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Bibliometric review on flexible pressure sensor design strategies†

Xin Li, ‡[a,b] Qisheng Yang, ‡[a,c] Zetian Zhao,‡[a] Mingyuan Li,‡[c] Yuhan Zhao,‡[a] Jiarong Fan,‡[a] Qi Mao,[e] Xudong Fang,*[d] Daixuan Wu,*[a] Jingbo Liu,*[e] Hao Guo *[b] and He Tian *[a]

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Flexible pressure sensors have developed rapidly in recent years, with wide applications in wearable devices, healthcare, human–machine interaction, and other fields, showing great potential. Multiple cluster analyses of the relevant literature were performed using bibliometric methods to provide a comprehensive understanding of the research progress in this area. Additionally, the annual publication trends were analyzed, showcasing breakthrough technological developments in flexible pressure sensors. This review provides a comprehensive overview of the evolution of flexible pressure sensors, with a focus on the latest advancements in materials, device design, and system integration. Special attention is given to the recent advancements in conductive gels and liquid metal materials, which have seen rapid progress in recent years. Despite the significant progress made, there are still key challenges to address in order to further advance flexible pressure sensors. Finally, the review concludes with a discussion on the future outlook of this rapidly evolving technology.

1. Introduction

The rapid evolution of intelligent technologies has led to the widespread integration of flexible electronic materials,[1,2] smart home systems,[3] and the Internet of Things[4,5] into everyday life. This evolution is driving significant innovation and transformation across various sectors. Among the key technological advancements, flexible pressure sensors have attracted considerable attention from both academic researchers and industry professionals.[6] Their exceptional mechanical and electrical properties make flexible pressure sensors highly promising for a range of applications. Characterized by high flexibility, sensitivity,[7–10] and resolution,[11] and rapid response times,[12] they are particularly well-suited for use in human–machine interfaces,[13] soft robotics,[14,15] electronic skin,[16,17] and healthcare monitoring.[18,19] With ongoing breakthroughs in related technologies, the industrialization of flexible pressure sensors is accelerating.

As research in this area grows rapidly, traditional methods of literature review are insufficient for keeping up with the vast amount of information. Bibliometrics enables the systematic analysis of the literature to uncover the underlying patterns and trends in the development of academic disciplines.[20] Bibliometric research involves cluster analysis and includes citation analysis, co-citation analysis, bibliographic coupling, co-authorship analysis, and co-word analysis.[21] Citation analysis primarily examines citation relationships between publications. Analysis of the frequency and patterns of academic citations can identify significant works and core researchers within a specific discipline or field. Co-citation analysis helps identify research themes and knowledge structures within academic fields by analyzing documents that are frequently cited together. Existing bibliometric studies have primarily focused on the quantitative analysis of individual indicators, lacking a comprehensive exploration of complex disciplinary networks and dynamic developments.[22–24] This review aims to offer a holistic analysis of the core topics and development trends in the field of flexible pressure sensing through the application of bibliometric methods, providing valuable insights and guidance for future research.

[a]*School of Integrated Circuit and Beijing National Research Center for Information Science and Technology (BNRist), Tsinghua University, Beijing 100084, China. E-mail: tianhe88@tsinghua.edu.cn, Xymems@stu.xjtu.edu.cn*
[b]*State key Laboratory of Extreme Environment Optoelectronic Dynamic Testing Technology and Instrument, North University of China, Taiyuan 030051, China. E-mail: guohao@nuc.edu.cn*
[c]*College of Semiconductors (College of Integrated Circuits), Hunan University, Changsha 430001, China*
[d]*School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China. E-mail: dongfangshuo30@xjtu.edu.cn*
[e]*School of Energy and Automotive Engineering, Shunde Polytechnic, Foshan 528000, People's Republic of China. E-mail: liu.jingbo@qq.com*
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‡These authors contributed equally to this work.

The design and evolution of flexible pressure sensors have continuously advanced alongside developments in materials science, electronic engineering, and nanotechnology. Through bibliometric methods, this paper systematically traces the research dynamics in this field. Using the CiteSpace bibliometric analysis tool and the relevant literature from the Web of Science Core Collection, this study performs a visual analysis of research outcomes in the domain of flexible pressure sensors. This approach offers an intuitive representation of current hot topics and emerging research trends. Specifically, this work focuses on the development history and technological advancements of flexible pressure sensors in the areas of materials, devices, algorithms, and systems. By combining the results of bibliometric analysis, it also explores the future development potential of these areas. Additionally, the paper predicts the challenges and technological bottlenecks that the field of flexible pressure sensors may face, offering insights and directions for future research. This comprehensive analysis contributes to a deeper understanding of the current state of research in flexible pressure sensors and provides a scientific foundation for innovation and industrialization in related fields.

2. Literature review methodology

We retrieved the latest research data on flexible pressure sensor design from the Web of Science Core Collection, encompassing a total of 78 271 records published between 2014 and November 21, 2024, along with their cited references. The search query used for this retrieval was: "TS = ((wearable or flexible) sensor* AND (design) AND (pressure))". To conduct a comprehensive analysis of the research trends and emerging hotspots in this field, we performed a bibliometric analysis using CiteSpace v6.1.R6 (Advanced Edition). As a specialized bibliometric tool, CiteSpace enables the systematic identification and visualization of the knowledge structure and evolutionary trajectory within a specific research domain. By utilizing this tool, we conducted a cluster analysis on all the relevant literature, revealing key research themes and their development over time. CiteSpace automatically generates clusters by analyzing the co-occurrence of the literature, citation relationships, and keywords, grouping related studies based on their similarities. Each cluster represents a distinct research theme or area.[25,26] Furthermore, CiteSpace provides trend graphs for each research cluster, along with statistical data on core papers and influential authors. These features allow for a deeper understanding of the historical context, current focal points, and potential future directions of research in the field. Through these analyses, we are able to clearly outline the major research trends in flexible pressure sensor design, predict possible future developments, and offer valuable insights for researchers in the field. The cluster analyses were conducted separately for the periods 2014–2019 and 2020–2024. Fig. 1 presents the cluster map for the period 2020–2024. To generate the citation co-citation network and identify clusters, CiteSpace applies a modularity optimization algorithm to the co-citation relationships between documents. The algorithm detects tightly connected groups of documents based on their co-citation patterns, which are then classified into distinct clusters, each representing a unique research theme. The algorithm evaluates the similarity between documents based on their co-citation frequency, grouping documents that share common citations. The resulting clusters are visually represented in a network map, where each node represents a document or keyword, and the edges reflect their co-citation relationships. In the figure, the size of each node represents the frequency of occurrence of the corresponding keyword. As the frequency increases, the size of the node's circle also enlarges. High-frequency keywords are generally consistent with those located at the core of the clusters, indi-


Xudong Fang

Xudong Fang is currently a professor at the School of Mechanical Engineering, Xi'an Jiaotong University (XJTU), China. He received his BSc and MSc in mechanical engineering from XJTU, and Ph.D. in materials science and engineering from Georgia Institute of Technology, USA. Following the completion of his Ph.D., he joined XJTU, where he continues to work. His research interests include MEMS sensors, micro/nano manufacturing and measurement, flexible electronics, etc.


Daixuan Wu

Daixuan Wu received her Ph.D. in engineering from the University of Pennsylvania. She previously served as Chief Engineer at AVIC gyroscope (Xi'an) Optoelectronic Technology Co., Ltd, and is currently a researcher at the School of Integrated Circuits, Tsinghua University. She holds positions as a Master's supervisor at Xi'an Jiaotong University and a Ph.D. supervisor at Xiamen University. She has long been engaged in research on MEMS sensors and low-dimensional materials. Dr Wu has participated in the design of over 40 different models, covering fields such as aviation, aerospace, weaponry, and naval engineering.

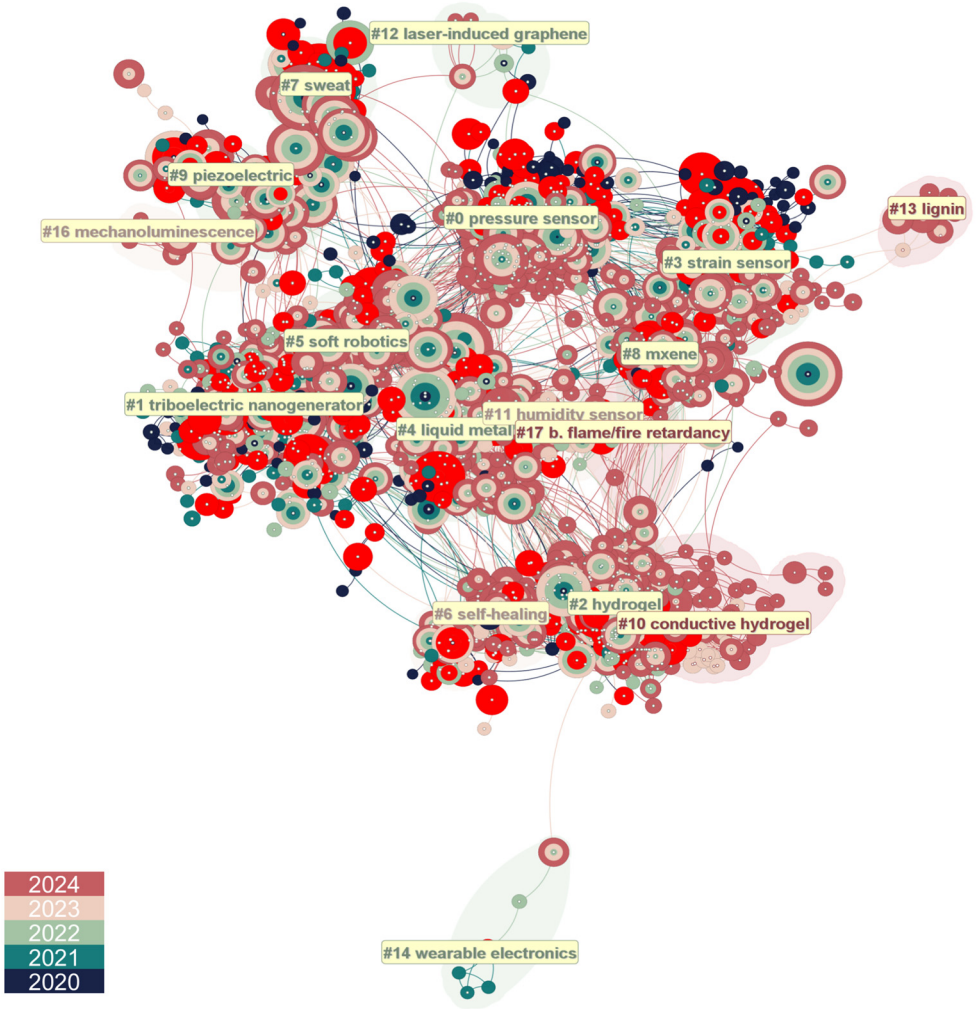


Fig. 1 Citation clusters mapping and historical roadmap (2020–2024) in terms of research trends and key topics.

Jingbo Liu

Jingbo Liu is currently an Associate Professor at Shunde Polytechnic. He received his Ph. D. degree from the University of Electronic Science and Technology of China in 2016. He was awarded the National Natural Science Foundation of China grant and conducted post-doctoral research at Xi'an Jiaotong University and Dongguan University of Technology. His research focuses on terahertz imaging technology, two-dimensional nanomaterials, and their applications in electronic devices.

Hao Guo

Hao Guo is currently a full professor at the School of Instrument and Electronics, Instrument Science and Technology, North University of China. He obtained his Ph.D. degree (2016), Master's degree (2013), and Bachelor's degree (2010) in Instrument Science and Technology from North University of China. He was selected for the Postdoctoral Innovation Talents Support Program and won the National Excellent Doctoral Thesis Nomination Award of China Instrument and Control Society. His research interests focus on micro- and nano-scale quantum sensing and precision measurement and integration and application of micro and nano devices.

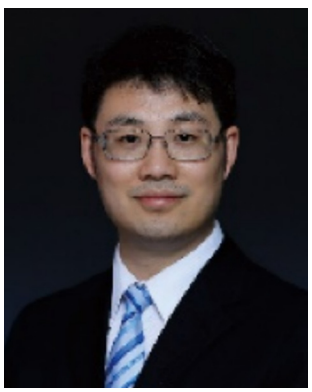
Table 1 Top 5 most cited articles in the field of flexible pressure sensing (from 2014 to present)

Citation counts	Article	DOI	Research focus
1092	Gao W, 2016, *Nature*[27]	https://doi.org/10.1038/nature16521	Flexible wearable sensor array; multiplexed perspiration analysis
713	Gong S, 2014, *Nat. Commun.*[28]	https://doi.org/10.1038/ncomms4132	Ultrathin gold nanowires
669	Amjadi M, 2014, *ACS Nano*[29]	https://doi.org/10.1021/nn501204t	Silver nanowire–elastomer nanocomposite
541	Wang SH, 2018, *Nature*[30]	https://doi.org/10.1038/nature25494	Intrinsically stretchable transistor array
494	Hua QL, 2018, *Nat. Commun.*[31]	https://doi.org/10.1038/s41467-017-02685-9	Stretchable and conformable matrix network

cating that keywords with a higher frequency tend to be positioned at the center. The centrality of keywords can, to some extent, reflect shifts in research hotspots and key turning points, revealing the evolving trends in this field across different time periods. Fig. S1 and S2† provide an insightful analysis of author collaboration patterns in the field of flexible pressure sensors. Panel A of both Fig. S1 and S2† shows the clustering of authors based on their collaborative relationships, with the clusters being defined according to relevant keywords. Panel B of both figures presents the authors corresponding to these clusters. Based on the results of our clustering analysis, we observe that the Zhonglin Wang team from the Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, stands out as the most influential in this field, with significant contributions to the development of flexible pressure sensors, particularly through their work on triboelectric nanogenerators (TENGs). Additionally, Fig. S3† presents a cluster analysis of Web of Science subject categories for two time periods: (a) 2014–2019 and (b) 2020–2024. The results show that research in the field of flexible pressure sensors is primarily concentrated in disciplines such as physics, chemistry, energy, nanoscience, and engineering. With the advancement of machine learning, the field of computer science has also become increasingly integrated into flexible pressure sensor research.

Additionally, Table 1 presents the top five most-cited articles in this field (from 2014 to present), providing further insights into influential research papers that have significantly contributed to the development of flexible pressure sensing technologies. The papers by Gao W (2016),[27] Gong S (2014),[28] and Amjadi M (2014)[29] are particularly noteworthy for their groundbreaking approaches to material selection and integration, which have propelled the capabilities of wearable pressure sensors. Gao's work on a flexible wearable sensor array that enables multiplexed perspiration analysis has set the standard for non-invasive health monitoring, showing the potential for real-time, personalized healthcare. Gong's use of ultrathin gold nanowires to create flexible and highly conductive sensor materials has opened new avenues for highly responsive and durable sensors. Meanwhile, Amjadi's research on silver nanowire–elastomer composites demonstrates an innovative material design that combines the flexibility of elastomers with the high conductivity of silver nanowires, improving sensor performance under mechanical deformation. Furthermore, the contributions of Wang SH (2018)[30] and Hua QL (2018)[31] highlight the progression towards more complex and adaptable sensor systems. Wang's intrinsically stretchable transistor array presents a significant leap in integrating stretchable electronics with flexible sensors, creating a path for sensors that can maintain performance over a wide range of deformations. Hua's development of a stretchable and conformable matrix network also brings new opportunities for creating adaptable sensor arrays that can fit diverse surfaces, enhancing the application potential of flexible pressure sensors in dynamic environments.

