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**Review**
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# Flexible magnetic force sensors: manufacture, mechanisms, and applications

Huimin SHEN[1✉], Zhexin XIANG[1], Shaowen ZHANG[1], Geng YANG[2]

[1]*School of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China*
[2]*State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310058, China*

**Abstract:** In recent years, flexible magnetic sensors have undergone rapid development in cutting-edge fields such as wearable devices, robotic hand interaction, and soft robotics, demonstrating remarkable performance in sensitivity, multi-dimensional force perception, and deformability. The core component of these sensors is a flexible magnetic film, fabricated by blending magnetic particles with a soft polymer matrix using specific forming processes. Flexible magnetic force sensors work by decoding the link between magnetic signals and mechanical forces to sense touch. This review systematically examines the research framework of flexible magnetic sensors for force sensing from four critical dimensions. First, the manufacturing processes are analyzed, including the preparation of soft magnetic functional films and commonly used magnetosensitive elements. Subsequently, two primary force-decoupling methodologies are discussed: analytical modeling and data-driven approaches, with a comparative evaluation of their respective strengths and limitations. The review summarizes the key performance characteristics of flexible magnetic sensors, focusing on sensitivity, multi-dimensional force detection and deformability. Furthermore, emerging applications in wearable devices and robotic hand interaction are highlighted, illustrating the capability of these sensors for high precision feedback and multi-axis force decoupling. Finally, we assess several key challenges. These include performance variation due to non-uniform magnetic particle distribution, which necessitates laborious calibration, and signal drift following repeated use. Future directions, including bioinspired designs and artificial intelligence enhanced system integration, are also outlined. By synthesizing these perspectives, we aim to advance research toward higher sensing performance and broader application horizons for flexible magnetic sensors.



**Keywords**: Magnetic film; Sensor; Microstructure; Decoupling; Performance; Super-resolution; Robotics

## 1 Introduction

The increasing demand for human physiological signal monitoring in wearable electronics (Huang et al., 2023; He et al., 2021) and tactile feedback for robotic manipulation (Bartolozzi et al., 2016) has driven the advancement of flexible force sensing technology. Leveraging their inherent compliance and passive adaptability to conform to irregular surfaces (Wan et al., 2020; Pan et al., 2023), flexible sensors can meet the deformability requirements of diverse applications. Concurrently, progress in flexible materials and circuit design has further improved the performance of these sensing devices (Nag et al., 2017; Qu et al., 2024).

Flexible force sensors offer notable advantages, including high flexibility, light weight, and ease of integration, and commonly operate by transducing mechanical force into measurable electrical signals through various mechanisms, such as piezoresistive (Shi et al., 2018; Yang et al., 2021), piezoelectric (Min et al., 2023; Xu et al., 2024), and capacitive (Ha et al., 2021a; Li et al., 2024b) effects. However, conventional flexible sensors often face limitations such as wired connectivity requirements, relatively low signal-to-noise ratio (SNR), and susceptibility to environmental factors like temperature and humidity (Liu et al., 2023b).

In contrast, magnetic-based flexible sensors

✉ Huimin SHEN, hmshen@usst.edu.cn
Huimin SHEN, https://orcid.org/0000-0001-6092-1467
Zhexin XIANG, https://orcid.org/0009-0004-4531-0763
Shaowen ZHANG, https://orcid.org/0009-0009-0263-8490
Geng YANG, https://orcid.org/0000-0002-8685-5426

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integrate flexible magnetic films with magnetic sensing elements (Man et al., 2022). Their operating principle relies on magnetic fields as the sensing medium: applied force induces changes in the spatial distribution or vectors of the magnetic field. These alterations are detected by an array of magnetic sensors and subsequently processed through decoupling algorithms to reconstruct key force parameters, including magnitude, direction, and location. Unlike their traditional counterparts, magnetic-based sensors allow for spatial separation between the sensing (magnetic film) and readout (magnetic sensor array) layers, eliminating the need for direct wiring. This feature enables non-contact operation, making them suitable for sterile, humid, or otherwise challenging environments. Moreover, magnetic signals are inherently robust against common environmental interferences such as temperature and humidity, offering enhanced reliability compared to conventional flexible sensing approaches.

While researchers have made significant progress in the study of flexible magnetic force sensors, several critical challenges remain to be addressed. These include inconsistent magnetic field responses across different regions of the sensor surface due to non-uniform distribution of magnetic particles in the film (Chitrakar et al., 2022), which necessitates complex calibration procedures for practical deployment (Bhirangi et al., 2021). Additionally, unpredictable signal drift after repeated use introduces measurement errors (Hu et al., 2023). Therefore, research on integrated flexible sensing systems, including fabrication processes, decoupling models, and applications, is crucial for future advancements.

