ICCK Transactions on Sensing, Communication, and Control
http://dx.doi.org/10.62762/TSCC.2025.665257

REVIEW ARTICLE

Strain Sensing Technologies: Recent Developments in Materials, Performance, and Applications

Maryam Bibi[1], Gul Hassan[1,*], Arfa Asif[1], Ahmed Shuja[1], Habib Ahmad[3], Bilal Mushtaq[4,*] and Memon Sajid[4]

[1] Centre for Advanced Electronics and Photovoltaic Engineering, International Islamic University, Islamabad, Pakistan
[2] Department of Electrical and Electronic Engineering, Beaconhouse International College, Islamabad, Pakistan
[3] School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, United States
[4] Faculty of Electrical Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, K.P.K, Pakistan

Abstract

Strain sensors have become fundamental to contemporary sensing technology driven by the growing demand for flexible, sensitive, and durable sensors, transforming across a broad range of applications including medical care, robotics, structural monitoring, human-machine interface and robotics. The swift progress in the fields of materials and nanotechnology has facilitated the fabrication of very flexible, resilient, and ultra-sensitive strain sensors, enabling the emergence of next-generation electronic devices. This mini review covers sensors, strain sensors' fundamentals, classifications, innovative materials utilized, applications overall provide an in-depth analysis of the latest developments in strain sensor. Emerging materials that have together pushed the limits of sensor performance in terms of gauge factors, stretchability, reaction time, and durability are highlighted, including self-healing polymers, hybrid nanomaterials, graphene derivatives, carbon nanotube composites, and hydrogels. Even with impressive advancements, issues like biocompatibility, durability and many more factors continue to be major roadblocks to practical integration. Additionally, innovative solutions that enhance mechanical conformance and long-term stability are addressed in conjunction with challenges associated with packaging, integration, and other factors. This article offers a thorough roadmap for future research and real-world application of strain sensors in wearable electronics, soft robotics, and healthcare monitoring systems by combining recent literature and emphasizing important insights into the engineering of materials and functional performance. Finally, the analysis highlights emerging trends and possible prospects for next-generation strain sensing technologies that combine multi-functionality, self-healing, and scalable fabrication to fulfill real-world application demands.

Keywords: strain sensors, hydrogels, flexible wearable technology, biomedical applications, nano materials, polymers.

Submitted: 19 May 2025
Accepted: 18 June 2025
Published: 28 July 2025

Vol. 2, **No.** 3, 2025.
10.62762/TSCC.2025.665257

***Corresponding authors:**
✉ Gul Hassan
gulhassan.rahi5@gmail.com
✉ Bilal Mushtaq
bilalmushtaq88@outlook.com; bilal.mushtaq@bic.edu.pk

Citation
Bibi, M., Hassan, G., Asif, A., Shuja, A., Ahmad, H., Mushtaq, B., & Sajid, M. (2025). Strain Sensing Technologies: Recent Developments in Materials, Performance, and Applications. *ICCK Transactions on Sensing, Communication, and Control*, 2(3), 168–199.

1 Introduction

With advances in wearable and flexible electrical materials and devices, next-generation strain sensors have intriguing significance for tracking health, human movement detection, robotics and human-computer interaction. Sensors sense and convert the physical characteristics of their surroundings into measurable electrical signals. Flexible wearable strain sensors, in contrast to typical rigid sensors that are built on silicon substrates, offer improved flexibility, bio-compatibility, and mechanical durability. As a result, they are extremely well suited for use in biomedical applications [1]. Strain sensors have gained significant attention due to their ability to convert mechanical deformation into readable electrical signals, enabling a wide range of applications across various fields. Traditional strain sensors, typically based on metallic foils or semiconductor materials, offer high sensitivity and reliability but often suffer from limited flexibility, poor stretchability, and susceptibility to mechanical damage. In contrast, recent advancements have focused on developing next-generation strain sensors using novel materials and design strategies that offer enhanced mechanical compliance and multifunctionality [2]. The present investigation on strain sensors focuses on enhancing different parameters such as sensitivity, linearity, and stability, and incorporating self-healing characteristics and multi-functionality to ensure long lifespan and real-time health monitoring [3]. For example, strain sensors are extensively utilized in a variety of industrial solutions, including the following: continuous tracking of blood pressure [4], human movement detection [5], implantable biomedical devices [6], and human-machine interfaces (HMI) [7, 8].

Self-healing materials are advantageous for flexible wearable strain sensors, which are an essential component of wearable electronics. These materials effectively handle wear and tear that occurs during operation, therefore greatly extending the lifespan of the device [9, 10]. In addition, self-powered strain sensors that use piezoelectric or triboelectric energy harvesting have the potential to assist in overcoming the difficulties associated with energy supply [11]. Strain sensors can work successfully on soft, malleable surfaces while retaining good sensing performance. This is made possible by the incorporation of flexible and biocompatible materials. To improve the precision of signals, various processing techniques have been utilized for accurate material deposition on flexible substrates as well as to fabricate flexible hydrogels devices [12].

Material selection is one of the key parameters that affects the performance of strain sensors needed to be considered One of the most important factors affecting the performance of strain sensors is the material selection. Conductive materials, such as carbon-based nanomaterials (for example, graphene and carbon nanotubes) [13], metal nanoparticles [14], and developing materials such as 2-Dimensional transition metal carbides/nitrides (MXenes) enhancing sensitivity, their surface functional groups strengthen polymer matrix interactions, boosting signal stability and longevity had been utilised extensively [15]. Notably, the integration of self-healing polymers, hybrid nanomaterials, and conductive networks has opened up new frontiers in sensor technology. These emerging materials provide not only improved sensitivity and durability but also enable the sensors to recover functionality after mechanical damage, significantly extending device lifespan and reliability. Such innovations mark a clear departure from traditional sensor technologies and represent a paradigm shift toward intelligent and adaptive sensing platforms.

In addition, a study is being conducted to investigate the stretchability and biocompatibility of hydrogels and conductive polymers [16]. Even though significant breakthroughs have been made, there are still obstacles must be considered to overcome to fabricate strain sensors that are scalable, environmentally friendly, and cost-effective. Because biomaterials offer a sustainability alternative with enhanced wearability, biodegradability, and biocompatibility, traditional flexible materials frequently require synthetic additives that could pose environmental risks. With growing attempts to use environmentally friendly materials, sustainability is emerging as a major priority in strain sensor development. As an instance, biodegradable substrates [17] offer reusable possibilities for flexible sensing platforms, while recyclable hydrogels [18] limit the amount of electronic waste that is produced by biomedical sensors that are disposable or only used for a short period of time. These developments meet the increasing need for sustainable and ecologically friendly innovations in technology.

Biomaterials also provide an alternative that is more environmentally friendly. In addition, self-healing polymers provide an efficient method for extending the lifespan of devices by allowing for the repair of functional layers. Because of these properties, biomaterials are promising candidates for flexible wearable strain sensors of the next generation. This opens the door for wearable electronics that are multi-functional, self-powered, and biocompatible [19, 20].

A detailed review of recent advancements in strain sensors is presented in this paper. The paper focuses on the classification, different performance optimization parameters, selection of materials, and the variety of applications that incorporate these sensors. Several important aspects, including platform layout, conductive material integration, and advanced sensing mechanisms, will be discussed, with an emphasis placed on the role that these aspects play in enhancing the functionality of strain sensors and finding practical applications for them. Finally, key challenges and future perspectives in the promising fields of wearable electronics using different materials are discussed.

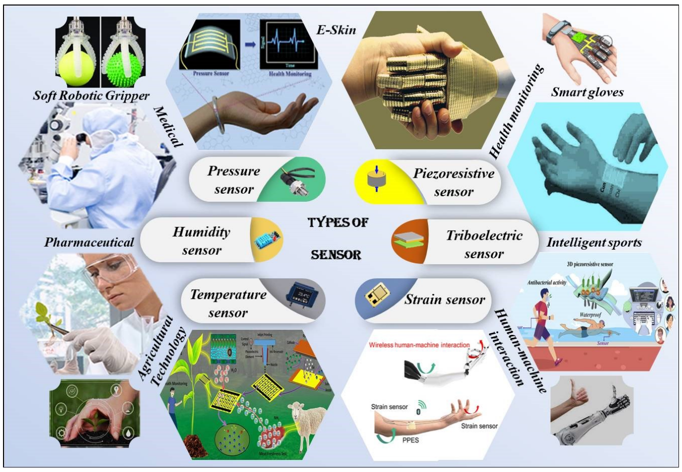

Figure 1. Robotic mechanism as robotic grippers. Reproduced with permission [20]Copyright © 2018 WILEY-VCH. Pharmaceutical industry. Agricultural technology (fabrication procedure of humidity sensor).(Nature-2021) [21]. Schematic illustration of the PPES for remote human-machine interaction. Reproduced with permission [22] Copyright © 2020, American Association. Robotic arm. 3D piezoresistive wearable sensor. Reproduced with permission [23] Copyright © 2023 Elsevier. Health monitoring sensor adhered on pulse. Smart gloves. E-skin. Medical application. Reproduced with permission [24] Copyright © 2015 Royal Society of Chemistry.

2 Classification of Sensors

In this section of the review article, we discuss different types of sensors, including pressure, humidity, temperature, piezoresistive, triboelectric, and strain sensors. These devices record data in real time, enabling automation, monitoring, and control across technological realms. Sensor technology drives innovation, improving efficiency and functionality in everyday technology and systems. These subsections analyse some fundamental sensors used in daily life, shown in Figure 1.

2.1 Pressure Sensor

The force per unit area on the surfaces of pressure sensors is measured and then translated into electrical signals for control or monitoring. The pressure sensor takes data from the real world and converts them into an electrical signal; the user may then make sense of the data on the screen [25]. Early pressure sensors were invented in the early 1900s. Pressure sensors advanced after Evangelista Torricelli's (1643) mercury barometer, but not until the mid-20th century. Strain gauge-based pressure sensors improved measurement accuracy and adaptability in the 1940s. Pressure sensors increased performance and reliability throughout the next decades due to material, manufacturing, and electronic component developments [26].

A number of devices employ liquid or pressure. Pressure-based IoT systems are easier to build using these sensors. Pressure deviations alert the system administrator. Factory and water and heating system maintenance benefit from these sensors' pressure change detection. New materials and smart technologies have made pressure monitors more accurate, better at communicating, and using less power. From simple instruments, pressure sensors are now essential parts of modern automotive, medical, environmental, and Internet of Things technology. Pressure sensors using MEMS technology are popular because they have advantages over electromechanical sensors. MEMS technology offers small size, low mass, low price, better functionality, extensive integration, low energy consumption, wider temperature range, and greater output signal [27, 28]. Table 1 illustrates different kind of pressure sensor by using different materials reported.

2.2 Humidity Sensor

Humidity refers to the amount of water vapor present in a gas. There are several ways to measure humidity, but the two most common are relative and absolute humidity. Quantifying the amount of water vapor in each volume uses absolute humidity. The ratio of the present water vapor pressure to the water vapor pressure needed for saturation at a given

Table 1. Comparison of pressure sensors with different materials.

Ref.	Materials	Sensing Mechanism	Detection Rate	Response	Sensitivity
[28]	Multi-layer textile materials	Pressure	0-120 kPa	N/A	0.0012 kPa^{-1}
[29]	PVDF: AgNWs: TiO_2	Capacitive	1500 kPa	166.9ms	1.448 kPa^{-1}
[30]	MWCNT: Polydimethylsiloxane	Capacitive	0.2 Pa	N/A	17.8 kPa^{-1}
[31]	0AFICPS	Capacitive	5 Pa	11ms	0.49 kPa^{-1}
[32]	Gr: PEDOT PSS	Piezo resistive	N/A	42 ms	17.65 kPa^{-1}
[33]	RGO: Polydimethylsiloxane	Piezo resistive	3.2 kPa	N/A	164.5 kPa^{-1}
[34]	PAAMPSA/PEDOT: PSS	Piezo resistive	N/A	19 ms	44.31 $VkPa^{-1}$
[35]	PEDOT: PSS fabric	Tribo electric	10 kPa	N/A	0.228 V/N

temperature is known as relative humidity or RH. The temperature directly impacts the relative humidity [36]. A hygrometer employs a humidity-sensitive material that changes physically or electrically with moisture. Water vapor is a big part of air and its concentration varies, thus it's vital to predict the exact amount for varied needs. Hygrometry is the art and science of humidity measurement [37]. Nicolas Cryfts invented the hygrometer in 1450 to measure humidity. It monitored humidity using wool. Over a century later, this hygrometer was modified to measure moisture with a sponge instead of wool. After that, acetate, paper, hair, and nylon replaced sponge. As humidity sensors became increasingly popular, it was crucial to develop a technique to build them that weren't expensive or harmful while offering accurate readings with low hysteresis, high sensitivity, and low power consumption. In response to industrial demand, capacitive, resistive, semi-conductive, optical, surface acoustic wave, and other humidity sensors were created [38]. Capacitive sensors offer power consumption, range, sensitivity, and cost. However, they have difficulty connecting with external circuitry and have non-linear responses. Resistive sensor materials are complicated, expensive, and temperature dependent. Resistive sensors are more linear and easy to connect [39]. Table 2, illustrates different nanomaterials-based humidity sensor and their responses.

2.3 Temperature Sensor

A temperature sensor is a device that detects and monitors the thermal energy in its environment, transforming it into an electrical signal or digital output to measure temperature. Skin temperature sensing improves illness diagnosis, accident prevention, and environmental data collection. Normal body temperature is necessary for health, but variations might signify serious disease. Most people maintain a core temperature of 37–37.5 degrees Celsius. Temperature sensors measure skin temperature and changes in real time [45, 46]. Skin temperature can usually be monitored with thermometers. The biggest challenge is placing hard sensor devices against the skin to monitor conditions in tight spaces like garments or prosthetics. Kids shouldn't utilize this procedure since thermometers are not appealing beneath the arm [47]. Skin-to-skin contact boosts temperature measurements. However, stiff temperature detectors cannot handle uneven surfaces. Flexible and wearable temperature sensor research is hampered by this issue. Wearable temperature sensors should be soft, flexible, biocompatible, lightweight, durable, and skin-friendly. Comfort matters, especially for long-term use [48]. Flexible temperature sensors include thermocouple, resistance, chromic, and thermistor. Seebeck effect powers many self-powered temperature sensors by converting temperature into electricity. These sensors have energy and temperature monitoring capabilities [49–54]. Resistance temperature detectors measure temperature using material temperature dependency on electrical resistance. Thermocouples are temperature sensors that use Seebeck's thermoelectric phenomena to generate a potential difference or voltage. Seebeck states a thermal voltage (electromotive force, EMF) arises between conductor ends when heat is introduced. Electromotive force moves electrons from hot to cold. This force, named "Seebeck electromotive force" and the event "Seebeck Thermoelectric Effect," opposes electron movement. Temperature sensors enhance daily comfort, safety, and efficiency. They control house heating and cooling using thermostats for comfort. Weather station temperature sensors give accurate weather data for forecasting and climate monitoring. Diagnostic medical thermometers detect body temperature correctly using sensors. Sensors regulate food storage and transit temperatures to preserve fragile items. Environmental control, health monitoring, and industrial process optimization are

Table 2. Comparison of different materials-based humidity sensors.

Ref. #	Sensing Materials	RH Range	Response/recoverytime	Response/Sensitivity
[38]	PEDOT/PSS	0–28.4	0.63/2.05 s	13 %
[39]	$FeCl_4$/PVDF composite	35–90	About 120/180 s	75 %
[40]	Graphene/methyl-red composite	35–100	0.251s/0.35s	96.36 %
[41]	DMAc/LiCl	5–98	99/110 s	up to 4191 %
[42]	$Ti_3C_2T_x$ MXene/WS_2	11–97	4.65 s/1.33 s	1707 %

improved by temperature sensors [55, 56]. Table 3 illustrates the reported temperature sensor that are flexible and have enormous features.

2.4 Piezoresistive Sensor

A piezoresistive sensor is a sensor that alters its electrical resistance when exposed to mechanical stress or pressure, appropriate for measuring and identifying pressure fluctuations in electronic devices and applications in industry. The electron tunneling paths are affected by variations in the spacing between conductive fillers or particles under strain. Greater gaps decrease the potential of tunneling when the material extends, increasing resistance. Because of its extreme sensitivity to nanoscale separations, this tunneling technique allows for accurate strain monitoring [62, 63]. In the late 1990s, piezoresistive sensors used rigid metal ions or metallic substrates integrated with silicon circuits, which caused mechanical mismatches with human tissue, poor bio interface, high noise-to-signal ratios, inflammation, and metal toxicity. In the early 21st century, piezoresistive sensors were integrated with human skin to create tactile-perception-focused "electronic skin" (E-skin). Since 2020, piezoresistive sensors have improved in flexibility, biocompatibility, lightweight design, high sensitivity, stability, cheap cost, and power consumption. These improvements have expanded their applications into IoT, flexible touch displays, soft robotics, electronic textiles, energy harvesting, and mobile healthcare, making soft piezoresistive sensors promising for future wearable technology and long-term health monitoring [64, 65]. A wide range of research projects employs piezoresistive processes, which entail the utilization of conductive nanomaterials alongside flexible substrates. Many nanomaterials have been studied as flexible wearable sensors, including carbon-based nanomaterials like CNTs [66], and metallic nanomaterials like nanowires (NWs), silver/gold NPs [67] and MXene, graphene [68, 69] offers high stability, sensitivity and flexibility by utilization of polymers. Using multiple graphene layers on a PVDF substrate, an alternative electronic skin sensor displayed a gauge factor (GF) of 320 at 2% strain and 67 at 0.2% strain that detect tiny stimuli and minute deformations [70].

2.5 Triboelectric Sensor

Triboelectric sensor utilizes both electrostatic induction and the triboelectric phenomenon to transform mechanical input into electrical impulses. Triboelectric phenomena have been observed within nano-generators with the purpose of generating self-powered sensors. For wearable and portable electronics that demand battery-free operation, this feature is extremely beneficial [71]. Mechanical disturbances can affect time and place, which affect power generation. A human finger gains a positive charge (+) when it touches the sensor surface. The sensor's insulating surface holds negative charges for a long period since they are hard to induce. Raising the finger off the surface transfers positive charge to the electrodes [72]. The generated current enters and leaves the electrodes as the finger approaches or leaves the gadget. With a reaction time of 68 milliseconds, the sensor can monitor extremely low pressure. A nanotexture-enhanced nano-generator array used triboelectricity for self-powering sensing. Even in wet conditions, the sensor provides reliable voltages. When no load is attached, the sensor produce 1.613 V [73–75]. The device can detect both the lateral force resulting from friction and the perpendicular force exerted on it. The voltage frequencies produced in response to various external stimuli, such as sliding and pressure, exhibited distinct differences [76]. Triboelectric-piezoresistive sensor development is intriguing. The structures' porosity makes the embedded sensor more sensitive [77]. Table 4, illustrates the reported triboelectric sensor with different features.

2.6 Strain Sensors

Movement causes both tiny and major deformations. Flexible strain sensors are needed to detect and monitor the movement of the intended parts of the human body, whether they are caused by vocal

Table 3. Temperature sensor comparison with different materials utilized.

Ref. #	Sensing Materials	Features	Nature
[57]	Non-ionic polymer, Polyelectrolyte layers	ultrahigh sensitivity, thermal index surpassing 10,000 K^{-1}, (10 mK min to exceeds 1.5 mK.)	Flexible
[58]	NiO/CNTF	broad working range(-15 to $60°C$) high sensitivity (max. $-20.2\%°C^{-1}$ and B value of 3332 K)	Flexible
[59]	(PAAm-SA) hydrogel, Parylene C, UV-cured resin	fast response ($2.02s$ of $40°C$), Sensing range (22–$100°C$)	Flexible
[60]	(Ag-MWCNT)/ (PEDOT: PSS)	high sensitivity of$-0.45\%\,°C^{-1}$ and linearity value of 0.998 in the temp. range of 25–$80°C$	Flexible
[61]	PANI/Fe^{3+}	(776 % at 55 ppm), wide detection range (547 ppb-547 ppm), excellent flexibility, selectivity, and cyclic stability.	Flexible

Table 4. Comparison of Triboelectric sensor materials.