The number of articles published from 2014 to the present is shown in Fig. 2. Except for the year 2020, the overall trend of article numbers has been steadily increasing year by year, indicating that the design of flexible pressure sensors is undergoing steady development. This trend can be divided into two phases: (1) 2014–2019: the number of articles increased annually. During this period, flexible pressure sensors, as an emerging technology, attracted increasing attention and research, indicating that the field was developing rapidly. Both academia and industry showed growing interest in the technology. (2) 2020–2024: this growth further demonstrates the rapid development and widespread application of flexible pressure sensor technology, especially in fields such as smart wearable devices, medical monitoring, robotics, and artificial intelligence, where demand is growing rapidly. The development of flexible sensor technology has also benefited from interdisciplinary collaborations, particularly advances in materials science, electronics, and nanotechnology, which have pro-



He Tian

He Tian received his Ph.D. degree from the Institute of Microelectronics, Tsinghua University in 2015. He is currently a Tenured Associate Professor and Deputy Director at the Institute of Integrated Electronics, School of Integrated Circuits, Tsinghua University. He is a recipient of the National High-level Leading Talents, National Outstanding Youth Foundation and Highly Cited Scholar in Web of Science 2024. His current research interests include various 2D material-based devices. He has more than 250 publications and has been cited for more than 10 000 times.

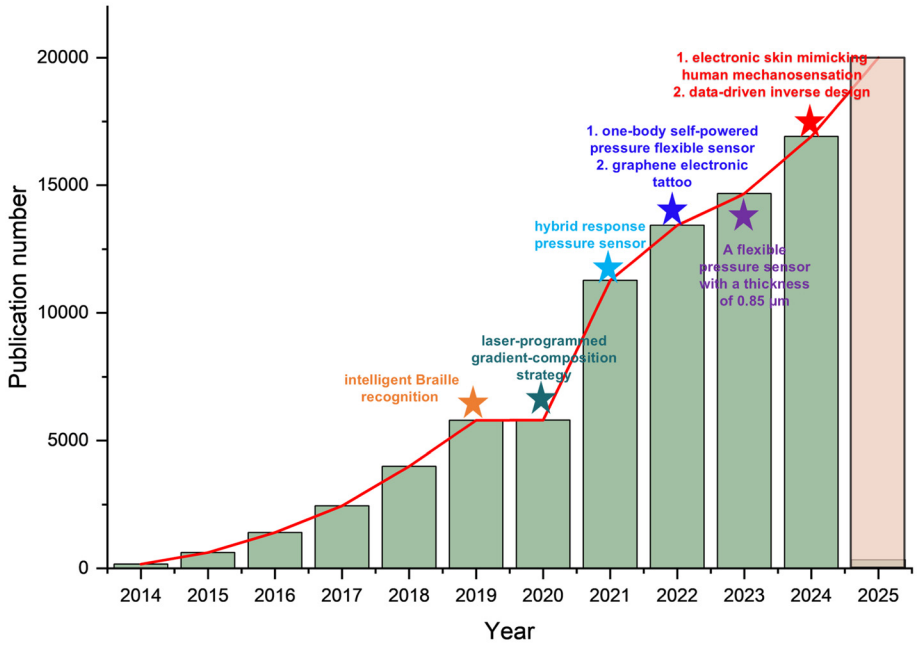


Fig. 2 Annual publication trends with key breakthroughs in flexible pressure sensing technologies.[32–39]

pelled the rapid progress of the technology. The development stagnated in 2020, possibly due to the following reasons: (1) the global pandemic impact: the large-scale outbreak of COVID-19 in 2020 led to certain disruptions in global scientific research activities. (2) Publication delay: some research results from 2020 may not have been published until 2021, which could explain the slower growth observed in the statistical data for 2020. The figure also highlights key advancements in the field of flexible pressure sensors. In 2019, researchers introduced an intelligent Braille recognition technology, which improved the efficiency and accuracy of Braille reading through skin-like sensors.[32] In 2020, the laser-programming gradient composition strategy was proposed, which utilized programmable gradient composition control to achieve an enhanced sensitivity effect for flexible pressure sensors, providing a new direction for sensor performance improvement.[33] In 2021, the "composite response" pressure sensor (HRPS) developed by the team of Lu was published in *Advanced Materials*, demonstrating high sensitivity over a wide pressure range, especially excelling in detecting small pressures.[34] In 2022, graphene electronic tattoo technology achieved a breakthrough, utilizing a heterogeneous serpentine strip structure to detect skin electrical activities on the palm without interference.[35] In the same year, a self-powered pressure sensor was proposed, solving the issue of needing external power for traditional sensors by using a zinc-ion battery for self-supply, thereby improving the device's durability.[36] In 2023, research on ultra-thin flexible pressure sensors made new progress, achieving ultra-high sensitivity and extremely low detection limits with a structure using carbon nanotube conductive layers and ultra-thin electrode layers.[37] In 2024, researchers proposed a three-dimensional structural electronic skin technology mimicking human mechanosensation. The spatial distribution of force and strain sensors in its structure emulates the arrangement of Merkel cells and Ruffini corpuscles found in human skin.[38] In the same year, a data-driven inverse design approach for flexible pressure sensors was also introduced, enabling the rapid generation of multiple solutions that exhibit a wide-range linear response across various materials.[39] These continuous breakthroughs signal a broad future for flexible pressure sensors in various fields, including healthcare, robotics, and wearable devices.

Through the analysis of multiple clusters, we have extracted the key research directions in this field and summarized them into several representative themes. Each theme encompasses various research hotspots and technological developments, ultimately leading to four core development trends: flexible pressure sensing materials, flexible pressure-sensing devices, algorithmic design, and intelligent sensing systems.

3. Flexible pressure sensing materials

Flexible pressure sensing materials have gained significant attention due to their versatility, adaptability, and integration capabilities in various emerging technologies.[40,41] These materials are designed to detect and respond to applied pressure while maintaining flexibility, making them ideal for use in soft robotics, wearable devices, and medical applications.[42] Depending on their functional properties, these materials can be classified into three main categories: conventional flexible pressure sensing materials, self-healing flexible pressure sensing materials, and multifunctional flexible pressure sensing materials. In the following sections, we will

Table 2 Comparison of flexible pressure sensing materials

Material category	Materials/bonding mechanism	Mechanism	Advantages	Disadvantages	Ref.
Conventional flexible pressure sensing materials	Carbon-based materials	Electron conduction	Relatively light	Not suitable for large-scale production	44, 45, 48, 49, 53 and 54
	Metal nanomaterials	Electron conduction	Strong conductivity	Prone to oxidation	46 and 52
	Polymeric materials	Electron and ionic conduction	Tunable conductivity	Prone to mechanical degradation	47, 70, 71 and 72
Self-healing flexible pressure sensing materials	Borate ester bond, Schiff base reaction	Dynamic covalent bonds	Strong bond, providing stability and durability	Slow healing or reformation; requires high energy or specific conditions	81, 82 and 83
	Hydrogen bonding, ionic interaction	Non-covalent interactions	Quick healing due to weaker interactions	Weaker interactions, leading to lower stability and durability	84, 85 and 86
Multifunctional flexible pressure sensing materials	GO and hydrogels	Electron and ionic conduction	Multiple physical mechanisms for sensing	Potential interference between physical fields, poor testing outcomes	106, 107 and 108

delve deeper into each of these classifications, exploring their characteristics, advantages, and potential uses in advanced technologies. A comparison of these flexible pressure sensing materials is presented in Table 2.

3.1 Conventional flexible pressure sensing materials

Conventional flexible pressure sensing materials mainly focus on pressure sensing functionality without additional intelligent or multifunctional features. These materials are typically composed of conductive fillers and elastic substrates, forming the foundation of stretchable electronic devices. In terms of conductive fillers (as shown in Fig. 3),[43] carbon-based materials,[44,45] metal nanomaterials,[46] and polymeric materials[47] have been widely studied. Carbon nanotubes (CNTs)[48,49] and graphene,[50] as typical carbon-based materials, are extensively used in stretchable strain sensors due to their excellent electrical conductivity, mechanical strength, and good flexibility.[44] CNTs, with their high aspect ratio and conductive properties, are ideal conductive fillers, particularly when constructing stretchable conductive networks, where they exhibit outstanding performance. Graphene, with its unique two-dimensional structure and excellent electrical properties, has also become a popular material for building high-performance strain sensors. Researchers have been able to scale up the production of high-quality graphene films using chemical vapor deposition (CVD) and solution processing methods. These films not only possess high conductivity but also demonstrate good mechanical compliance and stretchability, which make them suitable for applications in areas such as smart clothing and electronic skin. In the realm of metal nanomaterials, silver nanowires (Ag NWs) are widely used as conductive fillers due to their high electrical conductivity and flexibility.[51] The high aspect ratio and unique conductive properties of metal nanowires allow them to effectively enhance both the mechanical and electrical performance of sensors. However, silver nanowires are prone to oxidation in air and are sensitive to sulfur compounds in the environment, which limits their long-term stability.[52] In contrast, carbon-based materials, such as graphene and carbon nanotubes, exhibit superior chemical inertness and corrosion resistance, enabling them to maintain stability in various environments.[53] In terms of flexibility, graphene and carbon nanotubes demonstrate exceptional flexibility and mechanical strength due to their unique carbon bonding structures. The two-dimensional structure of graphene allows it to withstand significant deformation without fracturing, while carbon nanotubes, owing to their tubular structure, exhibit higher elasticity and can recover their original shape after deformation.[54] Silver nanowires, being metallic, are prone to fatigue and fracture after prolonged bending or stretching, which limits their mechanical performance compared with carbon-based materials. In terms of durability, graphene and carbon nanotubes show enhanced resistance to chemical degradation, maintaining their structural and chemical stability even in harsh conditions. Silver nanowires, by contrast, are more vulnerable to oxidation and chemical corrosion, particularly in humid or chemically polluted environments. Although coatings or composite materials can improve the durability of silver nanowires, these solutions often introduce additional complexity and cost.

Similarly, liquid metals, with their excellent compliance, self-healing properties, and good conductivity, have emerged as a new type of filler material, particularly suitable for flexible and stretchable sensor designs. Gallium-based alloys, such as eutectic gallium-indium (EGaIn),[55] have garnered attention for their exceptional conductivity, fluidity, self-healing ability, and zero volatility. The electrical conductivity of EGaIn alloy is approximately 3×10^6 S m^{-1}, which is comparable to that of conventional metals.[56] At the same time, due to its excellent thermal conductivity, EGaIn can be utilized as a coolant and thermal interface material, effectively managing device heat. For example, by applying a current, EGaIn generates Joule heating, which can be applied to heat devices; concurrently, the liquid metal can also function as a coolant, lowering the temperature of electronic components and preventing overheating. EGaIn readily reacts with oxygen in the air, forming

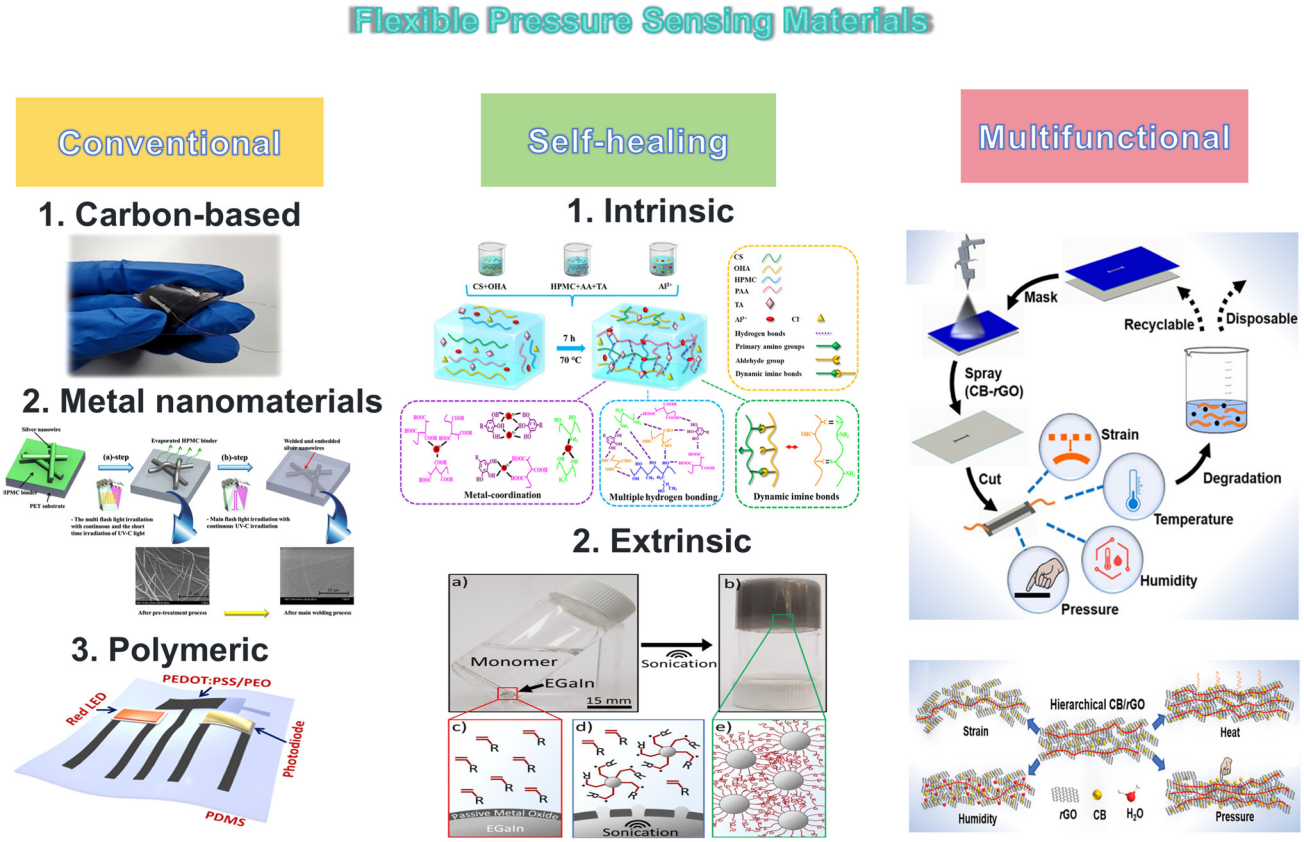


Fig. 3 Flexible pressure sensing materials: **Conventional materials:** (1) Carbon-based: schematic and structure of a flexible pressure sensor with LSG, two electrodes, and vertically integrated Eco-flex encapsulation. Reproduced from ref. 45 with permission from ACS, copyright 2020. (2) Metal nanomaterials: the schematic diagram for the welding mechanism of silver nanowire using combined flash white light irradiation. Reproduced from ref. 46 with permission from The Author(s), copyright 2016. (3) Polymeric: PEDOT : PSS-based stretchable polymer blend for wearable bioelectronic devices. Reproduced from ref. 47 with permission from ACS, copyright 2021. **Self-healing materials:** (1) Intrinsic: the CS/OHA/HPMC/PAA/TA/Al^{3+} hydrogel exhibits self-healing properties due to dynamic imine bonds, metal coordination, and reversible hydrogen bonding. This diagram illustrates the synthetic strategies for the preparation of the hydrogel. Reproduced from ref. 73 with permission from ACS, copyright 2024. (2) Extrinsic: liquid metal particles initiate free radical polymerization without traditional initiators. (a) Sonication breaks the liquid metal into small particles, exposing the metal and activating polymerization. (b) PAAm forms a physically cross-linked hydrogel. (c–e) Schematic of polymerization. Reproduced from ref. 75 with permission from ACS, copyright 2019. **Multifunctional materials:** degradable, multimodal flexible sensor fabricated from carbon black (CB) and reduced graphene oxide (rGO) for detecting multiple stimuli, including strain, humidity, temperature, and pressure. Reproduced from ref. 99 with permission from ACS, copyright 2019.

