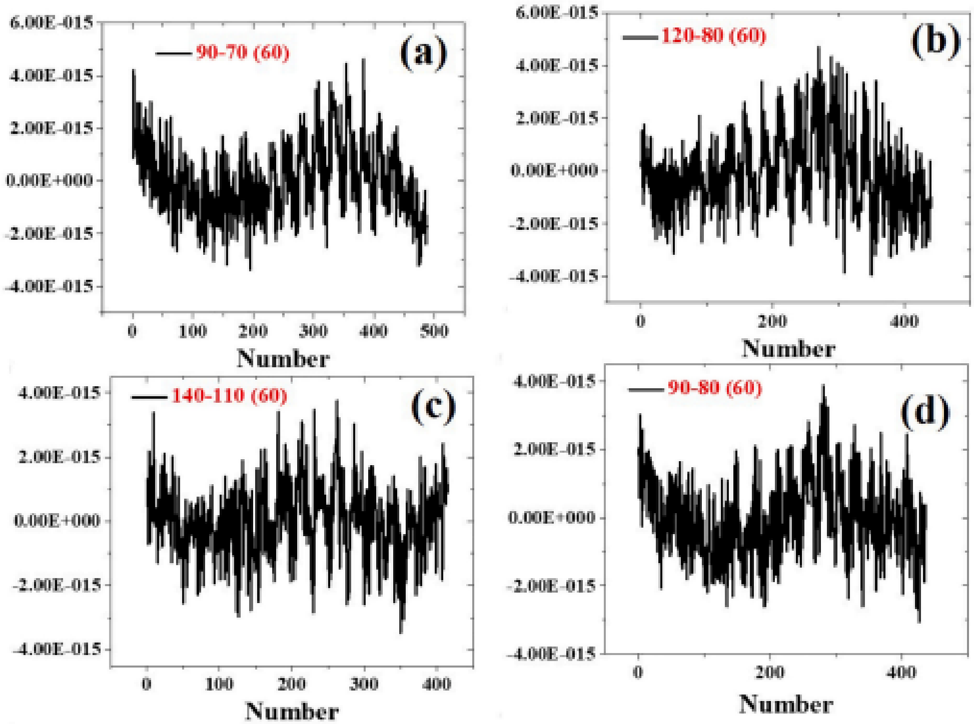

Fig. 17 Using a Heart Rate of 60 Beats Per Minute, the Artificial Sensor Measures Human Blood Pressure (BP) at Various Values. (a) When Blood Pressure Feels Low, (b) for a Normal Blood Pressure Reading, (c) in Cases where the Blood Pressure is Excessive, and (d) Given a Blood Pressure Reading between 90 and 80 [84].

3.CONCLUSIONS

This review focuses on polymer composite strain sensors, specifically discussing their design, sensing techniques, and potential applications in the biomedical fields. The present paper reviews the integration of conductive particles into polymers, highlighting their role in enhancing electrical conductivity and converting mechanical strain into measurable electrical signals. The review categorizes strain sensors based on their resistive, capacitive, and piezoelectric principles. Furthermore, it analyzes design components, such as filler materials, polymer matrices, and manufacturing techniques, which are crucial for enhancing sensor performance. In addition, the paper evaluates the current application of polymer strain sensors in biomedical fields, including their use in wearable health monitoring, prosthetics, and biofeedback systems. These applications showcase the capacity of polymer sensors to revolutionize personalized healthcare by providing accurate and instantaneous health monitoring data. The study highlights the significant impact that polymer sensors can exert on both sensor technology and healthcare practice. In the future, the authors argue that there is sufficient scope for scholarly investigation into the ongoing enhancement of functionality, the broadening of application possibilities, and the optimization of efficiency in polymer composite strain sensors, which may involve developing innovative polymer-based materials and state-of-the-art production procedures, leading to improved device performance at a lower cost and greater availability. Moreover, progress in medical technology may lead to increased utilization of sensors within the healthcare sector, encompassing the surveillance of chronic illnesses, assessing physical capabilities, and delivering personalized treatment.

