frontiers | Frontiers in Electronics

TYPE Perspective
PUBLISHED 04 April 2025
DOI 10.3389/felec.2025.1528802



OPEN ACCESS

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RECEIVED 15 November 2024
ACCEPTED 21 March 2025
PUBLISHED 04 April 2025

CITATION
Hu X, Guo S, Chen Y and Zhao F (2025) Functional materials-enabled flexible electronic skin for flow field decoding.
*Front. Electron.* 6:1528802.
doi: 10.3389/felec.2025.1528802



# Functional materials-enabled flexible electronic skin for flow field decoding

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Flexible electronic skin has garnered significant interest due to its promising applications in underwater robotics, aircraft monitoring systems, and human healthcare systems. A critical requirement for flexible electronic skin is to exhibit high sensitivity, stretchability, and stability. Functional materials, as essential components of flexible electronic skin, significantly influence the overall performance of the device. Consequently, a variety of material and structural designs have been developed to enhance the performance of functional materials. This perspective delves into recent advances in the development of functional materials and engineering strategies that endow electronic skin with sensitivity, stretchability, and stability. The applications of the smart electronic skin for precise decoding of flow field are highlighted. Finally, a forward-looking perspective is provided on the future of flexible electronic skin for flow field decoding, which outlines the challenges and opportunities for ongoing research and innovation in this field.

KEYWORDS

**flexible electronic skin, functional materials, engineering strategy, flow field decoding, sensitivity**

## 1 Introduction

Flexible electronic skin is an innovative technology that emulates the properties of human skin, offering remarkable sensitivity and adaptability. Composed of advanced functional materials, electronic skin enables real-time monitoring of environmental and physiological signals, making it crucial for applications in healthcare, robotics, and wearable devices (Zarei et al., 2023; Yang et al., 2024).

To replicate the properties of the natural skin, two approaches are employed from the perspective of materials consideration and engineering strategies. A rich set of high-performance functional materials are integrated with soft substrate for tactile sensation, including piezoelectric materials (Qiu et al., 2024), metal nanowires (Raman and Arunagirinathan, 2022), carbon-configured materials (Min et al., 2023), hydrogels (Hu L. et al., 2023), etc. Owing to their intrinsically flexibility, multifunctionality, ultrahigh stretchability, and long-term stability, these materials endow the electronic skin with superior capability to detect multiplexed and broad-range of stimuli such as pressure (Li J. et al., 2023), strain (Dai W. et al., 2024), temperature (Liao et al., 2024; Mao et al., 2024) and so on.

However, simply employing high-performance functional materials tend to exhibit insufferable hysteresis and response time, which is insufficient to meet the increasingly complex demands of electronic skin (Liu et al., 2021). Therefore, a preferred tactic is to introduce engineering strategies to further modify the structures of functional materials, resulting in further enhancements to the performance of electronic skin. Techniques such as