an oxide layer approximately 0.7–3 nm thick. This naturally formed oxide layer imparts good mechanical stability to the material.[57] Consequently, EGaIn can be processed into various shapes using methods such as photolithography, injection molding, and additive or subtractive manufacturing, making it suitable for applications in flexible devices, sensors, and printed circuits.[58,59] Traditional rigid metals are more prone to fracture during stretching, whereas the liquid metal EGaIn, due to its self-healing properties and excellent stretchability, offers higher durability and longer service life in flexible and stretchable devices. The self-healing property of EGaIn ensures that it maintains stable electrical conductivity even under extreme deformation and is capable of repairing broken circuits through its flowability and self-healing characteristics, significantly enhancing the device's durability. In addition to the aforementioned applications in electronics and sensors, EGaIn liquid metal also holds significant potential in the biomedical field. Its biocompatibility and excellent adhesion allow it to form stable core–shell structures with drug molecules, playing an important role in drug delivery, tumor treatment, and neural connections.[60,61] Moreover, the movement of liquid metals can be controlled using external fields such as light and magnetic fields, reducing the risk of vascular blockages and enabling precise drug targeting and release, thus advancing the field of nanobiomedicine.[62] However, liquid metals pose challenges such as high surface tension, poor wettability with substrates, and intense flow characteristics, which can lead to aggregation during deformation and affect the transmission of electrical signals. To address these issues, a new structure has been proposed in which CNTs are introduced as an intermediate layer between the liquid metal and the flexible substrate. This structure not only ensures the

stable adhesion of the liquid metal but also protects it from excessive oxidation, eliminating the need for post-treatment to activate conductive channels. Conductors with this structural modification demonstrate excellent conductivity and stability under extreme deformation, capable of withstanding numerous stretch-and-recover cycles, providing a high-performance, stretchable conductor solution for flexible electronic devices. Regarding the choice of elastic substrates, polymeric materials are commonly used as supports to form flexible substrates. In the design of elastic substrates, elastomers with chemical or physical cross-linking are the most frequently used approaches, as they can effectively maintain the stability of the conductive filler network. By combining conductive fillers with elastic substrates, it is possible to enhance both the conductivity and stretchability of the sensors while maintaining their excellent mechanical properties.

In addition to optimizing the materials themselves, manufacturing processes and post-treatment techniques play a crucial role in enhancing the performance of stretchable strain sensors. For example, surface modification and welding technologies can effectively reduce the contact resistance between conductive fillers, thereby improving the electrical conductivity of the composite materials. Chung *et al.* developed a welding process for highly conductive and transparent silver nanowire films by coating silver nanowire inks with hydroxypropyl methylcellulose (HPMC) binders onto polyethylene terephthalate (PET) substrates, which were then welded at room temperature and under ambient conditions using a combination of flash white light and ultraviolet C irradiation.[63] Furthermore, advanced fabrication methods, such as electrospinning and light-assisted manufacturing, allow for precise control over the morphology of micro-nanostructures, significantly boosting the sensor's performance at both the micro and macro levels. The researchers developed textile-based sensors with high sensitivity and mechanical stability by constructing a loosely arranged MXene-modified textile interface structure and employing a thermal transfer method with a melt–permeation–solidification adhesion process.[64] Gao *et al.* introduced a flexible wearable strain sensor based on the theory of polarity-induced adsorption, which enhanced the loading rate of carbon nanomaterials on TPU electrospun nanofibers.[65] The resulting PDA/CB/CNF/TPU strain sensor (PCCT) exhibits high sensitivity and a wide strain range, making it suitable for monitoring human body movements. In terms of design, scientists have incorporated stretchable structures, such as wrinkled or serpentine patterns,[66] into the conductive layers on polymer substrates. These structures can deform during strain, distributing part of the applied stress, thus mitigating the impact of deformation on the continuity of the conductive layer. The design not only reduces the strain-induced disruptions to the conductive layer but also ensures the stability of the layer's conductivity and resistance even under significant stretching. Researchers have proposed two main design principles: structures that stretch (STS) and materials that stretch (MTS).[67] The STS approach forms wavy or serpentine patterns[68] through pre-straining techniques, enabling rigid materials, such as metals and semiconductors, to maintain stable electrical properties even under substantial stretching. On the other hand, MTS utilizes inherently stretchable materials, such as CNTs and metal nanowires, to construct stretchable electrodes and active materials. These materials, with their excellent mechanical and electrical properties, ensure both high stretchability and stable electrical performance. For example, single-walled CNTs films can withstand strains of up to 150% without pre-straining, while horizontally aligned CNTs are used to create stretchable supercapacitor electrodes.[69] This integration of novel materials and inventive designs enables the creation of high-performance, stretchable sensors that can withstand both mechanical deformation and electrical strain, paving the way for their use in a variety of advanced applications.

Stretchable strain sensors have broad application potential in fields such as health monitoring, wearable technology, and robotics, particularly in accurately tracking human movements like finger gestures,[64] pulse rate, and wrist motions. As a result, these sensors have become an integral component of electronic skin, smart clothing, and health monitoring devices. Graphene-based sensors, with their outstanding flexibility and high sensitivity, are particularly effective in detecting physical signals such as pressure, strain, and torsion. This makes them highly suitable for applications in physiological signal monitoring, particularly pulse measurement, where they enable continuous, interference-free health data tracking, thereby driving the development of smart health devices. Notable studies include one by Boutry *et al.*, who developed implantable, biodegradable pressure and strain sensors capable of real-time tendon healing monitoring.[70] These sensors offer high sensitivity, minimal hysteresis, and excellent biocompatibility, eliminating the need for device removal surgeries. Kim *et al.* demonstrated a transparent, stretchable ionic touch panel made from polyacrylamide hydrogel and lithium chloride salt, which can withstand strains exceeding 1000%.[71] This technology has wide applications in epidermal interfaces, such as writing, playing piano, and gaming. Moreover, Shengshun Duan and colleagues developed a highly sensitive and mechanically stable smart data glove, which uses MXene-modified textile sensors and a near-sensor adaptive machine learning model to achieve 99.5% gesture recognition accuracy for 14 hand gestures, maintaining 98.1% accuracy even when the dataset was expanded to 20 gestures.[72] This glove can locally update model parameters without requiring external computing resources, demonstrating efficient self-recognition and control in robotic sorting tasks and highlighting its significant potential in human–machine interaction.

Despite these advances, stretchable conductors still face several challenges, particularly in enhancing conductivity and electrical stability. To address these issues, researchers are focusing on techniques such as extending the length of nanomaterials or using rolling post-processing methods to reduce resistance, thereby improving conductivity and overall stability. With continuous advancements in related technologies, stretchable strain sensors are expected to see more widespread

application in wearable electronics, medical monitoring, and smart devices in the future. However, challenges related to conductivity and stability still need to be resolved in order to facilitate their large-scale application and commercialization.

3.2 Self-healing flexible pressure sensing materials

Self-healing mechanisms can be categorized into intrinsic[73] and extrinsic types,[74,75] as shown in Fig. 3. Extrinsic self-healing materials repair damage through the activation of embedded healing agents by external environmental changes, such as temperature, pressure, or mechanical stress. Intrinsic self-healing materials rely on dynamic covalent or non-covalent bonds,[76] such as hydrogen bonds, π–π stacking,[77] and ion–dipole interactions.[78] Dynamic chemical bonds undergo reversible bond dissociation and recombination in response to environmental changes, such as variations in temperature or pH, thereby exhibiting self-healing properties.[79,80] Hydrogels based on dynamic covalent bonds typically demonstrate higher mechanical performance, although they may require longer self-healing times. Due to the robust nature of dynamic covalent bonds, they provide more durable repair under repetitive mechanical stress, helping to maintain structural integrity and significantly extend the lifespan of sensors.[81–83] In contrast, materials based on non-covalent interactions (such as hydrogen bonding and ionic interactions) exhibit weaker self-healing properties, enabling rapid recovery from minor damage.[84–86] However, due to the inherent weakness of non-covalent bonds, performance degradation may occur under sustained stress. To enhance mechanical strength, multiple non-covalent interactions often work synergistically within the same hydrogel, improving its overall performance.[87] The presence of cooperative hydrogen bonding helps to stabilize the hydrogel network and promotes ionic crosslinking, further enhancing its mechanical properties.

Conductive hydrogels,[88–90] as a novel class of materials, exhibit significant potential for applications in flexible electronic devices and artificial intelligence, particularly in wearable sensors and health monitoring systems. The three-dimensional hydrophilic network structure of hydrogels enables them to absorb water while maintaining structural integrity, imparting excellent biocompatibility, high stretchability, and shape adaptability. A significant body of research has explored various strategies to enhance the mechanical properties and conductivity of hydrogels with self-healing capabilities. For instance, Deng *et al.* proposed a conductive hydrogel based on grape seed extract and polyvinyl alcohol (PVA), which utilizes hydrogen bond-mediated self-healing.[91] This hydrogel is able to rapidly repair itself after damage and, when incorporated with CNTs, exhibits excellent strain sensitivity, enabling the detection of minute strain changes. This material is particularly suitable for the fabrication of flexible strain sensors for real-time monitoring of human motion and health conditions. A novel wet-adaptive electronic skin (WADE-skin) can be constructed by combining a skin-adhering wet adhesive fiber layer, a waterproof fiber layer, and a stretchable liquid metal electrode layer.[92] The wet adhesive layer is composed of *N*-hydroxysuccinimide (NHS) and dopamine-modified polyacrylic acid (PAAND) fibers, which enable rapid and robust adhesion to moist skin surfaces. The waterproof layer, made of polystyrene–butadiene–styrene (SBS) fibers, provides excellent water resistance. The liquid metal electrode layer, consisting of EGaIn alloy, ensures both electrical conductivity and stretchability of the electronic skin.

The flexibility and biocompatibility of hydrogels confer on them irreplaceable advantages in the field of flexible sensors.[93] To further enhance the mechanical properties of hydrogels, researchers have optimized their structures by incorporating fillers such as metal ions, liquid metals, graphene, and CNTs. The introduction of two-dimensional (2D) MXene nanosheets into a self-catalyzed enhancement system composed of tannic acid-modified cellulose nanofibers (CNF) and zinc chloride enables the preparation of an amphoteric ion-conductive hydrogel with self-adhesive and antifreezing properties within one minute. This system exhibits remarkable environmental adaptability (−60 to 40 °C), excellent stretchability (elongation ≈ 980%), long-lasting adhesiveness (even after being exposed to air for 30 days), and strong conductivity (20 °C, 30 mS cm^{-1}).[94] Cong *et al.* synthesized a conductive hydrogel based on a double-network (DN) structure, composed of dynamic crosslinked chitosan and doped polyaniline in a flexible polyacrylamide matrix. The hydrogel exhibited excellent mechanical properties, remarkable conductivity, outstanding freezing resistance, and superior strain sensitivity for flexible electronic sensors.[95] Currently, traditional flexible strain sensors exhibit poor stability in complex and extreme environments, often requiring additional encapsulation for protection. To address this issue, researchers have developed a novel fluorinated ionic gel that possesses tunable strain limits, high conductivity, and excellent multi-environment adaptability, enabling flexible strain sensing in challenging environments such as marine, oil, vacuum, and extreme temperature conditions.[96] The gel utilizes ion–dipole and dipole–dipole interactions, which facilitate good compatibility between the fluorinated polyacrylic ester matrix and the hydrophobic ionic liquid, ensuring that the sensor can maintain high sensitivity and stability in various harsh environments without the need for additional encapsulation.

In addition to traditional material modifications, there is an increasing trend towards the use of natural bio-based materials for the fabrication of self-healing hydrogels. *Tremella* is a commonly used food ingredient and traditional Chinese medicine.[97] The natural polysaccharide *Tremella fuciformis* polysaccharide (TFP) can be extracted from the mycelium or fungus of *T. fuciformis*. Han *et al.* developed a self-healing, antifreezing, and fire-resistant hydrogel strain sensor by crosslinking *Tremella* polysaccharides, silk fibers, and a polyvinyl alcohol matrix with borax. The sensor exhibits excellent transparency, stretchability (1107.3%), self-healing ability (91.11%), and stability, making it suitable for human health monitoring and interactive smart electronic devices.[98]

3.3 Multifunctional flexible pressure sensing materials

Recent advancements in flexible sensors have enabled the development of multifunctional sensing platforms capable of

responding to various external stimuli, such as pressure, strain, temperature, and humidity. Liu *et al.* demonstrated a novel approach for creating such sensors by combining carbon black (CB) and reduced graphene oxide (rGO), with carboxymethyl cellulose (CMC) as a dispersing agent to form a uniform suspension.[99] This mixture was repeatedly applied to a paper substrate through a spray-drying process to create the sensitive layer. The addition of CMC facilitates the formation of a homogeneous hierarchical structure on the paper substrate, where CB particles are adsorbed onto the surface of rGO and stacked together, forming a conductive network with porous micro-gaps. This structure enhances the sensor's responsiveness to a variety of external stimuli, including strain-induced changes in conductivity, moisture variations that cause the CMC chains to absorb or release water, temperature fluctuations that lead to adsorption or desorption of air molecules, and pressure changes that compress or expand the sensitive layer (Fig. 3).[99] Experimental results show that the sensor exhibits rapid response times and high sensitivity to these stimuli, making it suitable for applications in human motion and respiration monitoring, as well as environmental sensing. Additionally, the sensor's biodegradable nature makes it an environmentally friendly, multifunctional sensing solution.

