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# AI-integrated wearable strain sensors: advances in e-skin, robotics, and personalized health monitoring

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Due to their growing adaptability, there has been an increased awareness and interest in artificial intelligence and wearable strain sensors across various fields of study and industry. Researchers are developing new instruments to investigate novel gadgets, electronic skins, wearable wellness care, and robotics for precise detection needs. Machine learning and AI techniques are gaining attention for their ability to enhance analytical procedures. This review examines the benefits of using AI techniques and wearable sensors to modernize and optimize data analysis tasks. Developing wearable strain sensor technology is crucial in overcoming the current challenges and achieving breakthroughs in nanotechnology. Wearables with AI have the potential to enhance early detection, intelligent diagnosis, and lifelong monitoring for improved well-being. There's great potential in wearable strain sensors, particularly those with flexible features such as stretchability and high detection power. The growing interest in skin-attachable wearable devices is fueled by their diverse applications in human–machine systems, healthcare, and AI. This review provides a brief overview of flexible wearable strain sensing systems, existing challenges, and prospects.

## 1. Introduction

Wearable sensing technology[1–5] has rapidly evolved from a concept of scientific imagination to a wide array of consumer and healthcare products, garnering significant attention in recent years. Wearable and flexible strain sensors, in particular, have emerged as critical components for the future Internet-of-Things (IoT), with extensive applications in health monitoring,[1–3] human motion detection,[4,5] monitoring mechanical deformation in engineering materials,[6] human–machine interfaces,[7–10] and soft robotics.[11,12] These sensors typically convert mechanical deformations into electrical signals, such as changes in current or voltage. The rapid advancement of wearable sensors can be attributed to several factors, including their relatively low cost, ergonomic designs, miniaturization of electronic components, the widespread adoption of smartphones and related devices, increasing public interest in health awareness, and unmet medical needs for continuous, accurate, and high-quality patient data.[6–9] Despite these advancements, significant challenges remain in

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accurately capturing and interpreting bodily data. Many current wearable technologies[10–12] rely on non-specific sensing modalities, limiting their precision. Additionally, many wearable sensor products still rely on conventional manufacturing techniques that have been used for decades. Even cutting-edge wearables, such as continuous glucose monitoring devices, are built upon decades-old advancements in enzyme electrode technology, originating from inexpensive and straightforward glucose test strips.[13] Transdermal glucose monitoring remains one of the few widely adopted wearable sensors capable of providing continuous, disease-specific data.[13–16] However, the field still requires further innovation to meet the growing demand for more precise, reliable, and versatile wearable sensing solutions.

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Doctors rely on traditional diagnostic tools to detect diseases and monitor patient health for nearly every analyte. However, these methods often require drawing blood from patients due to their non-wearable nature and reliance on outdated benchtop testing procedures.[17–22] A critical question remains unresolved: can wearable sensor technology be advanced to monitor peculiar physiological phenomena accurately? For instance, could it enable the monitoring of a baby's health inside the mother's womb by detecting subtle mechanical movements of the fetus? Could it distinguish between a life-threatening seizure and physical exertion?[23–26] Or could it alert athletes or workers to dangerous dehydration levels caused by excessive exercise or overwork through continuous health data analysis.[9,27,28] Wearable electronic devices are typically constructed using non-toxic materials, smart sensors, wireless communication modules, actuators, power supplies, control and processing units, user interfaces, software, and advanced algorithms for data acquisition and decision-making. These systems monitor physiological information by analyzing body temperature, blood pressure, mechanical strain, and the concentrations of gases, ions, and biomolecules in the bloodstream. Smart sensors must be fabricated on flexible substrates with conductive electrodes to be integrated into wearable systems. These materials must also be lightweight, highly adaptable, ultrathin, and possess low moduli and high stretchability. The figure above illustrates various cutting-edge applications of AI-based wearable strain sensors, highlighting their potential to revolutionize healthcare and beyond.

In this concise review, we will focus on wearable technologies capable of extracting data from the body's interior without requiring the implantation of sensors. Environmental sensors and accelerometers for limb movement tracking fall outside the

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scope of this discussion. Instead, this report emphasizes the emerging frontier of wearable technologies and terminology traditionally associated with analytical chemistry. Specifically, it outlines the classification of wearable strain sensors, the fundamental physics principles underlying body-to-signal transduction methods, the latest advancements in various applications, a critical analysis of unresolved challenges, and insights into prospects. The authors believe this mini-review will serve as an introductory guide for newcomers to the field of wearable sensors while also providing experienced researchers with a deeper understanding of advanced sensing modalities and the key obstacles currently hindering the development of wearable sensors and devices.

## 2. Historical viewpoint & principle of wearable sensing mechanics

Wearable strain sensors have been around for a long time. During the early 1960s, scientists working on the Apollo Space Program recognized the need for non-invasive sensors to monitor astronauts' health in extreme conditions. They developed wearable sensors, including electrocardiograms, heated thermistors to track breathing, and rectal probes to measure body temperature. Wireless EKG heart rate monitors became standard in 1977, and these wearable sensors gained popularity in the early 1980s. They eventually transitioned from being used mainly by astronauts to being used by the general public in the late 1980s.[29]

Historically, wearable chemical sensors have been employed in commercial environments since the 1960s, with early examples including the development of a precise glucose enzyme sensing electrode by Leland Clark and Ann Lyons in 1962. Notwithstanding these advancements, developing non-invasive wearable sensors has proven an elusive goal. One avenue explored in this context involves electro-osmotic flow, which enables the generation of interstitial fluid through paracellular pathways and facilitates the movement of negatively charged ions. This concept has been employed in FDA-approved devices, such as the GlucoWatch developed by Cygnus, which utilizes a non-invasive approach for diabetes monitoring. Nevertheless, non-invasive wearable chemical sensors remain largely unavailable as commercial products.[30] Finally, it is worth briefly discussing AI-based wearable strain sensors based on the latest knowledge. Commercially available wearable sensors like watches by Fitbit and Apple, and medical patches by Medtronic's SEEQ cardiac monitoring system, are the latest wearable strain sensors.