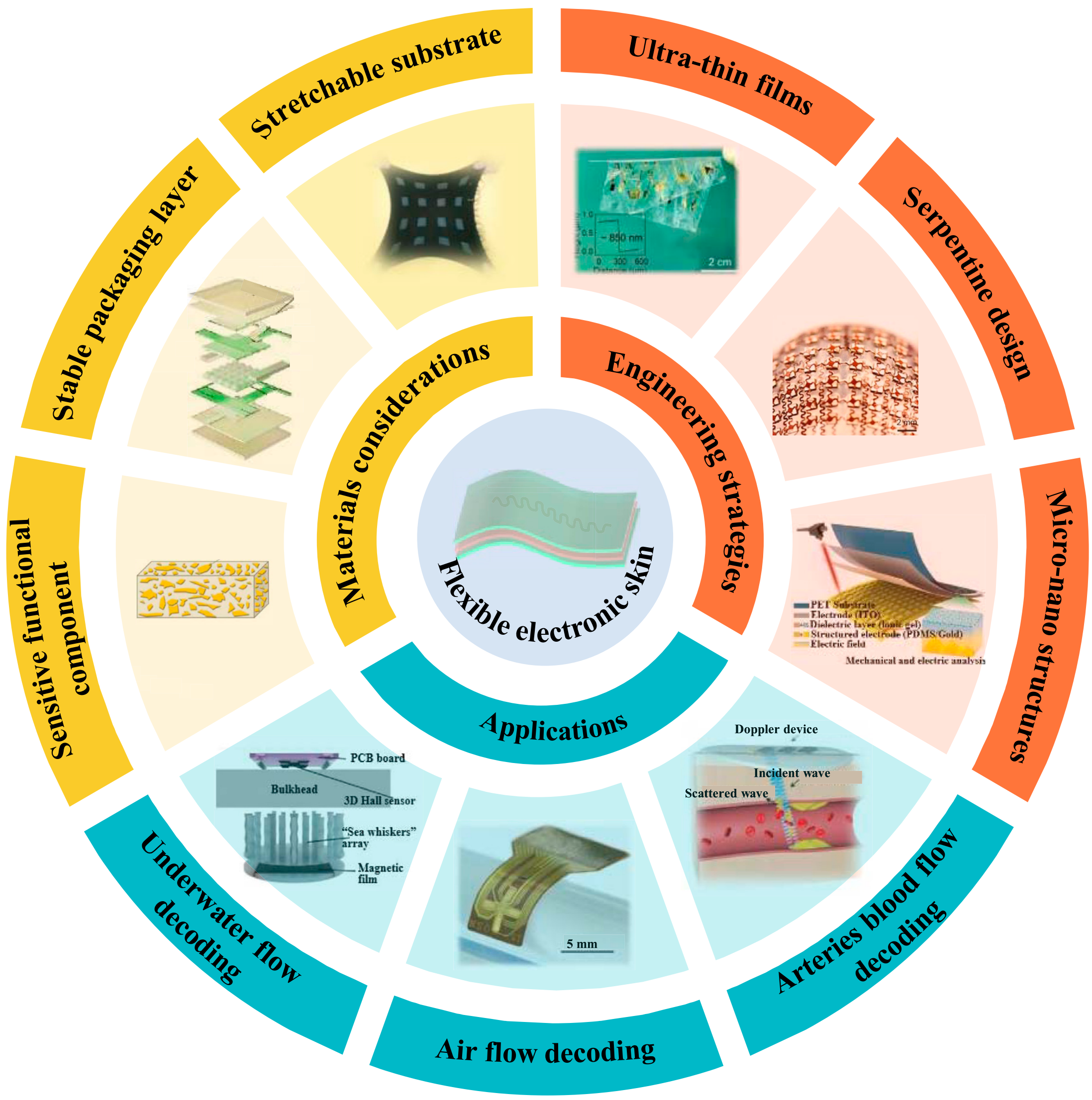


FIGURE 1
Schematic of the overall contents of this perspective. Reprinted with permission from refs. (Wu et al., 2017; Li et al., 2020; Wang F. et al., 2021; Hu X. et al., 2023; Yang et al., 2023; Dai H. et al., 2024; Gong et al., 2024; Shao et al., 2024; Wang X. et al., 2024). Copyright 2017 American Chemical Society; Copyright 2020 Oxford University Press; Copyright 2021 The American Association for the Advancement of Science; Copyright 2024 John Wiley and Sons; Copyright 2023 John Wiley and Sons; Copyright 2023 Springer Nature; Copyright 2024 John Wiley and Sons; Copyright 2024 Springer Nature.

ultra-thin films, serpentine or island bridge design and nano-micro structures (Niu et al., 2023) have been employed. These advancements have resulted in the creation of smart electronic skin, which seamlessly integrates flexible electronic technology with machine learning-supported smart systems (Kim et al., 2019; Jung et al., 2020).

Flow fields are of utmost importance in numerous domains, including water flow, airflow, and blood circulation. The rapid evolution of underwater exploration, aerospace, and medical surveillance has heightened the demand for precise flow field decoding, notably transformed by the advent of flexible electronic skin (Wu et al., 2020). The flexible electronics enable profound understanding and accurate quantification of the role of flow fields in diverse environments and biological systems, thereby propelling technological advancements and sparking innovations in these fields.