Ref.	Materials	Stability Cycle	Response Time	Sensitivity
[78]	PVA/PU/3D structure	3000	7.9 milliseconds	6.875 $VkPa^{-1}$
[79]	Ag NWs/TPU/PA	stable	75 milliseconds	0.048 kPa^{-1}
[80]	PU film/Nylon/Mica	excellent	0.25 milliseconds	0.082 kPa^{-1}
[81]	Cellulose nanofiber material	stable	52 milliseconds	10.3 kPa^{-1}
[82]	PVDF-BTO	stable	26 milliseconds	2.620.11 $VkPa^{-1}$

cord vibrations or joint activity. Unlike traditional silicon-based strain sensors, the strain sensors must be made of a stretchy and flexible material due to the flexibility requirements. Wearable strain sensors require their component materials to be sensitive, flexible, mechanically dependable, possess hysteresis, and provide an output signal in a linear form. The strain sensor measures and quantifies material deformation or strain. The classification of wearable flexible strain sensors is according to the working mechanism used for sensing. Resistive and capacitive strain sensors collect mechanical deformation and convert it into an electrical signal. Resistive strain sensors measure strain using electrical resistance, while capacitive sensors use capacitance. Due to their transformational feature, strain sensors are essential for monitoring and understanding material structural behavior. Figure 2 illustrates typical strain sensor architecture.

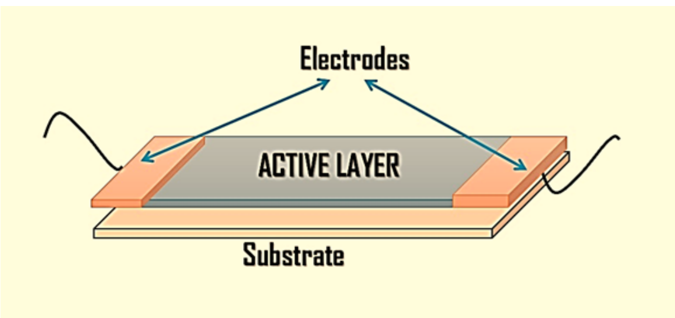

Figure 2. Typical strain sensor architecture.

Strain sensors benefit civil engineering, aircraft, biomechanics, and biomedical applications. Strain sensors quantify tissue biomechanical deformations to improve prostheses, rehabilitation, and musculoskeletal mechanics for patient care. These sensors advance medical technology and personalized treatment. Strain sensors are essential for material and construction integrity and reliability due to their adaptability. Strain sensors have advanced technology and enable us to detect environmental changes in innovative ways. Recent growth in sophisticated carbon nanomaterials-based films for sensing applications is due to their excellent characteristics. Nanomaterials' unique structure increases strength and multifunctionality. The strain sensors made from nanocomposite material possess exceptional characteristics such as remarkable flexibility, affordability, and lightweight. These sensors can be easily synthesized, and their sensitivity can be enhanced by optimizing the synthesis procedure and using suitable nanofillers. Stretchability and sensitivity are key strain sensor parameters. Other significant characteristics are response time, durability, flexibility and stability [84, 85].

2.6.1 Flexibility

The flexible strain sensor has received considerable attention in recent years due to its immense potential for use in electronic skin (E-Skin), human-computer interface, human health monitoring, movement detection, and soft robotics, as advancements in science and technology proceed. Flexible strain sensors (FSSs), owing to their inherent flexibility, lightweight nature, and compatibility with living organisms, are very important. Conventional devices composed of metals or semiconductors have a limited ability to detect slight deformations, typically below 5% strain, and are inflexible, causing discomfort when worn [86]. Due to its high performance, flexible strain sensors are employed in structural health monitoring, display technology, and pressure sensing. Flexible strain sensors can detect small muscle, skin, and pulse movements from movement, breathing, vocalization, and heartbeat in electrical equipment or on garments and skin. Additionally, they may detect considerable joint bending-induced body stresses. Also, robots can use them to govern joint mobility [87]. Given their conductivity and mechanical qualities, flexible strain sensors are often made from carbon materials, conductive polymers, metallic nanoparticles, and nanowires [88–90]. Nanomaterials based on carbon, such as carbon nanotubes (CNTs), graphene (both have high Young's modulus of about 1 TPa, graphene is a good choice for ultra-thin, wearable electronics and CNTs have great tensile strength and resilience with repeated deformation) and carbon-based nanoparticles (CBNPs), exhibit a significant amount of potential, particularly when combined with polymers to produce strain sensors that are both flexible and stable [91, 92]. Huang et al. [93] reported PU PU-based flexible strain sensor that can detect small movements when mounted on different parts of the body, such as human joints. Zhang et al . [94] recently reported a flexible strain sensor that employs an MXene/BC double network-based hydrogel for human motion detection, achieving remarkable results with stability surpassing 2000 cycles.

2.6.2 Sensitivity

The sensitivity of the strain sensor is determined by the ratio of the change in resistance ($\Delta R/R_0$) to the applied strain (ϵ). Strain sensors built of conductive polymer and metal sheets show promise because of their great flexibility and high sensitivity [95]. The strain sensor must have great flexibility and stretchability ($\epsilon > 50\%$) to accurately replicate human body movements and severe deformations. Strain sensors should also have a higher gauge factor (GF) and a lower limit of detection of 1% strain. This lets it identify and respond to sensitive stresses like pulse, respiration, phonation, and microexpressions. Even with little strain, reducing conduction routes is important for high sensitivity. However, conductivity must be maintained under extreme strain to have a wide sensing range [96]. By converting an Au film into a brittle conductive layer, Li et al. [97] achieved a 100% maximum tensile limit and high sensitivity. Nevertheless, the properties of "wide stretchability" and "high sensitivity and low limit of detection are in a trade-off relationship due to the specific demands of the sensing materials [98]. Silk fibroin-based conductive hydrogels designed by Tao [99] and colleagues are recyclable, freeze-resistant, and dry-resistant. Strain sensors are sensitive to macro and micro human motions due to their gauge factor of 2.18. Strain sensors and integrated supercapacitors excel in harsh situations. Cai et al. [84] coated 2D MXene and 1D CNT to develop strain sensors. The sensor showed a considerable improvement in sensitivity (GF 772.6) when purposely creating fractures in MXene and bridging them with CNTs. The sensor's detection range was approximately 80%, and a GF of 772.6 at $40-70\%$ strain. The strain sensors, which utilize metal nanoparticles (e.g., Pd nanoparticles molded into polyimide substrates), exhibit excellent sensitivity (GF = 390) and a low limit of detection (0.06%), but they lack stretchability ($\epsilon = 0.2\%$) due to their rigidity. An instance of a strain sensor, which is adaptable, is constructed using ternary nanocomposites consisting of zero-dimensional materials based sensor exhibits a remarkably high gauge factor of 2393 when subjected to a strain of 62% [100].

Wang et al. [101] developed a star-nose-inspired multi-mode flexible sensor composed of parallel polyimide films mimicking the nasal rays of the star-nosed mole. The sensor achieved a high gauge factor of up to 4000 under 55% strain. Although the work highlights high sensitivity, the exact limit of detection is not clearly stated, and further improvements may be required for detecting ultralow strains. Flexible strain sensors with a high gauge factor (GF), long-term durability, extensive stretchability, and a low limit of detection are in demand. Recent research by Huang et al. [102] generated strain-detecting polymer nanoball-adorned graphene sensors. The sensors have a high gauge factor (GF) of 51 in the strain range of 0% to 5% and 87 in the strain range of 5% to 8%. The researchers wove a serpentine-shaped gauze piece from porous fiber that tested over 100% strain.

2.6.3 *Self-Healing*

Self-healing materials in strain sensors can repair damages on their own, either with or without external triggers. This repair process involves the restoration of reversible chemical bonds or the utilization of healing chemicals that are contained in polymers [103, 104]. Scientific research into self-healing, initially envisaged in science fiction, has grown. The idea is to provide electronic devices with healing qualities like those of beings to help them heal structural damage like scratches and wounds and regain functioning [105, 106]. Self-healing is employed to enhance the resilience and longevity of materials. It has demonstrated usefulness across several materials and applications, such as enhancing structural integrity, producing durable super-hydrophobic coatings, prolonging material lifespan, and enhancing environmental sustainability [107, 108]. Virtually all self-healing materials and systems can repair and recover from harm. Autonomic and non-autonomic self-healing materials exist. Autonomic materials can mend themselves without external help, but non-autonomic materials need light, heat, or humidity to restore and maintain the process [109].

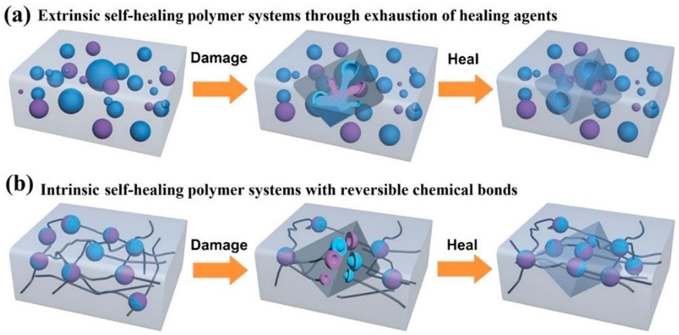

Figure 3. Schematic illustration of (a)Intrinsic self-healing (b) Extrinsic self-healing polymer systems. Reproduced with Permission. [110] Copyright © 2017 WILEY-VCH.

Self-healing materials categorised into two types: intrinsic and extrinsic self-healing materials shown in Figure 3. Extrinsic self-healing materials work by embedding tiny capsules or small channels filled with a healing agent inside the material, which helps repair any damage when needed. When the containers are damaged, they break and release the healing agent, which allows the entire system to heal itself [111, 112]. Intrinsic self-healing relies on reversible dynamic bonds, which can either be covalent or non-covalent [113]. Physical features like as the mobility of polymeric chains, interfacial flow, and shape-recovery qualities are also important contributors to the self-healing process of intrinsic materials. These elements play a crucial part in the process. When compared to extrinsic self-healing, intrinsic self-healing is often more dependable and long-lasting [114]. Table 5 shows a comparison of different materials-based strain sensor healing efficiencies.

Table 5. Comparison of different material-based fabricated strain sensor self-healing efficiencies.

Ref. #	Materials	Self-healing efficiency
[115]	MWCNTs-UPy/IU-PAM	95%
[116]	PAAm/NaCl	99%
[117]	Fe_3O_4@PAA/PAA	>95%
[118]	Col/$AlCl_3$/ DCMC	100%
[119]	CNFs/PU	97.7%
[120]	(P(AM-co-AA)) /Al^{3+} network	97%
[121]	(PVA)/(TP)/EG/AgNPs/ MWCNTs	96.07%
[122]	glutaraldehyde (GA)-(PVA)/ (CNC/ (PEDOT: PSS)	>98.3 %

2.6.4 *Adhesiveness*

Recent years have seen remarkable progress in the development progress of stretchable, flexible, and durable electronics. However, it is equally important to visualize Human Machine Interfaces and determine the precise appropriate interaction of sensors with human skin.

As technology grows such as the Internet of Things (IoT), people expect better living conditions, multiple sensors that monitor both health and environmental conditions are now gradually making their way into the everyday lives of people globally such as (E-skin) electronic skin, speech recognition, health monitoring, human-computer interactions and soft roboticswith flexibility, adhesiveness, and biocompatibility, used to monitor minute changes that are brought on by external factors [123, 124]. In terms of all attributes, Strain sensor adhesiveness directly influences the sensor's ability to be firmly attached to the surface undergoing evaluation. Achieving high adhesion is essential for reliable strain-sensing data collection [125]. Maintaining a stable connection with the substrate and minimizing the possibility of slippage or detachment is essential for a well-designed strain sensor with high adhesiveness, especially in dynamic or harsh situations. Across a broad spectrum of structural monitoring techniques, and industrial and

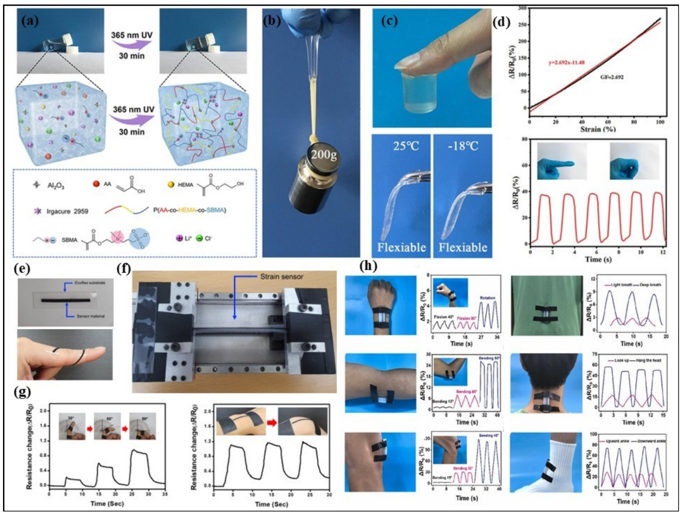

Figure 4. (a) Fabrication mechanism of PAHS gels (b) Under various external forces-mechanical properties (c) Adhering to substrates and at different temperatures (d) PAHS gel sensor strain sensitivity. Reproduced with permission [127] Copyright © 2023 Elsevier (e) Stretchable strain sensor stretched by hand rolling. (f) A home-made tensile tester stretched a strain sensor of 300% strain. (g) Response to bending motion detection. Reproduced with permission [134] Copyright © 2023 the Korean Institute of Metals and Materials. (h) Strain sensor for movement detection. Reproduced with permission [135] Copyright © 2025 The Authors. Published by Elsevier B.V

biomedical applications, this is critical for getting accurate strain data and making sure the sensor lasts a long time. A strain sensor's whole performance and usefulness are greatly affected by the adhesiveness factor, which in turn affects the sensor's practical utility in real-world circumstances [126].

2.6.5 Stretchability

The stretchability of strain sensors varies significantly based on factors such as the strain sensor's nature, nanomaterial used, micro-nanostructures, and the fabrication mechanism applied. A single-step in situ free-radical polymerization technique based PAHS gels-based strain sensor (Figure 4 (a)) shows more than 85% transparency at 550 nm, 800% stretchability, and 2.25 S/m ionic conductivity as shown in Figure 4 (a, b, d). Furthermore, these gels maintained their flexibility and conductivity even at a temperature as low as -18 ℃ (Figure 4 (c)), superior strain sensitivity (GF = 2.69), and application of using PAHS gel sensors to detect human action, the finger bends and straightens repeatedly, indicating high repeatability [127]. Resistive-type sensors with a high stretchability (ε = 280%) were made using aligned carbon nanotube (CNT) thin film and polydimethylsiloxane (PDMS) composites [128]. Additionally, capacitive-type sensors with exceptional stretchability ($\varepsilon \approx$ 300%) are made by percolating carbon nanotube (CNT) network-silicone elastomer composites [129]. Strain sensors that utilize high aspect ratio metal nanowires (such as silver nanowires) and carbon nanotubes often exhibit a high level of stretchability, exceeding 50% [130, 131]. Additionally, when carbonized plain weave silk and cotton fabrics are placed between two layers of Ecoflex, they can stretch impressively-up to 140% for silk and as much as 500% for cotton [132, 133]. A stretchable strain sensor designed by using multi-walled carbon nanotubes (MWCNTs)-Ecoflex composite paste on an Ecoflex substrate using a straightforward stencil printing method (Figure 4(e,f,g)) exhibits maximum stretchability of 1,000% (Figure 4(f,g)) and a sensitivity range that extends from 3 to 12,287 [134] . Long et al. [135] reported a flexible strain sensor with a stretchability feature mounted on different parts of the body to detect movement, shown in Figure 4(h). Table 6 illustrates different materials-based strain sensor comparison in terms of stretchability, gauge factor and response time.

3 Parameters of Strain Sensor

3.1 Gauge Factor

The gauge factor is defined as the ratio of the percentage change in the sensor's response to the strain that is being applied. Strain sensors that have been reported for use in a variety of applications have been found to exhibit a stretchability of several hundred percent in terms of linear strain and a sensitivity that ranges from less than ten to about one thousand($<$ 10 to around $\approx$ 1000) [141–143]. For resistive and capacitive sensors, GFs are calculated as resistance variation ΔR/R0 / ϵ and capacitance variation (Δ C/C0)/ϵ, respectively. Metal-foil strain gauges have GFs of (two to five) 2–5, while semiconducting strain sensors can have GFs of 100 or more [144–146].
Resistive-type sensors based on CNTs and Ecoflex Nanocomposites demonstrated GFs ranging from 1 to 2.5 accomplished by changing the tunneling resistance [147]. Carbon Black-Filled Elastomer Composites-based ultra stretchable strain sensors have (capacitive) gauge factors of 0.83–0.98 and (resistive) gauge factors of 1.62–3.37 [148]. Graphene thin films and polymer composites generate maximum high-density microcracks in a crisscross(crosswise) arrangement for ultra-high sensitivity (GFs $>$ 1000)[149].

Table 6. Comparison of different material-based strain sensor gauge factor, stretchability, and response time.

Ref.	Materials	Stretchability	Gauge factor	Response time
[136]	TPU/PDA/MWCNTs/GO	760 %	41.57	59 milliseconds
[137]	CNTs/AgNWs hybrid network	100%	79	42 milliseconds
[138]	P(HEA-co-AA) DES-IL gels	1783%	1.01	143 milliseconds
[139]	CNC)/ (A-MWCNT) conductive hydrogel	431.6 %	4.32	100 milliseconds
[140]	polyolefin elastomer (POE)/carbon nanostructures (CNS)	952.5%	5230	200 milliseconds

In comparison to prior piezoresistive techniques, stretchable strain sensors that included microcracks and disconnection processes provided a higher level of sensitivity [150]. Despite having great stretchability, capacitive-type sensors exhibited poor sensitivity (GF ≤ 1) due to the implementation of theoretical constraints. Stretchable strain sensors based on the AgNW network that was constructed with PDMS and ecoflex dielectric layers displayed GFs of 1 and 0.7, respectively [151, 152]. In particular, larger CNT content increases stretchability, but random CNT entanglement lowers strain sensor performance (bad gauge factor). Table 5 shows different material-based strain sensor gauge factors [153–159].

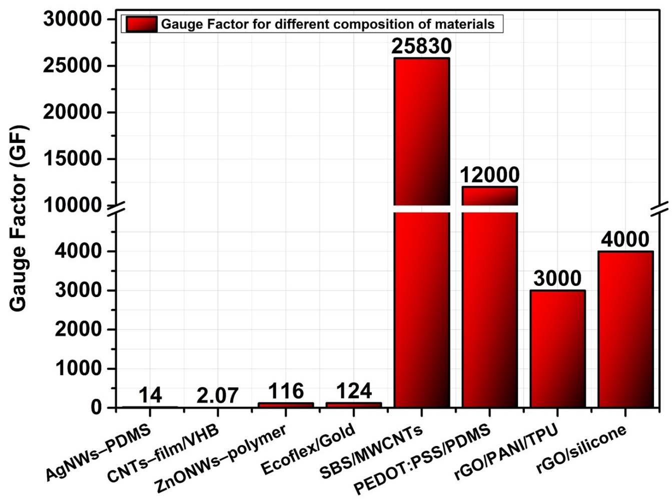

Figure 5. Graphical bar chart comparison of gauge factor of strain sensor fabricated by utilizing different materials.