In recent years, significant attention has been given to the research of flexible multifunctional sensors with both pressure and humidity detection capabilities. For instance, Ho *et al.* developed a stretchable and multifunctional graphene-based electronic skin by spraying rGO or graphene oxide (GO) onto polydimethylsiloxane (PDMS), which exhibited a sensitive response to humidity changes in capacitive mode.[100] This material not only functions as a humidity sensor but also demonstrates flexibility and stretchability, making it suitable for real-time monitoring of human skin or as an electronic skin for prosthetics. Xuan *et al.* proposed a surface acoustic wave (SAW) humidity sensor based on ZnO piezoelectric thin films and GO as the sensing layer, which not only demonstrated high sensitivity but also fast response characteristics.[101] These multifunctional sensors are not just limited to humidity detection; they also integrate piezoelectric and acoustic properties, enabling them to monitor multiple environmental parameters simultaneously. Moreover, some researchers have developed new humidity sensors using nitrogen-doped rGO fibers and platinum nanoparticles, which exhibit higher sensitivity and stability over a wide humidity range. These sensors not only offer improved performance but also integrate self-healing, transparency, and stretchability, making them ideal for real-world applications such as wearable health-monitoring devices. For example, a flexible humidity sensor based on organic hydrogels, which has high stretchability and self-healing capability, was developed.[102] The addition of ethylene glycol and glycerol enhances the humidity response speed and stability, making it suitable for human respiration monitoring. Additionally, Wu *et al.* developed a humidity sensor based on self-healing organic hydrogels that can withstand up to 1225% strain and stably operate over a wide humidity range.[103] A flexible humidity sensor based on titanium dioxide nanowire networks was also proposed, which can rapidly respond to humidity changes and convert them into voltage signals, maintaining good performance even after bending.[104] This capability is crucial for real-time, non-invasive respiratory monitoring, a growing area in health technology. To reduce costs, Su *et al.* introduced a resistive humidity sensor based on PMMA/PMAPTAC copolymer, which exhibits low hysteresis and high sensitivity. Its cost-effectiveness and versatility make it well-suited for environmental monitoring and smart wearable devices. Paper-based flexible humidity sensors, owing to their low cost, eco-friendly characteristics, and flexibility, have attracted considerable attention. By utilizing ordinary paper and conductive tape, this sensor demonstrated excellent humidity response performance, particularly in the 41.1% to 91.5% relative humidity (RH) range, showing a good linear relationship, making it suitable for low-cost applications such as respiratory rate monitoring and diaper moisture detection.[105] While these developments show significant promise, challenges remain. For instance, expanding the sensor's response range to cover lower humidity levels and reducing the power consumption of the signal processing system are ongoing research priorities.

Hydrogels, known for their excellent flexibility and biocompatibility, have become increasingly prominent in the development of multifunctional flexible pressure sensors. Their unique properties, such as high water content, mechanical flexibility, and responsiveness to external stimuli, make them ideal candidates for diverse sensing applications, particularly in the field of healthcare and wearable technologies. For instance, Zhang *et al.* developed a highly flexible, multifunctional sensor system based on a fluorescent nanodiamond boronic hydrogel, which was integrated with porous microneedles for continuous glucose monitoring.[106] This hydrogel offers exceptional optical stability, biocompatibility, and the ability to detect glucose levels in real time, making it a promising material for long-term, non-invasive health monitoring. Similarly, Xiong *et al.* introduced an innovative flexible, wireless, and battery-free sensor, utilizing a bacteria-responsive DNA hydrogel for smartphone-based wound infection detection.[107] The sensor operates by detecting changes in dielectric properties, which occur in response to bacterial infection. This enables continuous, real-time monitoring of wound conditions, providing an early warning for infections before visible symptoms arise. Such a system could significantly enhance patient care by allowing for timely intervention and preventing complications associated with untreated infections. Additionally, Zhang *et al.* developed a highly stretchable ionic-conductive hydrogel embedded with nanoclay.[108] This combination improves the mechanical strength, electrical conductivity, and biosafety of the hydrogel, making it an excellent candidate for use in a wide range of applications. This multifunctional hydrogel exhibits superior strain-sensing capabilities and enhanced protein resistance, which are crucial for monitoring dynamic biological processes such as myocardial infarction and heart disease. Its real-time, *in vivo* monitoring

capabilities enable continuous tracking of cardiac conditions, which is essential for managing and diagnosing heart-related diseases. These examples demonstrate the broad versatility of hydrogels in real-world applications. They not only enable integrated sensing and monitoring in healthcare but also open up new possibilities in areas such as wearable electronics, environmental sensing, and smart materials. With ongoing advancements in hydrogel technology, these materials hold great promise for the future of personalized medicine and advanced healthcare systems, offering non-invasive, efficient, and continuous monitoring of various physiological and environmental parameters.

4. Flexible pressure sensing devices

Flexible pressure sensing devices can be categorized into piezoresistive, capacitive, triboelectric and piezoelectric[109,110] types based on their underlying principles.[111–113] In addition to material advancements, recent innovations in device architecture, such as microstructured substrates and hybrid designs, have significantly enhanced their performance and applicability in various fields. This section will explore these categories in detail, discussing both the principles and design strategies—such as structural innovations—that contribute to the effectiveness of each type, as shown in Table 3.

4.1 Piezoresistive devices

The working principle of flexible piezoresistive pressure sensors is based on the piezoresistive effect, where the resistivity of the material changes when subjected to external forces. This change can be achieved through various mechanisms, including changes in the energy band structure of semiconductor materials,[96,97,114,115] percolation theory in conductive polymer composites,[116] tunneling effects,[117,118] and variations in interface contact resistance. For example, in semiconductor materials, external forces alter the energy band structure, resulting in a decrease in carrier mobility, which increases resistivity. Conductive polymer composites, on the other hand, change the resistivity by controlling the volume fraction and distribution of conductive fillers, which form a conductive network; the pressure-induced changes in the conductive pathways lead to changes in resistivity. Additionally, variations in interface contact resistance are an important mechanism for achieving the piezoresistive effect. By optimizing the microscopic structure of the material's surface, the sensitivity of the sensor can be significantly improved.

To further enhance the performance of flexible piezoresistive pressure sensors, microstructure design has become a critical factor. By designing different microstructures, the contact area change under force can be significantly increased, thereby improving the sensitivity.[119–122] Common microstructure designs include single micro-protrusion structures (such as pyramid structures, hemispherical structures, *etc.*), composite micro-protrusion structures (such as interlocking structures), and three-dimensional porous structures. For example, the stress concentration effect of pyramid structures can cause significant changes in the contact area under force, thus enhancing the sensor's sensitivity. Composite micro-protrusion structures optimize sensor performance by increasing the number and area of contact points. Moreover, the design of three-dimensional porous structures not only reduces the compression modulus of the sensor, allowing significant deformation under lower pressure, but also increases the number of conductive pathways, improving sensitivity.[123,124] In addition to traditional microstructural design, hybrid design strategies have emerged as another key approach to improving piezoresistive sensors. These hybrid strategies combine different types of microstructure or integrate piezoresistive materials with other functional materials to create multifunctional sensors. For example, hybrid designs that combine piezoresistive materials with conductive polymers, carbon-based nanomaterials, or even triboelectric materials can significantly enhance the sensor's sensitivity and response speed, making them more versatile for various applications.[125] Furthermore, combining these materials in a layered or composite manner allows for better optimization of both electrical and mechanical properties, achieving higher sensitivity and durability.[126] Advanced fabrication techniques are also pivotal in realizing the full potential of these design strategies. The use of techniques such as 3D printing, soft lithography, and biomimetic templating enables the creation of complex micro- and nanoscale structures that would otherwise be difficult to achieve with conventional fabrication methods. For instance, freeze-drying techniques have been used to fabricate three-dimensional porous structures of graphene, which not only provide enhanced elasticity but also improve the pressure response time.[127,128] The combination of 3D printing and biomimetic

Table 3 Flexible pressure sensing devices: types, design, and applications

Category	Principle	Microstructure design	Applications	Ref.
Piezoresistive devices	Change in resistance with applied pressure	Nanostructured films or microstructures to improve sensitivity	Wearable electronics, health monitoring, robotics, touch sensing	119, 120, 121, 122, 123 and 124
Capacitive devices	Change in capacitance with applied pressure	Microstructured electrodes, patterned dielectric layers	Touch screens, pressure sensors	137, 138, 139 and 140
Triboelectric devices	Generation of electricity due to friction between materials	Sandwich structure, vertical contact-separation mode	Self-powered sensors, energy harvesting	153 and 154
Piezoelectric devices	Generation of electrical charge in response to mechanical stress	Origami structure, microspheres	Wearable devices, environmental monitoring, motion detection	167 and 16

designs inspired by natural structures further allows for the fine-tuning of mechanical properties such as flexibility and sensitivity.[129,130] These fabrication strategies offer new possibilities for developing high-performance, flexible piezoresistive sensors with tailored properties for specific applications. Wang's research group, for instance, first employed latex assembly technology to develop a flexible strain sensor based on rGO and polydimethylsiloxane (PDMS) conductive elastic composites. By excluding the latex particles' volume, rGO selectively positioned itself between the gaps, forming a three-dimensional conductive network with an ultra-low content (0.44 vol%) that endows the rGO/PDMS composite with mechanical stability and flexibility.[131] In addition to the microstructure design, optimizing the fabrication process is also a key approach to enhancing sensor performance. For example, three-dimensional porous graphene structures prepared by freeze-drying not only exhibit excellent elasticity but also allow for a fast pressure response and high sensitivity detection. By combining 3D printing technology and biomimetic template methods, more complex micro-nano structures can be designed, further improving sensor performance.

With the development of new sensing mechanisms, the integration of functionalized nanomaterials, and innovations in flexible device fabrication techniques, flexible piezoresistive pressure sensors are expected to achieve breakthroughs in more fields, providing strong support for the development of human health monitoring, intelligent robotics, artificial intelligence, and other areas.

4.2 Capacitive devices

Flexible capacitive pressure sensors have attracted significant attention in fields such as smart wearables and health monitoring due to their unique properties.[132–136] These sensors detect external pressure with high sensitivity by altering the distance or contact area between electrodes, which leads to changes in capacitance. Compared with resistive sensors, capacitive sensors offer lower power consumption and higher spatial resolution, and are less affected by thermal noise. Unlike piezoelectric and triboelectric sensors, capacitive sensors can detect static pressure, making them suitable for a wider range of monitoring scenarios. However, capacitive sensors also face challenges, such as small capacitance variation, susceptibility to parasitic capacitance and environmental electromagnetic noise, which can affect signal accuracy and stability. Additionally, issues related to long-term stability, detection range, and fabrication costs need further optimization to meet practical application demands.

In recent years, researchers have significantly improved the performance of capacitive pressure sensors through various strategies. On the one hand, the introduction of porous or micro-nano structures, such as micro-pillars and micro-villous designs, can effectively reduce the elastic modulus of the dielectric layer or increase the change in the electrode contact area, thereby enhancing the sensor's sensitivity and response speed. For example, Wan *et al.* used freeze-dried graphene oxide foam material,[137] and the Hwang team prepared a layered porous PDMS dielectric layer using a particle template method, both of which significantly improved the sensor's sensitivity and measurement range.[138] Moreover, hybrid designs that integrate capacitive and piezoresistive sensing mechanisms have been explored to overcome the interference challenges posed by stretching in flexible pressure sensors. A notable example is the stretchable hybrid response pressure sensor (SHRPS), which combines a barely conductive porous nanocomposite with an ultrathin dielectric layer between two stretchable electrodes.[139] This design leverages the piezoresistive effect to enhance sensitivity while utilizing the piezocapacitive response to minimize signal distortion caused by mechanical stretching. Experimental validations have demonstrated that this hybrid approach enables ultrahigh pressure sensitivity while maintaining stability under deformation, making it well-suited for applications such as soft robotics, prosthetics, and bio-integrated sensing. Additionally, SHRPS-based sensors have been successfully implemented in inflatable probes for precise human wrist palpation and adaptive gripping of contoured objects, showcasing their potential for advanced e-skin technologies. The geometry of the dielectric layer is also an essential design consideration. The introduction of microstructured dielectric layers, which feature unique patterns like micro-ridges or cylindrical ladder structures, allows for improved adaptability to external deformations, enhancing the sensor's performance in real-world applications. These microstructures are particularly effective in boosting sensitivity and operational stability. For instance, sensors with cylindrical ladder microstructure dielectric layers have shown a sensitivity approximately 3.9 times higher than those without any microstructure.[140] This approach not only increases the sensitivity but also contributes to the sensor's dynamic response, making it an ideal solution for applications such as real-time monitoring of rainfall frequency. Additionally, microstructured layers can help mitigate the effects of parasitic capacitance and electromagnetic interference by providing better insulation and noise resistance. On the other hand, the application of new composite materials, such as combining conductive fillers like carbon nanotubes and graphene with flexible polymer matrices, not only enhances the dielectric layer's conductivity but also improves its mechanical properties and flexibility. Furthermore, the advent of electric double layer (EDL)-based capacitive sensors has further enhanced the capacitive sensor's anti-interference ability and unit area capacitance (UAC), which enables it to maintain high-precision detection in complex environments, as shown in Fig. 4b.[141] These sensors feature a charge separation distance of around 1 nm, and their capacitance density can be increased by six orders of magnitude compared with conventional capacitive sensors, which results in significantly improved sensitivity. The Wu research group successfully developed a fully fabric-based pressure sensor with a wireless, battery-free monitoring system. This sensor sandwiches a three-dimensional permeable fabric between two highly conductive fabric electrodes to serve as the dielectric layer. The breathable fabric can be attached to the skin, enabling wireless

