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Review article

SENSING MECHANISM AND APPLICATION OF MECHANICAL STRAIN SENSOR: A MINI-REVIEW

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Abstract. *This study reviews the potential of flexible strain sensors based on nanomaterials such as carbon nanotubes (CNTs), graphene, and metal nanowires (NWs). These nanomaterials have excellent flexibility, conductivity, and mechanical properties, which enable them to be integrated into clothing or attached to the skin for the real-time monitoring of various activities. However, the main challenge is balancing high stretchability and sensitivity. This paper explains the basic concept of strain sensors that can convert mechanical deformation into electrical signals. Moreover, this paper focuses on simple, flexible, and stretchable resistive and capacitive sensors. It also discusses the important factors in choosing materials and fabrication methods, emphasizing the crucial role of suitable polymers in high-performance strain sensing. This study reviews the fabrication processes, mechanisms, performance, and applications of stretchable strain sensors in detail. It analyzes key aspects, such as sensitivity, stretchability, linearity, response time, and durability. This review provides useful insights into the current status and prospects of stretchable strain sensors in wearable technology and human–machine interfaces.*

Key words: *Strain Sensor, Flexible, Nanomaterials, Mechanical Property, Deformation*

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1. INTRODUCTION

Flexible and wearable devices that adhere to the skin are garnering interest and are actively developed [1-5]. These devices offer valuable features, such as the ability to interact with and monitor the human body [6-11]. However, conventional strain sensors that rely on metals or semiconductor materials exhibit limited sensitivity and stretchability, making their integration into wearable devices challenging [12-15]. Notably, these sensors possess high stretchability to adhere to the skin or body joints effectively. Moreover, they must satisfy various requirements, including high elasticity, flexibility, durability, low power consumption, and biocompatibility [16, 17].

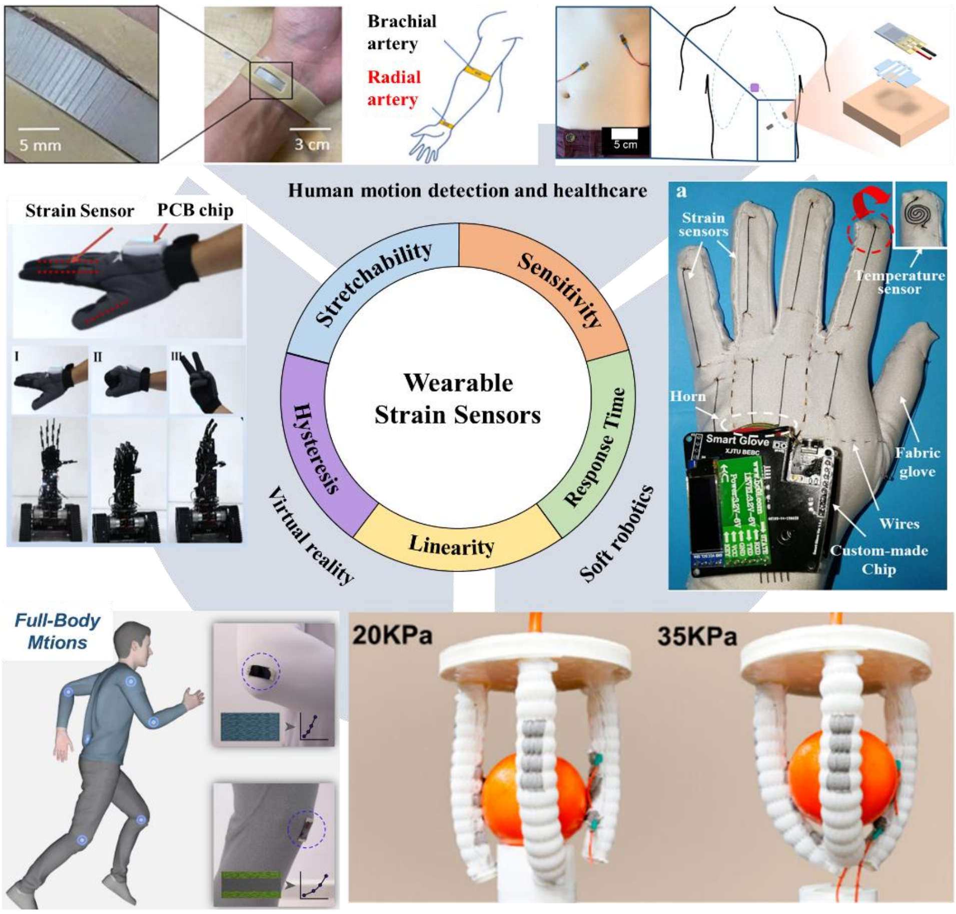

Fig. 1 State-of-the-art flexible, wearable strain sensors made of nanomaterials and polymer composites. Reprinted with permission from [11], copyright 2023 American Chemical Society. Reprinted with permission from [18], copyright 2022 Springer Nature. Reprinted with permission from [19], copyright 2021 Wiley. Reprinted with permission from [20] under the Creative Commons Attribution 4.0 International (CC BY 4.0) License. Reprinted with permission from [21], copyright 2020 American Chemical Society.

Hence, carbon nanotubes (CNTs) [22-31], graphene [26, 32-36], metal thin films [5, 37], and nanomaterials, such as metal nanowires (NWs) [38-45] , have emerged as promising candidates for flexible strain sensors. These materials exhibit remarkable flexibility and conductivity, as well as exceptional mechanical, electrical, optical, and chemical properties. Using these nanomaterials, flexible strain sensors can be seamlessly integrated into clothing or adhered directly to the human body for the real-time monitoring of physical activities with impressive efficiency. These materials are often combined with polymers to achieve desired flexibility, durability, and biocompatibility. However, balancing stretchability and sensitivity remains a challenge, hindering the development of high-performance strain sensors [46].

A strain sensor converts mechanical deformations into electrical signals. Various types of strain sensors exist, including fiber Bragg gratings [47], triboelectric sensors [38], and piezoelectric sensors [48, 49]. However, using strain sensors for wearable applications poses challenges owing to limitations such as the need for sophisticated measurement equipment, low resolution, and dynamic performance issues [50].

Some highly sensitive strain sensors can detect small strains and offer excellent electrical responses. However, they tend to lose their conductivity when subjected to relatively large strains, which makes them incapable of detecting subtle changes. For instance [51], while graphene-based strain sensors have a high gauge factor (GF) of 103, indicating substantial changes in electrical resistance owing to deformation, their detectable range is limited to 6%. Conversely, highly elastic sensors are better equipped to handle substantial strains but exhibit poor sensitivity. Strain sensors based on materials such as finely crushed graphene, graphene nanopaper, and silver nanowires can detect a wide range of strains exceeding 70%. However, within the range of 20% or less strain, they exhibit a low GF value and insufficient sensitivity.

Wearable sensors are broadly categorized into two types: resistive [52] and capacitive [53]. Both require relatively simple systems and offer high flexibility and stretchability. Resistive sensors typically consist of conductive sensing films integrated with flexible substrates. As the composite material expanded, the microstructure of the sensing film changed, altering its resistance in response to the applied strain. When the strain was removed, the composite returned to its original state, and the resistance returned to its initial value. However, capacitive sensors rely on electrodes and an insulator. The capacitance changes with the applied strain, leading to alterations in the electric field.

An essential consideration in fabricating flexible strain sensors is the selection of the appropriate materials and manufacturing methods. The fabrication process should facilitate low-cost, large-scale production and convenience. To date, stretchable strain sensors have been created by incorporating materials such as carbon black (CB) [54-56], carbon nanotubes (CNTs), NWs, nanoparticles (NPs) [57, 58], silicone-based elastomers (e.g., polydimethylsiloxane (PDMS) [11, 26, 59-61], polyurethane (PU) [62-64], or ecoflex [30, 48, 65]), and rubbers (natural rubber and thermoplastic elastomers) [66-69]. The impact of the choice of the polymer type on the strain-sensing performance, although relatively minor, is explored in detail in another section. Various methods for fabricating stretchable strain sensors, including filtration [70], printing [27, 37, 71, 72], transfer [73, 74], coating [75, 76], and chemical synthesis [77], have been reported. For example, a highly stretchable and sensitive strain sensor was produced by filtering silver nanowire (AgNW)-PDMS through a filtration process. This involves coating the AgNWs onto a silicon substrate, followed by PDMS filtration to create a film by curing and peeling. In addition, a flexible and sensitive strain sensor was fabricated by spray coating graphene flakes onto a PET substrate [73]. Numerous other methods have also been explored, such as strain sensor fabrication through printing and solution mixing to create nanocomposites (Fig. 2).

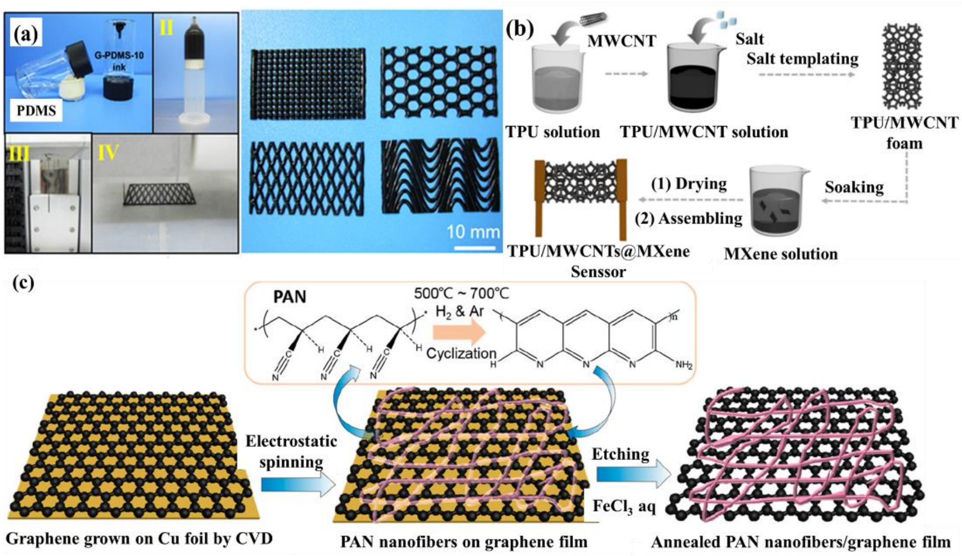

Fig. 2 Fabrication processes of stretchable strain sensors. a) Printing technology. Reprinted with permission from [71], copyright 2019 American Chemical Society. b) Solution mixing. Reprinted with permission from [64], copyright 2021 American Chemical Society. c) Spinning and Transfer method. Reprinted with permission from [74], copyright 2019 American Chemical Society.