In this perspective, we summarize the advances in the development of functional materials and engineering strategies that give electronics high sensitivity, stretchability, and stability. We highlight the applications of smart electronic skin in precisely decoding flow fields (Figure 1). Lastly, we provide a forward-looking perspective on the challenges and opportunities for future research and innovation in the field of flexible electronic skin for flow field decoding.

## 2 Engineering strategies of functional materials for flexible electronic skin development

### 2.1 Materials considerations

For flexible electronic skin, the structure typically consists of three parts: stretchable substrate, sensitive functional component,

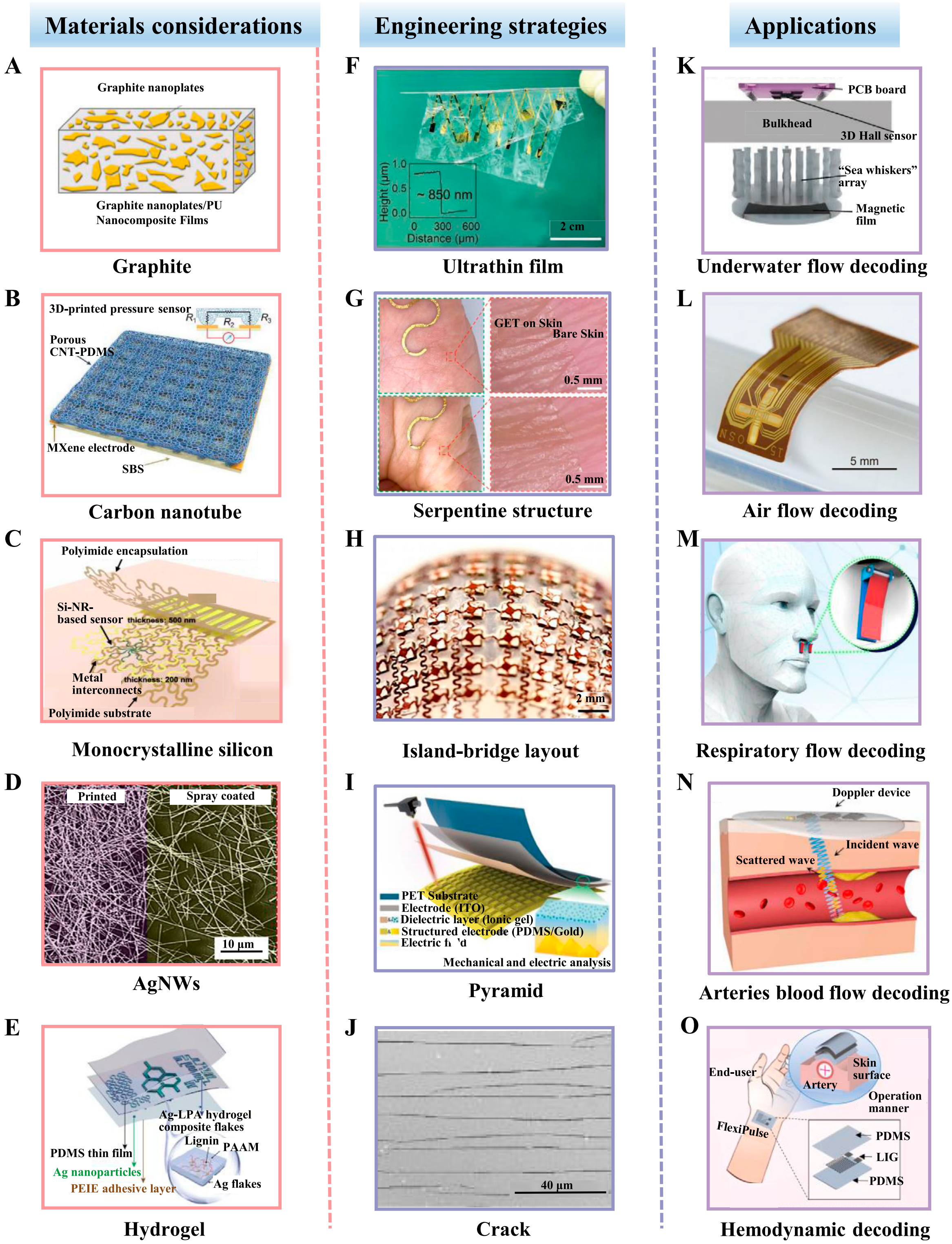


FIGURE 2
Engineering strategies of functional materials for flexible electronic skin development. Materials considerations: **(A)** Graphite (Wu et al., 2017). Reprinted with permission. Copyright 2017 American Chemical Society. **(B)** Carbon nanotubes (Song et al., 2023). Reprinted with permission. Copyright 2023 The American Association for the Advancement of Science. **(C)** Monocrystalline silicon (Hu et al., 2024). Copyright 2024 The American Association for the Advancement of Science. **(D)** AgNWs (Liu et al., 2022). Copyright 2022 The American Association for the Advancement of Science. **(E)** Hydrogel (Liao et al., 2024). Reprinted with permission. Copyright 2024 John Wiley and Sons. Engineering strategies: **(F)** Ultrathin film (Hu X. et al., 2023). Reprinted with permission. Copyright 2023 John Wiley and Sons. **(G)** Serpentine structure (Jang et al., 2022). Reprinted with permission. Copyright 2022 Springer Nature. **(H)** Island-bridge structure (Zhu et al., 2018). Reprinted with permission. Copyright 2018 The American Association for the Advancement of Science. **(I)** Pyramid (Yang et al., 2023). Reprinted with permission. Copyright 2023 Springer Nature. **(J)** Crack (Kim et al., 2020). Reprinted with permission. Copyright 2020 Springer Nature. Applications of smart electronic skin for precise decoding of flow field. **(K)** Underwater flow decoding

(*Continued*)

FIGURE 2 (Continued)
(Dai H. et al., 2024). Reprinted with permission. Copyright 2024 John Wiley and Sons. **(L)** Air flow decoding (Gong et al., 2024). Reprinted with permission. Copyright 2024 Springer Nature. **(M)** Respiration flow decoding (Li Y. et al., 2023). Reprinted with permission. Copyright 2023 Elsevier. **(N)** Arteries blood flow detection (Wang F. et al., 2021). **(O)** Hemodynamic detection (Ma et al., 2023). Reprinted with permission. Copyright 2023 Elsevier.