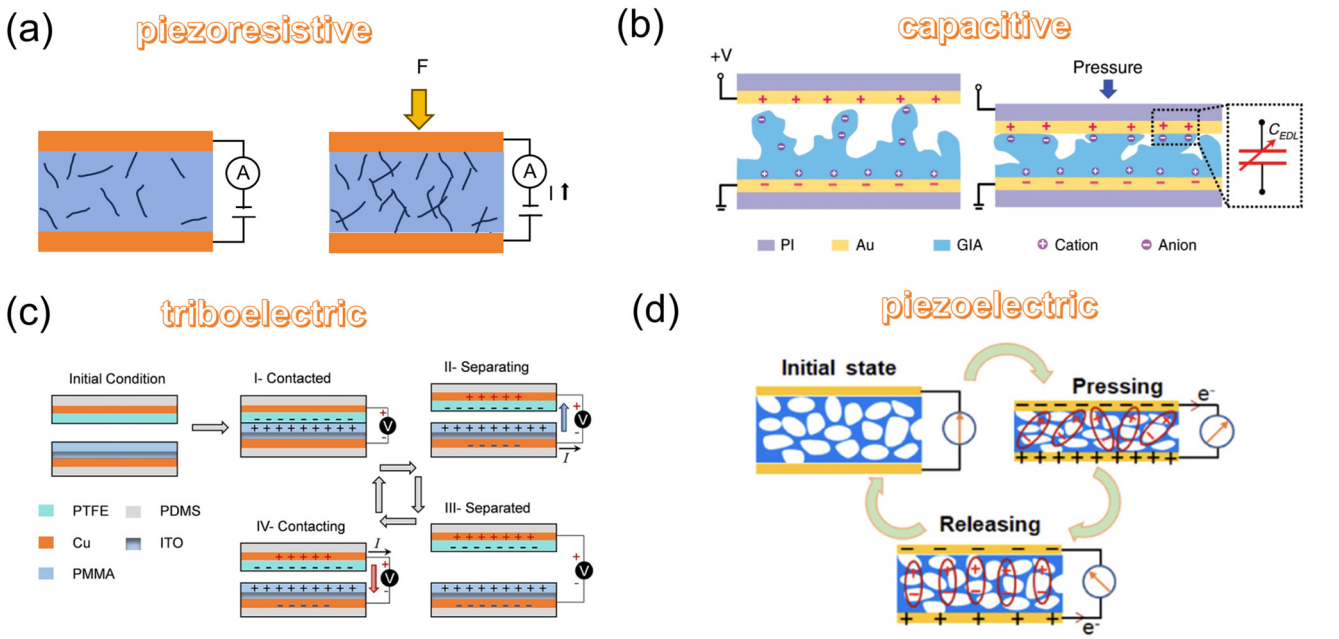


Fig. 4 Flexible pressure sensing devices based on different principles. (a) Schematic diagram of the principle of a piezoresistive sensor. (b) Schematic illustration for the functioning of the iontronic pressure sensor before and after applying pressure. Reproduced from ref. 141 with permission from The Author(s), copyright 2020. (c) Working mechanism of TENGs based on contact-separation mode. Reproduced from ref. 148 with permission from The Author(s), copyright 2024. (d) The principles of piezoelectric response in porous membrane-based PENGs under periodic impact and release. Reproduced from ref. 164 with permission from ACS, copyright 2021.

real-time pressure detection using a fiberoptic inductive coil with a resonant frequency shift sensitivity of 6.8 MHz/kPa.[142]

These optimization strategies lay the foundation for the widespread application of capacitive pressure sensors, showing promising prospects in fields such as electronic skin, wearable devices, and health monitoring. In the future, with the continuous development of materials science and micro-nano processing technologies, capacitive pressure sensors are expected to achieve further breakthroughs in performance, cost, and stability, bringing more innovative applications to fields such as smart wearables and the Internet of Things.

4.3 Triboelectric devices

Triboelectric devices operate based on the phenomena of frictional electrification and electrostatic induction. When friction layers composed of materials with differing electron affinities come into contact, opposite triboelectric charges are generated. These charges are then separated when the materials are detached or moved relative to each other, producing a potential difference that can be harnessed for energy generation or sensing applications. One prominent example of triboelectric devices is the triboelectric nanogenerator (TENG), which converts mechanical energy into electrical energy using this principle.[143,144]

Due to their high sensitivity, light weight, flexibility, and self-powered characteristics,[145,146] TENGs are ideal for human motion monitoring and medical applications. In 2024, Zhang *et al.* designed a self-powered sensor based on a grating structure. By optimizing the overlap area between the friction layer and the slider, external interference was minimized, resulting in efficient body movement evaluation. Simulation tests indicated that the sensor output signal amplitude was 7–8 V, while the interference signal was only 0.2 V.[147] In 2024, Jan *et al.* reported a self-powered pressure sensor made of biocompatible materials. The device is fabricated by layer-by-layer deposition technology, and the structure and principle of the device are shown in Fig. 4c. The surface of the PDMS is treated by oxygen plasma to enhance the performance of the electrode and friction layer. It shows excellent pressure sensing ability and ability to track physiological movements, such as wrist and finger movements.[148] In 2023, Son *et al.* designed a BB-TENG that integrates energy harvesting and sensing functions, operating in dual modes (contact separation and independent). It can capture kinetic energy from human movements such as pressing and walking, and detect falls and wandering behaviors in patients with dementia. Its flexibility and sealed structure make it suitable for wearable applications, ensuring stable performance in outdoor environments.[149] In 2024, Jan *et al.* proposed a flexible TENG design that combines a microdome array and a carbon black/Ecoflex composite material, improving the output voltage performance.[150] It exhibited excellent pressure sensitivity across both low and high voltage ranges, and the energy harvesting capacity reached 89.4 V when two TENGs were connected in series. The packaged TENG sensor can be integrated into insoles for self-powered gait analysis. In 2024, Guo *et al.* demonstrated a flexible, self-powered piezoelectric sensor patch (SPP) using a poly-

vinylidene fluoride (PVDF) fiber membrane as the functional layer for wrist rehabilitation and motion recognition.[151] The SPP exhibited high sensitivity in the pressure range of 1 to 75 kPa and can be used as a tactile sensor for wrist flexibility evaluation. Combined with a long short-term memory network model, the SPP achieved an accuracy of 92.6% in motion recognition.[151] In 2025, Hu *et al.* proposed a baby fall detection sensor that integrates a bridge-structured PDMS layer and copper foil electrodes. When attached to the skin or joints, the sensor can detect the fall status, frequency, impact intensity, and location. It offers a minimum detectable acceleration of 0.4 g and a sensitivity of 2.6 V g^{-1}. The sensor remains stable after tens of thousands of cycles. When integrated with artificial intelligence, it achieves over 94% accuracy in detecting the fall location.[152]

Additionally, several research works have achieved significant advancements in TENG performance through structural design and enhancements. In 2024, Shi *et al.* introduced a sandwich structure that utilizes the vertical contact-separation mode of TENG, coupling contact electrification and electrostatic induction to significantly enhance its performance. This design enables the EI-TENG to exhibit excellent environmental adaptability, durability, high sensitivity, and stable output, providing new approaches for pressure monitoring and cost-effective self-powered devices.[153] In 2025, Zhu *et al.* developed a friction nanogenerator (BJ-TENG) with a biomimetic jellyfish structure, which improved wave energy collection efficiency by mimicking the flexible umbrella-like structure and buoy design of jellyfish. By incorporating a power management circuit, this system achieved efficient energy output, providing an innovative solution for marine self-powered sensing applications.[154]

The ability to achieve multifunctional integration is another major advantage of TENGs, and many research efforts are focusing on this direction. In 2024, Zhu *et al.* prepared a PDMS/LM film with a hierarchical structure by the gravity-induced deposition of liquid metal (LM), which was used for multifunctional flexible sensors with excellent flexibility and pressure sensing capabilities. It can also function as a self-powered triboelectric nanogenerator (TENG). The sensor demonstrated good sensitivity, fast response, and stability, making it suitable for dynamic force measurement.[155] In 2023, Zhou *et al.* developed a stretchable, self-adhesive, antifreezing, and moisturizing ion-conductive organic hydrogel with adjustable optical properties and excellent responsiveness to strain, pressure, and human body sensing. When combined with Ecoflex elastomer to form a friction nanogenerator (TENG), the hydrogel also exhibited excellent energy harvesting capabilities, achieving stable close-range sensing in non-contact capacitive sensors.[156] In 2022, Hu *et al.* developed an organic hydrogel with a triple network structure composed of PVA, sodium alginate (SA), and CNF, which demonstrated high toughness and excellent sensing performance. By incorporating MXene and GO nanocomposites into the hydrogel matrix, the strain sensing, pressure strain sensing, and temperature sensing functions were enhanced. The hydrogel was also used in TENGs and supercapacitors, showing good electrical properties and stability.[157]

4.4 Piezoelectric devices

Piezoelectric devices operate based on the piezoelectric effect, which occurs when certain materials experience external mechanical stress (such as compression, stretching, or bending). This stress causes charge separation within the material, generating an electric potential difference on its surface. The phenomenon arises from the deformation of the material's molecular or crystal structure under external force, which shifts the positive and negative charge centers, leading to charge accumulation on the material's surface. One important example of piezoelectric devices is the flexible piezoelectric nanogenerator (PENG), which converts mechanical energy into electrical energy using this principle.

Unlike TENGs, which are more versatile and can operate at lower frequencies, PENGs generally require a specific direction of external force and typically necessitate strong mechanical stress. Research on PENGs has primarily focused on improving their performance.[158–160] In 2024, Godzierz *et al.* introduced a wearable PENG using 0–3 type composite materials and investigated the relationship between matrix stiffness and piezoelectric properties. The composite material, containing 10% by mass of $BiFeO_3$ particles, demonstrated good energy conversion performance under various vibrations and pressures, showing significant potential for wearable devices such as smart shoes.[161] In 2022, Zheng *et al.* developed a self-powered UV detector based on a composite fabric that integrates a liquid crystal polymer containing an ionic liquid and a piezoelectric polyvinylidene fluoride–trifluoroethylene nanogenerator. This fabric converts UV signals through resistance and piezoelectric effects, exhibiting a fast response and high stability, making it suitable for dynamic bending and wearable coding electronics.[162] In 2022, Cao *et al.* grew zinc oxide on molybdenum disulfide nanosheets through *in situ* polymerization to prepare PVDF/molybdenum disulfide@zinc oxide piezoelectric composite films with excellent piezoelectric properties. The introduction of ZnO promoted the transformation of the PVDF α phase to the β phase, significantly improving the piezoelectric performance and providing excellent mechanical properties and flexibility.[163] In 2021, Li *et al.* demonstrated a flexible piezoelectric nanogenerator based on a PVDF–HFP nanocomposite film with tunable piezoelectricity, high sensitivity, and multi-stimulus sensing capabilities. The application and mechanism of PENGs are shown in Fig. 4d. The piezoelectric performance and sensitivity were enhanced by adding Fe_3O_4 nanoparticles and creating a 3D porous structure using a template-free, non-solvent-induced phase separation method. The device can respond to contact pressure, magnetic fields, and organic solvent vapors, and can simultaneously harvest energy in both contact and non-contact modes, showing the potential for widespread application in wearable electronic devices.[164] In 2024, Xia *et al.* proposed a new PENG based on BT@Ag-coated barium titanate (PVDF) composite fiber core–shell heterostructures, which improved output per-

formance by nearly three times compared with traditional PENGs. This PENG can effectively harvest wind and sound energy, generating high output at high wind speeds and sound pressures. Its superior polarization and stress transfer mechanisms were validated through experiments and multi-physics simulations, demonstrating a self-powered wireless sensing system that can collect and transmit environmental data, offering new possibilities for self-powered sensing technology in the Internet of Things.[165] In 2022, Mitra *et al.* designed a polymer modulation strategy to improve the piezoelectric performance of PVDF-HFP-based nanogenerators by adjusting the concentration of TiO_2 nanofillers, achieving a peak voltage of 9.69 V and generating 2.22 V from the human blood circulation, providing an effective power supply solution for biomedical sensors and low-power devices.[166] Structural design and optimization are crucial avenues for improving PENG performance. In 2024, Deng *et al.* introduced an origami structure into a PENG, combining compression buckling to impart rich macroscopic properties to the flexible film. Through finite element simulations, they provided valuable theoretical guidance for structural design and material selection. The optimized device demonstrated strong performance in monitoring human pulse and plantar pressure, offering an effective strategy for enhancing the performance of piezoelectric pressure sensors.[167] In 2025, Chen *et al.* proposed a moisture-proof piezoelectric nanogenerator (PENG), which utilized microspheres inspired by the superhydrophobic structure of lotus leaves to enhance stability in wet environments. This PENG exhibited ultra-high voltage output, fast response, and excellent long-term stability, making it suitable for energy harvesting and flexible sensor applications.[168]

5. Algorithmic design in flexible pressure sensing devices

The rapidly growing field of wearable flexible sensors demands compact, high-performance, and cost-effective solutions, driving remarkable progress in the design of flexible pressure sensors. Beyond conventional methods, the need for miniaturization and efficiency is increasingly being addressed through inverse design techniques. Inverse design techniques use algorithms to find the best possible design for a given function. Instead of adapting old designs, they let computers discover entirely new ones. This has led to breakthroughs in areas like metasurfaces.[169] These techniques tackle the optimization of sensor device performance while navigating constraints like limited space and degrees of freedom.

At its heart, the inverse design problem is fundamentally an optimization challenge. Despite their potential, these strategies have yet to gain widespread application in flexible sensors. Few studies explore its benefits. For example, Liu *et al.* presented a data-driven method—combining reduced-order modeling and a jumping-selection algorithm—to efficiently design hundreds of validated flexible pressure sensors. These sensors exhibit a wide-range linear response across various materials.[170] Azadeh *et al.* demonstrated a different approach, employing adjoint-based topology optimization and an effective index method to create a highly compact (4 μm × 4 μm × 220 nm) refractive index sensor on an SOI platform. This sensor achieved a sensitivity exceeding 70 nm per RIU, suitable for biosensing and environmental monitoring.[171] In contrast to flexible sensors, photonic devices widely utilize inverse design largely because flexible sensors still lack a mature and well-defined standard for design and manufacturing. This disparity, however, is beginning to change, with researchers exploring optical-based flexible sensors. For example, the development of an optical-based multipoint 3-axis pressure sensor highlights the promising integration of optical technologies into flexible sensor designs.[172] Currently, there are four primary optimization methods widely employed. Specifically, they are: non-gradient-based, gradient-based, data-driven, and artificial intelligence-based approaches. Non-gradient-based methods, such as the lattice evolution algorithm (LEA) for subwavelength lattice optics, utilize evolutionary optimization techniques to explore vast configuration spaces efficiently, enabling dynamic light control in 3D and planar optical components through computationally efficient strategies like pre-computed field information storage.[173] Besides, Liu *et al.* used a cooperative coevolution algorithm to assist the inverse design.[174] Similarly, the direct-binary search (DBS) algorithm was employed in the design of an ultra-compact polarization beam splitter (PBS) with a 2.4 × 2.4 μm^2 footprint.[175] By discretizing the design space into 20 × 20 free-form metamaterial pixels and iteratively optimizing a figure-of-merit based on transmission efficiencies, DBS facilitated robust performance with CMOS-compatible fabrication. The results of PBS showcase the effectiveness of non-gradient-based optimization in device miniaturization. Gradient-based methods exploit local optimization capabilities through advanced algorithms like the adjoint method.[176] Examples include the compact broadband wavelength demultiplexer with robust functionality spanning 100 nm[177] and the wavelength-demultiplexing grating coupler, which achieves high extinction ratios and efficient spectral separation.[178] Data-driven approaches, such as dimensionality reduction and exhaustive mapping of nanophotonic design spaces, use supervised machine learning models and principal component analysis (PCA) to accelerate design discovery, as exemplified by the global optimization of vertical fiber grating couplers achieving coupling efficiencies over 77%, with computational subspace reduction yielding exponential speed-ups.[179] The above method is echoed in another inverse design method for flexible pressure sensors, moving beyond traditional structure-to-property approaches. This innovative method employs a reduced-order model to define design constraints and a "jumping-selection" method for efficient data screening, dramatically reducing the dataset size required for accurate model training. This method found hundreds of solutions that avoid signal saturation (as shown in Fig. 5d).[39] Artificial intelligence-based inverse design is also proving highly effective. This is clearly demonstrated in the presented research on a novel flex-