NOMENCLATURE

C_o	initial capacitance.
ε_o	Air's permittivity G is a geometrically related function of the capacitor.
ε_r	material dielectric constant.
G	a function that pertains to the capacitor's geometry.

REFERENCES

[1] Chen Z, Yan T, Pan Z. **Review of Flexible Strain Sensors Based on Cellulose Composites for Multi-Faceted Applications.** *Cellulose* 2021; **28**(2):615-645.

[2] Chen X, et al. **Flexible Strain Sensors with Enhanced Sensing Performance Prepared from Biaxially Stretched Carbon Nanotube / Thermoplastic Polyurethane Nanocomposites.** *ACS Applied Electronic Materials* 2022; **4**(6):3071-3079.

[3] Khalid MAU, Chang SH. **Flexible Strain Sensors for Wearable Applications Fabricated Using Novel Functional Nanocomposites: A Review.** *Composite Structures* 2022; **284**:115214.

[4] Jin L, et al. **Flexible Unimodal Strain Sensors for Human Motion Detection and Differentiation.** *NPJ Flexible Electronics* 2022; **6**(1):74.

[5] Shen Z, et al. **Progress of Flexible Strain Sensors for Physiological Signal Monitoring.** *Biosensors and Bioelectronics* 2022; **211**:114298.

[6] Green R, Goding J. **Biosynthetic Conductive Polymer Composites for Tissue-Engineering Biomedical Devices.** In: *Biosynthetic Polymers for Medical Applications*. Elsevier; 2016:277-298.

[7] Alemour B, Badran O, Hassan MR. **A Review of Using Conductive Composite Materials in Solving Lightening Strike and Ice Accumulation Problems in Aviation.** *Journal of Aerospace Technology and Management* 2019; **11**:e1919.

[8] Sulong AB, et al. **Rheological and Mechanical Properties of Carbon Nanotube/Graphite/SS316L/Polypropylene Nanocomposite for a Conductive Polymer Composite.** *Composites Part B: Engineering* 2013; **50**:54-61.

[9] Abramson A, et al. **A Flexible Electronic Strain Sensor for the Real-Time Monitoring of Tumor Regression.** *Science Advances* 2022; **8**(37):eabn6550.

[10] Chen H, Dejace L, Lacour SP. **Electronic Skins for Healthcare Monitoring and Smart Prostheses.** *Annual Review of Control, Robotics, and Autonomous Systems* 2021; **4**:629-650.

[11] Xu Y, et al. **Encapsulated Core-Sheath Carbon Nanotube-Graphene / Polyurethane Composite Fiber for Highly Stable, Stretchable, and Sensitive Strain Sensor.** *Journal of Materials Science* 2021; **56**:2296-2310.

[12] Zhou K, et al. **Flexible Conductive Polymer Composites for Smart Wearable Strain Sensors.** *SmartMat* 2020; **1**(1):e1010.

[13] Jia Y, et al. **Multifunctional Stretchable Strain Sensor Based on Polydopamine/Reduced Graphene Oxide/Electrospun Thermoplastic Polyurethane Fibrous Mats for Human Motion Detection and Environment Monitoring.** *Composites Part B: Engineering* 2020; **183**:107696.

[14] Khalili N, Asif H, Naguib H. **Towards Development of Nanofibrous Large Strain Flexible Strain Sensors with Programmable Shape Memory Properties.** *Smart Materials and Structures* 2018; **27**(5):055002.

[15] Sun J, et al. **Highly Stretchable and Ultrathin Nanopaper Composites for Epidermal Strain Sensors.** *Nanotechnology* 2018; **29**(35):355304.