Flexible force sensors based on magnetic principles involve mainly three key aspects: flexible magnetoresponsive functional materials, force-magnetic mapping models, and extended applications. Flexible magnetic films, which serve as the core component of such sensors, are typically fabricated by embedding magnetic particles into a flexible polymer matrix using specific preparation techniques (Ze et al., 2020; Shen et al., 2023). These films combine excellent mechanical compliance with controllable magnetic field generation, offering distinct advantages for sensing applications on complex curved surfaces or under dynamic conditions (Shu et al., 2022). Through the development of accurate force-magnetic response models and optimization aided by machine learning, researchers have achieved remarkable sensing performance. The resulting devices exhibit high sensitivity, fast response times, and precise multi-dimensional force perception, enabling their widespread application in wearable electronics and robotic tactile systems.

Despite significant progress, flexible magnetic force sensors still face challenges in fabrication and application (Peng et al., 2025; Mostufa et al., 2023). This review comprehensively discusses the entire process of these sensors, from manufacturing and signal decoupling to applications. It presents the current state of development, analyzes existing limitations, and highlights future research directions. Our aim is to help researchers better understand the development and future trends of flexible magnetic force sensors. This review outlines the current state and future prospects of force sensing technology using flexible magnetic films.

The paper is structured as follows: Section I examines the structural design of these sensors; Section II discusses the methods for modeling the force-to-magnetic-field mapping in flexible magnetic films; Section III summarizes the performance characteristics of existing sensor designs; and Section IV presents the diverse applications of flexible magnetic film-based force sensors; Section V summarizes the current state, challenges, and future trends (Fig.1).

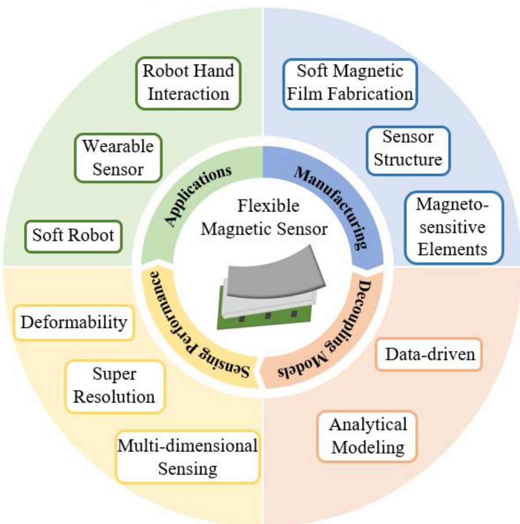

**Fig. 1 Overview of flexible magnetic force sensors**

## 2 Manufacturing engineering

The core of a flexible magnetic sensor comprises a flexible magnetic film and magnetic sensing elements. The working principle is illustrated in Fig. 2. As an integrated system, the design methodology and fabrication process influence both sensing performance and potential application domains. This section focuses on the overall design and manufacture of the sensor, systematically addressing the preparation of flexible magnetic functional films, the various underlying sensing mechanisms, and the structural design of the sensor body.

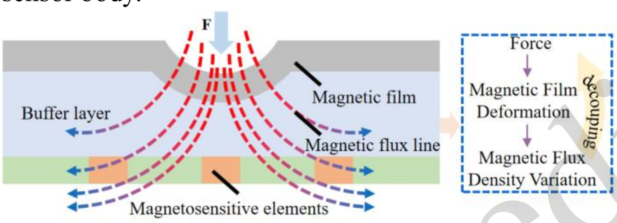


**Fig. 2 Working principle of flexible magnetic force sensors**

### 2.1 Preparation of soft magnetic functional films

The preparation of flexible magnetic films is crucial, determines fundamental magnetic and physical properties, and directly governs their suitability for diverse practical applications. The process relies on careful material selection, specific film deposition and magnetization techniques, as well as comprehensive characterization of the resulting microstructure, mechanical attributes, and magnetic performance (Yan and Wu, 2017; Zhang et al., 2024b). In these composite films, embedded magnetic particles act as the excitation source for magnetic field generation, while the flexible polymer matrix serves as the responsive medium that transduces mechanical force into a change in the magnetic signal (Wang et al., 2025).

#### 2.1.1 Magnetic particles

Magnetic particles serve as the source of force-to-magnetic signal transduction, and include mainly NdFeB (Lin et al., 2023), $SmCo_5$ (Yamkane et al., 2017), $Fe_3O_4$ (Shan et al., 2015; Peters et al., 2016), Fe (Yang et al., 2020), $Co_3O_4$ (Timonen et al., 2010), and $Ni_3O_4$ (Valverde-Tercedor et al., 2015). $SmCo_5$ is frequently used in applications that demand strong and stable magnetic fields, such as aerospace systems and harsh environmental conditions. $Fe_3O_4$ nanoparticles exhibit superparamagnetic behavior.

Huang et al. (2018) developed a biomimetic soft magnetic composite sensor with high responsivity using $Fe_3O_4$ particles, enabling detection in both contact and non-contact modes. NdFeB is characterized by an exceptionally high maximum energy product (BH) max and relatively high coercivity (Hc), rendering it a high-performance magnetic material (Li et al., 2019). The design and planning of the fabrication process are crucial, and directly govern the resulting material properties (Jumril et al., 2014). Specifically, the concentration and distribution of magnetic particles within the polymer matrix significantly influence the final magnetic characteristics of films. An insufficient particle loading leads to weak magnetic coupling and an inadequate sensor response, whereas an excessive concentration promotes particle agglomeration and magnetic domain defects, thereby compromising film uniformity.