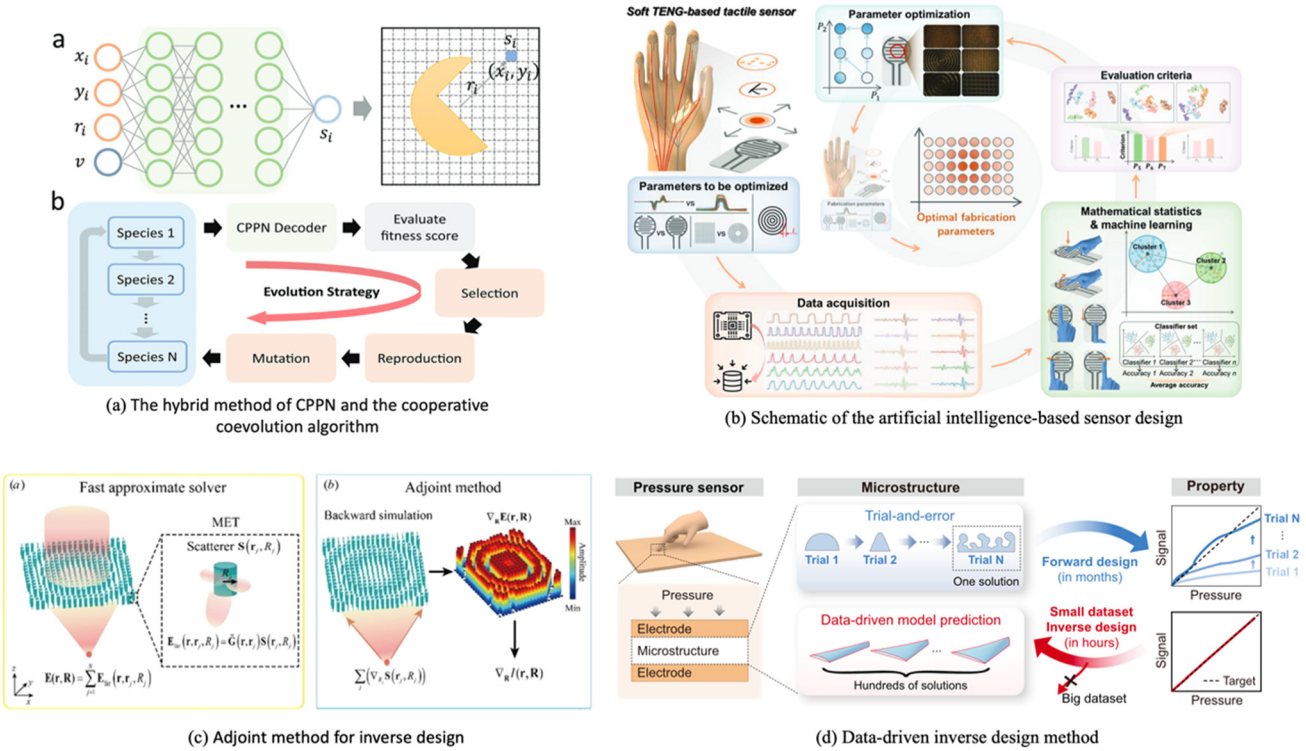


Fig. 5 Overview of different inverse design methods. (a) The hybrid method of CPPN and the cooperative coevolution algorithm (reproduced from ref. 174 with permission from WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, copyright 2019). (b) Schematic of the artificial intelligence-based sensor design *via* fabrication parameter optimization. Reproduced from ref. 180 with permission from The Author(s), *Adv. Sci.* published by Wiley-VCH GmbH, copyright 2023. (c) Adjoint method for inverse design. Reproduced from ref. 176 with permission from ACS, copyright 2022. (d) Inverse design of flexible pressure sensors using the data-driven method.[39]

ible tactile sensor. Employing machine learning, specifically SVMs and statistical criteria, the design process optimizes parameters for superior performance, achieving a remarkable 99.58% accuracy in distinguishing six dynamic touch modalities. Furthermore, its application extends to handwriting recognition and even real-time Braille decoding with a robotic hand (as shown in Fig. 5b).[180] Deep learning further pushes the frontier by enabling on-chip diffractive neural networks like the diffractive deep neural network (DDNN), which achieves over 88% accuracy in MNIST digit classification using multilayer design fabrication, and energy-efficient optical neural architectures such as spiking neurosynaptic networks that integrate phase-change materials for supervised and unsupervised learning at the speed of light.[181,182] Fu *et al.* proposed a method named the diffractive optical neural network (DONN) to speed up machine learning tasks, achieving high accuracy in image classification tests.[183] Besides the aforementioned studies, Liu *et al.*[184] pioneered a tandem architecture combining forward and inverse design networks, overcoming data inconsistencies. Peurifoy *et al.*[185] leveraged ANNs for fast and precise light scattering simulations and inverse design. Liu *et al.*[186] introduced a GAN for efficient metasurface inverse design, while Deng *et al.*[187] achieved a 4900-fold speed improvement with a combined neural network and optimization method. Deep learning also impacted microscopy image reconstruction[188] and coherent diffraction imaging,[189] with methods like PhysenNet[190] enhancing phase imaging. Jia *et al.*[191] recently introduced a synthetical neural network for efficient broadband metasurface inverse design. Fig. 5 showcases the four primary methods employed in inverse design. These techniques, each distinct in approach, are vital to the process. Together, these methods demonstrate a diverse and evolving computational landscape where algorithms shape the future of optical device design by addressing challenges ranging from performance scalability to fabrication robustness, ultimately paving the way for more compact, efficient, and intelligent photonic systems.

The development of photonic-based flexible pressure sensors has witnessed significant advancements, driven by the need for compact, high-performance, and cost-effective sensing solutions. Early research focused on improving reconstructive spectrometers, miniaturized devices offering single-shot operation with high spectral resolution.[192] The core challenge was designing efficient filter arrays, addressed through deep neural network (DNN)-assisted design,[192] optimizing the filter array size and correlation coefficients for improved spectral reconstruction accuracy. Simultaneously, the demand for low-power, flexible sensors for wearable biomedical applications led to the development of programmable Gaussian-derived wavelet filters,[193] achieving minimal power consump-

tion and high flexibility for processing diverse biosignals. Bio-inspired designs, mimicking nature's structural colors, emerged as a promising avenue.[194] This approach focuses on exploring sustainable materials and fabrication methods for creating stimulus-responsive sensors. Inverse design techniques were employed to create highly sensitive and compact integrated biosensors.[195] Topology optimization was used to enhance the performance and miniaturization. Finally, non-invasive methods for adjusting structural colors in sealed 2D photonic crystals were developed,[196] offering immediate and reversible color changes for applications in refractive index sensing. These advancements collectively showcase a shift towards more efficient, versatile, and miniaturized photonic sensors.

The future of flexible pressure sensors is poised for explosive growth, driven by several converging trends, like machine learning and materials science breakthroughs. Advanced machine learning, particularly DNNs, will accelerate the design of complex, multifunctional flexible pressure sensor structures, enabling more sensitive and selective sensing capabilities. Machine learning dramatically reshapes flexible pressure sensor design. One study cleverly used a data-driven inverse design method.[170] This innovative approach, employing a reduced-order model and a "jumping-selection" algorithm, efficiently generated numerous superior sensor designs. It elegantly sidestepped the limitations of traditional, time-consuming methods. Another study harnessed the power of neural networks.[197] This allowed for efficient inverse design, creating sensors precisely tailored to specific needs. Another impressive research used a DE-optimized BP neural network.[197] This accurately predicted electrical properties, streamlining the fabrication of improved Ag/PAA composite sensors. In short, these studies obviously showcase machine learning as a critical tool, accelerating design, enhancing performance, and optimizing the entire fabrication process. Besides, miniaturization will continue, pushing towards truly wearable and implantable devices. Integration with microfluidics and advanced signal processing will lead to sophisticated lab-on-a-chip systems for point-of-care diagnostics and environmental monitoring. New fabrication techniques, such as 3D printing and self-assembly, will enhance scalability and reduce costs. This convergence will result in a new generation of highly sensitive, selective, and versatile photonic sensors impacting healthcare, environmental monitoring, and industrial process control. This bright future is further enhanced by advancements in plasmonic metamaterials, particularly for wearable sensors. These metamaterials, combined with AI-driven design, offer non-invasive detection of physiological and pharmacological analytes in sweat *via* SERS. This approach allows the continuous monitoring of biomarkers like nicotine levels for personalized medicine.[198,199] AI optimization dramatically boosts detection sensitivity, already improving piezoelectric metamaterials for blood pressure sensors. We envision these technologies integrated into neonatal intensive care, advanced cochlear implants, and cutting-edge prosthetics, ushering in an era of truly intellectual healthcare.

Flexible pressure sensors, particularly in optoelectronics, are rapidly advancing in healthcare, fitness, and the IoT due to their precision, small size, and seamless integration. Despite their promising capabilities, challenges like nonlinear computation and slow design processes persist. To unlock their full potential, focusing on developing efficient nonlinear computation methods and optimizing design workflows is key. This progress also paves the way for innovations in flexible pressure sensors, which can be seamlessly integrated into wearable devices for real-time health monitoring, offering new avenues for personalized medicine and prosthetic technologies.

6. Intelligent sensing system

6.1 Soft robotics

Soft robots represent a transformative approach in the field of robotic engineering, diverging from traditional designs that rely on rigid components and structured movements.[200–202] This emerging domain leverages compliant materials to create robots that mimic the versatile and dynamic qualities of living organisms. Unlike conventional rigid-bodied robots, soft robots boast a construction predominantly made from elastomers,[203] gels,[204,205] and other pliable materials, allowing for more complex, adaptive, and resilient interactions with their environment.

Soft robots excel in complex manipulations due to their inherent flexibility, enabling them to delicately handle objects of various shapes and sizes without causing damage. To fully harness this ability, soft robots require precise feedback mechanisms that allow them to interact safely and effectively with their environment. Unlike rigid robots, which can rely on pre-programmed movements and fixed sensors to perform tasks, soft robots must continuously adjust their actions in response to real-time environmental stimuli. This requires the integration of sensing technologies that provide critical information about the robot's interaction with its surroundings, such as the force applied, the shape of the object being manipulated, and the robot's own deformation.

One of the most common and impactful applications of flexible sensors in soft robotics is in the field of soft grippers. Soft grippers are widely used in various industries for their ability to handle objects of diverse shapes, sizes, and fragilities with precision and care. Flexible tactile sensors embedded within soft grippers play a crucial role in this adaptation. These sensors enable the gripper to "sense" and respond to external forces such as pressure, strain, and deformation, ensuring that the robot applies the right amount of force without damaging the object. Boutry *et al.* developed a biomimetic e-skin that enhances robotic manipulators by mimicking the tactile sensing attributes of human skin.[206] This e-skin featured a hierarchically patterned array of capacitors embedded in a polyurethane matrix, closely emulating the microstructural arrangement at the human dermis–epidermis interface, increasing sensitivity to mechanical stimuli and the ability to differentiate between pressure types and directions.

Demonstrated on soft robotic grippers, the e-skin enabled precise manipulation of fragile objects by dynamically adjusting the grip based on a real-time detection of normal and shear forces, showcasing the potential to revolutionize robotic interaction with sensitive environments. Yan *et al.* introduced an innovative tactile sensor that significantly enhances the tactile feedback capabilities of robotic systems by closely mimicking human skin's sensory functions.[207] This sensor incorporated a sinusoidally magnetized flexible film paired with a Hall sensor that detected changes in magnetic flux densities as external forces deform the film, enabling it to measure both normal and shear forces accurately while naturally decoupling these forces—a substantial advancement over existing tactile sensors that often require complex structures and calibration. The sensor achieved super-resolution, enhanced by deep learning, providing a resolution 60 times more accurate than conventional sensors. Then they applied the sensors to a soft robotic gripper, allowing for precise manipulations such as threading a needle and securely grasping fragile objects under external disturbances, showcasing its practical application in tasks requiring delicate and precise force application. Yu *et al.* reported a groundbreaking robotic sensing system known as M-Bot, which leverages an innovative, all-printed soft e-skin to enhance robotic capabilities in hazardous environments.[208] Integrated with artificial intelligence, the e-skin enabled the decoding of human muscle activity for the intuitive control of robots, facilitating safer, remote operations. The technology equipped the soft gripper with ultrasensitive multimodal physicochemical sensing abilities, allowing for the safe handling and analysis of various objects in contaminated settings. Shen *et al.* represented an innovative strain sensor designed to significantly enhance the functionality of soft robotics.[209] This sensor utilized a conducting polymer hydrogel that combines PEDOT : PSS nanofibers with PVA through a novel fabrication process involving 3D printing and successive freeze–thaw cycles. Integrated into a soft robotic gripper, these hydrogel strain sensors demonstrate their practical value by enabling a precise and sensitive manipulation of varied objects, thereby broadening the scope of tasks soft robots can efficiently execute. Recently Zhou *et al.* developed a revolutionary e-skin inspired by the electroreception capabilities of mormyroidea fish, designed to perform active, non-contact 3D tracking and sensing.[210] This innovative e-skin, characterized by its thin, transparent make-up, realized a breakthrough in the interaction dynamics between robots and their environments, allowing for the manipulation of objects and control of devices through mere gestures in three-dimensional space without physical contact, as shown in Fig. 6a. This technology enhances robotic awareness and operational capabilities, providing precise real-time positioning and navigation that is crucial for advanced applications in virtual reality (VR), augmented reality, and complex automated systems where traditional touch-based sensors fall short.