3.2 Linearity

Linearity, in simple terms, represents a correlation where the resistance changes or variation is directly proportional to applied strain. A linear regression analysis is used to generate the coefficient of determination (R_2), which is then used to quantify the linearity of a flexible strain sensor. This is accomplished by determining the R2 value. The R_2 value of a linear strain sensor is higher, which indicates that the output signal follows a straight line with just a small amount of variance. When the value of R_2 is low, on the other hand, a strain sensor is said to be nonlinear [160]. The linearity parameter is crucial for stretchable strain sensors as it must be able to accommodate extremely large strains. The nonlinearity of sensors adds complexity and difficulty to the calibration process. The presence of nonlinearity is a significant disadvantage commonly found in strain sensors of resistive type. Typically, strain sensors exhibit a non-linear response to applied strain when the thin film microstructures transform from a "homogeneous morphology" to a "nonhomogeneous morphology" during stretching [161, 162]. When graphene flakes or NPs generate and propagate inhomogeneous micro-cracks in thin films, this strain sensor responds nonlinearly. The main cause of nonlinearity in (low-density) is identified as transformation or transition from a "homogeneous percolation network" to an "inhomogeneous percolation network" [135]. Polymer composites with carbon nanotubes (CNTs) based strain sensors typically showed non-linear electromechanical behavior and low sensitivity [163, 164]. Hybrid structures improved CNTs-polymer composites' sensitivity and linearity. Capacitive sensors have remarkably excellent linearity, even though their sensitivity is limited [165].

3.3 Response Time

Response time is the measure of how rapidly the stretchable strain sensors reach a stable state of response. All polymer-based strain sensors experience a slight delay in their response due to the stretchy and slow-to-relax nature of the polymers they're made from [166, 167]. The standard time-to-response value for stretchable sensors is often expressed by a time constant of 90% (also known as 90%) [168]. The resistive-type strain sensors, constructed using a nanocomposite of carbon nanotubes and Ecoflex, observed a reaction time of 332 milliseconds [169]. Capacitive strain sensors exhibited a faster response time [170]. As capacitive-type strain sensors made from AgNWs and CNTs exhibited response times of 50 and 100 ms, respectively. Table 7 Shows

Table 7. Comparison of strain sensor based on different materials and polymers composite highlighting response time.

Ref #	Materials	Response Time
[171]	methylpropiophenone/PVA	660 s
[172]	Poly(vinyl alcohol)/polyacrylamide (PVA/PAM)	368 ms
[173]	TPU@CNT	75 ms
[174]	Fe_3O_4/CB	78 ms
[175]	ECPCs/CNT/thermoplastic polyurethane	180 ms
[176]	zinc oxide	300 ms
[177]	CNT/silver nanowire (AgNW)	600 ms

Table 8. Comparison of strain sensor materials highlighting dynamic durability and stability cycles.

Ref #	Materials	Dynamic Durability and Stability
[180]	MWCNTs)/(GR)/(SR)/Fe3O4	9000 cycles
[181]	graphene/TPU	1000 cycles at 50% strain
[182]	CNTs-CB/PDMS composites	2500 cycles at 200
[183]	PDMS/AgNWs	1000 cycles at 50% strain
[184]	PET/ PUE	1000 cycles at 20

different material-based fabricated strain sensor and their response time, respectively reported.

3.4 Dynamic Durability and Stability

The term "dynamic durability" refers to the capacity of strain sensors to survive multiple cycles of stretching and releasing over a prolonged period, while simultaneously sustaining their electrical functioning. Stretchable wearable strain sensors need to have a high level of endurance since strain sensors are designed to detect stresses that are extremely vast, complicated, and continuously changing [178]. The fatigue and plastic deformation of polymer substrates under high stresses, as well as the fracture and buckling of sensing nanomaterials, lead to a decline in the performance of strain sensors, according to the conclusions drawn by several groups of researchers. However, there have only been a few stretchable strain sensors that have been researched to display outstanding dynamic persistence [179]. Table 8 shows different cycles and strain percentages of the strain sensor device reported.

3.5 Hysteresis

The term "hysteresis" is used to describe the connection between the current state of a strain sensor, which is the output signal of cycle n, and its previous record, which is the output signal of cycles 1 to $n-1$. Hysteresis is an essential key consideration component of strain sensors, particularly in wearable industries [185]. A significant amount of hysteresis behavior is responsible for the irreversible or inconsistent sensing performance of sensors when they are subjected to dynamic stressors. Strain sensor hysteresis produces signal drift and inconsistent readings during loading and unloading cycles, which can create severe measurement inaccuracies in long-term monitoring applications. Resistive sensors have higher hysteresis due to viscoelastic effects and material fatigue, making calibration difficult and limiting accuracy. Capacitive sensors have lower hysteresis and perform better in real-world applications like wearable health monitoring and robotics. Compared to resistive strain sensors, capacitive sensors perform better by showing less lag and delivering more accurate results [186]. Horizontal parallel inter-digital strain sensors have benefits over vertical sandwich resistive and capacitive strain sensors. It improves substrate transparency and reduces normal force connections. By using a low-pressure coupling effect under normal load, 3D electrodes in the substrate increase their endurance. Interdigital 3D electrodes are made from vertically aligned carbon nanotubes in the strain sensor. It is translucent, stretchy, and has 0.35% ultralow hysteresis. It also has great transparency, a 60 ms reaction time, strong long-term stability, and a pressure-insensitive performance of less than 0.8% [187]. Table 9 shows the hysteresis and strain parameters of different fabricated strain sensors.

4 Types of Strain Sensor

4.1 Capacitive strain sensor

Conventional flexible capacitive sensors are made up of a parallel-plate capacitor, which is made up of two flexible electrodes that are separated by a dielectric layer [193]. Stretchable dielectric materials, such as elastomers(silicone-based) like Dragon Skin, polydimethylsiloxane, Ecoflex and rubbers like thermoplastic elastomers and natural rubber, are often used as flexible supports for soft strain sensors [194–196]. The presence of a significant young modulus difference between thin

Table 9. Comparison of different material composite based strain sensor materials highlighting Hysteresis and strain percentage.

Ref.	Materials	Hysteresis	Strain
[188]	Ethylene glycol/sodium chloride	0.15%	250%
[189]	CB/PDMS foam	1.2%	70%
[190]	PEDOT: PSS nanofibers/PVA	<1.5%	300%
[191]	MWCNTs/ Ecoflex nanocomposites	1.63%	1300%
[192]	Polyacrylamide (PAAM) hydrogel	<3%	0–200%
[146]	P3HT-NFs/ PDMS	<12%	up to 100%

metallic coatings (such as gold, aluminum, and platinum) and flexible elastomer or rubber results in the material breaking and collapsing when it is stretched. A decrease in the conductivity of the metallic film is caused by the inhomogeneity between these two superposed layers [197, 198]. Conductive components for a conventional capacitive type of strain sensor are synthesized by altering the geometries of traditional materials, such as wavy geometry, helical structure, and mesh morphologies. This allows for the creation of the conducting elements [199]. Furthermore, the electrode's flexibility can be attained by integrating conductive substances, likewise carbon black, graphene, metal nanoparticles, and CNTs, within a polymer matrix [200]. Recently, certain research has incorporated additional ingredients, fillers to enhance the chemical, mechanical and electrical characteristics of the (stretchable) composite electrodes. Yun et al. [201] provided an in-depth analysis of the hybrid filler electrodes, including their design, fabrication method, a study on dynamic as well as static conductivity, and current recent applications.

To increase capacitive strain sensor sensitivity, researchers construct new geometries or adjust material mechanical properties beyond the parallel plate capacitor. Kim et al. [202] using AgNW electrodes on PDMS, designed an interdigitated capacitive type strain sensor(ICSS) as shown in Figure 6(a, b, c) [193]. Figure 6 (d) demonstrates that the interdigitated capacitive strain sensor (ICSS) has an electric conductivity (σ) (at 30% ε) of approximately $\tilde{4}2.2$ S/cm, indicating no major cracks in the electrodes and allowing for effective capacitor performance up to 30% ε and sensing performance as applicable application shown in Figure 6(e). Huang et al. [203] proposed homogeneous, water-retaining hydrogel electrodes for capacitive strain sensors.SPGLH sensor in detecting human motion (Figure 6 (f)) and in human-machine interface (Figure 6 (g)) as an application in real-time. Xue et al. [204] reported a capacitive-type strain sensor for strain movement(Figure 6 (h)). A popular way to make stretchable capacitive strain sensors is by placing a thin insulating film, called a dielectric layer, between two flexible electrodes-kind of like a sandwich. When a voltage is applied, the dielectric layer prevents the opposing charges on each electrode from passing through. This creates a capacitor that starts with an initial capacitance of C_o, which can be described as follows:

$$C_o = \epsilon_o \epsilon_r G \tag{1}$$

Where ϵ_o is air's permittivity, ϵ_r is the dielectric material's constant, and G corresponds to the capacitor shape.

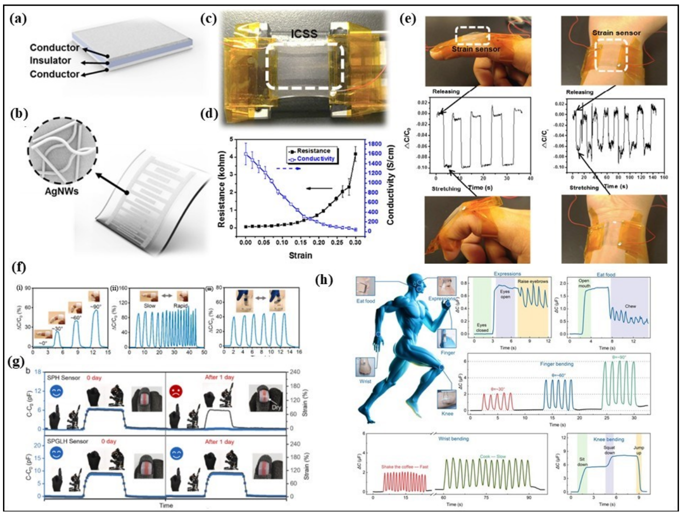

Figure 6. (a) Traditional strain sensor (parallel-plate type) (b,c) Interdigitated capacitive strain sensor (ICSS). (d) ICSS motion sensor performance for finger and wrist muscle cyclic motions. Reproduced with permission [202] Copyright © 2017 American Chemical Society (f) SPGLH-based sensor (detecting human motions) (i)finger angle(ii)response from slow-fast bending(iii)detecting/tracking curve under saline (g) For Robot control, SPH and SPGLH sensor response signals. Reproduced with permission [203] Copyright© 2023 Elsevier.(h)Capacitive-type strain sensor application. Reproduced with permission [204] Copyright © 2024, Springer.

4.2 Resistive Strain Sensor

At the beginning of the 1940s, the first strain sensors of the resistive type were developed. These strain sensors make use of metallic foils. It has been demonstrated that these sensors are capable of detecting strain of up to five percent(5%), particularly for very slight deformities in composites or nanocomposites and rigid materials or bodies [205, 206]. Resistive strain sensors consist of sensing elements, which are conductive networks, and a flexible polymer or fiber substrate that can be stretched. Their operation is based on the concept that the electrical resistivity of a material changes when subjected to the strain that is applied [207].

The fabrication of resistive-type strain sensors has seen a significant change, shifting from a rigid to a flexible structure, due to the increasing need for wearable electronic devices in the modern world. Stretchable strain sensors are generally made up of active sensing materials that are integrated with elastic and flexible supporting substrates throughout the fabrication process [208]. In most situations, active materials are micro- or nanoparticles/nanomaterials that conduct electricity. These materials can be polymer composites, conductive yarns or textiles, thin films, etc.

Using conductive Au clusters and Eco flex elastomeric films, Migliorini et al. [155] built a high-strain resistive sensor. This sensor is created using supersonic cluster beam deposition. A thorough electromechanical characterization of the sensor indicates steady functioning up to 4500 working cycles, 500% strain, and 124-gauge factor as shown in Figure 7 (a). The sensor can sense mechanical stimuli like stretching and compression as mounted on the finger and elbow (Figure 7(b)). Shang et al. [200] proposed a straightforward and efficient method for producing a superhydrophobic flexible resistive strain sensor. This method involved spraying carbon black (CB) nanoparticles in a thermoplastic elastomer (SEBS) solution onto a PDMS flexible substrate (Figure 7(c)). The behavior of strain sensing is depicted in Figure 7(d) under cyclic tensile testing with loads ranging from 10% to 70% (the maximum strain range), the normalized resistance ΔR/R0 increased significantly and showed a consistent signal across stretching-releasing strain cycles. Applications for human motion detection as finger straight or bending and resistance variation in strain sensors, are shown in Figure 7(e).

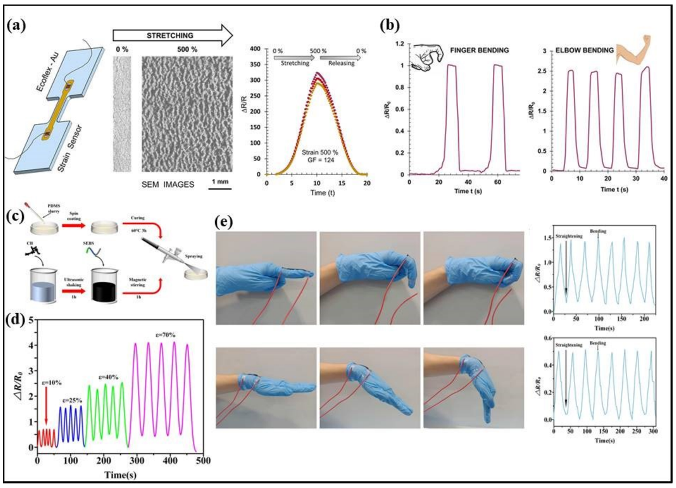

Figure 7. (a) Ecoflux-Au Based resistive strain sensor (b) RSS mounted on finger and elbow stretching vs. resistance. Reproduced with permission [155] Copyright © 2023, American Chemical Society.(c) Schematic representation of flexible strain sensor (d) The normalised resistance variation five cycles of stretching and releasing, with stresses ranging from 10% to 70%. (e) Output signal for various degrees (2023)[209].

5 Materials

5.1 Conductive Nanomaterials

Conductive nanomaterials' nanoscale mechanical and electrical characteristics make them potential strain sensors. Carbon nanomaterials have attracted scientific interest for decades due to their unusual structural features in one, two, and three dimensions, as well as their exceptional performance statistics. Consequently, the carbon-based structure is a potentially unlimited two-dimensional aromatic macromolecule and the basic structural unit for other dimensions. Nanotubes, graphite, and "buckyballs" or fullerene are examples. Graphene's introduction in recent years is an outstanding advancement. A hexagonal lattice of carbon atoms makes up graphene [210]. Graphene's unique molecular structure gives exceptional chemical, electrical, and mechanical features, such as notable flexibility, elasticity, and the ability to adapt to different surfaces [211]. Carbon black is amorphous like graphite. Although cheap, carbon black is a nanoparticle with electrical properties.

Its use in composites' elastic matrix increases strength and electrical conductivity [148]. Zhang et al. [212] demonstrated a carbon black/silver nanoparticle-based flexible strain sensor, as depicted in Figure 8 (a). The strain sensors that have been constructed have a high degree of stretchability and

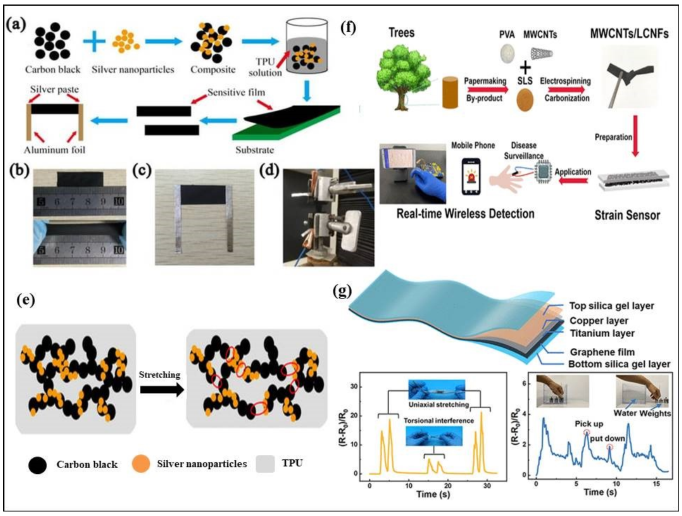

Figure 8. (a) Fabrication procedure of the CB/AgNPs composite based strain sensor (b) Stretchable characteristic of a strain sensor (c) strain sensor sample with electrodes (d) Sensor in testing machine (e) During stretching, the morphology of a CB/AgNPs-based strain sensor changes [21] 2018-Open Access. (f) MWCNTs based strain sensor fabrication and application. Reproduced with permission [213] Copyright © 2023, American Chemical Society (g) Strain-sensitive layer, a Cu/G micro crack composite film/self-adhesive silica gel-waterproofing and self-adhesive layer. Reproduced with permission [214] Copyright © 2023, American Chemical Society.

demonstrate good sensitivity, with a gauge factor of 21.12 at a tensile strain of 100%. Additionally, they show great performance in static conditions at a strain of 50% for 600 seconds, as well as dynamic stability as in Figure 8 (b, c, d) with 100 cycles and morphology changes of a strain sensor based on CB/AgNPs during stretching as shown in Figure 8 (e). Carbon nanotubes have gained substantial attention due to their quick fabrication, affordability, and chemical-based durability. Wang et al. [213] developed a strain sensor utilizing a combination of multi-walled carbon nanotubes and lignin-based carbon nanofibers as shown in Figure 8 (f). The fabricated sensor has wide stretching, repeatability, and high sensitivity with a gauge factor (GF) of 137.3 and 2746.4 in a strain range of 0-160% and 160-240%. Zhu et al. [214] researched a strain sensor that is flexible and utilizes composite films made of copper and graphene. The sensor has a broad response range, extending up to 110%. It demonstrates a high level of sensitivity, with values ranging from 92% to 110%. Additionally, it possesses excellent endurance in detection capabilities. Additionally, it can identify ultrasmall strains, namely strains as low as 0.2%. The sensor's self-adhesive silica gel clings directly to the skin, enhancing the monitoring of complicated strain status during underwater activities. The versatile strain sensor has the potential to become an advanced underwater sensor in the future as shown in Figure 8 (g). Metal nanoparticles, such as silver or MXene, improve strain-sensing conductivity and stability. These nanoparticles can be integrated into flexible and elastic materials to create strain sensors that can adapt to distinct surfaces and endure mechanical deformation. The integration of nanotechnology and strain sensing enhances sensor performance and enables efficient and potential applications in wearable devices, robotics and structural health monitoring, where accurate mechanical strain detection is essential [215, 216].

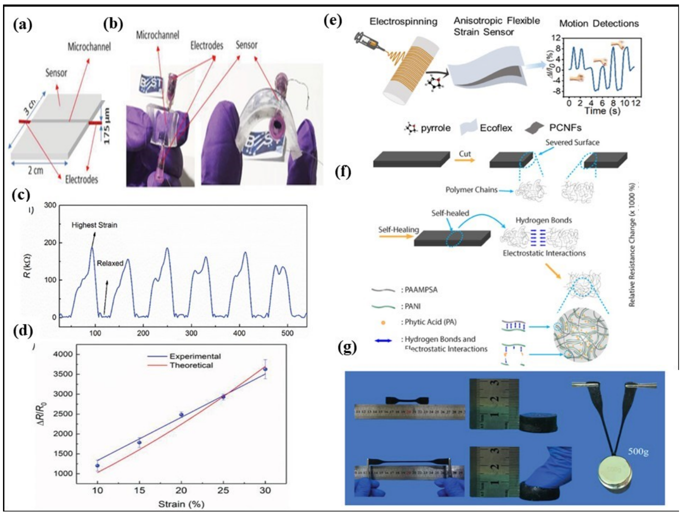

Figure 9. (a) Schematics illustration of the fabricated strain sensor (b) Flexible sensor optical image (c) Sensor's response to a 10% strain d) Sensor response (experimental and theoretical) for various strain values. Reproduced with Open Access [157], 2020.Wiley VCH (e) Aligned Cellulose and Polypropylene Composite Nanofibers through Electrospinning and ITS application. Reproduced with permission [218] Copyright © 2023, American Chemical Society (f) Polymer Complex-Conductive, self-healing and ultra-stretchable Strain Sensor.Reproduced with permission [108] Copyright © 2019, American Chemical Society. (g) Strain sensor polymer hydrogel mechanical characteristics with compression, stretch and accept 500 g's weight. Reproduced with permission. [220] Copyright © 2024 Wiley-VCH GmbH

5.1.1 *Conductive Polymer*

Conductive polymers, or intrinsically conducting polymers (ICPs), are organic polymers that can conduct electricity. Conducting polymers are generally polymers that have π-conjugation and possess inherent conductivity. Examples of conducting polymers are PEDOT: PSS, polyaniline (PANI), and polypyrrole [217]. PEDOT: PSS is highly regarded as the most favorable conjugated polymer for applications such as electrical fillers, stretchable electrodes, and tactile sensor active layers.