and stable packaging layer. In practical applications, polydimethylsiloxane (PDMS) (Nan et al., 2024), ecoflex (Li N. et al., 2024), dragon skin (Liu et al., 2024) and styrene-ethylene/butylene-styrene (SEBS) (Shao et al., 2023) films are widely used as the stretchable substrates. To enhance the sensitivity of the electronic skin, a prevalent approach is to integrate the sensitive functional component. In this regard, flexible electronic skin based on highly sensitive piezoelectric polymers and piezoelectric ceramics have been widely employed, facilitating the accurate detection of diverse stimuli (Ha et al., 2019; Han M. et al., 2019; Mahapatra et al., 2021). In addition to piezoelectric materials, most of the functional materials are used as conductors, either by penetrating within the elastic matrix or being dispersed on its surface to form piezoresistive sensors, such as carbon-framed materials (especially carbon nanotubes (CNTs) (Lin et al., 2022), graphene (Zheng et al., 2020), carbon black (CB) (Shao et al., 2023), and carbides (Mxene) (Guo et al., 2021)), metal-based nanomaterials (Raman and Arunagirinathan, 2022), inorganic semiconductor materials (Hu et al., 2024) and hydrogels (Tang et al., 2024).

Among these materials, graphene exhibits exceptional electrical conductivity and is widely employed. For instance, Figure 2A illustrates the graphite nanoplates penetrate with polyurethane (PU) to form nanocomposite film, which demonstrates superior electrical conductivity and extremely high flexibility (Wu et al., 2017). However, the percolation-based sensor rarely exhibits good linear performance on a larger scale due to the uneven mixing and the uncontrollable disruption of conductive filler network. Therefore, surface modification of the mentioned material is required to gain desirable mechanical properties (Lin et al., 2022). In addition, laser-induced graphene combined with an elastic ecoflex polymer forms a stretchable electronic skin that demonstrates high sensitivity and stability (Li Y. et al., 2024). Han Z. et al. (2019) drop casted the carbon black (CB) solutions onto airlaid paper to obtain an ultrahigh sensitivity and flexible pressure sensor. Song et al. (2023) presented a 3D-printed pressure sensor consisting of an interdigital MXene electrode and a porous CNT-PDMS active layer, which yields the highest sensitivity due to the increased contact area, as shown in Figure 2B.