Implementing stretch and electrochemical sensing modalities enables the detection of motor signals and physiological parameters. Physical sensors can accurately measure human limb movements, pulse rates, and other biosignals. Conversely, chemical sensors facilitate the detection and quantification of specific analytes, such as glucose concentrations. Inertial motion and plantar force sensors effectively monitor human movement kinematics, including acceleration, angular velocity, and changes in direction. The compact design of these sensors makes them suitable for portable applications. By analyzing

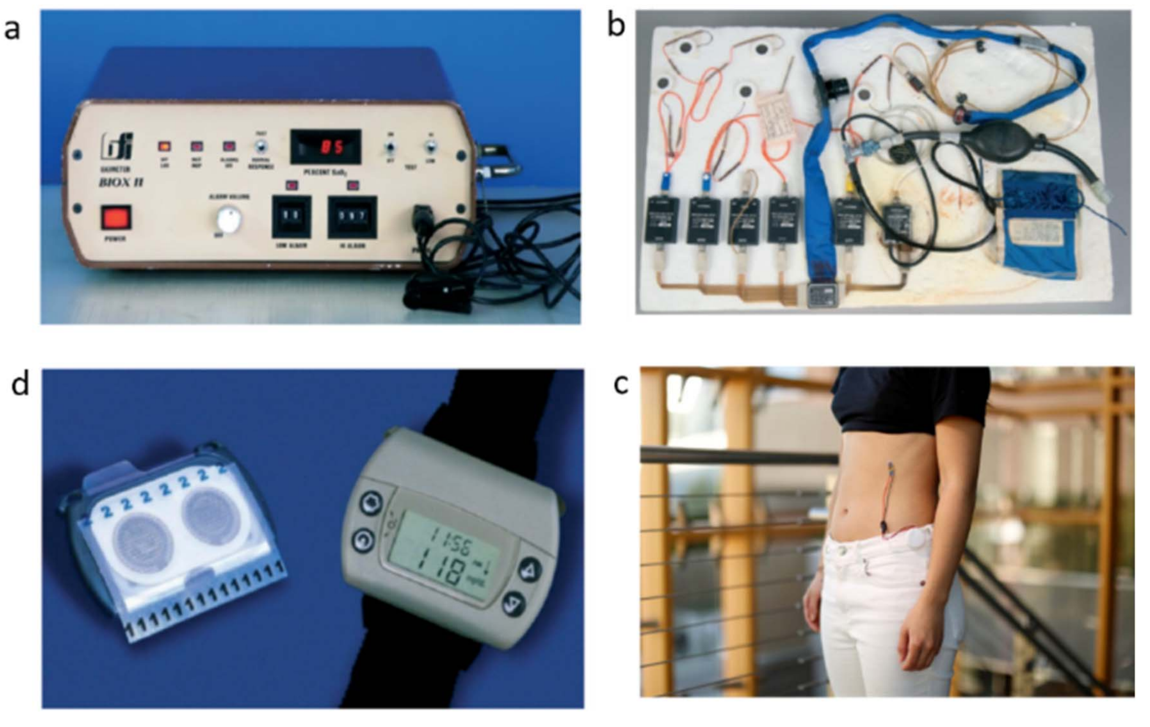


Fig. 1 Some historical glimpses of wearable sensors (a) pulse oximetry for wearing on the fingertip, (b) wearable sensors used during the Apollo Space Program, (c) wearable respiration sensor, and (d) 'Sport Tester PE2000' heart rate monitor by Polar. Reproduced from ref. 31. With permission from [Royal Society of Chemistry], copyright [2023].

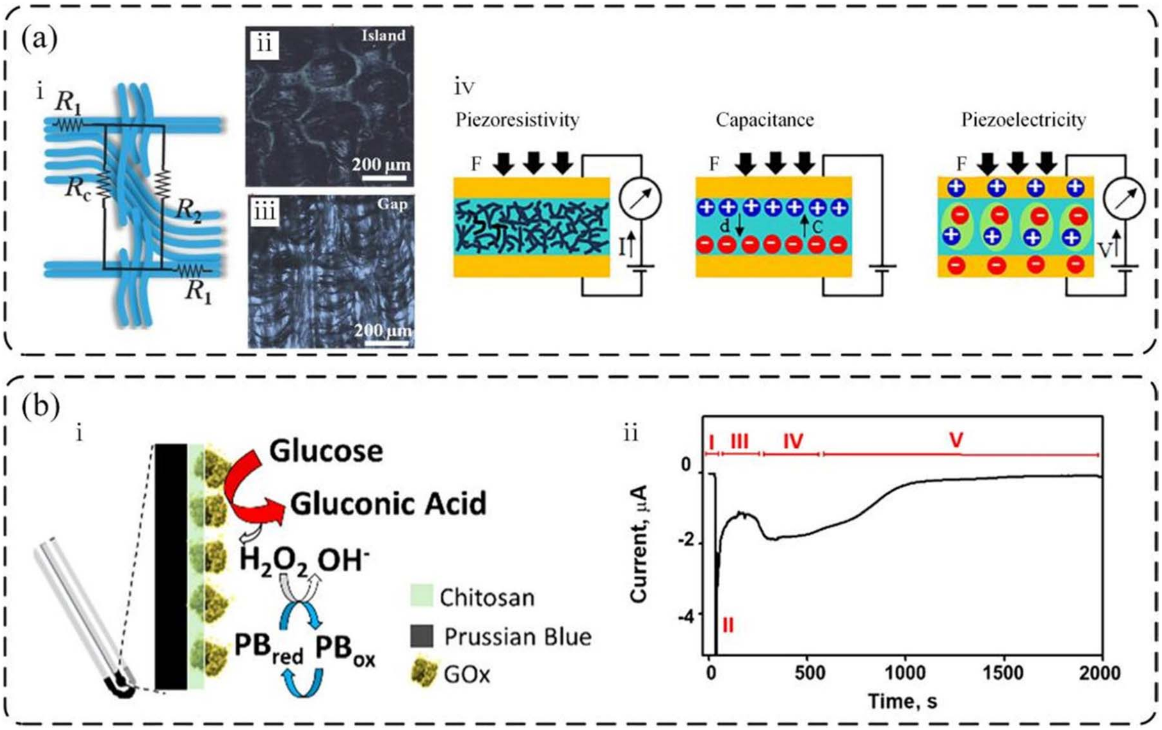


Fig. 2 Wearable sensor mechanism. A stress and strain detection mechanism. (a) (i) Schematic representation of the resistance model of an elementary unit. Optical image of (ii) the island and (iii) the gap formed under tensile stress. (iv) Flexible and stretchable pressure sensor. Reproduced from ref. 45 and 46. With permission from [Royal Society of Chemistry], copyright [2005]. Mechanism for recognizing biochemical signals. (i) Schematic representation of the enzymatic glucose biosensing approach on the PB electrode. (ii) Monitoring saliva on the body of a healthy person. Signal interpretation: a dry device. Reproduced with permission.[47,48] Similarly, plantar force sensors measure the center of pressure path on the plantar surface and stance/swing durations during ambulation, thereby facilitating the assessment of postural sway and gait variability. Recent interest in flexible wearables has led to the development of implantable electronics into textiles. (b) A key focus in this research area lies in measuring mechanical deformation variability. Additionally, designing strain sensors with a low gauge factor necessitates a higher strain sensing range; however, the mechanical properties of fragile materials often conflict with those of flexible textiles in integrated systems.[36,37]