This is mostly owing to its exceptional stability, tunable conductivity, and ease of processing. Bhattacharjee et al. [157] fabricated a PEDOT: PSS micro channel-based highly sensitive stretchable strain sensor as shown in Figure 9 (a,b). The sensor has a significantly low average level of hysteresis (<9%). The sensor displays roughly an order ($\Delta R/R\_0 \approx 1200$) increase in the resistance (R) with 10% applied strain (Figure 9 (c)). The response of the sensor (both experimental and theoretical) for various strain values is shown in Figure 9 (d). Polypyrrole (PPy) is extensively utilized in sensors and electronic devices due to its simple production process and exceptional electrical conductivity. Li et al. [218] demonstrated strain sensors through electrospinning on highly aligned cellulose/Polypyrrole composite. The strain sensor has exceptional anisotropic sensing capabilities with a sensitivity of 0.73 and 0.01 for tensile applied perpendicular and parallel to the nanofiber's alignment. Strong hydrogen bonding between cellulose nanofibers and polypyrrole makes the sensor durable (2000 cycles). Flexible strain sensors can also detect human joint movements, indicating prospective motion detection applications as in Figure 9 (e). Polyaniline (PANI), another prominent conducting polymer, has great electrical conductivity and chemical stability, making it valuable for sensor and corrosion protection applications. Conductive polymers offer a significant benefit in terms of their ease of processing, particularly through scattering. Conductive polymers typically lack thermoplastic properties, they cannot be easily shaped through heating and molding [219]. However, like insulating polymers, they are classified as organic compounds. While they possess excellent electrical conductivity, these polymers do not exhibit comparable mechanical qualities to other polymers that are already on the market. Lu et al. [108] Demonstrated ultra stretchable conductive polymer complex (composed of poly (2-acrylamido-2-methyl-1-propanesulfonic acid), polyaniline, and phytic acid)as a Strain Sensor with a repeatable autonomous self-healing ability as shown in Figure 9 (f). Its ultrahigh stretchability (1935%), repeatable autonomous self-healing (repeating healing efficiency >98%), quadratic strain response ($R2 >$ 0.9998), and linear flexion bending response ($R2 >$ 0.9994) exceed conventional wearable strain sensors. Wang et al. [220] reported a strain sensor based on polymer hydrogel with effective weight abilities (Figure 9(g)).

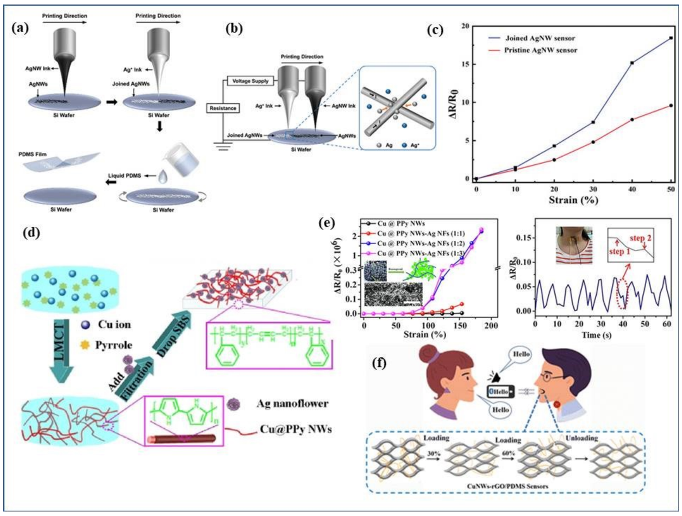

Figure 10. (a) High-resolution electro hydrodynamic (EHD) printing AgNW/PDMS based strain sensor. b) Schematic illustration of electrohydrodynamic (EHD) printing (c) Change in relative resistance with deformation-strain in sensor. Reproduced with permission [222] Copyright © 2023, Wiley VCH.(d) Fabricating strain sensor (based on Cu@PPy NW–threaded Ag NFs).(e) Plots of resistance vs. tensile strain of the composite-based strain sensor and Throat swallowing. Reproduced with permission [223] Copyright © 2021. Elsevier.(f) CuNW-rGO/PDMS strain sensor for speech recognition, lip reading. Reproduced with permission [224] Copyright © 2023, Royal Society of Chemistry.

5.1.2 *Metal based nanomaterials*

Metallic nanomaterials, such as nanometals, are noteworthy for their unique optical and electrical properties. The conductivity of various metals is as follows: copper-(Cu, σ=5.96*107S m^{-1}), silver-(Ag, σ = 6.30*107S m^{-1}), aluminium-(Al, σ=3.50*107S m^{-1}), gold-(Au, σ = 4.10*107S m^{-1}) and so on. Nanometals are engineered to exhibit numerous nanostructures with different dimensions, including 1 dimension, 2dimension and so on, such as nanoparticles (0D), nanowires-(NWs)/nanofibers (1D), and nanoflakes (2D). Conductive nanofillers, such as 0D (silver/gold/Copper nanoparticles) and 1D (silver/Copper nanowires and silver nanofibers) nanometals have been employed and utilized. However, 1D nanowires and nanofibers are employed more frequently [221]. Metal nanosheets, nanowires, and nanoparticles are classified as metallic nanomaterials. Using electrohydrodynamic printing, Hu et al. [222] fabricate (high-resolution) self-reduced soldered-based silver nanowire(AgNWs) patterns for flexible and wearable strain sensors as shown in Figure 10 (a,b) and resistance variation with applied strain shown in Figure 10 (c).

Copper nanowires (CuNWs) possess exceptional attributes such as high mechanical flexibility, transparency, and electrical conductivity. Zhao et al. [223] Construct wearable strain sensors by applying a layer of Polypyrrole onto copper nanowires (Cu@PPyNW) that are connected through silver nanoflowers (Figure 10 (d)). Electrical resistance increases slowly from 0 to 80% strain and then quickly as stretching strain increases, showing conductive network structural differences under different strains and can be stretched up to 150% before insulation and sensor test on throat swelling as shown in Figure 10 (e). Cheng et al. [224] developed a CuNW-rGO/PDMS piezoresistive strain sensor that is both extremely sensitive and stretchable. This sensor was designed specifically for lip-reading extraction and speech recognition Figure 10 (f).

5.1.3 Substrate Materials

Sensor and strain sensor design and performance require supporting materials as substrates. They boost device functioning, durability, and sensitivity. Polydimethylsiloxane (PDMS) is one of the common support materials. This silicone elastomer is transparent and flexible. Due to its mechanical properties and biocompatibility, PDMS is widely used to make sensors, especially flexible and stretchable ones. Its flexibility allows it to make uniform contact with non-uniform surfaces, making it suitable for wearable sensors and applications that require the sensor to adapt to the monitored component. PDMS is used as a substrate or coating to reinforce and protect sensor components [225]. Hassan et al. [226] fabricated an ink-jet printed strain sensor that is stretchable using a composite of Graphene and Zinc Oxide(ZnO) on (micro-random) ridged Polydimethylsiloxane (PDMS) substrate. The schematic diagram of the inkjet material printer and DMP-3000 insets is shown in Figure 11 (a). In Figure 11 (b), all strain sensor fabrication stages are illustrated as having a composite film thickness of 500 nm (Figure 11 (c)).

Zhang et al. [227] demonstrated the printed strain sensors based on polymer material substrates as polyethylene terephthalate (PET) substrates, as shown in Figure 11(d, e). MEMS strain sensors use silicon substrates. Silicon is rigid and stable for high-precision strain measurements. Some cheap and disposable strain sensors use flexible paper-based substrates soaked or coated with conductive materials. Polyester films like Mylar are also employed as strain sensor substrates as it is lightweight, flexible components so easily integrated into many applications [228–230]. Polyimide film, Kapton, is utilized in sensor technology due to its high-temperature resistance and dimensional stability [231]. Piezoelectric ceramics, such as lead zirconate titanate (PZT), are frequently used in strain sensors due to their distinctive capacity to transform mechanical strain into electrical signals [232]. Piezoelectric strain sensors are used in structural health monitoring, industrial applications, and robotics due to their high sensitivity [233].

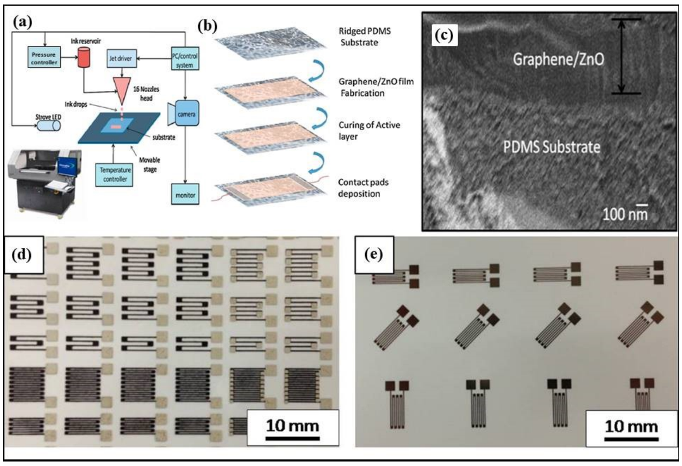

Figure 11. (a) Inkjet material printer layout with commercialised DMP-3000 inset. (b) Fabrication process for PDMS substrate-based strain sensor. (c) Cross-sectional SEM image of a strain sensor. Reproduced with permission [217] Copyright © 2018, Elsevier (d) Images of screen-printed and (e) Inkjet-printed strain sensors on PET substrates. Reproduced with permission [218] Copyright © 2017, Elsevier.

6 Application of Strain Sensors

6.1 Biomedical Application

As the population grows, providing high-quality medical care and pharmaceuticals becomes harder. Prospective solutions like remote and personalized health monitoring can improve diagnosis and early treatment, expand health care to the general population, and enhance existing medical systems [234]. Wearable devices such as strain sensors, are gaining popularity because they are easy to use, can diagnose issues early, and can monitor them for a long time [235]. Stretchable strain sensors naturally collect environmental and physiological data from the body. Data include oxygen saturation, blood pressure, heartbeat, breathing rate, motions, body temperature, and more. Strain sensors can communicate data to a device or access point via wireless or internet, updating a medical facility. Emergency service centers receive alerts for quick response. With correct treatment, doctors can remotely monitor and make medical decisions [236]. Researchers have developed strain sensors that are highly sensitive, can be mounted on the skin, and are wearable. These sensors are designed to detect small movements of the skin caused by activities such as speaking, making facial expressions, swelling of tissues, healing of wounds, breathing, and pulse [237].

Vital signs including blood flow, respiration rate and pulse rate can be monitored over time for personalized monitoring of health and early disease diagnosis. The patellar reflex has been evaluated with a stretchable capacitive sensor. Strain sensors are a promising solution for real-time monitoring of a variety of human motion signals. A strain sensor can detect finger touching, wrist bending, radial artery pulse, and ulnar artery pulse as shown in Figure 12(a-d) demonstrated by Shi et al. [238]. Figure 12(e) illustrates an e-skin-based ACG-strain sensor for heart cyclic volume or pressure fluctuations [239]. The metal NP-elastomer composite sensor was placed on the fifth intercostal space apex and measured in real time. Figure 12(f, g) compares volunteer ACG signals during rest and exercise. Interestingly, the sensor recorded respiration and ACG. Pre- and post-exercise respiration rates increased from 12 to 26 minutes, respectively. As shown in the figures, deep breathing increased the sensor's signal amplitude during exercise, allowing it to handle greater strains. Zhang et al. [240] reported strain sensors with applications in biomedical such as in soft tissues (Figure 12(h). You et al. [241] reported a sensor with application in limb actuation, hand gesture interpretation, human heart rate monitoring, etc (Figure 12(I)).

Elucidating In vivo sensors, signal drift and long-term biocompatibility are issues for biomedical strain sensors. For instance, despite their superior conductivity, metal nanoparticles (NPs) are still being studied for possible safety and long-term stability in medical applications [242]. Integration of wireless technologies is advancing the functionality of wearable strain sensors, enabling real-time, remote monitoring. For example, Radio Frequency Identification (RFID) technology allow for battery-free, wireless data transmission, making them ideal for continuous health monitoring [243].

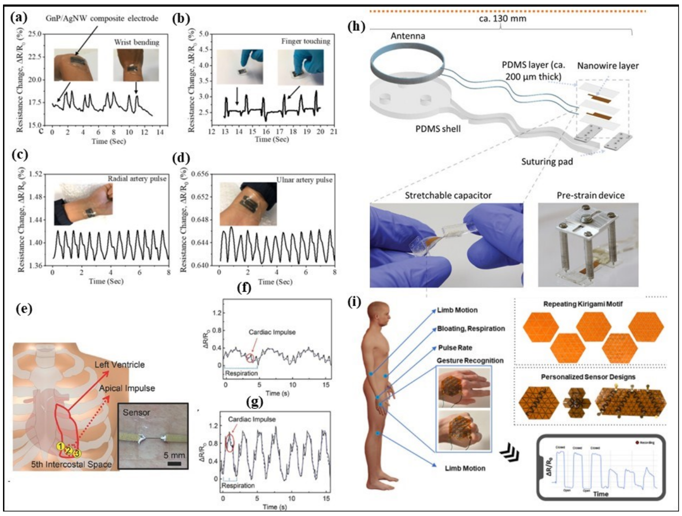

Figure 12. Real-time motion monitoring (a) wrist bending (b) finger contact, (c) radial artery pulse (d) ulnar artery pulse (2019) [238] (e) Schematic illustration of metal NPs–PDMS composite based ACG strain sensor. (f) ACG sensor response of the volunteer in the rest state. (g) ACG sensor response after exercise. Reproduced with permission [239] Copyright © 2016, Wiley-VCH. (h) In vivo monitoring of musculoskeletal soft tissue strain using wireless sensor technologies. Reproduced with permission [240] Copyright © 2023 The Authors. Advanced Materials Technologies published by Wiley-VCH GmbH (i) Examples of strain sensor mounted on different parts of body (2025) [241].

6.2 Sport and Fitness Monitoring

Stretchable, wearable strain sensors can be mounted or adhered in various body parts to assess athletic performance as well as for fitness monitoring. Due to societal pressure, more people are exercising to relax, decompress and gain muscles, maintain themselves. Wearable technology has assisted in goal setting and self-awareness. Acceleration sensors are a common feature of sports wearables that track movement. Heart rate and blood oxygen sensors can monitor the quality of sleep, and algorithms can accurately detect the user's movements if they are carried close. The user can use their own data, analyse the data, and create plans based on the reasonably accurate monitoring data from the smart bracelet and sent to their mobile phone via Bluetooth [91, 244]. Figure 13 (a) illustrates the way wearable graphene-fiber strain sensors assess soccer players' shooting gestures [245]. Players had strain sensors on their knees, ankles, and elbows to monitor their sensory reaction. The strain sensors monitored the whole soccer shot process, providing detailed data for gesture analysis, shown in the figure. Figure 13(b) presents the impressive performance

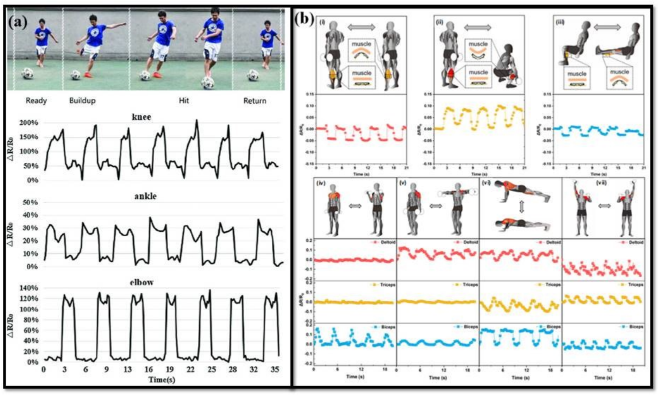

Figure 13. (a) Soccer game pictures during the shooting event, as well as the responses of strain sensors mounted to the ankle, elbow and knee. Reproduced with permission [245] Copyright © 2018, Elsevier. (b) muscle contractions monitoring (during extensions of standing heel lifts, legs and squats) (i-iii) and during standing, the state of biceps, triceps and deltoid (iv-vii) side lateral raise, dumbbell curls, push-ups and shoulder press.(Nature-2021) [240].

metrics of the fiber-junction bending sensor proposed by Li et al. [246]. The calf muscle epidermis sensor can measure and direct epidermis stresses in standing heel lifts, squats, and leg extensions (Figure 13 b (i–iii)). Furthermore, multichannel monitoring of contraction in various muscles is being analysed (Figure 13 b (iv-vii)). Three sensors were placed near the bicep, tricep, and deltoid muscles, and muscular contractions induced by standing dumbbell curls, side lateral raises, push-ups, and shoulder presses were detected simultaneously. In another instance, flexible strain sensors have been attached to the knee joint to observe and monitor varied knee motions, such as walking, running, and jumping from a hunched pose [247]. Stretchable and wearable strain sensors offer improvements in the on-going monitoring of health and fitness, rehabilitation that is compatible with human physiology, and the assessment of athletes' performance in sports [248, 249].

6.3 Human Machine Interface and Soft Robotics

Recent technologies aim to construct intelligence-based, sophisticated interactions between humans and machines. Wearable sensory systems with stretchability, flexibility, and adhesive qualities play a vital role. Smart robots can be controlled by strain sensor signals. Many smart gloves use adhesive, stretchable, and wearable strain sensors [250–252]. Wu et al. [253] reported a strain sensor based on liquid metal for human-machine interface-based applications with an ultralow detection limit, having a wide strain sensing range (105%), low detection limit of 0.05%, little hysteresis, high repeatability, and fast reaction time (58ms). This sensor successfully monitored voice intensity differentiation, blink motion, wrist pulse and heartbeat. In addition, the sensor identified numerous human gestures in smart gloves and knee caps. Figure 14(a,b) demonstrates its capacity to monitor human health and activities, as well as contact between human and machine interfaces and virtual reality applications.

Low-latency strain sensors are critical for delivering real-time control and feedback in human-machine interactions, particularly in robotic applications. Sensors with response rates under 100 milliseconds are critical for ensuring precise, seamless, and timely interaction between humans and machines. This is especially important in applications like implants, surgical robots, and collaborative robotics, where synchronized motion and quick response are required. As a result, optimizing sensor reaction time is an important design issue when building effective human-machine interfaces [254].

Wu et al. [255] work on both strain and pressure sensing capabilities based on piezoresistive strain sensors as human-machine interface, i.e., strain sensor attached to robotic hand as shown in Figure 14(c), pressure sensitivity (0.088kPa-1) with high sustainable strain (70%) and exhibit high gauge factor of 37. Truby et al. [20] work to create soft somatosensitive actuators (SSAs) based on embedded 3D printing with numerous conducting characteristics. A soft robotic gripper (Figure 14(d)) with embedded inflation, curvature, and contact sensors, including fine and deep touch sensors, gives proprioceptive and haptic feedback. Yang et al. [256] address ultra-robust strain sensors for soft robot sensing and autonomy (Figure 14(e)). In a particular research study, to determine the bending angle of the finger joints, strain sensors were carefully attached to the fingers of the gloves. Strain sensors monitored and responded to finger joint bending, varying electrical output. Straightening the finger relaxed the strain sensor, reducing strain and restoring the electrical signal. Soft-bodied robots could use stretchable and flexible strain sensors to send input to feedback controllers and sensory artificial skins to perceive and interact with their surroundings [257, 258]. Additionally, the smart glove wirelessly communicated sensor data to the gripper robot. The robot's actions were controlled by finger movements [259]. When it comes to performing surgical operations or executing intricate and hazardous duties that are beyond the physical capabilities of the human body, the utilization of smart glove systems to remotely supervise slave robots might be advantageous. Smart glove systems with wearable strain sensors have various advantages over conventional systems (cyber gloves) [260].