In this paper, we review the fabrication methods, mechanisms, strain-sensing performance, and applications of stretchable strain sensors. We begin by describing the general mechanism of these sensors, followed by an explanation of the responsive behavior mechanisms of both resistive and capacitive sensors. In addition, we discuss critical aspects, such as stretchability, sensitivity, linearity, response time, durability, and other factors that validate the performance of stretchable strain sensors. Finally, we provide relevant examples and offer insight into the future of this technology. This review enhances the crucial understanding of the presentation of novel ideas to resolve the limitations related to these sensors.

2. Strain-Response Mechanism

2.1. Geometrical Effect

The response of a strain sensor varies depending on factors such as material, micro/nanostructure, and manufacturing process. The traditional strain resistance response results from the geometry and piezoresistivity of a material [78]. However, unlike conventional strain gauges, modern stretchable strain sensors utilize mechanisms such as separation between sensing elements, crack propagation in films, and tunneling effects. When a material undergoes stretching, it tends to contract laterally owing to its Poisson ratio. In the case of a solid, its resistance (*R*) can be calculated using the formula:

$$R = \frac{\varphi L}{A} \tag{1}$$

where φ represents the resistance, L is the length, and A is the cross-sectional area of the solid. As the length increases and the cross-sectional area decreases owing to contraction, the resistance of the solid increases. However, when a capacitive sensor is subjected to stretching, an increase in capacitance arises from changes in the thickness of the dielectric layer and alterations in the capacitor area [79]. The formula for calculating the capacitance (*C*) is based on the overlap area between the two electrodes (*A*) and thickness (*d*) of the dielectric layer. This is expressed as follows:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \tag{2}$$

where ε_0 and ε_r are the permittivity of vacuum and relative permittivity of the dielectric, respectively.

As the sensor experiences strain, its capacitance of the capacitive sensor increases by preserving the capacitive region while reducing the thickness of the dielectric layer. Assuming that the stretchable electrode and the dielectric layer of the stretchable strain sensor share the same Poisson ratio, calculating the capacitance is possible during stretching. In this scenario, the capacitance of the capacitive sensors increased linearly with applied strain. However, importantly, if the applied strain becomes excessively large, the linear relationship dictated by Poisson's ratio may not hold for polymers. Therefore, recognizing that this linear function is valid within a specific range of strains and may not be applicable beyond that range is essential.

2.2. Piezoresistive Effect

Piezoresistance refers to the change in the resistance of a material owing to structural deformation [80-83]. This piezoresistance can be expressed as following Eq. (3):

$$\frac{\Delta R}{R} = (1 + 2v)\tau + \frac{\Delta p}{p} \tag{3}$$

where v is the Poisson’s ratios for the stretchable layer, τ is the applied strain, R is the measured resistance and p is the applied pressure. Semiconductor materials such as Si and Ge can significantly increase the sensor resistance by altering the bandgap between atoms [84]. Conversely, some metals and metal alloys exhibit piezoresistive properties that can substantially increase strain gauge resistance. Moreover, materials at the nanoscale, such as carbon nanotubes (CNTs) and nanowires (NWs), can exhibit ultrahigh resistance depending on factors such as chirality and barrier height [85, 86]. This makes semiconductors and nanoscale materials promising for fabricating highly sensitive strain gauges. However, despite their potential, the flexibility required for human attachment and wearable strain sensors surpasses that of conventional strain gauges fabricated using metals and semiconductors. These limitations are attributed to technical challenges, inconsistent electrical and mechanical properties, and low elasticity. Consequently, SWCNTs (single-walled carbon nanotubes) and NW-based sensors have not been widely adopted for strain-sensing applications.

To address these limitations, novel approaches were introduced to create more flexible and sensitive deformation sensors by incorporating nanomaterials into elastic polymer composites. Unlike previous methods, these approaches aimed to enhance the flexibility and sensitivity of strain sensors. However, notably, the contribution of piezoresistive nanomaterials to the overall resistance and strain behavior of elastic strain sensors is expected to be limited. This limitation arises from the weak interfacial bonding strength between the nanomaterials and polymers, as well as the anticipated significant elastic mismatch between the two components [87].

2.3. Disconnection Mechanism

In a conductive film comprising conductive nanomaterials, electrons traverse the percolation network formed by stacked nanomaterials [16, 88]. As the film underwent stretching, the area of overlap between the connected nanomaterials decreased, increasing the resistance. At the microstructural level, the disconnection of overlapping nanomaterials during stretching occurs because of weak interfacial bonding between the materials and significant elastic mismatch between the nanomaterials and polymer.

Open circuits within conductive nanomaterials obstruct electrical pathways, resulting in exceptionally high resistance and diminished performance of the strain sensors. As the strain level increases, the disconnection mechanism becomes more pronounced, and the performance of the sensor becomes heavily reliant on this process of disconnection and reconnection, leading to irreversible sensitivity degradation (Fig. 3).

Elastomer composite sensors incorporating nanomaterials, such as graphene flakes [89], AgNWs [42], and ZnONWs [90], have been reported. Similar mechanisms have been observed where disconnections occur at the junctions between NWs after expansion, causing increased resistance and decreased performance.

Stretchable and sensitive strain sensors were developed using thin films of NW networks and graphene flakes, focusing on disconnection mechanisms. For instance [11], in the case of AgNWs embedded in PDMS, where the AgNWs possess Young's modulus of 81–176 GPa, and PDMS exhibits a modulus of 2–3.5 MPa, during stretching cycles, the AgNWs within the PDMS slip into the PDMS matrix, leading to disconnections at the NW–W junctions. Another example involves sensors using AgNW, graphene and PDMS that exhibit a GF of 9156 under strain of >36% [91]. Even with various temperature range, these sensors rely on a disconnection mechanism to detect changes in resistance. In this context, the rigid nature of graphene sheets result in microcrack junctions allowing resistance changes to be observed. Similar mechanisms have been identified for sensors that use the rolling resistances of ZnO NWs and graphene flakes.

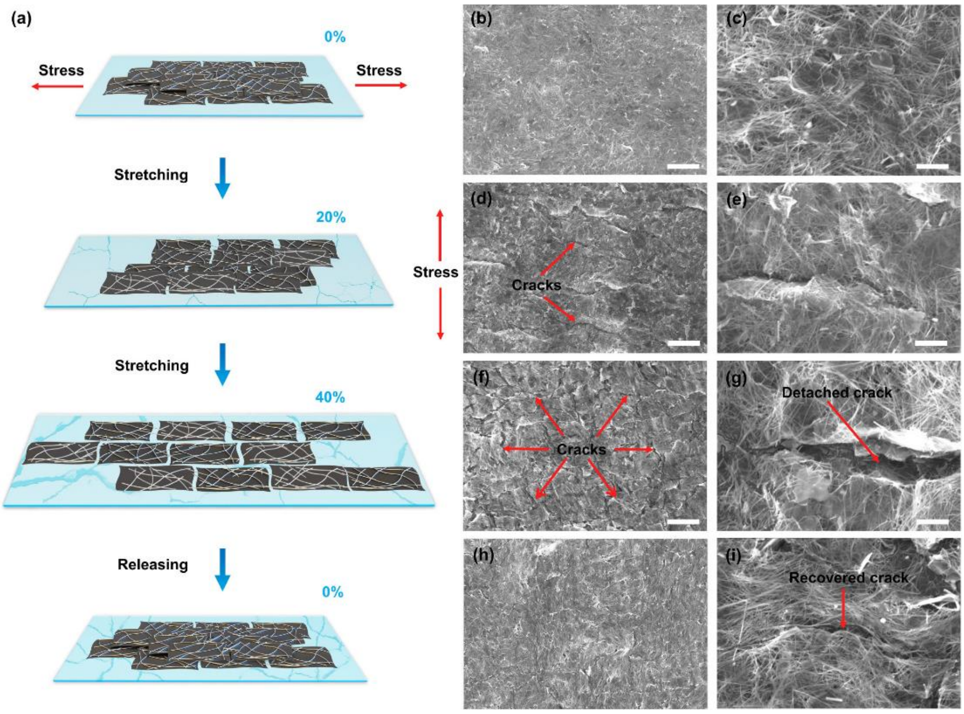

Fig. 3 (a) Schematic of the sensing mechanism and SEM images of the strain sensors at various stretching states: (b,c) 0%, (d, e) 20%, (f, g) 40%, (h, i) and back to 0%. Scale bars in (b), (d), (f) and (h) are 20 μm. Scale bars in (c), (e), (g) and (i) are 5 μm. Reprinted with permission from [91], copyright 2021 American Chemical Society.

2.4. Crack Propagation

Cracks tend to form in thin and delicate coating layers on the film and can be easily initiated and propagated when subjected to stretching. These cracks typically originate from regions where the stress is concentrated, thereby effectively releasing localized stress. Fine cracks developed in the CNTs, NWs, NPs, and graphene films coated on stretched substrates [58, 92, 93]. As the stretching process continued, these cracks expanded within the thin film, significantly increasing the resistance. This mechanism is used to create highly sensitive and flexible strain sensors.

Moreover, several methods have been explored to enhance the strain sensitivity and GF further. One approach involves peeling off the AgNWs in conjunction with the PDMS and cutting the composite material mechanically [11]. As shown in Fig. 4, owing to the structural alterations induced by mechanical cutting, certain areas experienced partial cutting, allowing the strain to reach up to 30% and consequently yielding a GF value of 290.1. Notably, the resistance returned to its original state, indicating complete recovery.