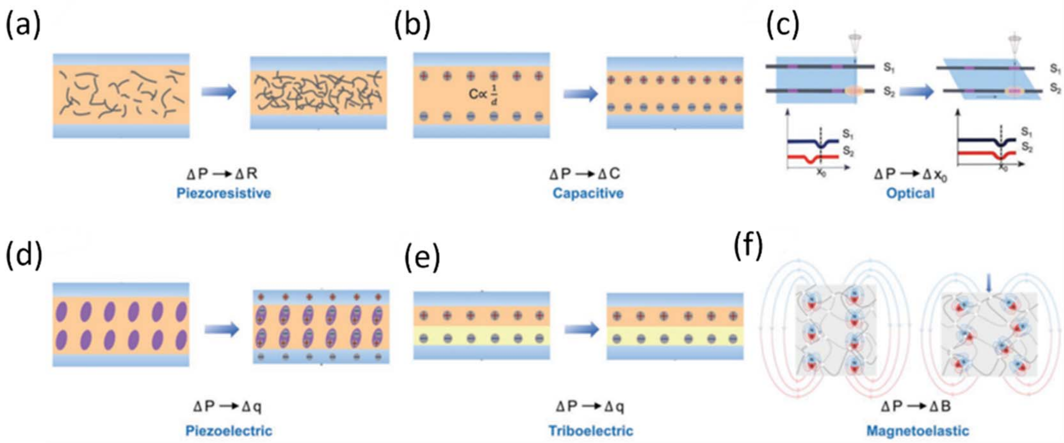


Fig. 3 Changing resistance with applied pressure and converting it into electrical signals is the basic principle of piezoresistive sensors. These sensors have been extensively studied due to their remarkably high pixel density, comparatively simple device structure, and proprietary readout mechanism algorithms.[47,48] The suitability of piezoresistive sensors over a wide pressure range enables the precise measurement of large strains. The change in contact resistance ($R_c$) between two materials is determined by the applied forces ($F$). It is the leading cause of the change in electrical signal,[49,50] and the resistance of a pressure sensor changes due to the pressure applied to the device. The power law $R_c \sim F - 1/2$ confirms the remarkably high sensitivity of piezoresistive sensors at low pressures and their relatively wide operating range. In addition, these devices have a fast response speed.[50]

 

linear acceleration, angular velocity, and changes in direction, inertial motion sensors can detect postural sway patterns in humans (Fig. 2).[31–35]

Another approach is to fabricate sensing devices from soft and flexible materials. Polymer composites and conductive fillers have been successfully demonstrated for this purpose. Such materials can sense mechanical stress through electron transfer between adjacent particles or by detecting changes in electrical resistance due to the opening and closing of micro-cracks through mechanical deformation.[35–41] These schemes demonstrate a wider strain sensing range with measurement coefficients similar to those of rigid materials. Additionally, they can be integrated into textiles at a low manufacturing cost. Conductive composites are usually obtained by blending an insulating polymer with carbon black powder[36,37] or carbon nanotubes.[40,41] These flexible strain sensors are typically fabricated using thin-film technology with limited placement and configuration options.

### 2.1. Piezoresistive mechanism

Numerous transduction mechanisms are involved, including piezoresistivity, capacitance, and piezoelectricity. Exist to transform electrical signals from tactile stimuli.[42–46] Every transduction technique has distinctive qualities (Fig. 3). Their information is provided in the following paragraph. $R = \rho L/A$, where $\rho$ is the resistivity, $L$ is the length, and $A$ is the conductor's cross-sectional area, is the equation showing how the conductive material's resistance $R$ changes. Portable electronic devices frequently use the piezoresistive effect.[47]

Piezoresistive sensors operate based on the change in resistance in response to applied pressure, translating that change into electrical signals. Because of these sensors' unusually high pixel density, relatively straightforward device design, and proprietary readout mechanism algorithms have been the subject of much research.[49] Accurately measuring high strains is made possible by the piezoresistive sensors' suitability over broad pressure ranges. The applied forces ($F$) determine the change in contact resistance ($R_c$) between two materials, which is the primary factor causing the electrical signal to change.[51] When pressure is applied to a pressure sensor, the resistance of the sensor changes. The comparatively broad operating range and exceptionally high sensitivity of piezoresistive sensors at low pressures are confirmed by the current power law $R_c \sim F - 1/2$. A person's capacity is their ability to hold an electrical charge. When pressure is applied, the plate deflects, which alters the capacitance of the parallel plate capacitor (Fig. 6b). Several picofarads (pF) may be involved in these changes, which are not always linear. The coupling of an alternating current (AC) signal through a network or the frequency of an oscillator can be adjusted by adjusting the pressure-induced capacitance. These sensors typically have low capacitance because of slight variations in parallel plate capacitance.

Piezoelectricity is a popular transduction technique used to create pressure sensors. When mechanical stress is applied to certain solid materials, a phenomenon known as the piezoelectric[52] effect occurs. This effect arises due to the presence of electric dipole moments in solids (Fig. 6c). Piezoelectric sensors exhibit exceptionally high sensitivity and fast response times, making them suitable for detecting dynamic pressures, such as sound vibrations, in various applications. Furthermore, their efficiency suggests promising potential for developing ultra-low-power or even self-sufficient pressure sensors.[53,54]

## 3. Classification of wearable sensors

In this section of the review article, AI-based wearable sensors[55–60] and various sensor types, including optical, mechanical, electrical, and chemical sensors, are discussed in detail. The primary body-to-signal transduction method for each sensing modality is also briefly explained. Furthermore, the real-life devices and their practical applications will be carefully and critically addressed. Newly developed wearable physical sensors possess sufficient stretchability and flexibility to resist deformations caused by human activities.[61–64] For example, portable sensors measure physical factors in a patient's body condition, including the body's temperature, skin, wrist, blood pressure, and skin fatigue. These aspects critically indicate a person's complete health. With this capability, physical sensors can measure these physical parameters and electronically monitor the human–machine interface, skin, person, or overall patient health.[65–67]

### 3.1. Pressure sensors

Pressure ranges vary from one part or target of the body to another to measure the parameters. For wearable pressure sensors, pressure ranges can be divided into three categories: a range of low pressure (100 kPa),[62] which includes a person's weight, and high-altitude atmospheric pressure.[63] Diseases related to the eye, heart, and damaged vocal cords, among others, can be monitored by sensing changes in different types of pressure. The extensive studies of portable pressure sensors have paved the way for their utilization in personal health-related wellness and medical diagnostic instruments. Many sensing mechanisms can convert physical stimuli into measurable electric signals, including piezoresistivity, piezoelectricity, and capacitance. The basic principle of piezoelectric pressure sensors is founded on the piezoelectric effect, which is the change in electrical charge that occurs in certain solid materials when pressure is applied to them.