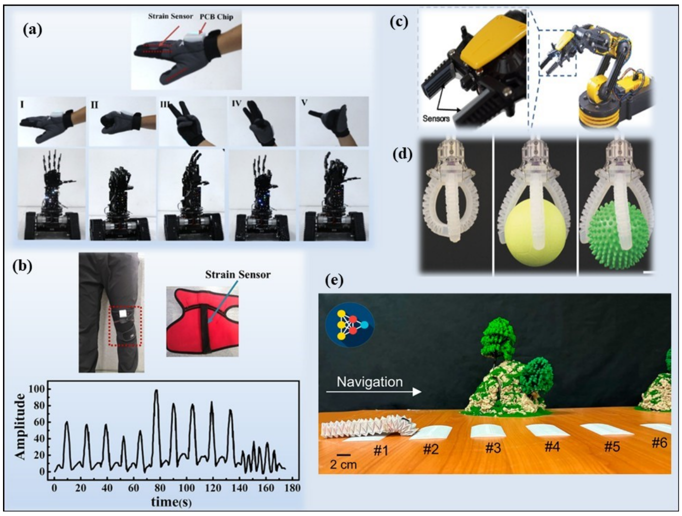

Figure 14. (a) Robotic hand operation (b) Monitoring of the amplitude of human knee motion in real time using sensor (Wiley-VCH-2021) [242] (c) One of the grippers of a robotic hand has a strain sensor connected to its surface. Reproduced with permission [243] Copyright © 2018, Elsevier (d) Soft robotic gripper. Reproduced with permission [75] Copyright © 2018, Wiley-VCH. (e) Robot navigation across a synthetic landscape with different heights. Reproduced with permission [244] Copyright © 2024, Springer Nature.

7 Challenges

Flexibility, sensitivity, and other properties of strain sensors are difficult to design, especially for delicate and soft sensors used in personalized healthcare. Researchers have tried to develop sensors that function in one direction and clusters, but no strain sensor architecture has been identified that can detect decoupled or detached stresses in various planes and directions for large sensor arrays like robot skin sensors. Many strain-based sensors combine pressure and strain sensitivity. Innovative materials and micro/nanostructures are needed for flexible decoupled strain sensors.

When it comes to the development of flexible strain sensors, packaging and integration continue to be important obstacles, particularly when it comes to the interface between soft sensors and stiff electrical components. During repetitive deformation, certain techniques, such as serpentine interconnects [261] and liquid-metal electrodes [262], can assist in accommodating mechanical mismatch, hence improving the material's flexibility and durability.

Flexible stretchable strain sensors are challenging to pack with signal conditioning, processing modules, connectivity, and power. Many methods have been utilized to measure wearable strain sensor data. Standard data-gathering methods coupled flexible sensors to stiff wire with deformable connectors to analyze most sensor responses. Stretchable electrodes with buckle frames, serpentine-shaped structures (winding or spinning one way or the other), non-brittle conductive pastes, or liquid metals might be used as links. Most efforts focused on sensor performance, not packaging and integration. Many articles describe bespoke data management boards manufactured from stiff electronic components-based circuits as compact and portable sensor platforms. Combining solid components and flexible sensors on centimetre-sized boards seems unachievable. A recent study indicated that soft microfluidic assembly for mixing commercial, industrial, and chip-scale circuits, radios, and sensors offers great potential for human body applications. While building such a system is complex and time-consuming, its long-term usefulness is questionable. A recent study describes transmission and flexible energy storage modules that may be directly and effectively incorporated into elastic strain sensors. Not yet possible to combine sensor, power, and communication components into a flexible, small device with high compatibility, dependability, durability, and monitoring consistency. This subject needs more research. Sensors must be attached to the body for accurate strain readings. Falling sensors off the skin due to poor adhesion might disturb strain sensors and miscalculate strain. Strain sensors applied to the skin using micro hair adhesive structures for strong, conformal contact to prevent this phase. Another idea is mechanically flexible strain sensors like human skin.

8 Outlook

Innovations in materials science, nanotechnology, and sensor technologies will significantly enhance the performance of strain sensors. Current research and development endeavors seek to augment the durability, flexibility, and sensitivity of strain sensors to fulfill various application needs. The importance of strain sensors will be augmented by miniaturization and integration with other technologies, including the

Internet of Things (IoT). Health monitoring, structural health monitoring, and wearable technologies require prompt, precise, and high-quality data, which may catalyze improvements in strain sensor design and efficacy. The utilization of strain sensors in medicine holds substantial potential for important breakthroughs. This technology is crucial for the execution of personalized treatment as it allows precise and continuous monitoring of the patient's health status. Strain sensors aid healthcare workers in detecting irregularities, customizing treatment regimens, and enhancing patient outcomes in rehabilitation and chronic illness management. Advancements in materials science, sensor technology, and data analytics might transform healthcare through the integration of strain sensors into medical devices. This innovation can provide proactive and tailored patient care. The importance of strain sensors will increase as companies prioritize efficiency, safety, and performance enhancement. The future concept involves the incorporation of strain sensors into intelligent materials and structures. Strain sensors enable smart materials to adapt to changing environmental circumstances. Strain sensors will improve the optimization and safeguarding of systems across several industries as the use of smart technology and real-time data analytics escalates. The future of strain sensors promises substantial breakthroughs, seamless integration, and disruptive technologies that will positively influence several sectors, including technology, industry, and especially medicine. By utilizing artificial intelligence and machine learning (AI/ML), strain sensing systems of the future may be able to improve their signal interpretation capabilities. As an illustration, machine learning methods can assist in the decoupling of complex multi-axis strain signals [263], which enables more precise and intelligent sensing in settings that are frequently changing.

9 Conclusion

This study highlights strain sensing technology advances in material innovation, performance optimization, and application areas. Nanocomposites, conductive polymers, and hybrid materials have made strain sensors sensitive, flexible, and robust for real-time monitoring. Fitness monitoring and healthcare can benefit from these sensors' precise and continuous data for injury prevention and personalized therapy. However, contemporary technologies still struggle with long-term stability, wireless system integration, performance evaluation standardization, and large-scale, cost-effective production. Addressing these constraints is crucial for future advancement. Therefore, future research should build multifunctional and self-powered sensors, improve energy efficiency, integrate sophisticated data analytics and AI, and stimulate multidisciplinary collaboration to hasten real-world deployment. Strain sensors will alter next-generation smart systems, healthcare, wearable electronics, and engineering.

Data Availability Statement

Not applicable.

Funding

This work was supported by the National Research Program for Universities- NRPU (20-15054/NRPU/R&D/HEC/2021) funded by the Higher Education Commission, Pakistan.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Zhang, X., Chai, J., Zhan, Y., Cui, D., Wang, X., & Gao, L. (2025). Design, Fabrication, and Application of Large-Area Flexible Pressure and Strain Sensor Arrays: A Review. *Micromachines, 16*(3), 330. [CrossRef]

[2] Lv, R., Cao, X., Zhang, T., Ji, W., Muhammad, U., Chen, J., & Wei, Y. (2025). A highly stretchable, self-healing, self-adhesive polyacrylic acid/chitosan multifunctional composite hydrogel for flexible strain sensors. *Carbohydrate Polymers, 351*, 123111. [CrossRef]

[3] Fu, Q., Tang, J., Wang, W., & Wang, R. (2025). Biocomposite polyvinyl alcohol/ferritin hydrogels with enhanced stretchability and conductivity for flexible strain sensors. *Gels, 11*(1), 59. [CrossRef]

[4] Min, S., An, J., Lee, J. H., Kim, J. H., Joe, D. J., Eom, S. H., ... & Lee, K. J. (2025). Wearable blood pressure sensors for cardiovascular monitoring and machine learning algorithms for blood pressure estimation. *Nature Reviews Cardiology*, 1-20. [CrossRef]

[5] Li, X., Huang, X., Yang, L., Jung, S., Wang, J., & Zhao, H. (2025). Implantable physical sensors for in vivo organ monitoring. Med-X, 3(1), 1–32. [CrossRef]

[6] Li, S., Wang, H., Ma, W., Qiu, L., Xia, K., Zhang, Y., ... & Zhang, Y. (2023). Monitoring blood pressure

and cardiac function without positioning via a deep learning–assisted strain sensor array. *Science advances, 9*(32), eadh0615. [CrossRef]

[7] Wu, Z., Zhang, L., Wang, M., Zang, D., Long, H., Weng, L., ... & Xu, B. B. (2025). A wearable ionic hydrogel strain sensor with double cross-linked network for human–machine interface. *Advanced Composites and Hybrid Materials, 8*(1), 17. [CrossRef]

[8] Zhou, L., Zhao, B., Liang, J., Lu, F., Yang, W., Xu, J., ... & Liu, Z. (2024). Low hysteresis, water retention, anti-freeze multifunctional hydrogel strain sensor for human–machine interfacing and real-time sign language translation. *Materials Horizons, 11*(16), 3856-3866. [CrossRef]

[9] Chen, C., Pang, X., Li, Y., & Yu, X. (2024). Ultrafast self-healing, superstretchable, and ultra-strong polymer cluster-based adhesive based on aromatic acid cross-linkers for excellent hydrogel strain sensors. *Small, 20*(19), 2305875. [CrossRef]

[10] Sun, F., Liu, L., Liu, T., Wang, X., Qi, Q., Hang, Z., ... & Fu, J. (2023). Vascular smooth muscle-inspired architecture enables soft yet tough self-healing materials for durable capacitive strain-sensor. *Nature communications, 14*(1), 130. [CrossRef]

[11] Liu, L., Guo, X., Liu, W., & Lee, C. (2021). Recent progress in the energy harvesting technology—from self-powered sensors to self-sustained IoT, and new applications. *Nanomaterials, 11*(11), 2975. [CrossRef]

[12] Khalid, M. A. U., & Chang, S. H. (2022). Flexible strain sensors for wearable applications fabricated using novel functional nanocomposites: A review. *Composite Structures, 284*, 115214. [CrossRef]

[13] Wang, R., Sun, L., Zhu, X., Ge, W., Li, H., Li, Z., ... & Lan, H. (2023). Carbon nanotube-based strain sensors: Structures, fabrication, and applications. *Advanced Materials Technologies, 8*(1), 2200855. [CrossRef]

[14] Choi, Y. K., Park, T., Lee, D. H. D., Ahn, J., Kim, Y. H., Jeon, S., ... & Oh, S. J. (2022). Wearable anti-temperature interference strain sensor with metal nanoparticle thin film and hybrid ligand exchange. *Nanoscale, 14*(24), 8628-8639. [CrossRef]

[15] Gu, X., Sun, J., Yuan, Y., Tian, X., Ding, Y., & Qin, W. (2025). Flexible, stretchable MXene/polydopamine@ Natural rubber-based strain sensor with core-shell structures. *Sensors and Actuators A: Physical, 386*, 116350. [CrossRef]

[16] Dang, X., Fu, Y., & Wang, X. (2024). A temperature and pressure dual-responsive, stretchable, healable, adhesive, and biocompatible carboxymethyl cellulose-based conductive hydrogels for flexible wearable strain sensor. *Biosensors and Bioelectronics, 246*, 115893. [CrossRef]

[17] Lee, J. H., Bae, J. Y., Kim, Y. N., Chae, M., Lee, W. J., Lee, J., ... & Kang, S. K. (2024). A Fully Biodegradable and Ultra-Sensitive Crack-Based Strain Sensor for Biomechanical Signal Monitoring. *Advanced Functional Materials, 34*(41), 2406035. [CrossRef]

[18] Ding, H., Liu, J., Wang, B., Yang, X., Yin, B., Liang, T., ... & Shen, X. (2025). Tough and recyclable polyvinyl alcohol/carboxymethyl chitosan hydrogels with high strength, low modulus and fast self-recovery as flexible strain sensors. *International Journal of Biological Macromolecules*, 143430. [CrossRef]

[19] Yao, W., Lin, X., Zhang, Z., Sun, Q., & Yang, H. (2024). Pursuing superhydrophobic flexible strain sensors: From design to applications. *Advanced Materials Technologies, 9*(9), 2301983. [CrossRef]

[20] Truby, R. L., Wehner, M., Grosskopf, A. K., Vogt, D. M., Uzel, S. G., Wood, R. J., & Lewis, J. A. (2018). Soft somatosensitive actuators via embedded 3D printing. *Advanced materials, 30*(15), 1706383. [CrossRef]

[21] Furqan, C. M., Khan, M. U., Awais, M., Jiang, F., Bae, J., Hassan, A., & Kwok, H. S. (2021). Humidity sensor based on Gallium Nitride for real time monitoring applications. *Scientific reports, 11*(1), 11088. [CrossRef]

[22] Yu, Y., Nassar, J., Xu, C., Min, J., Yang, Y., Dai, A., ... & Gao, W. (2020). Biofuel-powered soft electronic skin with multiplexed and wireless sensing for human-machine interfaces. *Science robotics, 5*(41), eaaz7946. [CrossRef]

[23] Cao, M., Leng, M., Pan, W., Wang, Y., Tan, S., Jiao, Y., ... & Su, J. (2023). 3D wearable piezoresistive sensor with waterproof and antibacterial activity for multimodal smart sensing. *Nano Energy, 112*, 108492. [CrossRef]

[24] Zang, Y., Zhang, F., Di, C. A., & Zhu, D. (2015). Advances of flexible pressure sensors toward artificial intelligence and health care applications. *Materials Horizons, 2*(2), 140-156. [CrossRef]

[25] Zhou, X., Zhao, X., Wang, Y., Wang, P., Jiang, X., Song, Z., ... & Xu, W. (2023). Gel-based strain/pressure sensors for underwater sensing: Sensing mechanisms, design strategies and applications. *Composites Part B: Engineering, 255*, 110631. [CrossRef]

[26] Kim, Y., & Oh, J. H. (2020). Recent progress in pressure sensors for wearable electronics: From design to applications. *Applied Sciences, 10*(18), 6403. [CrossRef]

[27] Khoshnoud, F., & De Silva, C. W. (2012). Recent advances in MEMS sensor technology-mechanical applications. *IEEE Instrumentation & Measurement Magazine, 15*(2), 14-24. [CrossRef]

[28] Wang, D., Ma, G., Zhang, X., Zheng, K., Zhang, J., Ma, Z., ... & Ren, L. (2025). Flexible Pressure Sensor Composed of Multi-Layer Textile Materials for Human–Machine Interaction Applications. *ACS sensors, 10*(1), 350-359. [CrossRef]

[29] Han, R., Liu, Y., Mo, Y., Xu, H., Yang, Z., Bao, R., &

Pan, C. (2023). High anti-jamming flexible capacitive pressure sensors based on core–shell structured AgNWs@ TiO2. *Advanced Functional Materials, 33*(51), 2305531. [CrossRef]

[30] Lv, C., Tian, C., Jiang, J., Dang, Y., Liu, Y., Duan, X., ... & Xie, M. (2023). Ultrasensitive linear capacitive pressure sensor with wrinkled microstructures for tactile perception. *Advanced Science, 10*(14), 2206807. [CrossRef]

[31] Wang, Q., Li, Y., Xu, Q., Yu, H., Zhang, D., Zhou, Q., ... & Yao, Z. (2023). Finger–coding intelligent human–machine interaction system based on all–fabric ionic capacitive pressure sensors. *Nano Energy, 116*, 108783. [CrossRef]

[32] Yao, H., Yu, Z., Huang, F., Pan, T., Tang, C., & Zhang, H. (2023). A flexible piezoresistive pressure sensor comprising a microstructure printed with poly (3, 4-ethylenedioxythiophene): poly (styrenesulfonate) copolymers@ graphene hybrid ink. *Journal of Materials Chemistry C, 11*(39), 13324-13334. [CrossRef]

[33] Cao, W., Luo, Y., Dai, Y., Wang, X., Wu, K., Lin, H., ... & Zhu, J. (2023). Piezoresistive pressure sensor based on a conductive 3D sponge network for motion sensing and human–machine interface. *ACS Applied Materials & Interfaces, 15*(2), 3131-3140. [CrossRef]

[34] Su, X., Wu, X., Chen, S., Nedumaran, A. M., Stephen, M., Hou, K., ... & Leong, W. L. (2022). A highly conducting polymer for self-healable, printable, and stretchable organic electrochemical transistor arrays and near hysteresis-free soft tactile sensors. *Advanced Materials, 34*(19), 2200682. [CrossRef]

[35] He, T., Shi, Q., Wang, H., Wen, F., Chen, T., Ouyang, J., & Lee, C. (2019). Beyond energy harvesting-multi-functional triboelectric nanosensors on a textile. Nano Energy, 57, 338-352. [CrossRef]

[36] Korotcenkov, G. (2019). *Handbook of humidity measurement, volume 2: Electronic and electrical humidity sensors*. CRC Press.

[37] Kumar, A., Gupta, G., Bapna, K., & Shivagan, D. D. (2023). Semiconductor-metal-oxide-based nano-composites for humidity sensing applications. *Materials Research Bulletin, 158*, 112053. [CrossRef]

[38] Aggarwal, A., Dautta, M., Ayala-Cardona, L. F., Wudaru, A., & Javey, A. (2023). Wearable humidity sensor for continuous sweat rate monitoring. *Advanced Materials Technologies, 8*(17), 2300385. [CrossRef]

[39] Lee, C. Y., & Lee, G. B. (2005). Humidity sensors: A review. *Sensor Letters, 3*(1-2), 1-2. [CrossRef]

[40] Zhou, C., Zhang, X., Tang, N., Fang, Y., Zhang, H., & Duan, X. (2020). Rapid response flexible humidity sensor for respiration monitoring using nano-confined strategy. *Nanotechnology, 31*(12), 125302. [CrossRef]

[41] Fernandes, L. C., Correia, D. M., Pereira, N., Tubio, C. R., & Lanceros-Mendez, S. (2019). Highly sensitive humidity sensor based on ionic liquid–polymer composites. *ACS Applied Polymer Materials, 1*(10), 2723-2730. [CrossRef]

[42] Parthasarathy, P. (2023). Graphene/polypyrrole/carbon black nanocomposite material ink-based screen-printed low-cost, flexible humidity sensor. *Emergent Materials, 6*(6), 2053-2060. [CrossRef]

[43] Liu, X., Wang, L., Lei, Y., Li, X., Cheng, C., Yang, L., ... & Cheng, B. (2025). Highly sensitivity and wide-range flexible humidity sensor based on LiCl/cellulose nanofiber membrane by one-step electrospinning. Chemical Engineering Journal, 503, 158018. [CrossRef]

[44] Lu, J., Xu, X., Zhang, H. W., Huang, M. L., Wang, Y. S., Feng, Z. S., & Wang, Y. (2025). All-printed MXene/WS2-based flexible humidity sensor for multi-scenario applications. *Sensors and Actuators B: Chemical, 422*, 136605. [CrossRef]

[45] Yao, S., Swetha, P., & Zhu, Y. (2018). Nanomaterial-enabled wearable sensors for healthcare. *Advanced healthcare materials, 7*(1), 1700889. [CrossRef]

[46] Chen, Y., Lu, B., Chen, Y., & Feng, X. (2015). Breathable and stretchable temperature sensors inspired by skin. *Scientific reports, 5*(1), 11505. [CrossRef]

[47] Descent, P., Izquierdo, R., & Fayomi, C. (2018, May). Printing of temperature and humidity sensors on flexible substrates for biomedical applications. In *2018 IEEE international symposium on circuits and systems (ISCAS)* (pp. 1-4). IEEE. [CrossRef]

[48] Blasdel, N. J., Wujcik, E. K., Carletta, J. E., Lee, K. S., & Monty, C. N. (2014). Fabric nanocomposite resistance temperature detector. *IEEE Sensors Journal, 15*(1), 300-306. [CrossRef]