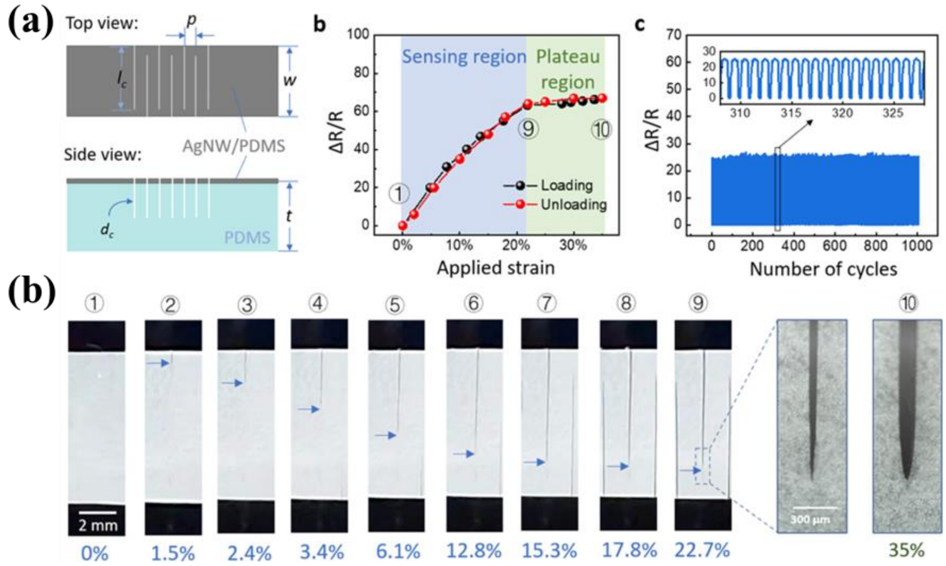

Fig. 4 (a) Schematic of the sensor and electrical performances of strain sensor under applied strain. (b) Optical images of the top surface of the sensor under applied strain showing the crack opening. Reprinted with permission from [11]; copyright 2023 American Chemical Society.

3. Performance of Stretchable Strain Sensors

3.1. Stretchability

The performance of strain sensors depends on various critical factors, including stretchability, sensitivity, GF, linearity, hysteresis, response and recovery times, and durability. These factors are significant for wearable strain sensors that can be exposed to prolonged, repeated strain.

The stretchability of a strain sensor exhibits substantial variability, contingent on factors such as the sensor type, utilized materials, structural design, and manufacturing techniques. For instance [94], a resistive sensor composed of an aligned CNT-PDMS composite achieved an impressive stretchability of ~280%. This exceptional stretchability was attributed to the consistent propagation of microcracks within the CNT film and interconnection of the aligned CNTs. Similarly, capacitive sensors demonstrated ~300% stretchability using CNT–silicone elastomer composites owing to the remarkable stretchability of the dielectric material and robust nature of the CNT-based strain electrodes.

The integration of 1D nanomaterial-polymer composites plays a pivotal role in significantly enhancing the stretchability of strain sensors [95]. Owing to the high aspect ratio of 1D nanomaterials, an effective network can be readily established, ensuring stable electrical and mechanical properties, even under conditions of substantial stretchability. Strain sensors employing CB, NPs, and graphene films exhibit stretchabilities >70% [96-98]. Examples include graphene–cellulose composites, fragmentized graphene foam

(FPF)–PDMS composites, and graphene–rubber composites. Conversely, the limited stretchability observed in CB-, NP-, and graphene-based strain sensors can be attributed to the absence of a well-connected network of nanomaterials with lower aspect ratios [99].

3.2. Sensitivity or Gauge Factor

The sensitivity or GF of the strain sensors was determined by the relative change in the electrical signal and slope of the applied strain. The GF can be calculated for both resistive and capacitive sensors using the following equation:

$$GF = \frac{\Delta R}{R_0 \rho}, GF = \frac{\Delta C}{C_0 \rho} \tag{3}$$

where C_0, R_0, and ρ, are the initial capacitance, resistance and the dielectric constant. Traditional metal film-based strain gauges typically offer a GF in the range of 2–5, while semiconductor-based strain sensors can provide GF values >100 [16]. By contrast, stretchable strain sensors can exhibit various GF values depending on factors such as the sensing mechanism, nanomaterial used, and structural design of the sensor. Among resistive sensors, a broad range of GFs can be achieved by adjusting the density of the AgNWs. Some studies have also aimed to attain high GF values and stretchability by reducing the AgNW concentration and employing a disconnection mechanism. However, these approaches have limited reliability. Highly sensitive sensors using cracks and disconnection mechanisms with graphene have been reported; however, they tend to have very low stretchability [100]. By contrast, capacitive-type sensors offer high stretchability but typically possess very low GF values. Most capacitive sensors have GF values <1. Theoretically, a GF of 1 represents the upper limit for capacitive sensors, making achieving a GF higher than this value impossible [101].

3.3. Linearity

Linearity is a crucial factor affecting the performance of stretchable strain sensors. This is particularly relevant for resistivity-based sensors, where nonlinearity can complicate data processing and adversely affect data collection. Nonlinearity often arises when the microstructure of a thin film changes from homogeneous to nonhomogeneous owing to stretching, causing the strain sensor to respond nonlinearly to the applied strain. Nonuniform generation and propagation of microcracks during deformation contribute to this nonlinear response in the strain sensor data calculation process.

Efforts have been made to address these limitations, including enhancing CNTs through hybrid structures that incorporate metals or other nanomaterials. However, these efforts mostly resulted in a trade-off between high linearity, sensitivity, and stretchability.

Conversely, capacitive sensors typically exhibit excellent linearity but lower sensitivity than sensors with a GF of 1 or higher. High-sensitivity strain sensors often exhibit high nonlinearity and low stretchability. Consequently, the development of a strain sensor with high stretchability and sensitivity remains a significant challenge.

3.4. Hysteresis

In the context of using strain sensors for body attachment and wearable applications, hysteresis is a critical consideration, particularly when the sensor is subjected to dynamic loading. Significant hysteresis can lead to irreversible sensing performance under dynamic loads. Capacitive sensors generally exhibit a better hysteresis performance than resistive sensors [53].

The performance of capacitive sensors relies on maintaining a stable overlapping area between the electrodes rather than on the conductivity of the electrodes. However, resistive sensors are more susceptible to hysteresis because they are affected by changes in the conductivity of the thin films, which can contribute to greater hysteresis effects. In addition, hysteresis can stem from interactions between the polymer and nanomaterial fillers as well as the viscoelastic properties of the polymer [94]. Strong interfaces between the polymer and filler materials improve strain sensor performance. Conversely, weak connections between nanomaterials and the polymers can lead to slipping and increased disconnections during stretching, thereby causing high hysteresis [102].

Researchers have endeavored to develop applications that can be attached to the body while significantly reducing hysteresis. For example [103], one approach involved creating a hydrogel using materials like PEDOT:PSS and polyvinyl alcohol (PVA), demonstrating a remarkably low hysteresis of ~1.44%, even in a strain range of 300%. However, room for improvement exists in terms of sensitivity, as this particular hydrogel exhibited a relatively low GF value of 4.07.

3.5. Response and Recovery Time

The response time is a crucial parameter that indicates how quickly a strain sensor returns to its normal state after experiencing a strain. Because of the viscoelastic properties of polymers, all polymer-based strain sensors inherently exhibit some degree of response delay. Typically, the standard response time of stretchable sensors is defined using a 90% time constant.

For resistivity sensors based on materials such as AgNW/PDMS [104] and AgNW/AgNP/PDMS [43], response times of 200 and 51 ms, respectively, were reported. By contrast, capacitive sensors exhibit faster response times. Capacitive sensors based on Mxene/PVP [105] and AgNW/PDMS [106] show response times of 30 ms.

The recovery time is another important performance factor for stretchable strain sensors. Capacitive sensors generally have recovery times in milliseconds, whereas resistive sensors require few hundred milliseconds to recover. For instance, capacitive strain sensor exhibit a 15 ms recovery time [105], while resistive strain sensors of AuNP/PDMS [107] and CNT/PDMS [108] composites require 250 and 500 ms to recover. The recovery time of nanocomposite-based strain sensors depends on the interactions between the fillers and polymers and varies based on the type and ratio of the fillers used.

Capacitive sensors offer advantages such as high linearity, stretchability, and low hysteresis. However, they have a very low GF and can exhibit unpredictable responses owing to unstable overlapping areas and interactions. Conversely, resistive sensors provide high GF values but often respond to applied strains with high hysteresis and nonlinearity.

4. APPLICATIONS

4.1. Human motion detection and healthcare

Flexible strain sensors can continuously record a wide spectrum of bodily movements ranging from significant joint actions to subtle deformations associated with physiological signals. Consequently, these strain sensors have garnered considerable attention as essential components in healthcare monitoring devices, serving purposes such as human motion detection and diverse healthcare applications. Developing highly sensitive sensors capable of generating high-resolution and accurate signals is important to meet the demands of detecting minute variations such as pulses or respiration [20, 25, 43, 44, 64].

Fig. 5A illustrates the application of strain sensors employing AgNW/PDMS composites to monitor pulse rates by attaching them to the brachial and radial arteries. After undergoing structural transformation via partial cutting, the sensors exhibited a strain of up to 30% and an impressive GF value of 290.1. In addition, the sensors demonstrated a rapid increase in resistance through a disconnection mechanism and exhibited exceptional performance stability even after 1000 reliability test cycles. The sensors respond to changes in blood flow pressure resulting from the pulse, enabling the tracking of various pulse characteristics. Furthermore, these sensors can be affixed to the back of a person to discern body movements in different directions, thereby facilitating human motion detection and healthcare monitoring, particularly for spinal issues [11].

In addition to the pulse and major body motions, wearable strain sensors can discern alterations in facial expressions and emotional states [64]. Capacitive sensors strategically placed around the eyes and mouth enable the detection of actions such as laughter, crying, and frowning with high sensitivity. Monitoring diverse emotional expressions is valuable in assessing conditions such as Alzheimer's disease. Fig. 5B further illustrates the application of these sensors to the neck, capturing changes in resistance corresponding to vocal cord movements, including phonetic sounds like “I,” “A,” and “M.”