Therefore, the piezoelectric impact is the induction of polarization in the dipole because of the strain imposed on the cloth. Furthermore, this polarization is proportional to the implemented strain. Piezoelectric strain sensors are notably used to detect extraordinary dynamic pressures, such as sound vibrations, due to their fast reaction time and relatively low electricity consumption. $PbTiO_3$, $BaTiO_3$, PVDF, and P(VDF-TrFE) are suitable for fabricating piezoelectric strain sensors. A consultant cloth for a movie kind sensor, P,[64–68] is notably used to manufacture wearable strain sensors. An ultrathin and ultra-brilliant PZT sheet is used as a component of a capacitor, and it connects to the gate electrodes of an FET (Fig. 4a). FETs amplify the piezoelectric output of the PZT and convert it into an output current. This is a fragile and lightweight tool with


Fig. 4 Wearable pressure-sensing gadgets. (a) A schematic diagram of the cross-section of the pressure sensor and its contacts in an accompanying transistor. (b) The pressure sensor is positioned on the wrist and neck to measure instantaneous variations in blood pressure. Produced with copyright permission from MDPI, Polymer.[69] (c) A printed pressure sensor is mounted on a commercially available elastomeric patch. (d) The skin-mounted sensor is positioned directly above the wrist artery (at a scale bar of 3 cm). (e) The heartbeat is measured by sensing the physical force under healthy and exercising conditions. (f) A representative picture of pressure-sensitive graphene FETs (g). A plot of changes in normalized drain current *versus* pressure applied to the device. Wearable pressure sensors for monitoring human health. By integrating biomechanical devices with artificial intelligence, including active materials, functional structures, wireless transmission technology, and big data analysis, convenient and biocompatible assessment of the cardiovascular system can be achieved. Such an intelligent platform provides personalized healthcare and therapy to individuals while maintaining user comfort, superior sensitivity, long life, ease of use, and mechanical durability. Reproduced from ref. 31 and 74. With permission from [Royal Society of Chemistry], copyright [2023] & Wiley 2022.

high sensitivity (~0.1/2 Pa) and a rapid reaction time (0.1 ms). It may be softly connected to the neck or wrist to display blood pressure[69,70] (Fig. 4b).

The human skin can successfully adopt this wearable porous PSR pressure sensor for several applications, *e.g.*, man–machine interface, sanitary healthcare observations, and remotely controlling the robots (Fig. 4c). Researchers have not only developed pressure sensors based on the microstructure and porous structures but also they successfully developed the piezoresistive pressure sensors based on several other materials.[71–73] Gong *et al.* fabricated a highly sensitive flexible pressure sensor by inserting the gold nanowires (AuNWs) between the two PDMS films.[71] The AuNW-incorporated flexible pressure sensors deliver real-time blood pressure monitoring with high precision and sensitivity, as shown in Fig. 4d and e.

As is evident by the name, capacitors are the ingredients of capacitive pressure sensors. Fundamentally, the magnitude of capacitance varies with the thickness of the dielectric material layer. The capacitance $C$ may be expressed by the relation $C = \varepsilon_0\varepsilon_r(A/d)$, where $A$ is the overlapping area between the two plates, $d$ is the thickness of the dielectric material, $\varepsilon_0$ is the electrical permittivity of free space, and $\varepsilon_r$ is the relative static electrical permittivity of the dielectric. As an inference, the capacitance increases while externally applied pressure reduces the thickness. Materials with small modulus values, such as polyurethane (PU), PDMS, and eco-flex, are generally used to alter the pressure-dependent thickness. K. Meng *et al.* fabricated a pressure sensor comprising a stretchable and transparent dielectric material crammed between two flexible ion conductors.[74] Due to its transparency, stretchability, and improved biocompatibility with the human body, this sensor can be proposed for implantable or wearable electronic devices. Heikenfeld J. *et al.* also developed a flexible and highly sensitive capacitive pressure sensor by raising an air gap between a single-walled carbon nanotube (SWCNT) film and a porous PDMS film.[17,75]

Nevertheless, capacitive pressure sensors have certain limitations, such as a slow response time and low sensitivity, due to the small modulus of the elastomer used in fabrication. The use of air as a dielectric layer improves sensitivity. To resolve this issue, Zang *et al.* successfully demonstrated a flexible pressure sensor of remarkably high sensitivity in the low-pressure region. It is constructed on the suspended FET gate electrode.[76,77] It can be worn on the wrist and can monitor the pulse waves. The pressure sensors described above are sensitive and can detect precise pressure intervals. However, a pressure sensor capable of detecting various pressures for diverse applications is always needed. Very recently, Shin *et al.* also demonstrated an alternative approach to fabricate a pressure sensor array filled with an air dielectric layer using folding panels (Fig. 4f). The sensor can be used successfully over a vast interval in tactile sensing, as shown in Fig. 4g. Hence, all the above results established that pressure sensing devices are arising as a promising candidate to monitor human movements, individual healthcare, and wellness.