[16] Chen J, Zhu Y, Jiang W. **A Stretchable and Transparent Strain Sensor Based on Sandwich-Like PDMS/CNTs/PDMS Composite Containing an Ultrathin Conductive CNT Layer.** *Composites Science and Technology* 2020; **186**:107938.

[17] Li J, et al. **Recent Progress in Flexible and Stretchable Piezoresistive Sensors and their Applications.** *Journal of the Electrochemical Society* 2020; **167**(3):037561.

[18] Wang C, et al. **Advanced Carbon for Flexible and Wearable Electronics.** *Advanced Materials* 2019; **31**(9):1801072.

[19] Bouiri EM, et al. **Improving Dielectric Properties of Composites Thin Films with Polylactic Acid and PZT Microparticles Induced by Interfacial Polarization.** *The European Physical Journal Applied Physics* 2022; **97**:64.

[20] Qu M, et al. **Electric Resistance of Elastic Strain Sensors-Fundamental Mechanisms and Experimental Validation.** *Nanomaterials* 2023; **13**(12):1813.

[21] Amjadi M, et al. **Stretchable, Skin-Mountable, and Wearable Strain Sensors and their Potential Applications: A Review.** *Advanced Functional Materials* 2016; **26**(11):1678-1698.

[22] Dong T, et al. **Resistive and Capacitive Strain Sensors Based on Customized Compliant Electrode: Comparison and their Wearable Applications.** *Sensors and Actuators A: Physical* 2021; **326**:112720.

[23] Seyedin S, et al. **Textile Strain Sensors: A Review of the Fabrication Technologies, Performance Evaluation and Applications.** *Materials Horizons* 2019; **6**(2):219-249.

[24] Shintake J, Nagai T, Ogishima K. **Sensitivity Improvement of Highly Stretchable Capacitive Strain Sensors by Hierarchical Auxetic Structures.** *Frontiers in Robotics and AI* 2019; **6**:127.

[25] Wu G, et al. **Fabrication of Capacitive Pressure Sensor with Extraordinary Sensitivity and Wide Sensing Range Using PAM/BIS/GO Nanocomposite Hydrogel and Conductive Fabric.** *Composites Part A: Applied Science and Manufacturing* 2021; **145**:106373.

[26] Zhang L, et al. **Highly Sensitive Capacitive Flexible Pressure Sensor Based on a High-Permittivity MXene Nanocomposite and 3D Network Electrode for Wearable Electronics.** *ACS Sensors* 2021; **6**(7):2630-2641.

[27] Xu H, et al. **An Ultra-Stretchable, Highly Sensitive and Biocompatible Capacitive Strain Sensor from an Ionic Nanocomposite for On-Skin Monitoring.** *Nanoscale* 2019; **11**(4): 1570-1578.

[28] Shin U-H, et al. **Highly Stretchable Conductors and Piezocapacitive Strain Gauges Based on Simple Contact-Transfer Patterning of Carbon Nanotube Forests.** *Carbon* 2014; **80**:396-404.

[29] Yao S, Zhu Y. **Wearable Multifunctional Sensors Using Printed Stretchable Conductors Made of Silver Nanowires.** *Nanoscale* 2014; **6**(4):2345-2352.

[30] Zhao H, et al. **Optoelectronically Innervated Soft Prosthetic Hand Via Stretchable Optical Waveguides.** *Science Robotics* 2016; **1**(1):eaai7529.

[31] Leber A, et al. **Stretchable Thermoplastic Elastomer Optical Fibers for Sensing of Extreme Deformations.** *Advanced Functional Materials* 2019; **29**(5):1802629.

[32] Wang D, et al. **Flexible and Optical Fiber Sensors Composited by Graphene and PDMS for Motion Detection.** *Polymers* 2019; **11**(9):1433.

[33] Guo J, et al. **Stretchable and Highly Sensitive Optical Strain Sensors for Human-Activity Monitoring and Healthcare.** *ACS Applied Materials & Interfaces* 2019; **11**(37):33589-33598.