Moreover, wearable sensors can gauge vital parameters, such as respiratory rate, oxygen saturation, and heart rate, and transmit these data wirelessly. These sensors can connect to emergency service centers to dispatch alarm messages during emergencies. This strain sensor was engineered to concurrently measure respiratory volume and rate using polystyrene, Au, and Pt [20]. These sensors were attached to the rib cage and abdomen to measure volume variations during respiration and to calculate the respiratory rate and volume. The precision was confirmed by comparing the resistance changes due to respiration with spirometer readings, yielding a high-precision level with an R^2 of 0.92. Unlike conventional wearable sensors, which typically measure only the respiratory rate, this sensor can also estimate the respiratory volume. It can monitor breathing across different activities, is not limited to stationary positions, and is invaluable for identifying individuals with chronic respiratory conditions through everyday wireless bluetooth devices. These versatile sensors, which are suitable for placement on various parts of the human body, hold promise for applications in diverse fields, including exercise, health monitoring, and disease management.

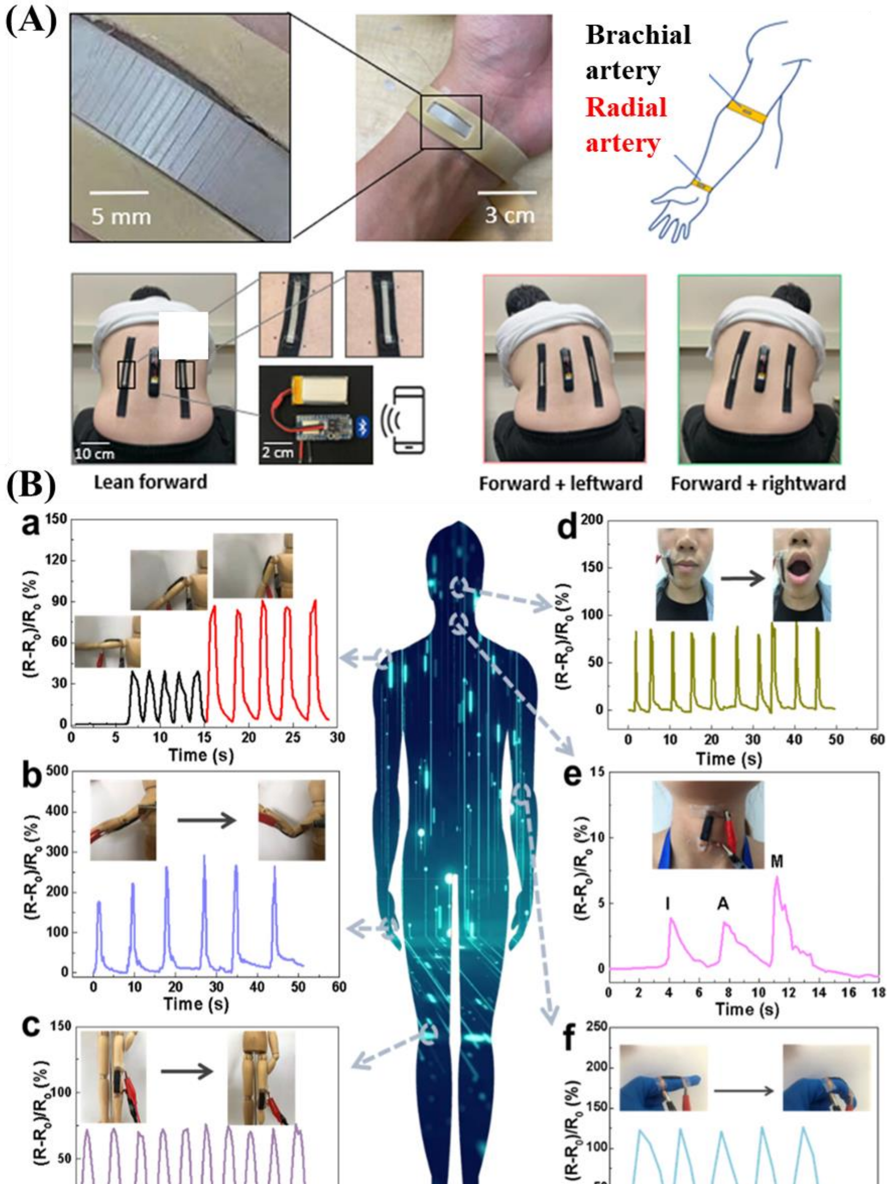

Fig. 5 Demonstrations of the strain sensor for personal health monitoring. (A) Blood pulse on the radial artery and brachial artery and spine for monitoring lower back strain. Reprinted with permission from [11], copyright 2023 American Chemical Society. (B) Detection of human joint movements and the vocal cord vibration. Reprinted with permission from [64], copyright 2021 American Chemical Society.

4.2. Soft robotics

Wearable strain sensors play a pivotal role in soft robotics, a field of technology characterized by robots crafted from pliable materials. These sensors are instrumental in overseeing and directing the shape, movement, and interactions of soft robots in their environment. Unlike their traditional counterparts, soft robots exhibit natural fluidity of motion and adaptability to their surroundings. They are typically affixed to soft grippers and detect the force and positioning required for secure object manipulation and lifting. The sensors transmit these data to the robot control system, enabling real-time control and interaction. Applications of soft robots span diverse fields, including medicine, structural inspections, environmental exploration, and disaster relief [8, 19, 24, 109].

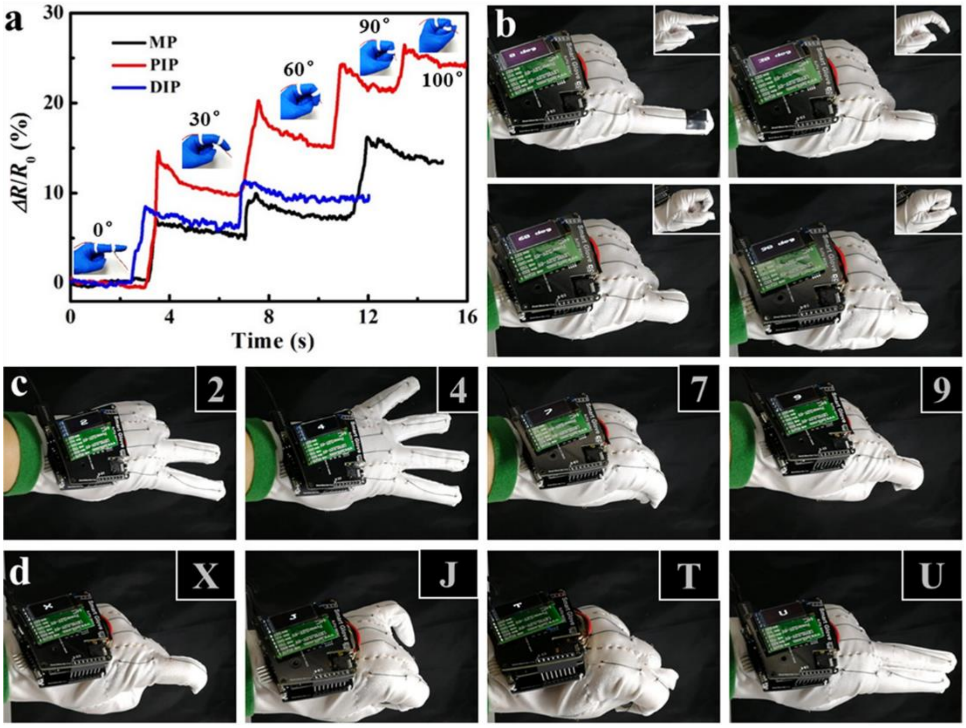

Fig. 6 Recognition of finger dexterity, gestures, and temperatures. (a) Relationship between the ΔR/R0 of MWNTs/PDMS fibers recorded by a tablet oscilloscope and the angle of finger joint bending. Metacarpophalangeal point (MP), proximal interphalangeal point (PIP), and distal interphalangeal point (DIP) are three important joints in the hand. (b–e) Photograph of the smart glove for recognition of (b) the bending angles of the finger, (c) numbers, and (d) alphabets. Reprinted with permission from [21], copyright 2020 American Chemical Society.

For example, a hydrogel-type strain sensor comprising PEDOT:PSS and PVA was applied in soft robotics [103]. This strain sensor was attached to the gripper where alterations in the gripper angle corresponding to the size of the grasped object were observed, changing the resistance. This relationship was linearly corrected by analyzing the bending angle and resistance variations. Furthermore, this study demonstrates that an industrial robot can be remotely guided by hand manipulation by integrating these sensors. The strain sensors continuously monitor the bending motion of each finger, allowing the controller to direct the movements of the robot based on automatically recognized signals. The experiment underscores that industrial robots can be precisely, reliably, and immediately controlled with minimal hysteresis, thereby ensuring stable performance and high resilience. In addition, other research explored the creation of a smart glove equipped with a strain sensor using MWCNT/PDMS fibers [21]. (Fig. 6) When worn, this smart glove detects resistance changes when the fingers are bent or flexed. Numbers and alphabets can be recognized according to the bending of the finger joints, and the corresponding information can be checked through the tablet on the back of the hand. Remarkably, this system exhibited an impressive high linear coefficient R^2 of >0.995 within the 0-120% strain range. Moreover, it demonstrated excellent durability, enduring 20,000 cycles of stretching and release with a 50% strain applied. Nevertheless, it shows the limitation of having very low GF values from 0.45 to 2.08 with different.

4.3. Virtual reality

Another compelling application of wearable strain sensors is as motion sensors for virtual reality (VR) and augmented reality (AR). By affixing these sensors to various parts of the human body, such as gloves, stockings, and clothing, users can engage in immersive gaming experiences that leverage motion detection, pressure sensing, and hand movements, all of which are facilitated by these motion sensors. Moreover, wearable strain sensors not only detect the user's movements and touches but also govern interactions within virtual environments, playing a pivotal role in gaming, educational simulations, and other forms of entertainment [110, 111].

As shown in Fig. 7A, this research [19] introduced a sensor embedded in a smart glove designed to track the intricate movements of an individual's fingers. These smart gloves, equipped with printed PCB chips, established Bluetooth connections with the robot’s hands, enabling them to respond to an array of gestures. The strain sensor using liquid metal and PDMS exhibited an impressive stretch capacity of up to 105% strain and a remarkable detection limit as low as 0.05%. By demonstrating remarkable durability over 8000 cycles at 50% strain, these smart gloves proved adept at tracking the movements of various body parts in the virtual reality realm.