Although promising, ongoing challenges for these carbon-framed functional materials-based devices typically suffer from device-to-device variation. In contrast, well-established inorganic semiconductor-based strain sensor exhibits uniformity and consistency in the device performance, demonstrating the omnidirectional capability (Figure 2C) (Hu et al., 2024).

Flexible electronic skin using metal nanowires have attracted notable attention, attributed to their high electrical conductivity and mechanical flexibility. Figure 2D illustrates a micromolding-based method for printing silver nanowires (AgNWs), which demonstrates potential applications in soft electronics (Liu et al., 2022).

As a promising alternative, hydrogels have gained widespread attention due to their exceptional high stretchability, good conductivity, biocompatibility, and mechanical properties. Figure 2E shows a programmable microfluidic-assisted hydrogel patch that features high stretchability and impressive conductivity (Liao et al., 2024). In addition, Wang et al. developed a stretchable hydrogel-based multimodal electronic skins that can self-calibrate the sensing of any two of three stimuli: strain, temperature, and humidity (Wang W. et al., 2024).

Stable packaging materials play a pivotal role in the performance of electronic skin, providing long-term durability under various conditions (Zhou et al., 2024). The materials such as parylene (Mariello et al., 2021), polyimide (Kim et al., 2018), PDMS (Li J. et al., 2024) and SEBS (Yi et al., 2023) are often employed as the packaging materials for 2D electronic device. For instance, Wang X. et al. (2024) employed PDMS silicone gel to package the flexible pressure sensor array, which serves to isolate the air. This isolation effectively safeguards oxidative behavior of the electrode and sensitive layers within the sensor, thereby ensuring the long-term usability of the sensor. For three-dimensionally (3D) architected electronic skin, Liu et al. (2024) proposed a heterogeneous encapsulation strategy that encapsulates functional components with different layers and materials, which ensures that the surrounding soft materials have similar mechanical properties to the human skin.

## 2.2 Engineering strategies

In addition to the material point of view, the property of flexible electronic skin can be improved from the engineering strategies, including ultra-thin films, serpentine design, micro-nano structures. The ultra-thin film ensures low modulus mechanics, which endows the sensor with good conformability to curved surfaces, avoiding any significant constraint on natural motions of the skin, when undergoing pressing or stretching (Wu et al., 2020). A dual-sacrificial-layer method has been employed to produce a CNT-based thinnest pressure sensor featuring a thickness of ≈850 nm, as shown in Figure 2F (Hu X. et al., 2023). The sensor achieves superior sensitivity and perfect conformability simultaneously. Most of the existing hydrogels are relatively thick and have poor air permeability. Zhang et al. (2024) presents a ~10-μm-thick hydrogel sensor, which exhibits great skin compliance.

The electronic skins demonstrate certain stretchability on highly elastic substrates; however, the conductive path is susceptible to fracture when subjected to high strain. To enhance the stretchability of the electronic skin, designs incorporating serpentine patterns and island-bridge structures are proposed. These designs possess low stiffness and good stretchability, avoiding the generation of large or irreversible cracks in a certain strain region and ensure good electrical interconnection between the sensing units (Jo et al., 2024). By analyzing various stretchable 2D and 3D sensing units, including zigzag, rhomb, serpentine, net, wave and spring, the results show that 2D structures have the superiority in thickness and attachable comfort as wearable devices attached on tendons (Shu et al., 2021). Taking advantage of the serpentine structure, Jang et al. (2022) proposed heterogeneous serpentine ribbons, which enable ambulatory electrodermal activity monitoring on the palm in free-living conditions, as shown in Figure 2G. Cai et al. (2021) reported a multifunctional electronic skin based on a patterned serpentine metal film for tactile sensing of pressure and temperature, which exhibited excellent flexibility and wearability. A stretchable ultrasound probe that exploits an island-bridge layout with multilayer electrodes, showing excellent stretchability (Zhu et al., 2018) (Figure 2H). In addition to serpentine patterns and island-bridge structures, spiral form, kirigami-inspired structures and watch-chain shapes (Li et al., 2020; Meng et al., 2022; Che et al., 2024) have also been used.