[34] Guo J, Niu M, Yang C. **Highly Flexible and Stretchable Optical Strain Sensing for Human Motion Detection.** *Optica* 2017; **4**(10):1285-1288.

[35] Wang H, et al. **Self-Powered Inhomogeneous Strain Sensor Enabled Joint Motion and Three-Dimensional Muscle Sensing.** *ACS Applied Materials & Interfaces* 2019; **11**(37):34251-34257.

[36] Almansoori MT, Li X, Zheng L. **A Brief Review on E-Skin and Its Multifunctional Sensing Applications.** *Current Smart Materials* 2019; **4**(1):3-14.

[37] Huang Y, et al. **Resistive Pressure Sensor for High-Sensitivity E-Skin Based on Porous Sponge Dip-Coated CB/MWCNTs/SR Conductive Composites.** *Materials Research Express* 2018; **5**(6):065701.

[38] Paosangthong W, Torah R, Beeby S. **Recent Progress on Textile-Based Triboelectric Nanogenerators.** *Nano Energy* 2019; **55**:401-423.

[39] Wang L, Chiang W-H, Loh KJ. **Topological Design of Strain Sensing Nanocomposites.** *Scientific Reports* 2022; **12**(1):9179.

[40] Kang B-H, Jeong I-Y, Park S-H. **Design of a Smart Conducting Nanocomposite with an Extended Strain Sensing Range by Conjugating Hybrid Structures.** *Polymers* 2022; **14**(13):2551.

[41] Zhu S, et al. **Interface Design of Stretchable and Environment-Tolerant Strain Sensors with Hierarchical Nanocellulose-Supported Graphene Nanocomplexes.** *Composites Part A: Applied Science and Manufacturing* 2023; **164**:107313.

[42] Sankar V, Balasubramaniam K, Sundara R. **Design Framework for Polymer Nanocomposite Flexible Strain Sensor Adhesive Tape.** *IEEE Journal on Flexible Electronics* 2023; **2**(3): 265-273.

[43] Hosseini S, Norouzi M, Xu J. **A Sensitive Strain Sensor Based on Multi-Walled Carbon Nanotubes/ Polyaniline/ Silicone Rubber Nanocomposite for Human Motion Detection.** *Science* 2023; **5**(3):36.

[44] Babu VJ, et al. **Intelligent Nanomaterials for Wearable and Stretchable Strain Sensor Applications: The Science Behind Diverse Mechanisms, Fabrication Methods, and Real-Time Healthcare.** *Polymers* 2022; **14**(11) :2219.

[45] Zhao L, et al. **A Multifunctional, Self-Healing, Self-Adhesive, and Conductive Sodium Alginate/Poly (Vinyl Alcohol) Composite Hydrogel as a Flexible Strain Sensor.** *ACS Applied Materials & Interfaces* 2021; **13**(9):11344-11355.

[46] Zhan P, et al. **Electrically Conductive Carbon Black/Electrospun Polyamide 6/Poly (Vinyl Alcohol) Composite Based Strain Sensor with Ultrahigh Sensitivity and Favorable Repeatability.** *Materials Letters* 2019; **236**:60-63.

[47] Li Y, et al. **Flexible TPU Strain Sensors with Tunable Sensitivity and Stretchability by Coupling AgNWs With RGO.** *Journal of Materials Chemistry C* 2020; **8**(12):4040-4048.

[48] Gao J, et al. **Electrically Conductive and Fluorine Free Superhydrophobic Strain Sensors Based on SiO2/Graphene-Decorated Electrospun Nanofibers for Human Motion Monitoring.** *Chemical Engineering Journal* 2019; **373**:298-306.

[49] Huang Y-T, et al. **Flexible Porous Carbon Black-Polymer Composites with a High Gauge Factor.** *Sensors & Materials* 2020; **7**(3): 2527–2538.