Fig. 7B shows the implementation of a strain sensor based on the MXene/SWCNT/PVA composite [18]. For human–machine interaction purposes, strain sensors were strategically positioned on the elbow, knee and other joints. These sensors were linked to a data acquisition circuit board that was meticulously designed to interpret finger movements, gather data, and transmit them to a computer via Bluetooth. This setup allows users to control VR movements by interacting with the strain sensors. Furthermore, these sensors highlight their potential as versatile motion sensors for both real-world movements and immersive realms of virtual and augmented reality. Notably, they offer several advantages over traditional camera setups and motion detection systems, including less power consumption, high sensitivity of > 1000, cost-effectiveness, and high accuracy.

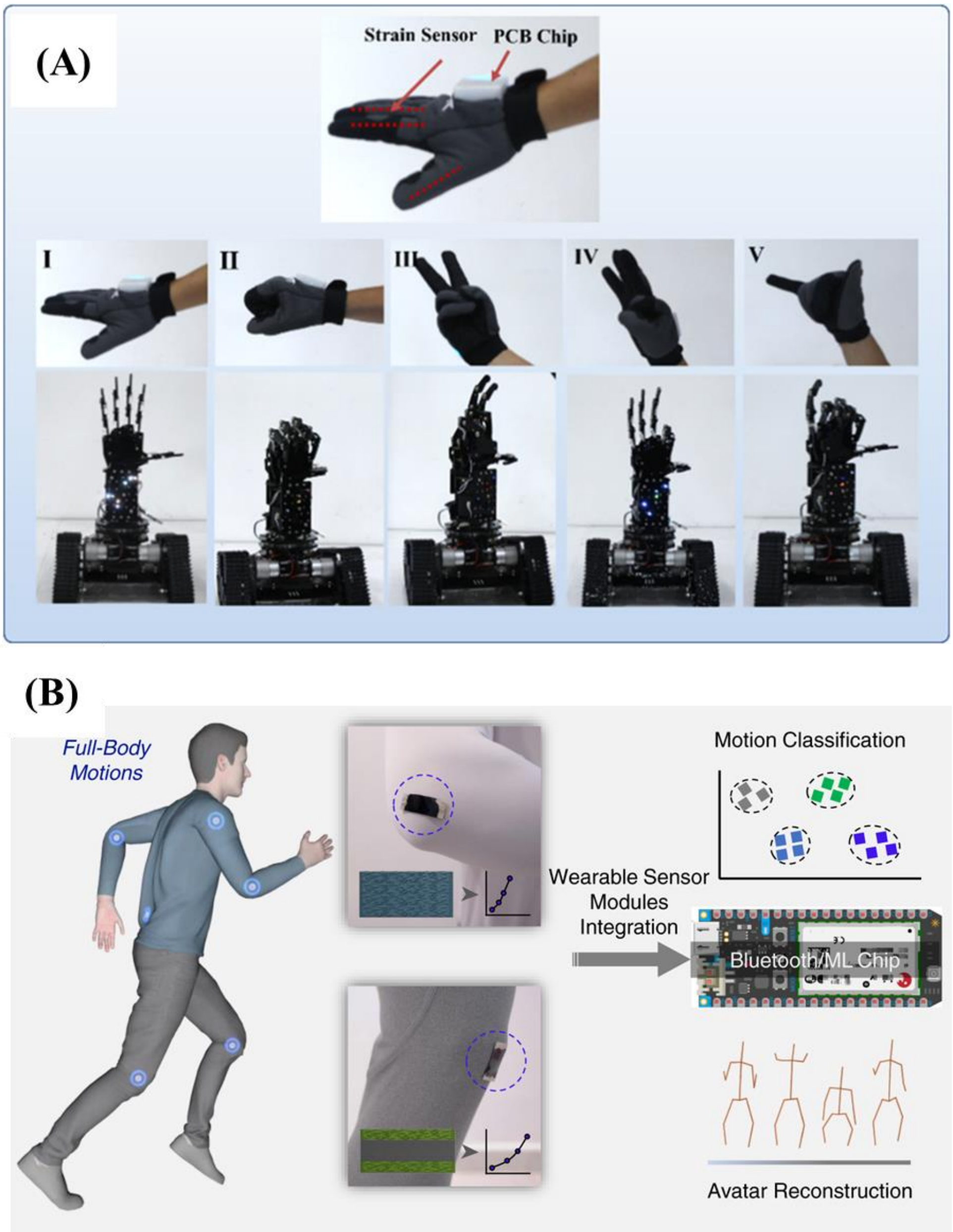

Fig. 7 (A) Demonstration of robotic hand operated by remote system. Reprinted with permission from [19], copyright 2021 Wiley. (B) Photos of the remote control system and snapshots of playing the game with fingers to control all the actions. Reprinted with permission from [18], copyright 2022 Springer Nature.

5. Conclusion and Future Work

Table 1 summarizes the strain sensor types, materials, and main features of their applications. This study provides an overview of recent developments in the production methods, mechanisms, strain-sensing capabilities, and practical applications of stretchable and wearable strain sensors. Wearable sensors using various materials, including carbon-based materials, 1D and 2D materials, and metals, have exhibited remarkable performance enhancements. This paper also discusses several prominent applications of wearable sensors. However, further performance improvements are vital for real-world applications.

Within the scope of wearable sensors, capacitive sensors offer advantages such as stretchability, linearity, and low hysteresis but exhibit limited sensitivity. By contrast, resistive sensors provide significantly higher sensitivity and stretchability but suffer from drawbacks such as high hysteresis and nonlinear responses.

Table 1 Summary of the strain sensor types, materials, and main features

Materials	Type	Key performance	Pros and cons	[Ref]
AgNW@PDMS	Resistive	GF : 290.1 (30% strain)	▪ High GF and multifunctional ▪ Low stretchability and still limited sensing area	[11]
Au/Pt@polystyrene	Resistive	High linearity	▪ Multifunctional ▪ Low GF (2.64)	[20]
PEDOT:PSS@PVA	Resistive	Ultralow hysteresis (<1.5%) Linearity ($R2 = 0.98$)	▪ Ultralow hysteresis, high linearity ($R2 = 0.98$) and high stretchability (~300%) ▪ Low GF (4.07) and limited sensing area	[103]
Graphene nanosheet@PU fiber	Resistive	GF : 661.59 (0%–75% strain)	▪ High stretchability(~500%), GF and reliability (>10,000 cycles) ▪ High hysteresis and limitations depending on strain area	[112]
CNT/MXene@TPU	Resistive	GF : 363 Light weight	▪ High GF and wide working strain range ▪ Nonlinearity depending on strain area	[64]
LM@PDMS	Capacitive	Ultralow detection limit (<0.05%)	▪ Excellent mechanical robustness (>8,000 cycles) and fast response time (58 ms) ▪ Limited sensitivity	[19]
AgNW@PMMA	Capacitive	GF : 1	▪ Transparent and low detection limit (<12 mg) ▪ Limited sensitivity	[113]

Recent advancements in material science and structural research led to the development of composite materials and functional structures to address these challenges. However, issues such as durability degradation over time, sensitivity concerns, and varying GF values persist as strain sensors exhibit nonlinear responses and variable GF values depending on the strain applied, making them suitable only for specific applications. Furthermore, to make these sensors practically viable, they must be evaluated under diverse conditions, including temperature and humidity variations, which can influence the sensor performance. Precise measurements are crucial for elastomers, which are commonly used elastic materials, because their physical properties can change with temperature. In addition, when fabricating wearable sensors from elastomers, they must be designed to ensure breathability and comfort for end users. Despite the proposals for fiber and nanowire composites, performance enhancements are still required. Furthermore, research is needed into new microstructures and nanostructures to enable multimodal sensing capabilities.

Addressing these challenges holds the potential for the application of strain sensors in physical stimulation, wearable medical devices, smart surgical equipment, drug delivery monitoring, and artificial organ research. Furthermore, the development of multifunctional strain sensors may open doors for various research and applications, including those involving biological components.

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REFERENCES

1. Dai, J., Ogbeide, O., Macadam, N., Sun, Q., Yu, W., Li, Y., Su, B.L., Hasan, T., Huang, X., Huang, W., 2020, *Printed gas sensors*, Chemical Society Reviews, 49(6), pp. 1756-1789.
2. Aftab, S., Al-Kahtani, A.A., Iqbal, M.Z., Hussain, S., Koyyada, G., 2023, *Recent Advances in 2D Wearable Flexible Sensors*, Advanced Materials Technologies, 8(14), 2202168.
3. Qaiser, N., Al-Modaf, F., Khan, S.M., Shaikh, S.F., El-Atab, N., Hussain, M.M., 2021, *A Robust Wearable Point-of-Care CNT-Based Strain Sensor for Wirelessly Monitoring Throat-Related Illnesses*, Advanced Functional Materials, 31(29), 2103375.
4. Ha, H., Müller, S., Baumann, R.-P., Hwang, B., 2023, *PeakForce Quantitative Nanomechanical Mapping for Surface Energy Characterization on the Nanoscale: A Mini-Review*, Facta Universitatis, Series: Mechanical Engineering, 10.22190/FUME221126001H.
5. Pour Rahmati Khalejan, S.H., Keskin, V., 2022, *Effects of Dynamic Shading on Thermal Exergy and Exergy Efficiency of a Photovoltaic Array*, Tehnički vjesnik, 29(6), pp. 1889-1895.
6. El-Atab, N., Mishra, R.B., Al-Modaf, F., Joharji, L., Alsharif, A.A., Alamoudi, H., Diaz, M., Qaiser, N., Hussain, M.M., 2020, *Soft Actuators for Soft Robotic Applications: A Review*, Advanced Intelligent Systems, 2(10), 2000128.
7. Gao, Y., Yu, L., Yeo, J.C., Lim, C.T., 2020, *Flexible Hybrid Sensors for Health Monitoring: Materials and Mechanisms to Render Wearability*, Advanced Materials, 32(15), 1902133.
8. Won, P., Kim, K.K., Kim, H., Park, J.J., Ha, I., Shin, J., Jung, J., Cho, H., Kwon, J., Lee, H., Ko, S.H., 2021, *Transparent Soft Actuators/Sensors and Camouflage Skins for Imperceptible Soft Robotics*, Advanced Materials, 33(19), 2002397.
9. Zheng, Y., Li, Y., Zhou, Y., Dai, K., Zheng, G., Zhang, B., Liu, C., Shen, C., 2020, *High-Performance Wearable Strain Sensor Based on Graphene/Cotton Fabric with High Durability and Low Detection Limit*, ACS Appl Mater Interfaces, 12(1), pp. 1474-1485.
10. Chang, X., Chen, L., Chen, J., Zhu, Y., Guo, Z., 2021, *Advances in transparent and stretchable strain sensors*, Advanced Composites and Hybrid Materials, 4(3), pp. 435-450.
11. Wu, S., Moody, K., Kollipara, A., Zhu, Y., 2023, *Highly Sensitive, Stretchable, and Robust Strain Sensor Based on Crack Propagation and Opening*, ACS Appl Mater Interfaces, 15(1), pp. 1798-1807.
12. Pyo, S., Lee, J., Bae, K., Sim, S., Kim, J., 2021, *Recent Progress in Flexible Tactile Sensors for Human-Interactive Systems: From Sensors to Advanced Applications*, Advanced Materials, 33(47), 2005902.
13. Araromi, O.A., Graule, M.A., Dorsey, K.L., Castellanos, S., Foster, J.R., Hsu, W.H., Passy, A.E., Vlassak, J.J., Weaver, J.C., Walsh, C.J., Wood, R.J., 2020, *Ultra-sensitive and resilient compliant strain gauges for soft machines*, Nature, 587(7833), pp. 219-224.