Beyond soft robotic grippers, the integration of advanced sensors into other types of soft robot enables more sophisticated functionalities across various applications. Yang *et al.* introduced an innovative machine learning framework that automates the design of strain sensors for soft robotics, significantly streamlining the process by using a support-vector machine classifier to select and refine nanomaterial compositions.[211] The study showcased the application of this technology in a soft swimmer robot, where the tailored strain sensors enable precise monitoring of the robot's deformations during aquatic maneuvers. Zhang *et al.* presented a breakthrough in sensor technology with the development of highly durable and stretchable conducting polymer hydrogels, designed specifically for the dynamic conditions of underwater environments.[212] Utilizing a pioneering directional freeze-casting technique complemented by a salting-out process, the researchers crafted hydrogels that exhibit anisotropic structures, which are capable of stretching over 600% and maintaining a low Young's modulus. These hydrogels were adeptly applied to an underwater robotic system modeled after a fish, where they functioned as both structural and sensory components. By embedding these hydrogels within the robot, it gains the ability to sensitively monitor and react to the hydrodynamic stresses it encounters while swimming, thereby enhancing its maneuverability and operational efficiency in complex aquatic settings. Yang *et al.* produced an innovative computational approach to engineer strain sensors specifically tailored for soft robotics.[213] These sensors, designed to endure extreme operational demands, were integral for soft robots that operate in unpredictable environments, enhancing their autonomy and responsiveness. The sensor design featured a unique arrangement of programmed crack arrays within micro-crumples, allowing for superior control over mechanical and sensory attributes. This enables the sensors to maintain functionality amidst varied disturbances such as noise interruptions and dynamic cyclic loadings. When integrated into soft robots as shown in Fig. 6b, these robust sensors empowered the machines to adaptively respond to complex surroundings and execute tasks with unprecedented precision, particularly in applications like exploration and rescue missions where traditional robotic systems fall short.

The soft robotic systems integrated with flexible sensors have demonstrated significant application potential across a wide range of fields. Their unique flexibility, adaptability, and high sensitivity enable them to perform tasks that are difficult or impossible for traditional rigid robots. Inspired by the way caterpillars crawl through narrow and winding tunnels, Yuan *et al.* designed a multi-airbag bionic soft robot. By integrating flexible triboelectric tactile sensors on the robot's underside and flexible curvature sensors on its upper surface, the robot can mimic the behavior of a caterpillar perceiving its environment to adjust its movement, thereby achieving adaptive mobility in narrow and complex tunnel environments.[214] These adaptive soft robots demonstrate broad application prospects in confined spaces within complex environments. In rubble search and rescue operations, the caterpillar robot can flexibly navigate through narrow gaps in debris to locate trapped individuals. Its soft structure and ability to sense the external environment enable it to avoid getting stuck or damaged in

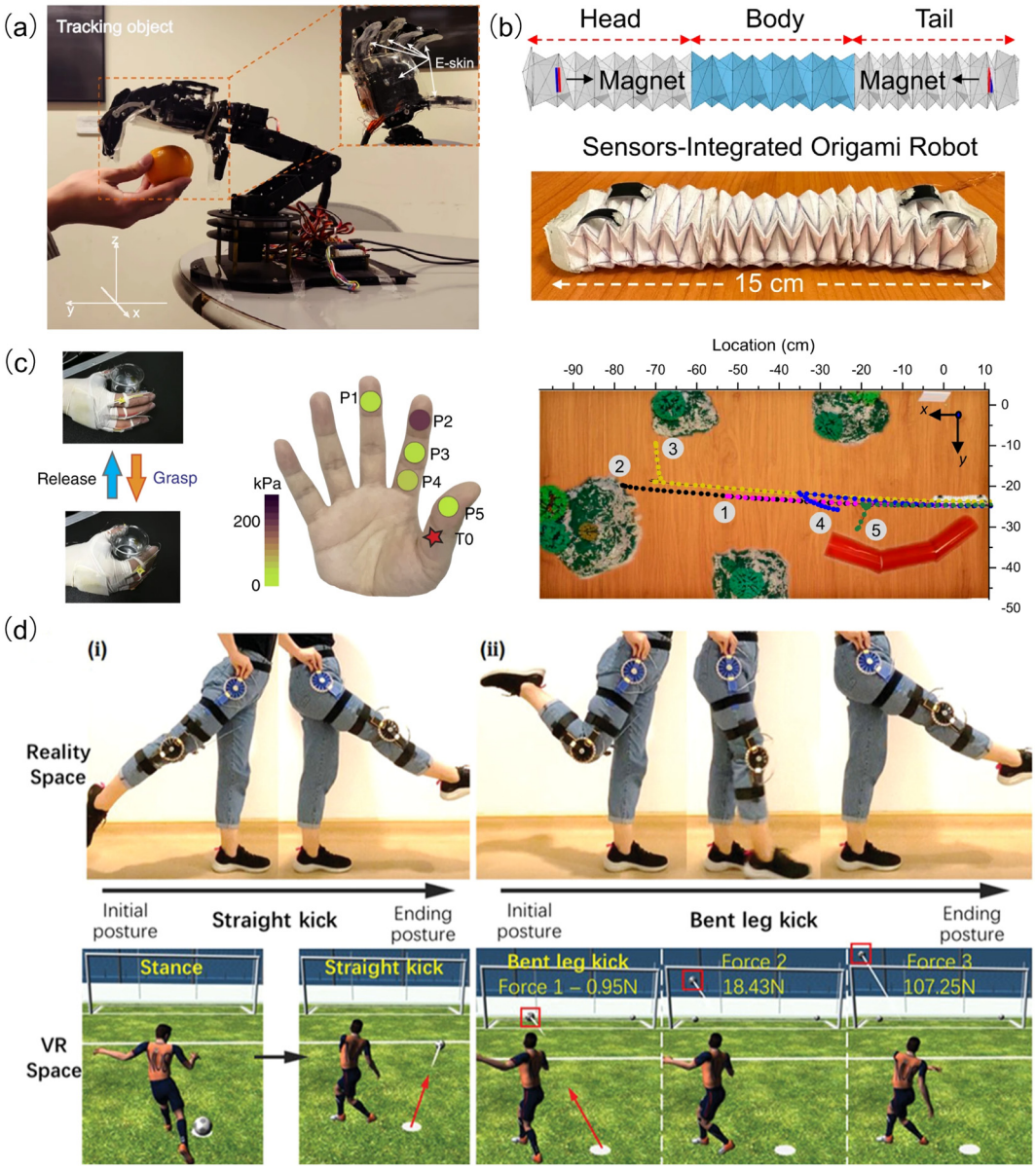


Fig. 6 Intelligent sensing system. (a) Photo of installing E-skin on the robotic arm for object tracking. Reproduced from ref. 210 with permission from The Author(s), copyright 2024. (b) Schematic illustration and digital photo of a sensor-integrated origami robot and its records of robot trajectories from five test sets. Reproduced from ref. 213 with permission from The Author(s), copyright 2024. (c) Images show operations of the intelligent prosthetic hand to grasp (left upper) and release (left bottom). The intelligent prosthetic hand equipped with five pressure sensors (P1, P2, P3, P4, and P5) and one temperature sensor (T0) on the fingers. The pressure distribution contour on the fingers when the intelligent prosthetic hand is grasping a water cup and sensing a temperature of 59.1 °C is shown on the right. Reproduced from ref. 226 with permission from The Author(s), copyright 2018. (d) Demonstration of football kicking VR control with two kinds of kicking motion: (i) straight kick, (ii) bent leg kick under different kicking forces. Reproduced from ref. 228 with permission from The Authors. *Adv. Sci.* published by Wiley-VCH GmbH, copyright 2021.

complex settings. For pipeline inspection, the robot can perceive environmental information to flexibly traverse complex pipeline systems, detecting cracks and leaks within the pipes. When it comes to exploring complex terrain, the robot's adaptive movement allows it to handle various ground conditions, making it suitable for exploring challenging landscapes such as mountains and caves. The caterpillar robot shows the potential of soft robots in complex environments, and is expected to evolve towards miniaturization and intelligence in the future. In the medical field, the robot can enter narrow human cavities or organs (such as the gastrointestinal tract and blood vessels) to conduct inspections or assist in surgical operations. The integration of flexible pressure sensors further enhances the robot's safety, enabling it to better adapt to the complex internal environment of the human body and avoid damaging cavities and organs. This technology not only reduces surgical

risks but also provides new solutions for minimally invasive surgery and precision medicine.

6.2 Wearable sensing for human–machine interaction

Other than robotic applications, wearable sensing technologies have emerged as a transformative component in advancing human–machine interaction, bridging the gap between humans and robotic systems through seamless and intuitive communication.[215–218] These sensors, often integrated into soft, flexible, and stretchable materials, enable real-time monitoring of physiological and mechanical signals such as muscle activity,[219] joint motion,[220,221] and tactile feedback.[222,223] By capturing these signals, wearable sensors allow machines to interpret human intent and respond accordingly, creating a more natural and efficient interaction. Such technologies have applications ranging from the gesture-based control of robotic systems to augmented reality environments and advanced prosthetics. The integration of wearable sensing systems into human–machine interfaces represents a significant step toward achieving more adaptive, responsive, and personalized robotic systems, paving the way for more sophisticated and intuitive collaborations between humans and machines.[224,225]

Hua *et al.* early introduced a revolutionary e-skin system designed to replicate the diverse sensory capabilities of human skin.[226] Built from a flexible polyimide-based matrix network, this e-skin integrated various sensory nodes capable of detecting multiple stimuli, including temperature, strain, pressure, humidity, and even ultraviolet light. They loaded the e-skin to an intelligent prosthetic hand as in Fig. 6c, where it facilitated real-time pressure and temperature feedback, allowing the prosthetic to discern object properties, such as identifying the temperature of a grasped item. Then Sundaram *et al.* introduced the scalable tactile glove (STAG), a low-cost, highly functional device designed to study and replicate human tactile interactions.[227] The glove was equipped with 548 piezoresistive sensors, capturing high-resolution tactile data across the hand, enabling a detailed analysis of how humans interact with objects through touch. The 2021 study developed a hybridized lower-limb system designed for motion capturing and energy harvesting, targeting applications in rehabilitation and sports.[228] This innovative system combined a sliding block-rail piezoelectric generator (S-PEG) for efficient biomechanical energy harvesting with a ratchet-based triboelectric nanogenerator (R-TENG) for accurate lower-limb motion sensing. By converting complex 3D movements into simplified mechanical signals, the system achieved dual functionality: generating power and tracking multidimensional motion parameters such as joint angles and step dynamics as illustrated in Fig. 6d. Fang *et al.* explored the integration of TENGs into wearable systems to elevate virtual and augmented reality (VR/AR) experiences.[229] Unlike traditional systems, which often relied on rigid and bulky components, TENG-based devices are lightweight, flexible, and self-powered, offering seamless compatibility with the human body. By translating gestures into commands and delivering real-time haptic responses, TENGs enable more immersive and intuitive VR/AR experiences. Duan *et al.* presented a novel smart glove that combines MXene-modified textile bending sensors with edge computing to achieve precise gesture recognition.[230] The sensors, which were created using a thermal transfer printing method, exhibited exceptional mechanical durability and high sensitivity, enabling accurate tracking of finger motion. Integrated with a lightweight machine learning model, the glove supports real-time recognition of gestures with an impressive accuracy of 99.7%, while also allowing for the seamless addition of new gestures without relying on external servers. The application was demonstrated in controlling a robotic arm, the glove effectively translates hand movements into commands for autonomous sorting tasks, such as picking and placing objects.

The intelligent human–machine interaction system integrated with flexible sensors demonstrates significant application potential across multiple fields, including medical and health care, industrial automation, and consumer electronics, thanks to its high sensitivity, adaptability, and flexibility. This technology not only enhances the efficiency and safety of human–machine interactions but also provides users with a smarter and more convenient experience. Yang *et al.* introduced a wearable artificial throat (AT) system that combines graphene-based mechanical sensors with advanced AI-driven algorithms to achieve precise and noise-resistant speech recognition.[231] By capturing both low-frequency muscle movements and sound vibrations, the AT generated mixed-modality signals that enable an accurate interpretation of phonemes, tones, and words, achieving a recognition accuracy of 99.05% even in noisy conditions. The artificial throat has a wide range of applications in the medical and health field. Equipped with graphene-based mechanical sensors, it can detect subtle muscle movements in the larynx and vibrations from sound waves. Even among patients who have undergone laryngectomy or have lost their voice due to diseases such as Parkinson's disease and stroke, the artificial throat can identify mixed-modality signals and convert them into recognizable speech through advanced AI algorithms processing, helping patients regain their ability to communicate. Moreover, this intelligent artificial throat mainly identifies low-frequency signals from muscle mechanical movements and mid-frequency signals from sound waves. Mid-low frequency signals are usually more stable than high-frequency signals and less affected by environmental noise, thus showing significant noise resistance, enabling speech recognition in noisy environments like airport cockpits and fire scenes. It is user-friendly and convenient to wear. The high sensitivity of the artificial throat allows it to detect low-frequency muscle movements, which can be used to monitor the patient's physiological status, such as breathing rate and swallowing actions, providing assistance for medical diagnosis. Beyond the medical and health field, this intelligent artificial throat can be integrated into industrial equipment. By identifying mid-low frequency signals, it can be used to detect minor vibrations and abnormal sounds during equipment operation, helping technicians to identify faults in a timely manner. With its high sensitivity, noise resistance, and ability to detect mixed-modality signals,

the artificial throat shows broad application prospects in medical, industrial detection, and daily life assistance fields. This technology not only provides a new way of communication for voiceless patients but also offers a new solution for the next generation of speech recognition and interaction systems. Future designs can focus on optimizing the detection of mid-low frequency signals instead of pursuing high precision across the full frequency band, thereby reducing hardware complexity and cost.

7. Emerging trends in flexible technologies

The comparison of the research clusters from the first five years (Fig. 7b) and the last five years (Fig. 7a) reveals that hydrogels and liquid metals have seen significant development in recent years, gradually emerging as research hotspots. Hydrogels possess excellent biocompatibility and flexibility, making them widely used in fields such as flexible sensors, smart materials, and medical devices. Conductive hydrogels can be broadly categorized into two main types: electronically conductive gels (ECGs) and ionically conductive gels (ICGs).[232] ECGs, such as conductive polymer gels and nanoparticle conductive gels, rely on the transfer of electrons for conductivity. Conductive polymer gels made from materials like polypyrrole (PPy) and polyaniline (PANI) have demonstrated high conductivity, biocompatibility, and mechanical strength, making them suitable for bioelectronic applications. Nanoparticle conductive gels, incorporating materials like silver nanoparticles (AgNPs) or carbon nanotubes (CNTs), also show enhanced mechanical properties and electrical performance. In contrast, ICGs utilize the movement of ions for conductivity. These gels, often based on ionic liquids, exhibit excellent thermal stability, anti-freezing properties, and self-healing abilities, which are beneficial for flexible devices used in extreme environments. The development of conductive hydrogel strain sensors has not only improved their mechanical properties but also enhanced their electrical performance, which has made them a crucial component of smart wearable technology. Various strategies have been employed by researchers to improve the stretchability and durability of hydrogels, such as material doping,[233] fiber reinforcement,[234] structural optimization, and multi-crosslinking. These approaches effectively enhance the mechanical properties of hydrogels, which allows them to better adapt to complex application environments. However, despite significant progress in unidirectional strain detection (*e.g.*, tensile strain), the capability of bidirectional strain detection (simultaneous detection of both tensile and compressive strains) remains in the exploratory stage. Researchers have proposed hybrid liquid metal–hydrogel composites as a solution, which combine liquid metals with hydrogels, thus expanding the potential applications of hydrogels. A multi-interpenetrating network is formed in the hydrogel matrix through the incorporation of gallium-based liquid metals (such as EGaIn), GO, polydopamine (PDA), and potassium chloride (KCl).[235] This structure not only enhances the mechanical properties of the material but also improves its electrical performance, which results in excellent performance in bidirectional strain sensing, temperature sensing, and other complex applications.