### 3.2. Strain sensors

While a person moves, small and large deformations occur. Now, wearable strain sensors must be able to precisely detect and continuously monitor the movements of the targeted organs in the human body, whether these movements are generated by the faint vibration of the vocal cords or the activities of the joints. Therefore, the need for flexible strain sensors arises. Due to the flexibility requirements, the strain sensors must consist of a flexible and stretchable material, which distinguishes them from conventional silicon-based strain sensors.[78–81]

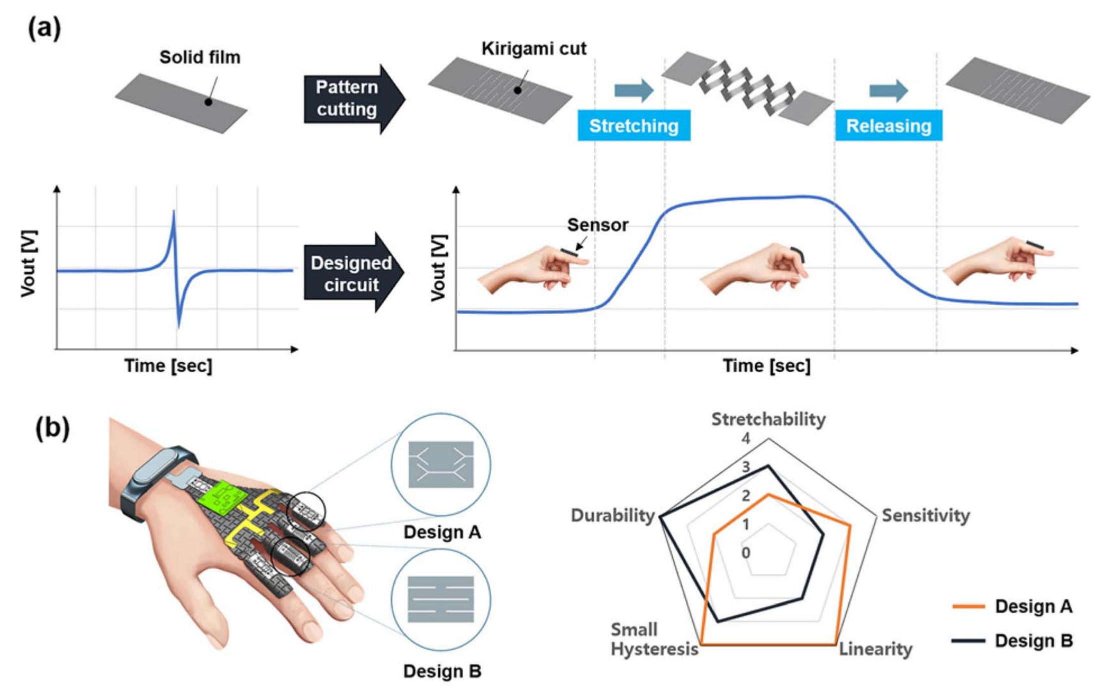


Fig. 5 Concept of the kirigami piezoelectric strain sensor. (a) Strain sensing mechanism. (b) Sensor property design with kirigami patterns. Reproduced from ref. 80 and 82. With permission from [MDPI], copyright [2025] & npj Flexible Electronics 2022.

Table 1 Summary of pressure sensors based on sensing elements

| Sensing element | Substrate | Mechanism | Sensitivity | Detection limitation |
|---|---|---|---|---|
| CNTs/leather | Leather | Piezoresistive | 8.03–32.42 $kPa^{-1}$ | 50 kPa (ref. 83) |
| MXene/$Ti_3C_2T_x$ | Paper | Piezoresistive | 3.81 $kPa^{-1}$ | 23 Pa–30 kPa (ref. 84) |
| AM/$MoS_2$/$Al_2O_3$ | Microchem SU8 | Piezoresistive | 0.011 $kPa^{-1}$ | 1–120 kPa (ref. 85) |
| Nanoparticles | PET | Piezoresistive | 0.13 $kPa^{-1}$ | 0.5 Pa (ref. 86) |
| Graphene oxide | PDMS | Piezoresistive | 25.1 $kPa^{-1}$ | 0–2.6 kPa (ref. 87) |
| Carbon/MXene | PET | Piezoresistive | 12.5 $kPa^{-1}$ | 0–10 kPa (ref. 88) |
| SF@MXene | PET | Piezoresistive | 25.5 $kPa^{-1}$ | 0.1–20 kPa (ref. 89) |
| MXene/PVDF | PDMS | Capacitive | 0.51 $kPa^{-1}$ | 0–400 kPa (ref. 90) |
| Ferrite | Fabric | Capacitive | 0.19 $kPa^{-1}$ | 0–20 kPa (ref. 91) |
| $MoS_2$/$WSe_2$ | PET | Capacitive | 44 $kPa^{-1}$ | 0–5 kPa (ref. 92) |
| Conductive fiber | Paper | Iontronic | 1.0 nF $kPa^{-1}$ $cm^{-2}$ | 5.12 Pa–200 kPa (ref. 93) |
| Cellulose fiber | Paper | Iontronic | 10 nF $kPa^{-1}$ $cm^{-2}$ | 6.25 Pa (ref. 94) |
| ZnO | PDMS | Piezoelectric | 84.2–104.4 meV $MPa^{-1}$ | 0–1 Mpa (ref. 95) |
| PVDF-HFP/PEDOT | PET | Piezoelectric | 13.5 $kPa^{-1}$ | 1 Pa–30 kPa (ref. 96) |
| ZnO | Cr/Au | Piezoelectric | 60.97–78.23 meV $MPa^{-1}$ | 2 kPa–3.64 MPa (ref. 97) |

Fig. 5 shows the working mechanism of the piezoelectric kirigami strain sensor. The piezoelectric film was cut according to a kirigami pattern, and the structural deformation of each cut segment resulted in extensibility. Since the fabricated sensor uses a piezoelectric material, the output voltage generated can be measured to detect strain. When the load is unloaded, the voltage drops to zero. Typically, the voltage spike generated by the piezoelectric materials cannot be measured because it disappears quickly. The designed circuit can accurately measure and maintain the output voltage over a specific period. This feature allows the use of piezoelectric materials as strain sensors. Fig. 1a shows a wearable sensor attached to the fingers. The sensors stretch when the fingers are bent and return to their original shape when unfolded. This means that movement can be detected by analyzing the output voltage. Fig. 5b shows the advantages of the piezoelectric kirigami strain sensor. Sensors with different kirigami designs have different properties, including stretchability, sensitivity, linearity, hysteresis, and durability. The kirigami pattern can be designed to meet the target characteristics requirements for different