14. Yi, J., Xianyu, Y., 2022, *Gold Nanomaterials-Implemented Wearable Sensors for Healthcare Applications*, Advanced Functional Materials, 32(19), 2113012.
15. Guo, R., Fang, Y., Wang, Z., Libanori, A., Xiao, X., Wan, D., Cui, X., Sang, S., Zhang, W., Zhang, H., Chen, J., 2022, *Deep Learning Assisted Body Area Triboelectric Hydrogel Sensor Network for Infant Care*, Advanced Functional Materials, 32(35), 2204803.
16. Amjadi, M., Kyung, K.U., Park, I., Sitti, M., 2016, *Stretchable, Skin-Mountable, and Wearable Strain Sensors and Their Potential Applications: A Review*, Advanced Functional Materials, 26(11), pp. 1678-1698.
17. Tan, C., Dong, Z., Li, Y., Zhao, H., Huang, X., Zhou, Z., Jiang, J.W., Long, Y.Z., Jiang, P., Zhang, T.Y., Sun, B., 2020, *A high performance wearable strain sensor with advanced thermal management for motion monitoring*, Nature Communications, 11(1), 3530.
18. Yang, H., Li, J., Xiao, X., Wang, J., Li, Y., Li, K., Li, Z., Yang, H., Wang, Q., Yang, J., Ho, J.S., Yeh, P.-L., Mouthaan, K., Wang, X., Shah, S., Chen, P.-Y., 2022, *Topographic design in wearable MXene sensors with in-sensor machine learning for full-body avatar reconstruction*, Nature Communications, 13(1), 5311.
19. Wu, Y., Zhou, Y., Asghar, W., Liu, Y., Li, F., Sun, D., Hu, C., Wu, Z., Shang, J., Yu, Z., Li, R.-W., Yang, H., 2021, *Liquid Metal-Based Strain Sensor with Ultralow Detection Limit for Human–Machine Interface Applications*, Advanced Intelligent Systems, 3(10), 2000235.
20. Chu, M., Nguyen, T., Pandey, V., Zhou, Y., Pham, H.N., Bar-Yoseph, R., Radom-Aizik, S., Jain, R., Cooper, D.M., Khine, M., 2019, *Respiration rate and volume measurements using wearable strain sensors*, NPJ Digital Medicine, 2(1), 8.
21. Li, Y., Zheng, C., Liu, S., Huang, L., Fang, T., Li, J.X., Xu, F., Li, F., 2020, *Smart Glove Integrated with Tunable MWNTs/PDMS Fibers Made of a One-Step Extrusion Method for Finger Dexterity, Gesture, and Temperature Recognition*, ACS Applied Materials & Interfaces, 12(21), pp. 23764-23773.
22. Khan, M., Shah, L.A., Rahman, T.U., Yoo, H.-M., Ye, D., Vacharasin, J., 2022, *Hydrophobically Associated Functionalized CNT-Reinforced Double-Network Hydrogels as Advanced Flexible Strain Sensors*, ACS Applied Polymer Materials, 4(10), pp. 7397-7407.
23. Yan, T., Wu, Y., Yi, W., Pan, Z., 2021, *Recent progress on fabrication of carbon nanotube-based flexible conductive networks for resistive-type strain sensors*, Sensors and Actuators A: Physical, 327, 112755.
24. Tang, J., Wu, Y., Ma, S., Yan, T., Pan, Z., 2022, *Flexible strain sensor based on CNT/TPU composite nanofiber yarn for smart sports bandage*, Composites Part B: Engineering, 232, 109605.
25. Liu, Z., Li, C., Zhang, X., Zhou, B., Wen, S., Zhou, Y., Chen, S., Jiang, L., Jerrams, S., Zhou, F., 2022, *Biodegradable Polyurethane Fiber-Based Strain Sensor with a Broad Sensing Range and High Sensitivity for Human Motion Monitoring*, ACS Sustainable Chemistry & Engineering, 10(27), pp. 8788-8798.
26. Liu, K., Yang, C., Song, L., Wang, Y., Wei, Q., Alamusi, Deng, Q., Hu, N., 2022, *Highly stretchable, superhydrophobic and wearable strain sensors based on the laser-irradiated PDMS/CNT composite*, Composites Science and Technology, 218, 109148.
27. Zhu, W.-B., Xue, S.-S., Zhang, H., Wang, Y.-Y., Huang, P., Tang, Z.-H., Li, Y.-Q., Fu, S.-Y., 2022, *Direct ink writing of a graphene/CNT/silicone composite strain sensor with a near-zero temperature coefficient of resistance*, Journal of Materials Chemistry C, 10(21), pp. 8226-8233.
28. Liu, L., Zhang, X., Xiang, D., Wu, Y., Sun, D., Shen, J., Wang, M., Zhao, C., Li, H., Li, Z., Wang, P., Li, Y., 2022, *Highly stretchable, sensitive and wide linear responsive fabric-based strain sensors with a self-segregated carbon nanotube (CNT)/Polydimethylsiloxane (PDMS) coating*, Progress in Natural Science: Materials International, 32(1), pp. 34-42.
29. Sun, X., Qin, Z., Ye, L., Zhang, H., Yu, Q., Wu, X., Li, J., Yao, F., 2020, *Carbon nanotubes reinforced hydrogel as flexible strain sensor with high stretchability and mechanically toughness*, Chemical Engineering Journal, 382, 122832.
30. Lee, J., Pyo, S., Kwon, D.S., Jo, E., Kim, W., Kim, J., 2019, *Ultrasensitive Strain Sensor Based on Separation of Overlapped Carbon Nanotubes*, Small, 15(12), 1805120.
31. Yue, X., Yang, J., Gao, J., Xu, X., Jing, Y., Wang, X., Li, W., Li, X., 2022, *Wearable hydroxylated MWCNTs/ecoflex composite strain sensor with high comprehensive performance based on electron irradiation*, Composites Science and Technology, 226, 109537.
32. Wu, J., Huang, W., Wu, Z., Yang, X., Kottapalli, A.G.P., Xie, X., Zhou, Y., Tao, K., 2022, *Hydrophobic and Stable Graphene-Modified Organohydrogel Based Sensitive, Stretchable, and Self-Healable Strain Sensors for Human-Motion Detection in Various Scenarios*, ACS Materials Letters, 4(9), pp. 1616-1629.
33. Iqra, M., Anwar, F., Jan, R., Mohammad, M.A., 2022, *A flexible piezoresistive strain sensor based on laser scribed graphene oxide on polydimethylsiloxane*, Scientific Reports, 12(1), 4882.
34. Hu, Q., Nag, A., Zhang, L., Wang, K., 2022, *Reduced graphene oxide-based composites for wearable strain-sensing applications*, Sensors and Actuators A: Physical, 345, 113767.