[50] Gul JZ, Sajid M, Choi KH. **Retraction: 3D Printed Highly Flexible Strain Sensor Based on TPU-Graphene Composite for Feedback from High Speed Robotic Applications.** *Journal of Materials Chemistry C* 2020; **8**(7):2597-2597.

[51] Zhou J, et al. **Highly Sensitive and Stretchable Strain Sensors Based on Serpentine-Shaped Composite Films for Flexible Electronic Skin Applications.** *Composites Science and Technology* 2020; **197**:108215.

[52] Sun S, et al. **A Wearable, Waterproof, and Highly Sensitive Strain Sensor Based on Three-Dimensional Graphene/Carbon Black/Ni Sponge for Wirelessly Monitoring Human Motions.** *Journal of Materials Chemistry C* 2020; **8**(6):2074-2085.

[53] Wei Y, et al. **Silver Nanowires Coated on Cotton for Flexible Pressure Sensors.** *Journal of Materials Chemistry C* 2016; **4**(5):935-943.

[54] Fu W, et al. **Electronic Textiles Based on Aligned Electrospun Belt-Like Cellulose Acetate Nanofibers and Graphene Sheets: Portable, Scalable and Eco-Friendly Strain Sensor.** *Nanotechnology* 2018; **30**(4):045602.

[55] Wang L, et al. **Highly Compressible, Thermally Stable, Light-Weight, and Robust Aramid Nanofibers/Ti3AlC2 MXene Composite Aerogel for Sensitive Pressure Sensor.** *ACS Nano* 2020; **14**(8):10633-10647.

[56] Ma Y, et al. **3D Synergistical MXene/Reduced Graphene Oxide Aerogel for a Piezoresistive Sensor.** *ACS Nano* 2018; **12**(4):3209-3216.

[57] Liu X, et al. **A Highly Sensitive Graphene Woven Fabric Strain Sensor for Wearable Wireless Musical Instruments.** *Materials Horizons* 2017; **4**(3):477-486.

[58] Huang S, et al. **Stretchable Strain Vector Sensor Based on Parallelly Aligned Vertical Graphene.** *ACS Applied Materials & Interfaces* 2018; **11**(1):1294-1302.

[59] Guo X, et al. **Highly Stretchable Strain Sensor Based on SWCNTs/CB Synergistic Conductive Network for Wearable Human-Activity Monitoring and Recognition.** *Smart Materials and Structures* 2017; **26**(9):095017.

[60] Lee J, et al. **Ultrasensitive Strain Sensor Based on Separation of Overlapped Carbon Nanotubes.** *Small* 2019; **15**(12):1805120.

[61] Choi JH, et al. **Fabrication and Performance Evaluation of Highly Sensitive Flexible Strain Sensors with Aligned Silver Nanowires.** *Micromachines* 2020; **11**(2):156.

[62] Xu K, et al. **Highly Stable Kirigami-Structured Stretchable Strain Sensors for Perdurable Wearable Electronics.** *Journal of Materials Chemistry C* 2019; **7**(31):9609-9617.

[63] Davoodi E, et al. **Drop-on-Demand High-Speed 3D Printing of Flexible Milled Carbon Fiber/Silicone Composite Sensors for Wearable Biomonitoring Devices.** *Additive Manufacturing* 2020; **32**:101016.

[64] Liu G, Xiong Y, Zhou L. **Additive Manufacturing of Continuous Fiber Reinforced Polymer Composites: Design Opportunities and Novel Applications.** *Composites Communications* 2021; **27**:100907.

[65] Petroni JM, et al. **Development of Highly Sensitive Electrochemical Sensor Using New Graphite/ Acrylonitrile Butadiene Styrene Conductive Composite and 3D Printing-Based Alternative Fabrication Protocol.** *Analytica Chimica Acta* 2021; **1167**:338566.