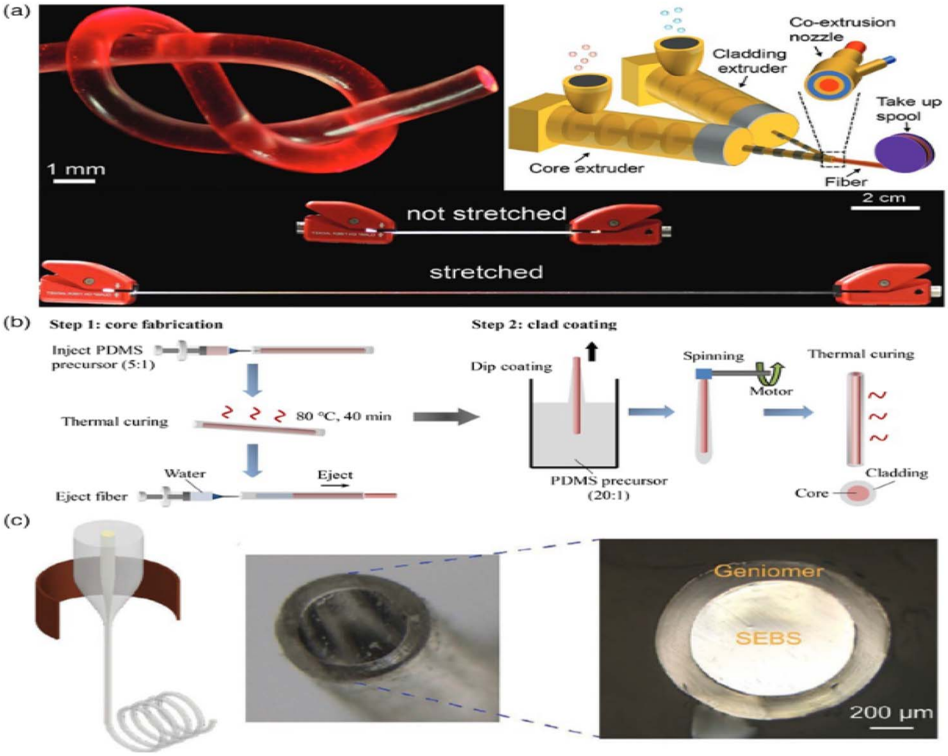


Fig. 6 Stretchable optical strain sensors are being manufactured. (a) The optical waveguides made of stretchable thermoplastic elastomer undergo coextrusion. (b) Stretchable optical fibers are made in two steps using a core/cladding step-index structure. (c) Using heat drawing to create superelastic multimaterial optical fibers. Reproduced from ref. 106. With permission from [WILEY], copyright [2019].

 

Table 2 Summary of main characteristic parameters of strain sensors based on sensing element and elastic substrates

| Sensing material | Substrate | Mechanism | Gauge factors | Stretchability |
|---|---|---|---|---|
| $SnS_2$ | PDMS | Piezoelectric | 23–3933 | 1.4% (ref. 108) |
| Ag/PU | PDMS | Capacitive | 12 | 0–40% (ref. 109) |
| VNO | PDMS | Piezoresistive | 2667 | 0–100% (ref. 110) |
| PDMS–PDCA | SEBS | Piezoresistive | $5.75 \times 10^5$ | 100% (ref. 111) |
| GO/AgNWs | Sponge | Piezoresistive | 1.5 | 0–60% (ref. 112) |
| SWCNTs | PDMS | Piezoresistive | 2 | 60% (ref. 113) |
| MWCNTs | PDMS | Piezoresistive | 7.22 | 40% (ref. 114) |
| MWCNTs | TPU | Piezoresistive | 1.5–3 | 50% (ref. 115) |
| GO | Paper | Piezoresistive | 66.6 | 6% (ref. 116) |
| MCG | Paper | Piezoresistive | 73 | 0.25% (ref. 117) |
| Carbonized paper | Paper | Piezoresistive | 0.14–10.1 | 5% (ref. 118) |
| CB/CNT | Paper | Piezoresistive | 7.5 | 0.7% (ref. 119) |
| SACNT | PDMS | Piezoresistive | 0.1 | 400% (ref. 120) |
| EGaIn | Silicone | Piezoresistive | 2.5 | 0–100% (ref. 111) |

applications, and different kirigami patterns can achieve different sensor characteristics to target different body parts (Table 1).[82]

## 4. Promising state-of-the-art strain sensing applications

Flexible stress-sensitive materials have a lot of potential uses because of their exceptional flexibility and fit, particularly in the monitoring of stresses and stress distributions on surfaces with three-dimensional irregularly curved structures. As illustrated in Fig. 6. Applications with varying voltage ranges frequently use flexible materials for voltage measurement.[98–104] Ultra-low load (<1 Pa) signal monitoring applications include: B. recording of sound; acquisition of signals under low stress (<1 kPa), e. G. B. low-stress signal detection (<10 kPa), which includes motion monitoring during daily activities, high-sensitivity electronic skin, touchpad, and medium-pressure signal acquisition (<100 kPa), which provides for plantar pressure acquisition. According to their intended use, wearable, flexible stress sensors are primarily used in flexible motion and gesture detection,[105] wearable robotics, touch switches, electronic skin, and human physiological signal monitoring. These areas are covered in brief below. The various strain-sensing mechanisms of resistive,[107] capacitive, and optical strain sensors are described in this section. When capacitive and optical sensors are stretched, their dimensional changes serve as the primary sensing mechanism. Stretchable resistive-type strain sensors have been effectively created by the disconnection of micro-/nanomaterials, tunnels, and the inherent resistive response of the materials themselves and geometrical effects (Table 2).

### 4.1. Human physiological signal & motion, and gesture recognition

The flexible wearable stress sensor can evaluate and provide real-time and long-term feedback on individual physiological

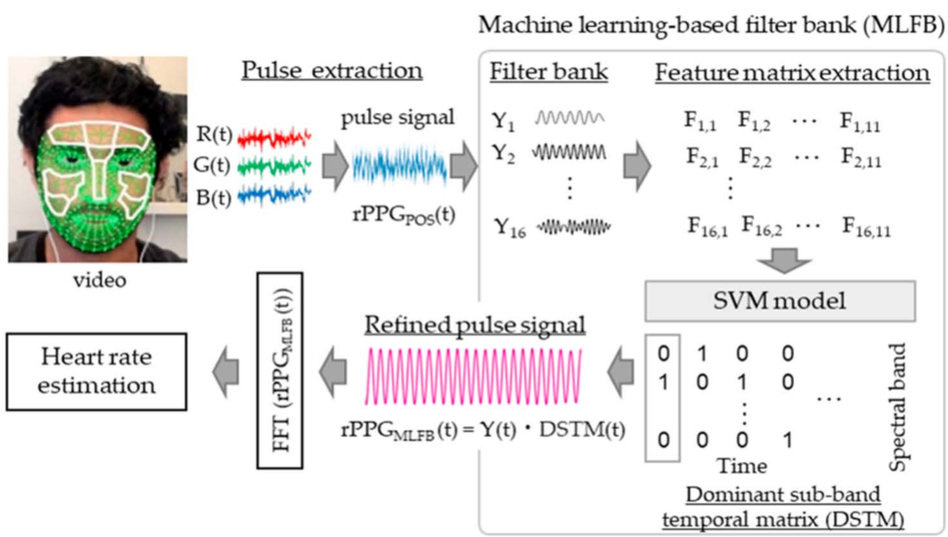


Fig. 7 Shows the proposed machine learning-based filter bank (MLFB) algorithm. The pulse signal of remote photoplethysmography (rPPGPOS) is derived using the plane-to-orthogonal-skin (POS) algorithm. The signal is then processed through a 16-subband filter bank, and the feature matrix is computed. Reproduced from ref. 130. With permission from [MDPI], copyright [2024].