35. Zhu, S., Lu, Y., Wang, S., Sun, H., Yue, Y., Xu, X., Mei, C., Xiao, H., Fu, Q., Han, J., 2023, *Interface design of stretchable and environment-tolerant strain sensors with hierarchical nanocellulose-supported graphene nanocomplexes*, Composites Part A: Applied Science and Manufacturing, 164, 107313.
36. Zhang, M., Yang, H., Li, H., Tong, L., Su, C., Feng, K., Wang, Q., Yan, H., Yin, S., 2023, *Transparent single crystal graphene flexible strain sensor with high sensitivity for wearable human motion monitoring*, Journal of Alloys and Compounds, 967, 171724.
37. Qi, X., Ha, H., Hwang, B., Lim, S., 2020, *Printability of the Screen-Printed Strain Sensor with Carbon Black/Silver Paste for Sensitive Wearable Electronics*, Applied Sciences, 10(19), 6983.
38. Tran, N.-H., Tran, P., Lee, J.-H., 2022, *Copper Nanowire-Sealed Titanium Dioxide/Poly(dimethylsiloxane) Electrode with an In-Plane Wavy Structure for a Stretchable Capacitive Strain Sensor*, ACS Applied Nano Materials, 5(5), pp. 7150-7160.
39. Asad, U., K, Muhammad, Hwan, C., Seung, 2023, *Characterization of highly linear stretchable sensor made of Gr-PEDOT:PSS/MnO2 nanowires/Ecoflex composite*, Composite Structures, 311, 116824.
40. Kong, W.-W., Zhou, C.-G., Dai, K., Jia, L.-C., Yan, D.-X., Li, Z.-M., 2021, *Highly stretchable and durable fibrous strain sensor with growth ring-like spiral structure for wearable electronics*, Composites Part B: Engineering, 225, 109275.
41. Yang, Y., Duan, S., Xiao, W., Zhao, H., 2022, *Silver nanowire-based stretchable strain sensors with hierarchical wrinkled structures*, Sensors and Actuators A: Physical, 343, 113653.
42. Madhavan, R., 2022, *Flexible and stretchable strain sensors fabricated by inkjet printing of silver nanowire-ecoflex composites*, Journal of Materials Science: Materials in Electronics, 33(7), pp. 3465-3484.
43. Zhang, X., Li, Z., Liu, C., Shan, J., Guo, X., Zhao, X., Ding, J., Yang, H., 2022, *Silver Nanowire/Silver/Poly(dimethylsiloxane) as Strain Sensors for Motion Monitoring*, ACS Applied Nano Materials, 5(10), pp. 15797-15807.
44. Azadi, S., Peng, S., Moshizi, S.A., Asadnia, M., Xu, J., Park, I., Wang, C.H., Wu, S., 2020, *Biocompatible and Highly Stretchable PVA/AgNWs Hydrogel Strain Sensors for Human Motion Detection*, Advanced Materials Technologies, 5(11), 2000426.
45. Hwang, B., Han, Y., Matteini, P., 2022, *Bending Fatigue Behavior of Ag Nanowire/Cu Thin-Film Hybrid Interconnects for Wearable Electronics*, Facta Universitatis, Series: Mechanical Engineering, 20, pp. 553-560.
46. Kang, D., Pikhitsa, P.V., Choi, Y.W., Lee, C., Shin, S.S., Piao, L., Park, B., Suh, K.Y., Kim, T.I., Choi, M., 2014, *Ultrasensitive mechanical crack-based sensor inspired by the spider sensory system*, Nature, 516(7530), pp. 222-6.
47. Shiratsuchi, T., Imai, T., 2021, *Development of fiber Bragg grating strain sensor with temperature compensation for measurement of cryogenic structures*, Cryogenics, 113, 103233.
48. Huo, Z., Wang, X., Zhang, Y., Wan, B., Wu, W., Xi, J., Yang, Z., Hu, G., Li, X., Pan, C., 2020, *High-performance Sb-doped p-ZnO NW films for self-powered piezoelectric strain sensors*, Nano Energy, 73, 104744.
49. Yu, Q., Ge, R., Wen, J., Du, T., Zhai, J., Liu, S., Wang, L., Qin, Y., 2022, *Highly sensitive strain sensors based on piezotronic tunneling junction*, Nature Communications, 13(1), 778.
50. Afsarimanesh, N., Nag, A., Sarkar, S., Sabet, G.S., Han, T., Mukhopadhyay, S.C., 2020, *A review on fabrication, characterization and implementation of wearable strain sensors*, Sensors and Actuators A: Physical, 315, 112355.
51. Wang, Y., Wang, L., Yang, T., Li, X., Zang, X., Zhu, M., Wang, K., Wu, D., Zhu, H., 2014, *Wearable and Highly Sensitive Graphene Strain Sensors for Human Motion Monitoring*, Advanced Functional Materials, 24(29), pp. 4666-4670.
52. Yan, T., Wu, Y., Yi, W., Pan, Z., 2021, *Recent progress on fabrication of carbon nanotube-based flexible conductive networks for resistive-type strain sensors*, Sensors Actuators A: Physical, 327, 112755.
53. Qin, J., Yin, L.J., Hao, Y.N., Zhong, S.L., Zhang, D.L., Bi, K., Zhang, Y.X., Zhao, Y., Dang, Z.M., 2021, *Flexible and Stretchable Capacitive Sensors with Different Microstructures*, Advanced Materials, 33(34), 2008267.
54. Wang, X., Liu, X., Schubert, D.W., 2021, *Highly sensitive ultrathin flexible thermoplastic polyurethane/carbon black fibrous film strain sensor with adjustable scaffold networks*, Nano-micro letters, 13, 64.
55. Hu, M., Gao, Y., Jiang, Y., Zeng, H., Zeng, S., Zhu, M., Xu, G., Sun, L., 2021, *High-performance strain sensors based on bilayer carbon black/PDMS hybrids*, Advanced Composites Hybrid Materials, 4, pp. 514-520.
56. Chen, Y., Wang, L., Wu, Z., Luo, J., Li, B., Huang, X., Xue, H., Gao, J., 2019, *Super-hydrophobic, durable and cost-effective carbon black/rubber composites for high performance strain sensors*, Composites Part B: Engineering, Composites Part B: Engineering, 176, 107358.
57. Huang, C.B., Yao, Y., Montes-García, V., Stoeckel, M.A., Von Holst, M., Ciesielski, A., Samori, P., 2021, *Highly Sensitive Strain Sensors Based on Molecules–Gold Nanoparticles Networks for High-Resolution Human Pulse Analysis*, Small, 17(8), 2007593.
58. Yang, Y., Shi, L., Cao, Z., Wang, R., Sun, J., 2019, *Strain sensors with a high sensitivity and a wide sensing range based on a Ti3C2Tx (MXene) nanoparticle–nanosheet hybrid network*, Advanced Functional Materials, 29(14), 1807882.

59. Xu, X., Chen, Y., He, P., Wang, S., Ling, K., Liu, L., Lei, P., Huang, X., Zhao, H., Cao, J., 2021, *Wearable CNT/Ti3C2T x MXene/PDMS composite strain sensor with enhanced stability for real-time human healthcare monitoring*, Nano Research, 14(8), pp. 2875-2883.
60. Chen, J., Zhu, Y., Jiang, W., Technology, 2020, *A stretchable and transparent strain sensor based on sandwich-like PDMS/CNTs/PDMS composite containing an ultrathin conductive CNT layer*, Composites Science, 186, 107938.
61. Kim, H., Qaiser, N., Hwang, B., 2023, *Electro-Mechanical Response of Stretchable PDMS Composites with a Hybrid Filler System*, Facta Universitatis, Series: Mechanical Engineering, pp. 51-61.
62. Yue, X., Jia, Y., Wang, X., Zhou, K., Zhai, W., Zheng, G., Dai, K., Mi, L., Liu, C., Shen, C., 2020, *Highly stretchable and durable fiber-shaped strain sensor with porous core-sheath structure for human motion monitoring*, Composites Science and Technology, 189, 108038.
63. Li, H., Chen, J., Chang, X., Xu, Y., Zhao, G., Zhu, Y., Li, Y., 2021, *A highly stretchable strain sensor with both an ultralow detection limit and an ultrawide sensing range*, Journal of Materials Chemistry A, 9(3), pp. 1795-1802.
64. Wang, H., Zhou, R., Li, D., Zhang, L., Ren, G., Wang, L., Liu, J., Wang, D., Tang, Z., Lu, G., Sun, G., Yu, H.D., Huang, W., 2021, *High-Performance Foam-Shaped Strain Sensor Based on Carbon Nanotubes and Ti(3)C(2)T(x) MXene for the Monitoring of Human Activities*, ACS Nano, 15(6), pp. 9690-9700.
65. Zhao, Y., Ren, M., Shang, Y., Li, J., Wang, S., Zhai, W., Zheng, G., Dai, K., Liu, C., Shen, C., 2020, *Ultra-sensitive and durable strain sensor with sandwich structure and excellent anti-interference ability for wearable electronic skins*, Composites Science Technology, 200, 108448.
66. Fan, M., Wu, L., Hu, Y., Qu, M., Yang, S., Tang, P., Pan, L., Wang, H., Bin, Y., Materials, H., 2021, *A highly stretchable natural rubber/buckypaper/natural rubber (NR/N-BP/NR) sandwich strain sensor with ultrahigh sensitivity*, Advanced Composites, 4, pp. 1039-1047.
67. Sang, Z., Ke, K., Manas-Zloczower, I., 2019, *Effect of carbon nanotube morphology on properties in thermoplastic elastomer composites for strain sensors*, Composites Part A: Applied Science Manufacturing, 121, pp. 207-212.
68. Seyedin, S., Uzun, S., Levitt, A., Anasori, B., Dion, G., Gogotsi, Y., Razal, J.M., 2020, *MXene Composite and Coaxial Fibers with High Stretchability and Conductivity for Wearable Strain Sensing Textiles*, Advanced Functional Materials, 30(12), 1910504.
69. Chen, Y., Wang, L., Wu, Z., Luo, J., Li, B., Huang, X., Xue, H., Gao, J., 2019, *Super-hydrophobic, durable and cost-effective carbon black/rubber composites for high performance strain sensors*, Composites Part B: Engineering, 176, 107358.
70. Shen, Y., Yang, W., Hu, F., Zheng, X., Zheng, Y., Liu, H., Algadi, H., Chen, K., 2022, *Ultrasensitive wearable strain sensor for promising application in cardiac rehabilitation*, Advanced Composites and Hybrid Materials, 6(1), 21.
71. Ma, J., Wang, P., Chen, H., Bao, S., Chen, W., Lu, H., 2019, *Highly Sensitive and Large-Range Strain Sensor with a Self-Compensated Two-Order Structure for Human Motion Detection*, ACS Applied Materials & Interfaces, 11(8), pp. 8527-8536.
72. Luo, C., Tian, B., Liu, Q., Feng, Y., Wu, W., 2020, *One-Step-Printed, Highly Sensitive, Textile-Based, Tunable Performance Strain Sensors for Human Motion Detection*, Advanced Materials Technologies, 5(2), 1900925.
73. Duan, S., Wang, Z., Zhang, L., Liu, J., Li, C., 2018, *A Highly Stretchable, Sensitive, and Transparent Strain Sensor Based on Binary Hybrid Network Consisting of Hierarchical Multiscale Metal Nanowires*, Advanced Materials Technologies, 3(6), 1800020.
74. Ren, H., Zheng, L., Wang, G., Gao, X., Tan, Z., Shan, J., Cui, L., Li, K., Jian, M., Zhu, L., Zhang, Y., Peng, H., Wei, D., Liu, Z., 2019, *Transfer-Medium-Free Nanofiber-Reinforced Graphene Film and Applications in Wearable Transparent Pressure Sensors*, ACS Nano, 13(5), pp. 5541-5548.
75. Qu, M., Qin, Y., Sun, Y., Xu, H., Schubert, D.W., Zheng, K., Xu, W., Nilsson, F., 2020, *Biocompatible, flexible strain sensor fabricated with polydopamine-coated nanocomposites of nitrile rubber and carbon black*, ACS Applied Materials & Interfaces, 12(37), pp. 42140-42152.
76. Xu, X., Wu, S., Cui, J., Yang, L., Wu, K., Chen, X., Sun, D., 2021, *Highly stretchable and sensitive strain sensor based on polypyrrole coated bacterial cellulose fibrous network for human motion detection*, Composites Part B: Engineering, 211, 108665.
77. Liu, W., Huang, Y., Peng, Y., Walczak, M., Wang, D., Chen, Q., Liu, Z., Li, L., 2020, *Stable wearable strain sensors on textiles by direct laser writing of graphene*, ACS Applied Nano Materials, 3(1), pp. 283-293.
78. Hempel, M., Nezich, D., Kong, J., Hofmann, M., 2012, *A novel class of strain gauges based on layered percolative films of 2D materials*, Nano Letters, 12(11), pp. 5714-5718.
79. Zhao, H., O'brien, K., Li, S., Shepherd, R.F., 2016, *Optoelectronically innervated soft prosthetic hand via stretchable optical waveguides*, Science robotics, 1(1), eaai7529.