Micro-nano structures located on the surface or inside the sensing layers have demonstrated their effectiveness in enhancing the sensitivity, stretchability, and stability of the flexible electronic skin. Various forms of micro-nano structures have been employed, such as porous (Xiao et al., 2024), micro-pyramids (Hu X. et al., 2023), nanofibers (Bai et al., 2023), cracks (Zhang et al., 2023), nanowires (Won et al., 2019), interlocking structure (Ilami et al., 2021), interface non-uniform structure (yarn structure) (Liang et al., 2020) and so on (Niu et al., 2021).

Compared with ordinary planar films, the porous structure can achieve higher tensile and perceptual properties (Park et al., 2012). Unlike the salt-templating method (Wang H. et al., 2021), the laser ablation can produce thinner porous structures. The porous structure of the laser-scribed graphene and PU nanomesh-based electronic skin can be attached on finger with clear fingerprint morphology (Qiao et al., 2022). The flexible electronic skin, which utilizes pressure-induced changes in the contact area of microstructures, typically demonstrates superior sensitivity and faster response times compared to alterations in the conductive network of porous structures (Liu et al., 2021). Figure 2I (Yang et al., 2023) presents a flexible electronic skin with gradient pyramidal microstructures fabricated by a multiple laser ablations method. The sensor allows the applications in subtle pulse detection, interactive robotic hand, and ultrahigh-resolution smart weight scale/chair. Besides, the all-fibrous based sensitive mechanoacoustic sensor demonstrates excellent heart signal detection ability (Zhi et al., 2023).

The spider-inspired cracked multifunctional electronic skin has been developed by employing a location-programmable uniaxial stretching method (Zhang et al., 2023). Owing to the strain sensitive cracked straight electrode, the device exhibits a high sensitivity. By employing a laser-induced nanoscale cracking method, Kim et al. (2020) combined the aforementioned engineering strategies and developed a novel flexible electronic skin featuring an ultra-thin crack-based layer and serpentine patterned structure with a thickness of ~50 μm, as shown in Figure 2J. The sensor allows conformal contact with the epidermis, enabling a more direct measurement of skin deformation.

## 3 Smart electronic skin for precise decoding of flow field

The flow field perception has been widely adopted in various fields, such as underwater robotics, aircrafts, and human healthcare monitoring. By incorporating engineering strategies for functional materials from the development of flexible electronic skin into flow field sensors, enhanced performance can be achieved. For example, the flexible polyvinylidene fluoride–trifluoroethylen/barium titanate [P(VDF-TrFE)/BTO] nanofiber mat-based flow sensor can be used for water flow detection (Hu et al., 2019). To enhance the sensitivity of the P(VDF-TrFE)/BTO nanofiber-based flow sensor, the involvement of hydrogel cupula is a viable approach (Ma et al., 2020). In addition, thermoresponsive hydrogel cupula can be designed to tune the sensitivity (Jiang et al., 2021). The harbor seal possesses ultrasensitive hydrodynamic trail-following capabilities, for the undulated geometric structure and material property of the whiskers (Kamat et al., 2023; Zheng et al., 2023). Inspired by the unique undulating morphology of harbor seal whiskers, the flow sensor featuring a 3D magnetic-based force-decoupling perception capability and a bionic seal whisker array structure proficient at detecting diverse hydrodynamic information, as shown in Figure 2K (Dai H. et al., 2024).