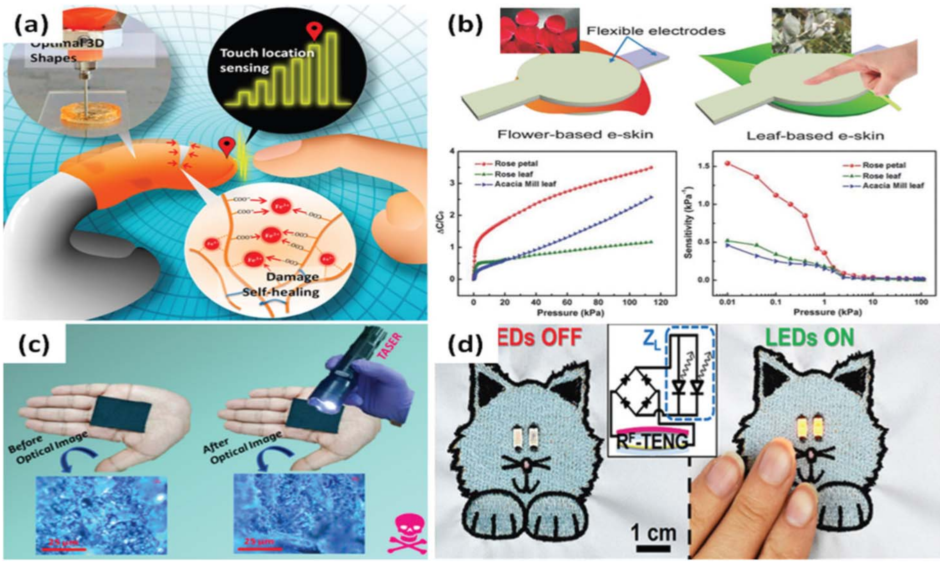


Fig. 8 (a) A 3D-printed fingertip-shaped artificial skin device capable of sensing precise touch locations and autonomously healing mechanical damage. (b) Schematic representation of an e-skin composed of two electrodes with a natural material (flower or leaf) serving as the dielectric layer. The graphs illustrate the capacitance changes and sensitivity for three types of e-skins based on critical point-dried rose petals, rose leaves, and acacia leaves. (c) Soft-touch textile sensors undergo a high-voltage TASER test to neutralize electrical shocks. (d) Omniphobic triboelectric nanogenerators (RF-TENGs) are made from e-textiles shaped like a cat, powering two LEDs embroidered as eyes when touched. Reproduced from ref. 154. With permission from [Taylor & Francis open access], copyright [2020].

data, eliminating the burden of heavy instruments and the need for complicated cables. It can continuously perceive, acquire, and transmit physiological signals[121] such as blood pressure without affecting the human body's daily activities. Thus, it can offer personal insight into medical treatment.[122–126] Researchers have designed and developed various flexible stress sensors that monitor the body's pulse, blood pressure, and respiratory rate. As shown in Fig. 7a, Wu J. *et al.*[127] designed a flexible stress sensor with a micro-hair structure that fits nicely on the surface of the human body. It uses the micro-hair structure to adhere to the skin and monitor its depth. To observe the pulsation of blood vessels, Xiao H. *et al.*[128] the sensor was integrated with the breathing mask to form a device that can monitor the human respiratory rate and accurately observe the breathing process in various human body states in real-time (Fig. 7b). Abdulrahaman L. Q. *et al.*[129] prepared a bending-insensitive stress sensor based on graphene and carbon tube composites, which can continuously monitor the pressure on the artificial heart and blood vessel wall in real time without being affected by activities such as human limb bending.

Statistics show that language transmits approximately 7% of the information when humans communicate, while expressions and physical movements convey about 50% of the messages. Therefore, facial expression recognition and gesture recognition have become increasingly prominent areas of research. A flexible and lightweight stress–strain sensor matrix is placed on the face or different joints to analyze the human body's expression and posture.[131–133]

**4.1.1. Electronic skin sensors.** Electronic skin is a flexible sensor device that mimics the human skin's perception and collection of external stimulus signals. Its main feature is the real-time ability to monitor stress distribution at pixel points on the 3D surface.[134–138] Similar to electronic skin, after integration, the trajectory of a finger or other object moving on the sensor can be observed, and the sensor array can also record the stress between them, allowing for its application in the flexible touch field.[139–143] Touch-sensing systems that mimic the stretchability and tactile sensing capabilities of human skin, along with additional features, are referred to as e-skins. Key application areas of the e-skins are skin-attachable devices, prosthetics, and robotics. Ultrathin material-based e-skins, such as poly(ethylene terephthalate) (PET), are a good choice for small, sustainable deformations, as shown in Fig. 8. However, elastomer substrates such as poly(polydimethylsiloxane) (PDMS), latex, and polyurethane (PU) are preferred for applications with stretchable requirements.[144] Asghar *et al.*[145] have demonstrated a piezo-capacitive flexible pressure sensor using magnetically grown microstructures (MPs/PDMS). Park *et al.*[146] developed a three-dimensional, fingertip-shaped artificial skin device (Fig. 7a) with a sizable electronic signal contact upon touch, utilizing capacitive sensing technology. It can sense the exact location of the touch and heal mechanical damage spontaneously. The touch device shows a good combination of 3D printing and ion-conductive hydrogel.[147–154] During the operation, e-skins can wear and tear over time. One solution to this is the use of self-healing materials. Energy self-sufficiency can be achieved by incorporating phototransduction and photosensory functions, as observed in the photosynthesis of plants.[155–161]

## 5. Challenges in wearable strain sensing technology

The intelligent use of flexible and stretchable wearable sensors has driven remarkable progress in this field over recent years.