[49] Kuzubasoglu, B. A., & Bahadir, S. K. (2020). Flexible temperature sensors: A review. *Sensors and Actuators A: Physical, 315*, 112282. [CrossRef]

[50] Li, M., Chen, J., Zhong, W., Luo, M., Wang, W., Qing, X., ... & Wang, D. (2020). Large-area, wearable, self-powered pressure–temperature sensor based on 3D thermoelectric spacer fabric. *ACS sensors, 5*(8), 2545-2554. [CrossRef]

[51] Sultana, A., Alam, M. M., Middya, T. R., & Mandal, D. (2018). A pyroelectric generator as a self-powered temperature sensor for sustainable thermal energy harvesting from waste heat and human body heat. *Applied Energy, 221*, 299-307. [CrossRef]

[52] Majumder, S., Mondal, T., & Deen, M. J. (2017). Wearable sensors for remote health monitoring. *Sensors, 17*(1), 130. [CrossRef]

[53] Prajapati, H., & Deshmukh, N. N. (2019). Design and development of thin wire sensor for transient

temperature measurement. *Measurement, 140*, 582-589. [CrossRef]

[54] Huang, L., Zhang, H., Leng, S., Li, M., & Li, Z. (2023). Electrical properties of NiO-based composite ceramics modified by La2 M O4 (M= Cu or Ni) for NTC thermistors. *Journal of Materials Science: Materials in Electronics, 34*(14), 1137. [CrossRef]

[55] Wang, P., Yu, W., Li, G., Meng, C., & Guo, S. (2023). Printable, flexible, breathable and sweatproof bifunctional sensors based on an all-nanofiber platform for fully decoupled pressure–temperature sensing application. *Chemical Engineering Journal, 452*, 139174. [CrossRef]

[56] Zhao, R., Shao, G., Cao, Y., An, L., & Xu, C. (2014). Temperature sensor made of polymer-derived ceramics for high-temperature applications. *Sensors and Actuators A: Physical, 219*, 58-64. [CrossRef]

[57] Li, F., Lin, X., Xue, H., Wang, J., Li, J., Fei, T., ... & Zhang, T. (2024). Ultrasensitive Flexible Temperature Sensors Based on Thermal-Mediated Ions Migration Dynamics in Asymmetrical Polymer Bilayers. *ACS nano, 18*(10), 7521-7531. [CrossRef]

[58] Lu, Y., Zhang, H., Zhao, Y., Liu, H., Nie, Z., Xu, F., ... & Huang, W. (2024). Robust fiber-shaped flexible temperature sensors for safety monitoring with ultrahigh sensitivity. *Advanced Materials, 36*(18), 2310613. [CrossRef]

[59] Zhang, J., Yan, K., Huang, J., Sun, X., Li, J., Cheng, Y., ... & Pan, L. (2024). Mechanically robust, flexible, fast responding temperature sensor and high-resolution array with ionically conductive double cross-linked hydrogel. *Advanced Functional Materials, 34*(21), 2314433. [CrossRef]

[60] Zhang, Z., Li, Q., Xu, L., Tian, W., & Li, Z. (2024). High-performance flexible temperature sensors based on laser-irradiated Ag-MWCNTs/PEDOT: PSS. *ACS Applied Materials & Interfaces, 16*(5), 6078-6087. [CrossRef]

[61] Liu, S., Shuai, L., Zhu, Q., Cao, L., Gu, F., Fan, L., & Xiong, S. (2025). All-aerosol-jet-printed Fe3+ modified bilayers polyaniline flexible room temperature sensor with enhanced ammonia sensing properties. *Talanta, 287*, 127684. [CrossRef]

[62] Ben Atitallah, B., Rajendran, D., Hu, Z., Ramalingame, R., Quijano Jose, R. B., da Veiga Torres, R., ... & Kanoun, O. (2021). Piezo-resistive pressure and strain sensors for biomedical and tele-manipulation applications. *Advanced Sensors for Biomedical Applications*, 47-65. [CrossRef]

[63] Kannichankandy, D., Pataniya, P. M., Narayan, S., Patel, V., Sumesh, C. K., Patel, K. D., ... & Pathak, V. M. (2021). Flexible piezo-resistive pressure sensor based on conducting PANI on paper substrate. *Synthetic Metals, 273*, 116697. [CrossRef]

[64] Jheng, W. W., Su, Y. S., Hsieh, Y. L., Lin, Y. J., Tzeng, S. D., Chang, C. W., ... & Kuo, W. (2021). Gold nanoparticle thin film-based strain sensors for monitoring human pulse. *ACS Applied Nano Materials, 4*(2), 1712-1718. [CrossRef]

[65] Mokhtari, F., Cheng, Z., Raad, R., Xi, J., & Foroughi, J. (2020). Piezofibers to smart textiles: A review on recent advances and future outlook for wearable technology. *Journal of Materials Chemistry A, 8*(19), 9496-9522. [CrossRef]

[66] Huang, Y., Zhang, J., Pu, J., Guo, X., Qiu, J., Ma, Y., ... & Yang, X. (2018). Resistive pressure sensor for high-sensitivity e-skin based on porous sponge dip-coated CB/MWCNTs/SR conductive composites. *Materials Research Express, 5*(6), 065701. [CrossRef]

[67] Gong, S., Lai, D. T., Wang, Y., Yap, L. W., Si, K. J., Shi, Q., ... & Cheng, W. (2015). Tattoolike polyaniline microparticle-doped gold nanowire patches as highly durable wearable sensors. *ACS applied materials & interfaces, 7*(35), 19700-19708. [CrossRef]

[68] Cao, M., Su, J., Fan, S., Qiu, H., Su, D., & Li, L. (2021). Wearable piezoresistive pressure sensors based on 3D graphene. *Chemical Engineering Journal, 406*, 126777. [CrossRef]

[69] Li, Q., Liu, Y., Chen, D., Miao, J., Lin, S., & Cui, D. (2021). Highly sensitive and flexible piezoresistive pressure sensors based on 3D reduced graphene oxide aerogel. *IEEE Electron Device Letters, 42*(4), 589-592. [CrossRef]

[70] Wu, J., Wang, H., Su, Z., Zhang, M., Hu, X., Wang, Y., ... & Xing, S. G. (2017). Highly flexible and sensitive wearable E-skin based on graphite nanoplatelet and polyurethane nanocomposite films in mass industry production available. *ACS applied materials & interfaces, 9*(44), 38745-38754. [CrossRef]

[71] Shin, Y. E., Sohn, S. D., Han, H., Park, Y., Shin, H. J., & Ko, H. (2020). Self-powered triboelectric/pyroelectric multimodal sensors with enhanced performances and decoupled multiple stimuli. *Nano Energy, 72*, 104671. [CrossRef]

[72] Pu, X., An, S., Tang, Q., Guo, H., & Hu, C. (2021). Wearable triboelectric sensors for biomedical monitoring and human-machine interface. *Iscience, 24*(1). [CrossRef]

[73] Luo, J., Gao, W., & Wang, Z. L. (2021). The triboelectric nanogenerator as an innovative technology toward intelligent sports. *Advanced materials, 33*(17), 2004178. [CrossRef]

[74] Jiang, X. Z., Sun, Y. J., Fan, Z., & Zhang, T. Y. (2016). Integrated flexible, waterproof, transparent, and self-powered tactile sensing panel. *ACS nano, 10*(8), 7696-7704. [CrossRef]

[75] Wang, Z., Sun, S., Li, N., Yao, T., & Lv, D. (2020). Triboelectric self-powered three-dimensional tactile sensor. *IEEE Access, 8*, 172076-172085. [CrossRef]

[76] Wang, X., Dong, L., Zhang, H., Yu, R., Pan, C., & Wang, Z. L. (2015). Recent progress in electronic skin. *Advanced Science, 2*(10), 1500169. [CrossRef]

[77] Chen, H., Song, Y., Cheng, X., & Zhang, H. (2019). Self-powered electronic skin based on the triboelectric generator. *Nano energy, 56*, 252-268. [CrossRef]

[78] Xu, Z., Wang, Z., Wang, J., Li, K., Liu, Y., Ji, X., ... & Zhang, D. (2025). A multi-indicator pulse monitoring system based on an ultra-sensitive and stable self-powered wearable triboelectric sensor with assistance of personalized deep learning. *Nano Energy*, 111039. [CrossRef]

[79] Chen, X., Peng, X., Wei, C., Wang, Z., He, J., Sheng, H., ... & Dong, K. (2025). A Moisture-Proof, Anti-Fouling, and Low Signal Attenuation All-Nanofiber Triboelectric Sensor for Self-Powered Respiratory Health Monitoring. *Advanced Functional Materials, 35*(7), 2415421. [CrossRef]

[80] Yang, J., Hong, K., Hao, Y., Zhu, X., Su, J., Su, W., ... & Li, X. (2024). Mica/nylon composite nanofiber film based wearable triboelectric sensor for object recognition. *Nano Energy, 129*, 110056. [CrossRef]

[81] Rivadeneyra, A., Marin-Sanchez, A., Wicklein, B., Salmeron, J. F., Castillo, E., Bobinger, M., & Salinas-Castillo, A. (2021). Cellulose nanofibers as substrate for flexible and biodegradable moisture sensors. *Composites Science and Technology, 208*, 108738. [CrossRef]

[82] Yang, J., Wang, M., Meng, Y., Niu, Z., Hao, Y., Liu, H., ... & Li, X. (2024). High-performance flexible wearable triboelectric nanogenerator sensor by β-phase polyvinylidene fluoride polarization. *ACS Applied Electronic Materials, 6*(2), 1385-1395. [CrossRef]

[83] Liu, P., Pan, W., Liu, Y., Liu, J., Xu, W., Guo, X., ... & Huang, Y. (2018). Fully flexible strain sensor from core-spun elastic threads with integrated electrode and sensing cell based on conductive nanocomposite. *Composites Science and Technology, 159*, 42-49. [CrossRef]

[84] Cai, Y., Shen, J., Ge, G., Zhang, Y., Jin, W., Huang, W., ... & Dong, X. (2018). Stretchable Ti3C2T x MXene/carbon nanotube composite based strain sensor with ultrahigh sensitivity and tunable sensing range. *ACS nano, 12*(1), 56-62. [CrossRef]

[85] Qiu, A., Li, P., Yang, Z., Yao, Y., Lee, I., & Ma, J. (2019). A path beyond metal and silicon: polymer/nanomaterial composites for stretchable strain sensors. *Advanced Functional Materials, 29*(17), 1806306. [CrossRef]

[86] Han, S. T., Peng, H., Sun, Q., Venkatesh, S., Chung, K. S., Lau, S. C., ... & Roy, V. A. L. (2017). An overview of the development of flexible sensors. *Advanced materials, 29*(33), 1700375. [CrossRef]

[87] Han, F., Li, M., Ye, H., & Zhang, G. (2021). Materials, electrical performance, mechanisms, applications, and manufacturing approaches for flexible strain sensors. *Nanomaterials, 11*(5), 1220. [CrossRef]

[88] Zhou, K., Dai, K., Liu, C., & Shen, C. (2020). Flexible conductive polymer composites for smart wearable strain sensors. *SmartMat, 1*(1), e1010. [CrossRef]

[89] Her, S. C., & Liang, Y. M. (2022). Carbon-based nanomaterials thin film deposited on a flexible substrate for strain sensing application. *Sensors, 22*(13), 5039. [CrossRef]

[90] Stoppa, M., & Chiolerio, A. (2014). Wearable electronics and smart textiles: A critical review. *sensors, 14*(7), 11957-11992. [CrossRef]

[91] 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), 1678-1698. [CrossRef]

[92] Liu, X., Tang, C., Du, X., Xiong, S., Xi, S., Liu, Y., ... & Kim, J. K. (2017). A highly sensitive graphene woven fabric strain sensor for wearable wireless musical instruments. *Materials Horizons, 4*(3), 477-486. [CrossRef]

[93] Huang, L., Huang, X., Bu, X., Wang, S., & Zhang, P. (2023). Flexible strain sensor based on PU film with three-dimensional porous network. *Sensors and Actuators A: Physical, 359*, 114508. [CrossRef]

[94] Zhang, X., Sun, H., Zhang, J., & Wang, Z. (2025). A highly sensitive and stable MXene/bacterial cellulose double network hydrogel flexible strain sensor for human activities monitoring. *Journal of Applied Polymer Science, 142*(6), e56468. [CrossRef]

[95] Wang, Z., Cong, Y., & Fu, J. (2020). Stretchable and tough conductive hydrogels for flexible pressure and strain sensors. *Journal of Materials Chemistry B, 8*(16), 3437-3459. [CrossRef]

[96] Zhao, Z., Li, X., Yan, S., Tian, K., Wang, X., Zhao, H., ... & Wang, P. (2024). Sensitivity-enhanced strain sensor based on a shape-modulated multimode fiber. *Optics Letters, 49*(5), 1329-1332. [CrossRef]

[97] Li, H., Tan, Z., Yuan, L., Li, J., Chen, X., Ji, D., ... & Li, L. (2021). Eggshell-inspired membrane—shell strategy for simultaneously improving the sensitivity and detection range of strain sensors. *Science China Materials, 64*(3), 717-726. [CrossRef]

[98] 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. [CrossRef]

[99] Tao, X. Y., Zhu, K. H., Chen, H. M., Ye, S. F., Cui, P. X., Dou, L. Y., ... & Feng, P. Z. (2023). Recyclable, anti-freezing and anti-drying silk fibroin-based hydrogels for ultrasensitive strain sensors and all-hydrogel-state super-capacitors. *Materials Today Chemistry, 32*, 101624. [CrossRef]

[100] Shi, X., Liu, S., Sun, Y., Liang, J., & Chen, Y. (2018). Lowering internal friction of 0D–1D–2D ternary nanocomposite-based strain sensor by fullerene to

boost the sensing performance. *Advanced Functional Materials, 28*(22), 1800850. [CrossRef]

[101] Wang, Z., Bi, P., Yang, Y., Ma, H., Lan, Y., Sun, X., ... & Xiong, R. (2021). Star-nose-inspired multi-mode sensor for anisotropic motion monitoring. *Nano Energy, 80*, 105559. [CrossRef]

[102] Huang, T., He, P., Wang, R., Yang, S., Sun, J., Xie, X., & Ding, G. (2019). Porous fibers composed of polymer nanoball decorated graphene for wearable and highly sensitive strain sensors. *Advanced Functional Materials, 29*(45), 1903732. [CrossRef]

[103] Yang, Z., Li, H., Zhang, L., Lai, X., & Zeng, X. (2020). Highly stretchable, transparent and room-temperature self-healable polydimethylsiloxane elastomer for bending sensor. *Journal of colloid and interface science, 570*, 1-10. [CrossRef]

[104] Qi, M., Yang, R., Wang, Z., Liu, Y., Zhang, Q., He, B., ... & Chen, M. (2023). Bioinspired self-healing soft electronics. *Advanced Functional Materials, 33*(17), 2214479. [CrossRef]

[105] Benight, S. J., Wang, C., Tok, J. B., & Bao, Z. (2013). Stretchable and self-healing polymers and devices for electronic skin. *Progress in Polymer Science, 38*(12), 1961-1977. [CrossRef]

[106] Wang, Y., & Zhang, X. (2023). Self-Healing Stress Sensors: Coupling Stress-Sensing Performance with Dynamic Chemistry. *Advanced Sensor Research, 2*(8), 2200093. [CrossRef]

[107] Su, G., Yin, S., Guo, Y., Zhao, F., Guo, Q., Zhang, X., ... & Yu, G. (2021). Balancing the mechanical, electronic, and self-healing properties in conductive self-healing hydrogel for wearable sensor applications. *Materials Horizons, 8*(6), 1795-1804. [CrossRef]

[108] Lu, Y., Liu, Z., Yan, H., Peng, Q., Wang, R., Barkey, M. E., ... & Wujcik, E. K. (2019). Ultrastretchable conductive polymer complex as a strain sensor with a repeatable autonomous self-healing ability. *ACS applied materials & interfaces, 11*(22), 20453-20464. [CrossRef]

[109] Priyadarsini, M., Sahoo, D. R., & Biswal, T. (2021). A new generation self-healing composite materials. *Materials Today: Proceedings, 47*, 1229–1233. [CrossRef]

[110] Chen, D., Wang, D., Yang, Y., Huang, Q., Zhu, S., & Zheng, Z. (2017). Self-healing materials for next-generation energy harvesting and storage devices. *Advanced Energy Materials, 7*(23), 1700890. [CrossRef]

[111] Zhang, J., Wang, Y., Wei, Q., Wang, Y., Lei, M., Li, M., ... & Wu, Y. (2021). Self-healing mechanism and conductivity of the hydrogel flexible sensors: A review. *Gels, 7*(4), 216. [CrossRef]

[112] Li, Q., Liu, C., Wen, J., Wu, Y., Shan, Y., & Liao, J. (2017). The design, mechanism and biomedical application of self-healing hydrogels. *Chinese Chemical Letters, 28*(9), 1857-1874. [CrossRef]

[113] Wang, J., Tang, J., Chen, D., Xing, S., Liu, X., & Hao, J. (2023). Intrinsic and extrinsic self-healing fiber-reinforced polymer composites: a review. *Polymer Composites, 44*(10), 6304-6323. [CrossRef]

[114] Yang, Y., Ding, X., & Urban, M. W. (2015). Chemical and physical aspects of self-healing materials. *Progress in Polymer Science, 49*, 34-59. [CrossRef]

[115] Dai, X., Huang, L. B., Du, Y., Han, J., & Kong, J. (2021). Self-healing flexible strain sensors based on dynamically cross-linked conductive nanocomposites. *Composites Communications, 24*, 100654. [CrossRef]

[116] Hang, C. Z., Zhao, X. F., Xi, S. Y., Shang, Y. H., Yuan, K. P., Yang, F., ... & Lu, H. L. (2020). Highly stretchable and self-healing strain sensors for motion detection in wireless human-machine interface. *Nano Energy, 76*, 105064. [CrossRef]

[117] Zhang, L. M., He, Y., Cheng, S., Sheng, H., Dai, K., Zheng, W. J., ... & Suo, Z. (2019). Self-healing, adhesive, and highly stretchable ionogel as a strain sensor for extremely large deformation. *Small, 15*(21), 1804651. [CrossRef]

[118] Ling, Q., Fan, X., Ling, M., Liu, J., Zhao, L., & Gu, H. (2023). Collagen-based organohydrogel strain sensor with self-healing and adhesive properties for detecting human motion. *ACS Applied Materials & Interfaces, 15*(9), 12350-12362. [CrossRef]

[119] Yang, G., Luo, H., Ding, Y., Yang, J., Li, Y., Ma, C., ... & Zhuang, X. (2023). Hierarchically structured carbon nanofiber-enabled skin-like strain sensors with full-range human motion monitoring and autonomous self-healing capability. *ACS Applied Materials & Interfaces, 15*(5), 7380-7391. [CrossRef]

[120] Zhao, R., Gao, M., Zhao, Z., & Song, S. (2024). Ultra-stretchable, high conductive, fatigue resistance, and self-healing strain sensor based on mussel-inspired adhesive hydrogel for human motion monitoring. *European Polymer Journal, 211*, 113024. [CrossRef]

[121] Ke, T., Zhao, L., Fan, X., & Gu, H. (2023). Rapid self-healing, self-adhesive, anti-freezing, moisturizing, antibacterial and multi-stimuli-responsive PVA/starch/tea polyphenol-based composite conductive organohydrogel as flexible strain sensor. *Journal of Materials Science & Technology, 135*, 199-212. [CrossRef]

[122] Cong, C., Wang, R., Zhu, W., Zheng, X., Sun, F., Wang, X., ... & Li, X. (2025). Self-powered strain sensing devices with wireless transmission: DIW-printed conductive hydrogel electrodes featuring stretchable and self-healing properties. *Journal of Colloid and Interface Science, 678*, 588-598. [CrossRef]