Liquid metals have emerged as highly attractive materials for flexible electronic devices due to their excellent electrical conductivity, inherent stretchability, and fluidity at room temperature.[233,234] Compared with traditional metallic materials, liquid metals not only possess the characteristics of fluids but also maintain the electrical properties typical of metals. This combination endows them with significant potential for applications in flexible pressure sensors, strain sensors, and other related fields. Gallium-based liquid metal materials, such as EGaIn alloys, exhibit high conductivity and outstanding intrinsic stretchability, which makes them ideal candidates for the fabrication of Joule heaters. These materials have been demonstrated to provide thermal feedback in haptic gloves for VR environments. The unique properties of liquid metals enable them to significantly enhance the sensitivity and stability of sensors. Even under high pressure or extreme conditions, they maintain excellent reversibility and durability. In addition, the fabrication of liquid metal pressure sensors is simple and exhibits high stability, which has made it a recent focal point of research. Researchers have successfully developed high-sensitivity, fast-responsive sensors by integrating liquid metals with conductive materials, such as graphene nanosheets. The flow properties of liquid metals allow them to rapidly adjust their internal structure under pressure, thereby influencing their electrical performance. This design enables liquid metal-based pressure sensors to achieve rapid response times, excellent recovery, and remarkable sensitivity. For instance, a recently developed liquid metal sponge sensor can swiftly adjust its contact area under pressure. This capability promotes efficient charge transfer and enables highly sensitive pressure monitoring. The sensor boasts an impressive response time of only 0.41 seconds and a recovery time of 0.12 seconds. Additionally, it exhibits a sensitivity of 476 kPa^{-1}, making it capable of real-time monitoring of physiological activities such as pulse, skin pressure, and throat swallowing.[236] As liquid metal sensors continue to evolve and improve for use in portable devices, they are poised to play a crucial role in areas such as real-time health monitoring, motion tracking, and intelligent human–computer interaction.

8. Latent challenges and opportunities in flexible pressure sensors

The development of flexible pressure sensors is moving towards multifunctional integration and intelligence. These sensors have vast potential for applications in wearable devices, biomedical monitoring, implantable sensors, and other fields, offering significant technical value. However, the

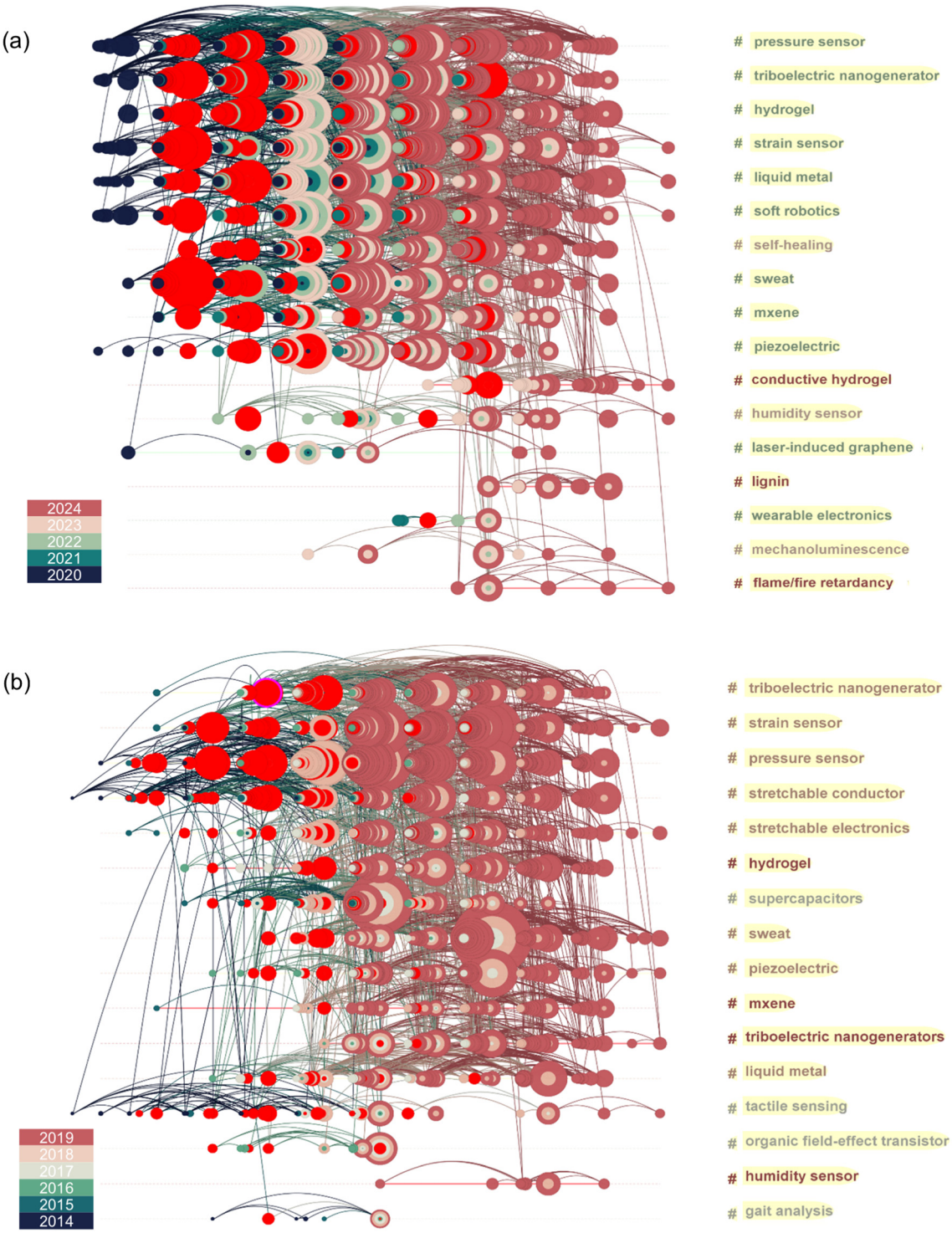


Fig. 7 Temporal evolution of research clusters in flexible pressure sensor design. (a) 2020–2024. (b) 2014–2019. Cluster dynamics and explosive growth. The figure presents the key research clusters from both the 2014–2019 and 2020–2024 periods. Each cluster is represented by a row of points, where the density of points in a row indicates the volume of publications for that cluster. Rows with higher point density represent clusters with more publications. Triboelectric nanogenerators consistently dominate the research output, while hydrogels and liquid metals show accelerated growth in the last five years, suggesting their emerging importance in flexible pressure sensor design. The red color highlights clusters that experienced explosive growth during this period.

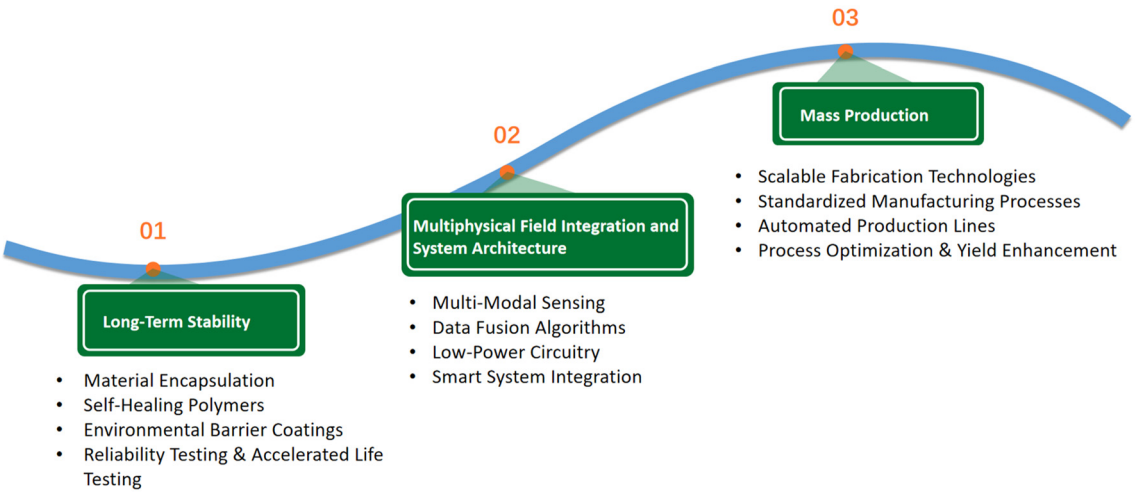


Fig. 8 A strategic roadmap for enhancing flexible pressure sensors through stability, integration, and scalable production.

optimization of flexible pressure sensors still face several inherent challenges in practical applications (Fig. 8):

1. Long-term stability: during prolonged bending, stretching, compression, and other strain processes, sensor performance may degrade, including baseline drift and reduced sensitivity. These issues arise from material fatigue and structural changes, while environmental factors such as temperature and humidity can exacerbate the problems. Specifically, MXene materials like Ti_3C_2Tx are susceptible to oxidation under certain conditions, which can significantly affect their electrical properties and mechanical performance.[237,238] Research indicates that exposure to moisture, oxygen, and elevated temperatures can accelerate the oxidation process. To mitigate oxidation, strategies such as surface passivation, coating with protective layers (*e.g.*, polymers or metals), and storage in inert atmospheres (*e.g.*, nitrogen or argon) have been proposed. To enhance long-term stability, strategies such as material encapsulation using biocompatible and flexible coatings (*e.g.*, PDMS or parylene) are essential to protect sensors from environmental degradation. Additionally, advanced fabrication techniques, like microfluidic embedding or multi-layered structures, can improve mechanical durability. Incorporating protective layers that are both conductive and resilient can help safeguard against fatigue, environmental changes, and material degradation. Research into novel materials with enhanced resistance to both fatigue and environmental stressors is also crucial for improving sensor longevity.

2. Multiphysical field integration and system architecture: with the advancement of flexible pressure sensing, there is an increasing demand for these sensors to integrate multiple physical fields, such as mechanical strain, temperature fluctuations, and humidity variations. In soft robotics, the ability to sense and respond to multiple physical fields is crucial for achieving the desired level of adaptability and functionality. For instance, soft robotic grippers need to detect not only the pressure applied to objects but also the temperature and humidity of the surrounding environment to prevent damage to delicate items or to adapt to changing conditions. Similarly, soft robotic actuators require precise sensing of mechanical strain and temperature to ensure accurate movement and control. However, integrating multiple sensing capabilities into a single soft robotic system presents several challenges. One of the primary issues is signal interference, where the detection of one physical field can interfere with the signals from another. For example, temperature fluctuations can affect the electrical properties of strain sensors, leading to inaccurate readings. Another significant challenge is maintaining system accuracy and stability in the presence of noise. Flexible sensors are often more susceptible to environmental noise due to their compliant nature, which can lead to false readings and reduced reliability. To address these challenges, advanced signal processing techniques are essential. For example, machine learning algorithms can be employed to filter out noise and correct for signal interference, thereby improving the accuracy and reliability of the sensor data. System architecture also plays a key role in ensuring seamless compatibility with other components. For instance, integrating sensors with wireless communication modules requires careful consideration of power consumption, data transmission rates, and signal integrity. Designing modular systems that allow for easy integration and replacement of components can improve the overall robustness and adaptability of soft robotic systems. In summary, the integration of multiple physical fields in flexible sensing systems requires a holistic approach that combines advanced material design, sophisticated signal processing, and robust system architecture to overcome challenges such as signal interference and environmental noise.

3. Mass production: the high cost of micro-nano fabrication, complex processes, and the difficulty in ensuring uniformity and consistency during production are key factors limiting large-scale production. Additionally, sensors are highly sensitive to external environmental disturbances during the manufacturing process, with even small variations potentially significantly affecting sensor performance. Developing cost-

effective and scalable manufacturing methods while ensuring sensor quality is essential for the commercialization and large-scale application of flexible pressure sensors. To address the challenges of mass-producing flexible pressure sensors, a multifaceted approach is essential. Developing cost-effective and scalable manufacturing methods, such as roll-to-roll printing, inkjet printing, and screen printing, can enable high-throughput and low-cost production by depositing conductive inks onto flexible substrates. Investing in advanced environmental control systems, such as cleanroom facilities, mitigates the impact of external disturbances and improves sensor reliability. By integrating these strategies, the industry is poised to overcome the significant challenges associated with mass production.

9. Conclusions and future outlook

Flexible pressure sensors have shown great potential for applications in fields such as health monitoring, human–machine interaction, and artificial intelligence. This review provides a systematic analysis of the development of this field using bibliometric methods. It covers the evolution of sensing materials, from conventional to advanced self-healing and multifunctional materials, improving sensor performance. The review also explores different sensor types—piezoresistive, capacitive, triboelectric, and piezoelectric—and their applications. Additionally, it discusses the role of algorithms in enhancing efficiency and the integration of sensors into intelligent systems like soft robotics and wearables. Emerging materials, including conductive gels and liquid metals, show promise, although challenges such as stability, multi-physics sensing, and large-scale manufacturing remain. Addressing these challenges is crucial for the commercialization of flexible pressure sensors, especially in high-growth areas like healthcare and robotics. Future research should focus on developing cost-effective and scalable manufacturing techniques, such as roll-to-roll printing and inkjet printing, to enable large-scale production. Enhancing long-term stability through material encapsulation and protective coatings is also essential. Additionally, innovations in multi-physics sensing, which integrate mechanical, thermal, and humidity sensing capabilities, will expand the versatility of these sensors. By overcoming these challenges, flexible pressure sensors can not only achieve broader commercial adoption but also play a pivotal role in advancing fields like wearable technology, soft robotics, and human–machine interfaces. The continuous development and refinement of these technologies will be key in unlocking their full potential and enabling the next generation of smart, adaptive systems.

Author contributions

Xin Li: conceptualization; data curation; formal analysis; methodology; project administration; supervision; writing – original draft; writing – review & editing. Qisheng Yang: conceptualization; data curation; formal analysis; methodology; project administration; software; validation; writing – original draft. Zetian Zhao: conceptualization; data curation; methodology; visualization; writing – original draft. Mingyuan Li: conceptualization; data curation; methodology; writing – original draft. Yuhan Zhao: conceptualization; data curation; methodology; visualization; writing – original draft. Jiarong Fan: conceptualization; data curation; methodology; visualization; writing – original draft. Qi Mao: data curation; investigation; methodology; software. Xudong Fang: formal analysis; investigation; writing – review & editing. Daixuan Wu: formal analysis; investigation; writing – review & editing. Jingbo Liu: formal analysis; investigation; writing – review & editing. Hao Guo: formal analysis; investigation; writing – review & editing. He Tian: conceptualization; formal analysis; funding acquisition; investigation; resources; validation; writing – review & editing.

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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