 

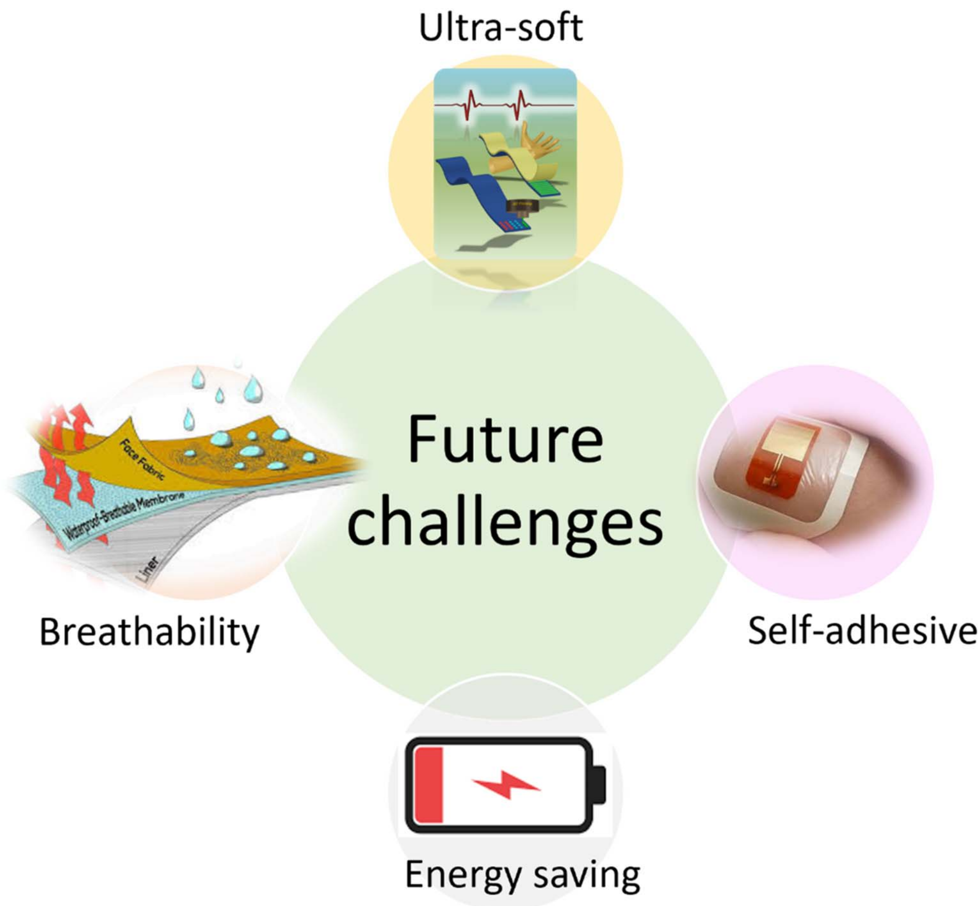


Fig. 9 Trends: future Challenges in various prospects.

The latest technological advancements have demonstrated that sensing conductors hold immense promise for various applications, particularly in detecting human body motion. This is achieved by measuring resistance changes, which translate into measurable variations in electric current under mechanical distortions. As a result, an entirely new sector of consumer healthcare has emerged. Once considered theoretical, many health-focused sensing devices have become a reality. However, significant challenges remain on the path toward achieving greater precision and expanding the diversity of applications. A deep understanding of the transduction mechanism is crucial for advancing the development of more innovative and versatile devices. This mechanism is essential for enhancing detection accuracy and improving the gain factor of the transduced signals generated by deformations. Recent studies have identified several mechanisms responsible for resistance and current variations in strain sensors, including piezoresistivity, connection–disconnection mechanisms, geometric effects, and quantum tunneling effects. The human skin's complex structure, particularly the stratum corneum, serves as a natural barrier that complicates the detection of mechanical strain. The skin's viscoelastic properties, influenced by hydration, age, and body location, result in nonlinear stress–strain responses, making it challenging to obtain accurate and consistent measurements. The skin's damping effect and frequency-dependent resistance to mechanical loads further reduce sensor sensitivity, especially during dynamic movements (Fig. 9).

Many strain sensors struggle to strike a balance between high stretchability and high sensitivity. Materials like graphene and carbon nanotubes offer excellent conductivity but often suffer from weak bonding to substrates, leading to instability under repeated strain. Durability and stability can cause material degradation, reducing sensor lifespan. 3D printing and inkjet printing are promising but face challenges in achieving uniform material deposition and high-resolution patterning for wearable applications. Most wearable strain sensors rely on batteries, which limit longevity and comfort. The scientific community must focus on refining its understanding of these mechanisms and the robust mechanical properties of materials to design highly effective sensors for monitoring specific human organs. Without such advancements, the current limitations could pose significant risks to individuals relying on these technologies. In severe circumstances, a secure data read-write mechanism and a stable and diverse signal output are vital for precise data measurement in real-world applications. Relying solely on robustly conductive wires as critical electrodes for sensor electrodes to obtain human activity signals is incompatible and impractical for implantable devices.

## 6. Conclusions and outlooks

A comprehensive analysis of recent advancements in artificial intelligence and wearable strain sensors has been undertaken, incorporating novel innovations and sophisticated applications within this domain. A thorough examination of recent advancements in artificial intelligence (AI) and wearable strain sensors has been conducted, highlighting innovative developments and advanced applications in this field. By evaluating recent studies from relevant research papers, the current state of the technology has been elucidated, offering insights into the microscopic physical mechanisms that govern strain responsiveness in these sensors. Various conventional and novel methodologies, including nanoparticle decomposition, morphological film variability, and quantum tunneling effects, have been employed to design highly efficient and flexible strain sensors. Over the past few decades, wearable strain sensors have seen significant progress, driving remarkable advancements in pressure sensor technology. The rise of organic electronics has further accelerated the development of highly sensitive and flexible pressure sensors, paving the way for ultrasensitive, stretchable, and adaptable pressure sensors ideal for wearable health and wellness monitoring applications.

The development of stretchable and flexible strain sensors exhibits considerable promise in various disciplines, including biomedicine, robotics, and entertainment. Nonetheless, several pertinent concerns necessitate resolution, including mitigating performance degradation, minimizing attachment resistance, eliminating hysteresis, ensuring durability and packaging, and enhancing compatibility with wearable technologies. Integrating artificial intelligence into healthcare delivery systems also presents opportunities and challenges, warranting further research in this domain. The advancement of intelligent, flexible wearable devices is heavily contingent upon developing interconnected modules encompassing energy, storage, transmission, and other essential functionalities. Consequently, comprehensive investigations into the stability, size, weight, and other key attributes of these devices are requisite to guarantee optimal performance, comfort, and usability.

## Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

## Conflicts of interest

The authors declare no conflict of interest.

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