[123] Wu, Z., Rong, L., Yang, J., Wei, Y., Tao, K., Zhou, Y., ... & Wu, J. (2021). Ion-conductive hydrogel-based

stretchable, self-healing, and transparent NO2 sensor with high sensitivity and selectivity at room temperature. *Small*, *17*(52), 2104997. [CrossRef]

[124] Zhang, Q., Liu, X., Duan, L., & Gao, G. (2020). Nucleotide-driven skin-attachable hydrogels toward visual human–machine interfaces. *Journal of Materials Chemistry A*, *8*(8), 4515-4523. [CrossRef]

[125] Kirang, A., Hikmaturokhman, A., & Ni'amah, K. (2023). 5G NR Network Planning Analysis using 700 Mhz and 2.3 Ghz Frequency in The Jababeka Industrial Area. *Journal of Informatics and Telecommunication Engineering*, *6*(2), 403-413. [CrossRef]

[126] Zhao, L., Ren, Z., Liu, X., Ling, Q., Li, Z., & Gu, H. (2021). A multifunctional, self-healing, self-adhesive, and conductive sodium alginate/poly (vinyl alcohol) composite hydrogel as a flexible strain sensor. *ACS Applied Materials & Interfaces*, *13*(9), 11344-11355. [CrossRef]

[127] Zhang, Y., Liu, H., Wang, P., Yu, Y., Zhou, M., Xu, B., ... & Wang, Q. (2023). Stretchable, transparent, self-adhesive, anti-freezing and ionic conductive nanocomposite hydrogels for flexible strain sensors. *European Polymer Journal*, *186*, 111824. [CrossRef]

[128] Yamada, T., Hayamizu, Y., Yamamoto, Y., Yomogida, Y., Izadi-Najafabadi, A., Futaba, D. N., & Hata, K. (2011). A stretchable carbon nanotube strain sensor for human-motion detection. *Nature nanotechnology*, *6*(5), 296-301. [CrossRef]

[129] Cai, L., Song, L., Luan, P., Zhang, Q., Zhang, N., Gao, Q., ... & Xie, S. (2013). Super-stretchable, transparent carbon nanotube-based capacitive strain sensors for human motion detection. *Scientific reports*, *3*(1), 3048. [CrossRef]

[130] Souri, H., & Bhattacharyya, D. (2018). Highly sensitive, stretchable and wearable strain sensors using fragmented conductive cotton fabric. *Journal of Materials Chemistry C*, *6*(39), 10524-10531. [CrossRef]

[131] Xu, L., Liu, Z., Zhai, H., Chen, X., Sun, R., Lyu, S., ... & Ye, T. T. (2020). Moisture-resilient graphene-dyed wool fabric for strain sensing. *ACS applied materials & interfaces*, *12*(11), 13265-13274. [CrossRef]

[132] Zhang, M., Wang, C., Wang, H., Jian, M., Hao, X., & Zhang, Y. (2017). Carbonized cotton fabric for high-performance wearable strain sensors. *Advanced Functional Materials*, *27*(2), 1604795. [CrossRef]

[133] Wang, C., Zhang, M., Xia, K., Gong, X., Wang, H., Yin, Z., ... & Zhang, Y. (2017). Intrinsically stretchable and conductive textile by a scalable process for elastic wearable electronics. *ACS Applied Materials & Interfaces*, *9*(15), 13331-13338. [CrossRef]

[134] Hwangbo, Y., Nam, H. J., & Choa, S. H. (2023). Highly stretchable strain sensor with a high and broad sensitivity composed of carbon nanotube and EcoFlex composite. *Korean Journal of Metals and Materials*, *61*(7), 500-508. [CrossRef]

[135] Long, W., Yao, Y., Ye, Y., Zhang, C., Xu, J., Zhong, D., ... & Xia, L. (2025). Flexible strain sensor based on carbonized corn stalk with three-dimensional network. *Industrial Crops and Products*, *225*, 120496. [CrossRef]

[136] Pei, L., He, L., Yang, Z., & Li, R. (2025). Highly Flexible and Stretchable TPU/PDA/MWCNTs/GO Flexible Strain Sensors for Human Motion Detection. *Fibers and Polymers*, 1-11. [CrossRef]

[137] Meena, J. S., Xiang, L. L. Y., & Lim, Y. K. (2025). Highly Stretchable, Sensitive, and Robust Wearable Strain Sensor Based on CNTs/AgNWs Nanocomposite for Health and Fitness Monitoring. *IEEE Sensors Letters*. [CrossRef]

[138] Zheng, Y., Cui, T., Wang, J., Chen, Y., Ou, M., He, H., ... & Gui, Z. (2025). Highly stretchable, low-hysteresis, and robust polymeric gels enabled by solvent engineering for wireless sensing and encrypted communication. *Chemical Engineering Journal*, 163610. [CrossRef]

[139] Hassan, H., Khan, M., Shah, L. A., & Yoo, H. M. (2025). CNC-mediated functionalized MWCNT-reinforced double-network conductive hydrogels as smart, flexible strain and epidermic sensors for human motion monitoring. *Journal of Materials Chemistry B*, *13*(16), 4796-4808. [CrossRef]

[140] Xiang, D., Chen, X., Li, J., Wu, Y., Zhao, C., Li, H., ... & Wang, J. (2023). Flexible strain sensors with high sensitivity and large working range prepared from biaxially stretched carbon nanotubes/polyolefin elastomer nanocomposites. *Journal of Applied Polymer Science*, *140*(4), e53371. [CrossRef]

[141] Escobedo, P., Bhattacharjee, M., Nikbakhtnasrabadi, F., & Dahiya, R. (2020). Smart bandage with wireless strain and temperature sensors and batteryless NFC tag. *IEEE Internet of Things Journal*, *8*(6), 5093-5100. [CrossRef]

[142] Karipoth, P., Christou, A., Pullanchiyodan, A., & Dahiya, R. (2022). Bioinspired inchworm-and earthworm-like soft robots with intrinsic strain sensing. *Advanced Intelligent Systems*, *4*(2), 2100092. [CrossRef]

[143] Duan, L., D'hooge, D. R., & Cardon, L. (2020). Recent progress on flexible and stretchable piezoresistive strain sensors: From design to application. *Progress in Materials Science*, *114*, 100617. [CrossRef]

[144] Yang, G., Liu, L., & Wu, Z. (2019). Improved strain sensing capability of nano-carbon free-standing buckypapers based strain gauges. *Smart Materials and Structures*, *28*(6), 065009. [CrossRef]

[145] Amjadi, M., Pichitpajongkit, A., Lee, S., Ryu, S., & Park, I. (2014). Highly stretchable and sensitive strain sensor based on silver nanowire–elastomer nanocomposite. *ACS nano*, *8*(5), 5154-5163. [CrossRef]

[146] Kim, H. J., Thukral, A., & Yu, C. (2018). Highly

sensitive and very stretchable strain sensor based on a rubbery semiconductor. *ACS applied materials & interfaces, 10*(5), 5000-5006. [CrossRef]

[147] Amjadi, M., Yoon, Y. J., & Park, I. (2015). Ultra-stretchable and skin-mountable strain sensors using carbon nanotubes–Ecoflex nanocomposites. *Nanotechnology, 26*(37), 375501. [CrossRef]

[148] Shintake, J., Piskarev, Y., Jeong, S. H., & Floreano, D. (2018). Ultrastretchable strain sensors using carbon black-filled elastomer composites and comparison of capacitive versus resistive sensors. *Advanced Materials Technologies, 3*(3), 1700284. [CrossRef]

[149] Kang, D., Pikhitsa, P. V., Choi, Y. W., Lee, C., Shin, S. S., Piao, L., ... & Choi, M. (2014). Ultrasensitive mechanical crack-based sensor inspired by the spider sensory system. *Nature, 516*(7530), 222-226. [CrossRef]

[150] Xiao, Y., Jiang, S., Zhao, X., Jiang, H., & Zhang, W. (2018). Crack-enhanced mechanosensitivity of cost-effective piezoresistive flexible strain sensors suitable for motion detection. *Smart Materials and Structures, 27*(10), 105049. [CrossRef]

[151] Xu, F., & Zhu, Y. (2012). Highly conductive and stretchable silver nanowire conductors. *Advanced materials, 24*(37), 5117-5122. [CrossRef]

[152] Yao, S., & Zhu, Y. (2014). Wearable multifunctional sensors using printed stretchable conductors made of silver nanowires. *Nanoscale, 6*(4), 2345-2352. [CrossRef]

[153] Hu, X., Yang, F., Wu, M., Sui, Y., Guo, D., Li, M., ... & 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. [CrossRef]

[154] Xiao, X., Yuan, L., Zhong, J., Ding, T., Liu, Y., Cai, Z., ... & Wang, Z. L. (2011). High-Strain Sensors Based on ZnO Nanowire/Polystyrene Hybridized Flexible Films. *Advanced Materials, 23*(45), 5440-5444. [CrossRef]

[155] Migliorini, L., Santaniello, T., Falqui, A., & Milani, P. (2023). Super-stretchable resistive strain sensor based on Ecoflex–gold nanocomposites. *ACS Applied Nano Materials, 6*(10), 8999-9007. [CrossRef]

[156] Li, W., Zhou, Y., Wang, Y., Jiang, L., Ma, J., Chen, S., & Zhou, F. L. (2021). Core–sheath fiber-based wearable strain sensor with high stretchability and sensitivity for detecting human motion. *Advanced Electronic Materials, 7*(1), 2000865. [CrossRef]

[157] Bhattacharjee, M., Soni, M., Escobedo, P., & Dahiya, R. (2020). PEDOT: PSS microchannel-based highly sensitive stretchable strain sensor. *Advanced Electronic Materials, 6*(8), 2000445. [CrossRef]

[158] Yan, W., Fuh, H. R., Lv, Y., Chen, K. Q., Tsai, T. Y., Wu, Y. R., ... & Wu, H. C. (2021). Giant gauge factor of Van der Waals material based strain sensors. *Nature communications, 12*(1), 2018. [CrossRef]

[159] Verma, R. P., Sahu, P. S., Rathod, M., Mohapatra, S. S., Lee, J., & Saha, B. (2022). Ultra-Sensitive and highly stretchable strain sensors for monitoring of human physiology. *Macromolecular Materials and Engineering, 307*(3), 2100666. [CrossRef]

[160] Zhang, D., Ren, B., Zhang, Y., Xu, L., Huang, Q., He, Y., ... & Zheng, J. (2020). From design to applications of stimuli-responsive hydrogel strain sensors. *Journal of Materials Chemistry B, 8*(16), 3171-3191. [CrossRef]

[161] Tadakaluru, S., Thongsuwan, W., & Singjai, P. (2014). Stretchable and flexible high-strain sensors made using carbon nanotubes and graphite films on natural rubber. *Sensors, 14*(1), 868-876. [CrossRef]

[162] Ma, C., Ma, M. G., Si, C., Ji, X. X., & Wan, P. (2021). Flexible MXene-based composites for wearable devices. *Advanced Functional Materials, 31*(22), 2009524. [CrossRef]

[163] Pan, X., Guo, D., & He, H. (2019, August). Investigation on Nonlinear Electromechanical Behavior of Conductive Polymer Composites-based Flexible Strain Sensor. In *2019 20th International Conference on Electronic Packaging Technology (ICEPT)* (pp. 1-5). IEEE. [CrossRef]

[164] Gong, S., & Zhu, Z. H. (2014). On the mechanism of piezoresistivity of carbon nanotube polymer composites. *Polymer, 55*(16), 4136-4149. [CrossRef]

[165] Yuan, H., Li, P., Wang, X., Yu, C., Wang, X., & Sun, J. (2024). Stretchable, ultrasensitive strain sensor with high-linearity by constructing crack-based dual conductive network. *Chemical Engineering Journal, 480*, 148102. [CrossRef]

[166] Nur, R., Matsuhisa, N., Jiang, Z., Nayeem, M. O. G., Yokota, T., & Someya, T. (2018). A highly sensitive capacitive-type strain sensor using wrinkled ultrathin gold films. *Nano letters, 18*(9), 5610-5617. [CrossRef]

[167] Seyedin, S., Zhang, P., Naebe, M., Qin, S., Chen, J., Wang, X., & Razal, J. M. (2019). Textile strain sensors: a review of the fabrication technologies, performance evaluation and applications. *Materials Horizons, 6*(2), 219-249. [CrossRef]

[168] Shajari, S. (2020). Development of multifunctional polymer nanocomposites with hybrid structures for fabrication of stretchable strain sensing and wearable electronic devices. *Development, 2020*, 06-25.

[169] Fu, X. (2019). *Stretchable strain sensors made of multi-wall carbon nanotube-based composite*. Auckland University of Technology.

[170] Xu, H., Lv, Y., Qiu, D., Zhou, Y., Zeng, H., & Chu, Y. (2019). An ultra-stretchable, highly sensitive and biocompatible capacitive strain sensor from an ionic nanocomposite for on-skin monitoring. *Nanoscale, 11*(4), 1570-1578. [CrossRef]

[171] Ibrahim, Z., Asif, A., Hassan, G., & Shuja, A. (2025). Fabrication of UV-curable and self-adhesive strain sensor based on

2-hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone and PVA composite for biomedical applications. *Sensors and Actuators A: Physical*, 116754. [CrossRef]

[172] Wu, Z., Liu, X., Xu, Q., Zhang, L., Abdou, S. N., Ibrahim, M. M., ... & Guo, Z. (2024). Poly (vinyl alcohol)/polyacrylamide double-network ionic conductive hydrogel strain sensor with high sensitivity and high elongation at break. *Journal of Polymer Science*, *62*(20), 4599-4611. [CrossRef]

[173] 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), 1795-1802. [CrossRef]

[174] Zhang, M., Wang, M., Zhang, M., Qiu, L., Liu, Y., Zhang, W., ... & Wu, G. (2019). Flexible and highly sensitive humidity sensor based on sandwich-like Ag/Fe3O4 nanowires composite for multiple dynamic monitoring. *Nanomaterials*, *9*(10), 1399. [CrossRef]

[175] Zhou, C. G., Sun, W. J., Jia, L. C., Xu, L., Dai, K., Yan, D. X., & Li, Z. M. (2019). Highly stretchable and sensitive strain sensor with porous segregated conductive network. *ACS applied materials & interfaces*, *11*(40), 37094-37102. [CrossRef]

[176] Asif, A., Bibi, M., Hassan, G., Shuja, A., Ahmad, H., Alam, S., & Ibrahim, Z. (2024). Highly sensitive strain sensor based on ZnO nanofiber mat for medical applications. *Journal of Materials Science: Materials in Electronics*, *35*(18), 1227. [CrossRef]

[177] Liu, M. Y., Hang, C. Z., Wu, X. Y., Zhu, L. Y., Wen, X. H., Wang, Y., ... & Lu, H. L. (2022). Investigation of stretchable strain sensor based on CNT/AgNW applied in smart wearable devices. *Nanotechnology*, *33*(25), 255501. [CrossRef]

[178] 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 and bioelectronics*, *123*, 167-177. [CrossRef]

[179] Amjadi, M. (2019). *Functional nanomaterial composites for soft sensing and actuation*. ETH Zurich.

[180] Guo, X., Hong, W., Zhao, Y., Zhu, T., Liu, L., Li, H., ... & Xing, G. (2023). Bioinspired dual-mode stretchable strain sensor based on magnetic nanocomposites for strain/magnetic discrimination. *Small*, *19*(1), 2205316. [CrossRef]

[181] Chen, S., Wei, Y., Yuan, X., Lin, Y., & Liu, L. (2016). A highly stretchable strain sensor based on a graphene/silver nanoparticle synergic conductive network and a sandwich structure. *Journal of Materials Chemistry C*, *4*(19), 4304-4311. [CrossRef]

[182] Zheng, Y., Li, Y., Dai, K., Wang, Y., Zheng, G., Liu, C., & Shen, C. (2018). A highly stretchable and stable strain sensor based on hybrid carbon nanofillers/polydimethylsiloxane conductive composites for large human motions monitoring. *Composites Science and Technology*, *156*, 276-286. [CrossRef]

[183] Tan, X., & Zheng, J. (2022). A novel porous PDMS-AgNWs-PDMS (PAP)-sponge-based capacitive pressure sensor. *Polymers*, *14*(8), 1495. [CrossRef]

[184] Zhou, X., Wang, G., Li, D., Wang, Q., Zhu, K., Hao, Y., ... & Li, N. (2024). Shape-memory polyurethane elastomer originated from waste PET plastic and their composites with carbon nanotube for sensitive and stretchable strain sensor. *Composites Part A: Applied Science and Manufacturing*, *177*, 107920. [CrossRef]

[185] Li, Q., Wang, Y., Jiang, S., Li, T., Ding, X., Tao, X., & Wang, X. (2020). Investigation into tensile hysteresis of polyurethane-containing textile substrates for coated strain sensors. *Materials & Design*, *188*, 108451. [CrossRef]

[186] Nankali, M., Nouri, N. M., Navidbakhsh, M., Malek, N. G., Amindehghan, M. A., Shahtoori, A. M., ... & Amjadi, M. (2020). Highly stretchable and sensitive strain sensors based on carbon nanotube–elastomer nanocomposites: the effect of environmental factors on strain sensing performance. *Journal of Materials Chemistry C*, *8*(18), 6185-6195. [CrossRef]

[187] Wang, X., Deng, Y., Jiang, P., Chen, X., & Yu, H. (2022). Low-hysteresis, pressure-insensitive, and transparent capacitive strain sensor for human activity monitoring. *Microsystems & Nanoengineering*, *8*(1), 113. [CrossRef]

[188] Choi, D. Y., Kim, M. H., Oh, Y. S., Jung, S. H., Jung, J. H., Sung, H. J., ... & Lee, H. M. (2017). Highly stretchable, hysteresis-free ionic liquid-based strain sensor for precise human motion monitoring. *ACS applied materials & interfaces*, *9*(2), 1770-1780. [CrossRef]

[189] Xia, Q., Wang, S., Zhai, W., Shao, C., Xu, L., Yan, D., ... & Shen, C. (2021). Highly linear and low hysteresis porous strain sensor for wearable electronic skins. *Composites Communications*, *26*, 100809. [CrossRef]

[190] Shen, Z., Zhang, Z., Zhang, N., Li, J., Zhou, P., Hu, F., ... & Gu, G. (2022). High-stretchability, ultralow-hysteresis conductingpolymer hydrogel strain sensors for soft machines. *Advanced Materials*, *34*(32), 2203650. [CrossRef]

[191] Zhang, Y., Zhu, X., Liu, Y., Liu, L., Xu, Q., Liu, H., ... & Chen, L. (2021). Ultra-stretchable monofilament flexible sensor with low hysteresis and linearity based on MWCNTs/Ecoflex composite materials. *Macromolecular Materials and Engineering*, *306*(8), 2100113. [CrossRef]

[192] Liu, J., Chen, X., Sun, B., Guo, H., Guo, Y., Zhang, S., ... & Tang, J. (2022). Stretchable strain sensor of composite hydrogels with high fatigue resistance and low hysteresis. *Journal of Materials Chemistry A*, *10*(48), 25564-25574. [CrossRef]

[193] Cohen, D. J., Mitra, D., Peterson, K., & Maharbiz, M. M. (2012). A highly elastic, capacitive strain gauge based on percolating nanotube networks. *Nano letters, 12*(4), 1821-1825. [CrossRef]

[194] Wang, R., Xu, W., Shen, W., Shi, X., Huang, J., & Song, W. (2019). A highly stretchable and transparent silver nanowire/thermoplastic polyurethane film strain sensor for human motion monitoring. *Inorganic Chemistry Frontiers, 6*(11), 3119-3124. [CrossRef]

[195] Wu, G., Li, S., Hu, J., Dong, M., Dong, K., Hou, X., & Xiao, X. (2021). A capacitive sensor using resin thermoplastic elastomer and carbon fibers for monitoring pressure distribution. *Pigment & Resin Technology, 50*(5), 437-443. [CrossRef]

[196] Dorsey, K. L. (2019, April). Reconfigurable soft capacitive sensor with variable stiffness ring. In *2019 2nd IEEE International Conference on Soft Robotics (RoboSoft)* (pp. 378-383). IEEE. [CrossRef]