80. Cao, J., Wang, Q., Dai, H., 2003, *Electromechanical properties of metallic, quasimetallic, and semiconducting carbon nanotubes under stretching*, Physical Review Letters, 90(15), 157601.
81. Marinković, D., Marinković, Z., 2012, *On FEM modeling of piezoelectric actuators and sensors for thin-walled structures*, Smart Structures and Systems, 9(5), pp. 411-426.
82. Marinković, D., Rama, G., Zehn, M., 2019, *Abaqus Implementation of a Corotational Piezoelectric 3-Node Shell Element with Drilling Degree of Freedom*, Facta Universitatis-Series Mechanical Engineering, 17(2), pp. 269-283.
83. Tomašević, Dž., Konjić, T., Kasapović, S., 2022, *Impact Assessment of the Power Line Channel Characteristics in Real Topology*, Tehnički vjesnik, 29(2), pp. 386-394.
84. Yan, C., Wang, J., Kang, W., Cui, M., Wang, X., Foo, C.Y., Chee, K.J., Lee, P.S., 2014, *Highly stretchable piezoresistive graphene–nanocellulose nanopaper for strain sensors*, Advanced Materials, 26(13), pp. 2022-2027.
85. Luo, S., Liu, T., 2013, *Structure–property–processing relationships of single-wall carbon nanotube thin film piezoresistive sensors*, Carbon, 59, pp. 315-324.
86. Zhao, J., He, C., Yang, R., Shi, Z., Cheng, M., Yang, W., Xie, G., Wang, D., Shi, D., Zhang, G., 2012, *Ultra-sensitive strain sensors based on piezoresistive nanographene films*, Applied Physics Letters, 101(6), 063112.
87. Wu, S., Peng, S., Yu, Y., Wang, C.H., 2020, *Strategies for designing stretchable strain sensors and conductors*, Advanced Materials Technologies, 5(2), 1900908.
88. Lu, Y., Biswas, M.C., Guo, Z., Jeon, J.-W., Wujcik, E.K., 2019, *Recent developments in bio-monitoring via advanced polymer nanocomposite-based wearable strain sensors*, Biosensors bioelectronics, 123, pp. 167-177.
89. Qi, X., Li, X., Jo, H., Bhat, K.S., Kim, S., An, J., Kang, J.-W., Lim, S., 2020, *Mulberry paper-based graphene strain sensor for wearable electronics with high mechanical strength*, Sensors Actuators A: Physical, 301, 111697.
90. Zhang, L., Kou, H., Tan, Q., Liu, G., Zhang, W., Xiong, J., 2019, *High-performance strain sensor based on a 3D conductive structure for wearable electronics*, Journal of Physics D: Applied Physics, 52(39), 395401.
91. Niu, S., Chang, X., Zhu, Z., Qin, Z., Li, J., Jiang, Y., Wang, D., Yang, C., Gao, Y., Sun, S., 2021, *Low-Temperature Wearable Strain Sensor Based on a Silver Nanowires/Graphene Composite with a Near-Zero Temperature Coefficient of Resistance*, ACS Applied Materials & Interfaces, 13(46), pp. 55307-55318.
92. Esmaeili, A., Sbarufatti, C., Ma, D., Manes, A., Jiménez-Suárez, A., Ureña, A., Dellasega, D., Hamouda, A., 2020, *Strain and crack growth sensing capability of SWCNT reinforced epoxy in tensile and mode I fracture tests*, Composites Science Technology, 186, 107918.
93. Wang, G., Yang, P., Chen, B., Liu, G., Qiu, J., 2020, *A novel combination of graphene and silver nanowires for entirely stretchable and ultrasensitive strain sensors: Sandwich-based sensing films*, Nanotechnology, 31(13), 135501.
94. Pan, S., Pei, Z., Jing, Z., Song, J., Zhang, W., Zhang, Q., Sang, S., 2020, *A highly stretchable strain sensor based on CNT/graphene/fullerene-SEBS*, RSC advances, 10(19), pp. 11225-11232.
95. Sui, X., Downing, J.R., Hersam, M.C., Chen, J., 2021, *Additive manufacturing and applications of nanomaterial-based sensors*, Materials Today, 48, pp. 135-154.
96. Zhai, J., Zhang, Y., Cui, C., Li, A., Wang, W., Guo, R., Qin, W., Ren, E., Xiao, H., Zhou, M., 2021, *Flexible waterborne polyurethane/cellulose nanocrystal composite aerogels by integrating graphene and carbon nanotubes for a highly sensitive pressure sensor*, ACS Sustainable Chemistry Engineering, 9(42), pp. 14029-14039.
97. Jeong, Y.R., Park, H., Jin, S.W., Hong, S.Y., Lee, S.S., Ha, J.S., 2015, *Highly stretchable and sensitive strain sensors using fragmentized graphene foam*, Advanced Functional Materials, 25(27), pp. 4228-4236.
98. Yang, H., Yao, X., Zheng, Z., Gong, L., Yuan, L., Yuan, Y., Liu, Y., 2018, *Highly sensitive and stretchable graphene-silicone rubber composites for strain sensing*, Composites Science Technology, 167, pp. 371-378.
99. Gan, D., Shuai, T., Wang, X., Huang, Z., Ren, F., Fang, L., Wang, K., Xie, C., Lu, X., 2020, *Mussel-inspired redox-active and hydrophilic conductive polymer nanoparticles for adhesive hydrogel bioelectronics*, Nano-micro letters, 12, 169.
100. Shi, G., Zhao, Z., Pai, J.-H., Lee, I., Zhang, L., Stevenson, C., Ishara, K., Zhang, R., Zhu, H., Ma, J., 2016, *Highly Sensitive, Wearable, Durable Strain Sensors and Stretchable Conductors Using Graphene/Silicon Rubber Composites*, Advanced Functional Materials, 26(42), pp. 7614-7625.
101. Mo, F., Huang, Y., Li, Q., Wang, Z., Jiang, R., Gai, W., Zhi, C., 2021, *A highly stable and durable capacitive strain sensor based on dynamically super-tough hydro/organo-gels*, Advanced Functional Materials, 31(28), 2010830.
102. Souri, H., Banerjee, H., Jusufi, A., Radacsi, N., Stokes, A.A., Park, I., Sitti, M., Amjadi, M., 2020, *Wearable and stretchable strain sensors: materials, sensing mechanisms, and applications*, Advanced Intelligent Systems, 2(8), 2000039.

103. Shen, Z., Zhang, Z., Zhang, N., Li, J., Zhou, P., Hu, F., Rong, Y., Lu, B., Gu, G., 2022, *High-Stretchability, Ultralow-Hysteresis ConductingPolymer Hydrogel Strain Sensors for Soft Machines*, Advanced Materials, 34(32), 2203650.
104. Chen, S., Guo, X., 2015, *Improving the sensitivity of elastic capacitive pressure sensors using silver nanowire mesh electrodes*, IEEE Transactions on nanotechnology, 14(4), pp. 619-623.
105. Qin, R., Hu, M., Li, X., Liang, T., Tan, H., Liu, J., Shan, G., 2021, *A new strategy for the fabrication of a flexible and highly sensitive capacitive pressure sensor*, Microsystems nanoengineering, 7(1), 100.
106. Shi, R., Lou, Z., Chen, S., Shen, G., 2018, *Flexible and transparent capacitive pressure sensor with patterned microstructured composite rubber dielectric for wearable touch keyboard application*, Science China Materials, 61(12), pp. 1587-1595.
107. Lo, L.W., Shi, H., Wan, H., Xu, Z., Tan, X., Wang, C., 2020, *Inkjet-printed soft resistive pressure sensor patch for wearable electronics applications*, Advanced Materials Technologies, 5(1), 1900717.
108. Tas, M.O., Baker, M.A., Masteghin, M.G., Bentz, J., Boxshall, K., Stolojan, V., 2019, *Highly stretchable, directionally oriented carbon nanotube/PDMS conductive films with enhanced sensitivity as wearable strain sensors*, ACS Applied Materials & Interfaces, 11(43), pp. 39560-39573.
109. Hu, X., Yang, F., Wu, M., Sui, Y., Guo, D., Li, M., Kang, Z., Sun, J., Liu, J., 2022, *A Super-Stretchable and Highly Sensitive Carbon Nanotube Capacitive Strain Sensor for Wearable Applications and Soft Robotics*, Advanced Materials Technologies, 7(3), 2100769.
110. Wang, K., Yap, L.W., Gong, S., Wang, R., Wang, S.J., Cheng, W., 2021, *Nanowire-Based Soft Wearable Human–Machine Interfaces for Future Virtual and Augmented Reality Applications*, Advanced Functional Materials, 31(39), 2008347.
111. Lee, K.T., Chee, P.S., Lim, E.H., Kam, Y.H., 2023, *Data Glove with Integrated Polyethylene-Carbon Composite-Based Strain Sensor for Virtual Reality Applications*, Chemical Engineering & Technology, 46, 10.1002/ceat.202200569.
112. Li, X., Koh, K.H., Farhan, M., Lai, K.W.C., 2020, *An ultraflexible polyurethane yarn-based wearable strain sensor with a polydimethylsiloxane infiltrated multilayer sheath for smart textiles*, Nanoscale, 12(6), pp. 4110-4118.
113. Chen, S., Peng, S., Sun, W., Gu, G., Zhang, Q., Guo, X., 2019, *Scalable Processing Ultrathin Polymer Dielectric Films with a Generic Solution Based Approach for Wearable Soft Electronics*, Advanced Materials Technologies, 4(7), 1800681.