The flexible electronic skin can be used for air flow field perception in a non-destructive manner. Xiong et al. (2021) proposed a smart flexible sensing skin with a thickness of ~80 μm, which used serpentine pattern Platinum (Pt) and Constantan alloy electrodes as temperature and strain sensors for multi-function flight perception. Gong et al. (2024) reported a flexible calorimetric sensor, less than 90 μm thick featuring a spiral heater and a thermistors array, which can be attached to a wing model to detect the angles of attack and slip, as shown in Figure 2L.

The flexible electronic skin inspired flow sensors demonstrate great potential in human breath detection. Li Y. et al. (2023) developed an integrated wearable smart respiratory monitoring sensor to analyze breath status, as shown in Figure 2M. Combined with artificial intelligence technology, the sensor facilitated the decoding of human respiratory flow and outperformed existing respiratory sensors in multi-parameter extraction. Meanwhile, the blockage of blood circulation will lead to serious cardiovascular disease. By employing advanced smart electronic skin technology, the dynamics of blood flow can be monitored in a non-invasive, continuous and accurate evaluation of vascular health (Wang et al., 2018; Fortin et al., 2021; Huang et al., 2024). Flexible Doppler ultrasound device with a 3 by 3 array of oblique 1–3 composite piezoelectric transducers, serpentine electrode structure and a soft silicone package can be used for the monitoring of carotid blood flow velocity, as shown in Figure 2N (Wang F. et al., 2021). The ultrasound patch with five layers of serpentine interconnections are used for continuous monitoring of cerebral hemodynamics, which enables screening and diagnosing brain disorders as well as understanding neurovascular functions (Zhou et al., 2024). Direct detection of blood flow provides critical insights into cardiovascular situation. Notably, changes in blood flow can significantly affect superficial blood pressure, making it possible to reflect blood flow through hemodynamic detection. The highly sensitive FlexiPulse with laser-engraved serpentine pattern, is capable of detecting subtle changes in strain induced by blood flow and enables independent clinical assessments of cardiovascular disease, as shown in Figure 2O (Ma et al., 2023). The kirigami-inspired highly sensitive and conformal pulse-wave sensor demonstrate accurate pulse waveforms compared with commercial medical device (Meng et al., 2022).

By leveraging the innovations in smart electronic skin, advanced flow sensing technologies hold the promise of providing improved robotic sensory systems, and more efficient aerodynamics in aircraft and real-time, precise monitoring capabilities that can lead to earlier detection of medical conditions.

# 4 Conclusions and perspectives

In conclusion, the recent advancements in functional materials have significantly propelled the development of flexible electronic skin. By integrating functional materials with structural strategies, remarkable progress has been achieved in enhancing the sensitivity, stretchability, and stability of this technology. Furthermore, the emergence of smart electronic skin has enabled precise decoding of flow fields, marking a significant milestone in this field. Looking ahead, future research should prioritize the development of even more adaptable and multifunctional materials to expand the capabilities of flow sensors. Interdisciplinary collaborations between materials science, bioengineering, and artificial intelligence could unlock new possibilities for real-time analysis and automated decision-making in robotics and medicine. Furthermore, exploring the miniaturization and energy efficiency of these sensors will be crucial for their integration into portable and long-term monitoring systems. Lastly, the integration of artificial intelligence in smart electronic skin will enable real-time data analysis and interpretation of flow fields. This will not only enhance the accuracy and efficiency of data acquisition but also facilitate the development of intelligent systems that can respond dynamically to their surroundings. Overall, the future of flexible electronic skin is promising and will continue to revolutionize various industries with its advancements in materials, engineering strategies, and integration with smart technologies.

# Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

# Author contributions

XH: Conceptualization, Formal Analysis, Funding acquisition, Supervision, Writing – original draft, Writing – review and editing. SG: Conceptualization, Formal Analysis, Funding acquisition, Supervision, Writing – original draft, Writing – review and editing. YC: Writing – review and editing. FZ: Writing – review and editing.

# Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the Fundamental Research Funds for the Central Universities, China (Grant No. 2023JBMC019), the National Natural Science Foundation of China (Grant No. 50305035 and 52275004), and Beijing Natural Science Foundation (Grant No.3242012).

# Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor ZM declared past co-authorship with the author XH.

# Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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