[197] Shi, H., Al-Rubaiai, M., Holbrook, C. M., Miao, J., Pinto, T., Wang, C., & Tan, X. (2019). Screen-printed soft capacitive sensors for spatial mapping of both positive and negative pressures. *Advanced Functional Materials, 29*(23), 1809116. [CrossRef]

[198] Alsharif, B., Alalwany, E., Ibrahim, A., Mahgoub, I., & Ilyas, M. (2025). Real-Time American Sign Language Interpretation Using Deep Learning and Keypoint Tracking. *Sensors, 25*(7), 2138. [CrossRef]

[199] Lee, C. J., Park, J. K., Piao, C., Seo, H. E., Choi, J., & Chun, J. H. (2018). Mutual capacitive sensing touch screen controller for ultrathin display with extended signal passband using negative capacitance. *Sensors, 18*(11), 3637. [CrossRef]

[200] Shang, Y., Zhang, B., Liu, J., Xia, C., Yang, X., Yan, D., & Sun, J. (2023). Facile and economical fabrication of superhydrophobic flexible resistive strain sensors for human motion detection. *Nanomanufacturing and Metrology, 6*(1), 2. [CrossRef]

[201] Yun, G., Tang, S. Y., Lu, H., Zhang, S., Dickey, M. D., & Li, W. (2021). Hybrid-filler stretchable conductive composites: from fabrication to application. *Small Science, 1*(6), 2000080. [CrossRef]

[202] Kim, S. R., Kim, J. H., & Park, J. W. (2017). Wearable and transparent capacitive strain sensor with high sensitivity based on patterned Ag nanowire networks. *ACS applied materials & interfaces, 9*(31), 26407-26416. [CrossRef]

[203] Huang, J., Zhou, R., Chen, Z., Wang, Y., Li, Z., Mo, X., ... & Pan, C. (2023). Highly stable and reliable capacitive strain sensor for wearable electronics based on anti-dry hydrogel electrode. *Materials Today Physics, 35*, 101123. [CrossRef]

[204] Xue, F., Peng, Q., Ding, R., Li, P., Zhao, X., Zheng, H., ... & He, X. (2024). Ultra-sensitive, highly linear, and hysteresis-free strain sensors enabled by gradient stiffness sliding strategy. *npj Flexible Electronics, 8*(1), 14. [CrossRef]

[205] Liu, H., Li, Q., Zhang, S., Yin, R., Liu, X., He, Y., ... & Guo, Z. (2018). Electrically conductive polymer composites for smart flexible strain sensors: a critical review. Journal of Materials Chemistry C, 6(45), 12121-12141. [CrossRef]

[206] Wang, C., Xia, K., Wang, H., Liang, X., Yin, Z., & Zhang, Y. (2019). Advanced carbon for flexible and wearable electronics. *Advanced materials, 31*(9), 1801072. [CrossRef]

[207] Li, J., Fang, L., Sun, B., Li, X., & Kang, S. H. (2020). Recent progress in flexible and stretchable piezoresistive sensors and their applications. *Journal of the Electrochemical Society, 167*(3), 037561. [CrossRef]

[208] Lou, Z., Wang, L., & Shen, G. (2018). Recent advances in smart wearable sensing systems. *Advanced Materials Technologies, 3*(12), 1800444. [CrossRef]

[209] Shang, Y., Zhang, B., Liu, J., Xia, C., Yang, X., Yan, D., & Sun, J. (2023). Facile and economical fabrication of superhydrophobic flexible resistive strain sensors for human motion detection. *Nanomanufacturing and Metrology, 6*(1), 2. [CrossRef]

[210] Mehmood, A., Mubarak, N. M., Khalid, M., Walvekar, R., Abdullah, E. C., Siddiqui, M. T. H., ... & Mazari, S. (2020). Graphene based nanomaterials for strain sensor application—a review. *Journal of Environmental Chemical Engineering, 8*(3), 103743. [CrossRef]

[211] Zhu, Y., Chen, X., Chu, K., Wang, X., Hu, Z., & Su, H. (2022). Carbon black/PDMS based flexible capacitive tactile sensor for multi-directional force sensing. *Sensors, 22*(2), 628. [CrossRef]

[212] Zhang, W., Liu, Q., & Chen, P. (2018). Flexible strain sensor based on carbon black/silver nanoparticles composite for human motion detection. Materials, 11(10), 1836. [CrossRef]

[213] Wang, H., Cao, H., Wu, H., Zhang, Q., Mao, X., Wei, L., ... & Liu, C. (2023). Environmentally friendly and sensitive strain sensor based on multiwalled carbon nanotubes/lignin-based carbon nanofibers. *ACS Applied Nano Materials, 6*(15), 14165-14176. [CrossRef]

[214] Zhu, W., Zhang, C., Lin, J., Pan, S., Wang, Q., Liao, N., ... & Zhang, M. (2023). Flexible strain sensor based on copper/graphene composite films. *ACS Applied Nano Materials, 7*(1), 358-369. [CrossRef]

[215] He, J., Li, A., Wang, W., Cui, C., Jiang, S., Chen, M., ... & Guo, R. (2023). Multifunctional Wearable Device Based on an Antibacterial and Hydrophobic Silver Nanoparticles/Ti3C2T x MXene/Thermoplastic Polyurethane Fibrous Membrane for Electromagnetic Shielding and Strain Sensing. *Industrial & Engineering Chemistry Research, 62*(23), 9221-9232. [CrossRef]

[216] De, A., & Kalita, D. (2023). Bio-fabricated gold and silver nanoparticle based plasmonic sensors for detection of environmental pollutants: an overview. *Critical Reviews in Analytical Chemistry, 53*(3), 672-688.

[CrossRef]

[217] Gao, X., Bao, Y., Chen, Z., Lu, J., Su, T., Zhang, L., & Ouyang, J. (2023). Bioelectronic applications of intrinsically conductive polymers. *Advanced Electronic Materials, 9*(10), 2300082. [CrossRef]

[218] Li, C., Mu, J., Song, Y., Chen, S., & Xu, F. (2023). Highly aligned cellulose/polypyrrole composite nanofibers via electrospinning and in situ polymerization for anisotropic flexible strain sensor. *ACS applied materials & interfaces, 15*(7), 9820-9829. [CrossRef]

[219] Sabry, F. (2022). *Conductive polymer: The medical industry is revolutionized for tissue engineering and biosensors, to restore whole organs, or diagnose infectious diseases* (Vol. 4). One Billion Knowledgeable.

[220] Wang, K., Zhang, Y., Hu, J., Li, M., & Wu, B. (2025). Flexible Strain Sensor Based on a Dual Crosslinked Network of PAMgA/GL/PANI Antifreeze Conductive Hydrogel. *Macromolecular Chemistry and Physics, 226*(2), 2400341. [CrossRef]

[221] Choi, S., Han, S. I., Kim, D., Hyeon, T., & Kim, D. H. (2019). High-performance stretchable conductive nanocomposites: materials, processes, and device applications. *Chemical Society Reviews, 48*(6), 1566-1595. [CrossRef]

[222] Hu, X., Feng, J., Zhang, H., Ma, J., Wu, Z., Wen, J., ... & Tian, Y. (2023). Electrohydrodynamic Printing of High-Resolution Self-Reduced Soldered Silver Nanowire Pattern for Wearable Flexible Strain Sensors. *Advanced Materials Technologies, 8*(19), 2300759. [CrossRef]

[223] Zhao, S., Meng, X., Liu, L., Bo, W., Xia, M., Zhang, R., ... & Ahn, J. H. (2021). Polypyrrole-coated copper nanowire-threaded silver nanoflowers for wearable strain sensors with high sensing performance. *Chemical Engineering Journal, 417*, 127966. [CrossRef]

[224] Cheng, L., Ruan, D., He, Y., Yang, J., Qian, W., Zhu, L., ... & Liu, A. (2023). A highly stretchable and sensitive strain sensor for lip-reading extraction and speech recognition. *Journal of Materials Chemistry C, 11*(25), 8413-8422. [CrossRef]

[225] Chen, J., Zheng, J., Gao, Q., Zhang, J., Zhang, J., Omisore, O. M., ... & Li, H. (2018). Polydimethylsiloxane (PDMS)-based flexible resistive strain sensors for wearable applications. *Applied Sciences, 8*(3), 345. [CrossRef]

[226] Hassan, G., Bae, J., Hassan, A., Ali, S., Lee, C. H., & Choi, Y. (2018). Ink-jet printed stretchable strain sensor based on graphene/ZnO composite on micro-random ridged PDMS substrate. *Composites Part A: Applied Science and Manufacturing, 107*, 519-528. [CrossRef]

[227] Zhang, Y., Anderson, N., Bland, S., Nutt, S., Jursich, G., & Joshi, S. (2017). All-printed strain sensors: Building blocks of the aircraft structural health monitoring system. *Sensors and Actuators A: Physical, 253*, 165-172. [CrossRef]

[228] Azrak, E., Michaud, L., Richy, J., Reinhardt, A., Tardif, S., Eymery, J., ... & Montmeat, P. (2023). *Large scale integration of functional radio-frequency flexible MEMS under large mechanical strain. Advanced Functional Materials, 33*(4), 2205404. [CrossRef]

[229] Qi, X., Matteini, P., Hwang, B., & Lim, S. (2023). Roll stamped Ni/MWCNT composites for highly reliable cellulose paper-based strain sensor. *Cellulose, 30*(3), 1543-1552. [CrossRef]

[230] Kubicek, R., Babaei, M., Weber, A. I., & Bergbreiter, S. (2023, May). A new sensation: Digital strain sensing for disturbance detection in flapping wing micro aerial vehicles. In *2023 IEEE International Conference on Robotics and Automation* (*ICRA*) (pp. 3390-3396). IEEE. [CrossRef]

[231] Paşahan, A. (2012). Sensor applications of polyimides. *High Performance Polymers–Polyimides Based–From Chemistry to Applications. InTech: Croatia, Rijeka*, 199-214.

[232] Dagdeviren, C., Su, Y., Joe, P., Yona, R., Liu, Y., Kim, Y. S., ... & Rogers, J. A. (2014). Conformable amplified lead zirconate titanate sensors with enhanced piezoelectric response for cutaneous pressure monitoring. *Nature communications, 5*(1), 4496. [CrossRef]

[233] Aabid, A., Parveez, B., Raheman, M. A., Ibrahim, Y. E., Anjum, A., Hrairi, M., ... & Mohammed Zayan, J. (2021, May). A review of piezoelectric material-based structural control and health monitoring techniques for engineering structures: Challenges and opportunities. In *Actuators* (Vol. 10, No. 5, p. 101). MDPI. [CrossRef]

[234] Jat, A. S., & Grønli, T. M. (2023, August). Harnessing the digital revolution: a comprehensive review of mHealth applications for remote monitoring in transforming healthcare delivery. In *International Conference on Mobile Web and Intelligent Information Systems* (pp. 55-67). Cham: Springer Nature Switzerland. [CrossRef]

[235] Lu, T., Ji, S., Jin, W., Yang, Q., Luo, Q., & Ren, T. L. (2023). Biocompatible and long-term monitoring strategies of wearable, ingestible and implantable biosensors: reform the next generation healthcare. *Sensors, 23*(6), 2991. [CrossRef]

[236] Morgenthal, G., Eick, J. F., Rau, S., & Taraben, J. (2019). Wireless sensor networks composed of standard microcomputers and smartphones for applications in structural health monitoring. *Sensors, 19*(9), 2070. [CrossRef]

[237] Lu, N., Lu, C., Yang, S., & Rogers, J. (2012). Highly sensitive skin-mountable strain gauges based entirely on elastomers. *Advanced Functional Materials, 22*(19), 4044-4050. [CrossRef]

[238] Shi, G., Liu, T., Kopecki, Z., Cowin, A., Lee, I., Pai, J. H., ... & Zhong, Y. L. (2019). A multifunctional

wearable device with a graphene/silver nanowire nanocomposite for highly sensitive strain sensing and drug delivery. *C*, *5*(2), 17. [CrossRef]

[239] You, I., Kim, B., Park, J., Koh, K., Shin, S., Jung, S., & Jeong, U. J. A. M. (2016). Stretchable E-Skin Apexcardiogram Sensor. *Advanced Materials* (*Deerfield Beach, Fla.*), *28*(30), 6359-6364. [CrossRef]

[240] Zhang, Q., Bossuyt, F. M., Adam, N. C., Zambrano, B. L., Stauffer, F., Rennhard, P., ... & Smith, C. R. (2023). A stretchable strain sensor system for wireless measurement of musculoskeletal soft tissue strains. *Advanced Materials Technologies*, *8*(12), 2202041. [CrossRef]

[241] You, S. S., Schober, M., Ben-Ayed, S., Babaee, S., Owyang, S., Jenkins, J., ... & Traverso, G. (2025). Personalized Kirigami Strain Sensors for in vivo Applications. *Advanced Intelligent Systems*, 2400886. [CrossRef]

[242] Hu, C., Wang, L., Liu, S., Sheng, X., & Yin, L. (2024). Recent development of implantable chemical sensors utilizing flexible and biodegradable materials for biomedical applications. *ACS nano*, *18*(5), 3969-3995. [CrossRef]

[243] Khan, S. R., Bernassau, A. L., & Desmulliez, M. P. (2024). Passive and battery-free RFID-based wireless healthcare and medical devices: A review. *IEEE Journal of Radio Frequency Identification*. [CrossRef]

[244] Chen, H., Wang, H., Yu, P., & Yang, X. (2023). Wearable strain sensors and their applications. In *SHS Web of Conferences* (Vol. 157, p. 03029). EDP Sciences. [CrossRef]

[245] Zhang, J., Cao, Y., Qiao, M., Ai, L., Sun, K., Mi, Q., ... & Wang, Q. (2018). Human motion monitoring in sports using wearable graphene-coated fiber sensors. *Sensors and Actuators A: Physical*, *274*, 132-140. [CrossRef]

[246] Li, Z., Hu, F., Chen, Z., Huang, J., Chen, G., Chen, R., ... & Luo, J. (2021). Fiber-junction design for directional bending sensors. *npj Flexible Electronics*, *5*(1), 4. [CrossRef]

[247] Lim, G. H., Lee, N. E., & Lim, B. (2016). Highly sensitive, tunable, and durable gold nanosheet strain sensors for human motion detection. *Journal of Materials Chemistry C*, *4*(24), 5642-5647. [CrossRef]

[248] Liu, Y., Wang, H., Zhao, W., Zhang, M., Qin, H., & Xie, Y. (2018). Flexible, stretchable sensors for wearable health monitoring: sensing mechanisms, materials, fabrication strategies and features. *Sensors*, *18*(2), 645. [CrossRef]

[249] Lim, H. R., Kim, H. S., Qazi, R., Kwon, Y. T., Jeong, J. W., & Yeo, W. H. (2020). Advanced soft materials, sensor integrations, and applications of wearable flexible hybrid electronics in healthcare, energy, and environment. *Advanced Materials*, *32*(15), 1901924. [CrossRef]

[250] Kim, K. K., Suh, Y., & Ko, S. H. (2021). Smart stretchable electronics for advanced human–machine interface. *Advanced Intelligent Systems*, *3*(2), 2000157. [CrossRef]

[251] Cheraghi Bidsorkhi, H., D'Aloia, A. G., Tamburrano, A., De Bellis, G., & Sarto, M. S. (2021). Waterproof graphene-pvdf wearable strain sensors for movement detection in smart gloves. *Sensors*, *21*(16), 5277. [CrossRef]

[252] Dong, W., Yang, L., & Fortino, G. (2020). Stretchable human machine interface based on smart glove embedded with PDMS-CB strain sensors. *IEEE Sensors Journal*, *20*(14), 8073-8081. [CrossRef]

[253] Wu, Y., Zhou, Y., Asghar, W., Liu, Y., Li, F., Sun, D., ... & Yang, H. (2021). Liquid metal-based strain sensor with ultralow detection limit for human–machine interface applications. *Advanced Intelligent Systems*, *3*(10), 2000235. [CrossRef]

[254] Qiu, H., Chen, Z., Chen, Y., Yang, C., Wu, S., Li, F., & Xie, L. (2024). A Real-Time Hand Gesture Recognition System for Low-Latency HMI via Transient HD-SEMG and In-Sensor Computing. *IEEE Journal of Biomedical and Health Informatics*, *28*(9), 5156-5167. [CrossRef]

[255] Wu, Y., Karakurt, I., Beker, L., Kubota, Y., Xu, R., Ho, K. Y., ... & Lin, L. (2018). Piezoresistive stretchable strain sensors with human machine interface demonstrations. *Sensors and Actuators A: Physical*, *279*, 46-52. [CrossRef]

[256] Yang, H., Ding, S., Wang, J., Sun, S., Swaminathan, R., Ng, S. W. L., ... & Ho, G. W. (2024). Computational design of ultra-robust strain sensors for soft robot perception and autonomy. *Nature Communications*, *15*(1), 1636. [CrossRef]

[257] Li, X., Wen, R., Shen, Z., Wang, Z., Luk, K. D. K., & Hu, Y. (2018). A wearable detector for simultaneous finger joint motion measurement. *IEEE transactions on biomedical circuits and systems*, *12*(3), 644-654. [CrossRef]

[258] Khan, H., Razmjou, A., Ebrahimi Warkiani, M., Kottapalli, A., & Asadnia, M. (2018). Sensitive and flexible polymeric strain sensor for accurate human motion monitoring. *Sensors*, *18*(2), 418. [CrossRef]

[259] Sun, Z., Zhu, M., & Lee, C. (2021). Progress in the triboelectric human–machine interfaces (HMIs)-moving from smart gloves to AI/haptic enabled HMI in the 5G/IoT era. *Nanoenergy Advances*, *1*(1). [CrossRef]

[260] Wang, H., Totaro, M., & Beccai, L. (2018). Toward perceptive soft robots: Progress and challenges. *Advanced science*, *5*(9), 1800541. [CrossRef]

[261] Xue, Z., Song, H., Rogers, J. A., Zhang, Y., & Huang, Y. (2020). Mechanically-guided structural designs in stretchable inorganic electronics. *Advanced Materials*, *32*(15), 1902254. [CrossRef]

[262] Silva, C. A., Lv, J., Yin, L., Jeerapan, I., Innocenzi, G., Soto, F., ... & Wang, J. (2020). Liquid metal

based island-bridge architectures for all printed stretchable electrochemical devices. *Advanced Functional Materials*, *30*(30), 2002041. [CrossRef]

[263] Chen, P., Li, Y., Gao, H., Zhang, X., Du, H., & Ren, T. (2025). Novel static decoupling algorithm for the multi-axis wheel force sensor based on the Informer network. Measurement, 241, 115766. [CrossRef]

Maryam Bibi received the M.S. degree in Physics from the International Islamic University, Islamabad. (Email: Maryamrabnawaz1999@gmail.com)

Gul Hassan received the PostDoc – Hanyang University, Seoul, South Korea. (E-mail: gulhassan.rahi5@gmail.com)

Arfa Asif received the MS Degree in Electrical Engineering from International Islamic University, Islamabad 44000, Pakistan (E-mail: arfaasif907@gmail.com)

Ahmed Shuja received the MS and Ph.D. in Electrical & and Electronic Engineering from Sweden and the UK. (E-mail: ahmed.shuja@iiu.edu.pk)

Habib Ahmad received the PhD ECE, Georgia Institute of Technology in 2021. (E-mail: habib.ahmad@iiu.edu.pk)

Bilal Mushtaq has done his PhD in electrical engineering from Riphah International University, Islamabad Pakistan. He is currently serving in the capacity of Assistant Professor in the Department of Electrical and Electronic Engineering, Beaconhouse International College, Islamabad Pakistan. He served as an Academic Editor for the ICCK Transactions on Sensing, Communication, and Control. (Email: bilalmushtaq88@outlook.com / bilal.mushtaq@bic.edu.pk.)

Memon Sajid received the Post Doctorate (Mechatronics Engineering) 2018, Jeju National University, Korea. (Email: memoonsajid@giki.edu.pK)