[66] Ben Atitallah B, et al. **Piezo-Resistive Pressure and Strain Sensors for Biomedical and Tele-Manipulation Applications.** In: *Advanced Sensors for Biomedical Applications*. 2021:47-65.

[67] Georgopoulou A, Clemens F. **Piezoresistive Elastomer-Based Composite Strain Sensors and Their Applications.** *ACS Applied Electronic Materials* 2020; **2**(7):1826-1842.

[68] Kim SJ, et al. **'Smart' Implantable Devices for Spinal Implants: A Systematic Review on Current and Future Trends.** *Journal of Spine Surgery* 2022; **8**(1):117.

[69] Souri H, et al. **Wearable and Stretchable Strain Sensors: Materials, Sensing Mechanisms, and Applications.** *Advanced Intelligent Systems* 2020; **2**(8):2000039.

[70] Low ZWK, et al. **Recent Innovations in Artificial Skin.** *Biomaterials Science* 2020; **8**(3):776-797.

[71] Moheimani R, et al. **Thermoplastic Polyurethane Flexible Capacitive Proximity Sensor Reinforced by CNTs for Applications in the Creative Industries.** *Scientific Reports* 2021; **11**(1):1104.

[72] Qi K, et al. **A Highly Stretchable Nanofiber-Based Electronic Skin With Pressure-, Strain-, and Flexion-Sensitive Properties for Health and Motion Monitoring.** *ACS Applied Materials & Interfaces* 2017; **9**(49):42951-42960.

[73] Chen M, et al. **Self-Assembly of Dendritic-Lamellar MXene/Carbon Nanotube Conductive Films for Wearable Tactile Sensors and Artificial Skin.** *Carbon* 2020; **164**:111-120.

[74] Zhao Y, et al. **Highly Sensitive Flexible Strain Sensor Based on Threadlike Spandex Substrate Coating with Conductive Nanocomposites for Wearable Electronic Skin.** *Smart Materials and Structures* 2019; **28**(3):035004.

[75] Yin F, et al. **Flexible and Highly Sensitive Artificial Electronic Skin Based on Graphene/Polyamide Interlocking Fabric.** *Journal of Materials Chemistry C* 2018; **6**(25):6840-6846.

[76] Ma H, et al. **Light-Weight Strain Sensor Based on Carbon Nanotube/Epoxy Composite Yarn.** *Journal of Materials Science* 2021; **56**(23):13156-13164.

[77] Alam T, et al. **Smart-Textile Strain Sensor for Human Joint Monitoring.** *Sensors and Actuators A: Physical* 2022; **341**:113587.

[78] Tao L-Q, et al. **Self-Adapted and Tunable Graphene Strain Sensors for Detecting Both Subtle and Large Human Motions.** *Nanoscale* 2017; **9**(24):8266-8273.

[79] He Z, et al. **A Wearable Flexible Acceleration Sensor for Monitoring Human Motion.** *Biosensors* 2022; **12**(8):620.

[80] Huang J, et al. **Highly Stretchable and Bio-Based Sensors for Sensitive Strain Detection of Angular Displacements.** *Cellulose* 2019; **26**:3401-3413.

[81] Zhang Y, et al. **Highly Stretchable Polymer/Silver Nanowires Composite Sensor for Human Health Monitoring.** *Nano Research* 2020; **13**:919-926.

[82] Li M, et al. **Stretchable Conductive Polypyrrole/Polyurethane (PPy/PU) Strain Sensor with Netlike Microcracks for Human Breath Detection.** *ACS Applied Materials & Interfaces* 2014; **6**(2):1313-1319.

[83] Liu X, Wei Y, Qiu Y. **Advanced Flexible Skin-Like Pressure and Strain Sensors for Human Health Monitoring.** *Micromachines* 2021; **12**(6):695.

[84] Kumar A. **Flexible and Wearable Capacitive Pressure Sensor for Blood Pressure Monitoring.** *Sensing and Bio-Sensing Research* 2021; **33**:100434.