#### 2.1.2 Flexible substrates

The flexible substrate functions as the supporting matrix for the magnetic particles and the medium for force-to-magnetic transduction. It fundamentally determines the coupling between magnetic flux variation and the substrate's deformation under applied force. Moreover, the uniformity of magnetic particle distribution within the substrate directly governs the homogeneity of the resulting excitation signal. The choice of substrate material further influences the robustness, sensitivity, and dynamic response characteristics of the overall flexible magnetic sensing system.

Common flexible substrate materials include polydimethylsiloxane (PDMS), polyurethane (PU), polyimide (PI), polyethylene terephthalate (PET), polyvinyl alcohol (PVA), and Ecological Flexibility (Ecoflex), each suited for different applications. PDMS is a transparent, colorless silicone material offering good flexibility and elasticity, along with excellent chemical stability and biocompatibility.

PU is a polymeric material formed through polymerization reactions, exhibiting higher tensile strength and abrasion resistance (Chan et al., 2016).

**Table1 Physical properties of flexible substrate materials**

| Materials | Glass Transition Temperature (°C) | Ultimate elongation (%) | Young's modulus (GPa) | Density (g/cm$^3$) | References |
|---|---|---|---|---|---|
| PDMS | -125 | 50-500 | 0.002 | 1.03 | Wang et al., 2019; Lim et al., 2020 |
| PU | 80 | 300-800 | 0.007 | 1.18 | Mai, et al., 2019 |
| PI | 270 | 80 | 2.76 | 1.36-1.43 | Shu et al., 2015 |
| PET | 70 | 90 | 2 | 1.39 | Hassan et al., 2021 |
| PVA | 25-85 | 10-1000 | 0.001-4 | 1.3 | Zhou, et al., 2021; Liu, et al., 2023a |
| Ecoflex-00-10 | -130 | 800 | 0.00005 | 1.04 | |
| Ecoflex-00-30 | -130 | 930 | 0.0001 | 1.07 | Gajula et al., 2024 |
| Ecoflex-00-50 | -130 | 960 | 0.0001 | 1.07 | |

**Table 2 Qualitative comparison of key properties of common flexible substrate materials**

| Properties | Excellent | Good | Poor |
|---|---|---|---|
| Transparency | PDMS/PET/PVA/Ecoflex | PU | PI |
| Thermal stability | PI | PDMS/PET/ Ecoflex | PU/PVA |
| Biocompatibility | PDMS/PVA/Ecoflex | PU/PI/PET | / |
| Insulating property | PDMS/PI/Ecoflex | PU/PET/PVA | / |
| Chemical stability | PDMS/PI/Ecoflex | PU/PET | PVA |
| Flexibility | PDMS/PU/PVA/Ecoflex | / | PI/PET |

These materials have been extensively studied and applied in wearable sensing devices due to their stable material properties and biocompatibility. Zhang et al. (2024c) used PDMS as a substrate to fabricate a flexible force sensor exhibiting high sensitivity (3707 kPa$^{-1}$), a wide linear range (80 kPa), and exceptional durability (2000 cycles). PI is a high-performance polymer material widely used in electronics, aerospace, and flexible circuits due to its heat resistance, excellent electrical insulation, chemical stability, and dimensional stability (Tzanis et al., 2022). PET is a crystalline thermoplastic polyester material with good insulation and mechanical strength, suitable for wearable flexible sensors. Ecoflex is a biodegradable, non-toxic plastic made from polybutylene adipate terephthalate (PBAT) (Zhang et al., 2025). Its Young's modulus closely matches that of human skin, minimizing foreign body sensation and mechanical irritation during wear. Widely used in bionic skin fabrication, it serves as a foundational material for constructing high-performance, highly reliable, and highly biomimetic flexible force sensors. PVA is a water-soluble polymer with strong dispersion capabilities that prevents agglomeration of magnetic particles (Aisyah Nurmaulia Entifar et al., 2025). Flexible magnetic films made from PVA exhibit excellent uniformity and superior mechanical properties. The physical properties of flexible substrate materials are summarized in Table 1. A qualitative comparison of the key properties of common flexible substrate materials is summarized in Table 2.

2.1.3 Methods for forming flexible magnetic film

The forming process of flexible magnetic film serves as the bridge connecting materials to flexible magnetic sensors. An optimal process ensures that magnetic domains are evenly distributed across the soft magnetic material. Such uniform distribution avoids uneven magnetic field patterns, which would otherwise degrade sensor performance. Consequently, material consistency is enhanced and performance loss is minimized. Common forming techniques include coating, chemical vapor deposition, and sputtering. With advancements in lithography and 3D printing technologies, researchers have also applied these patterning methods to magnetic film fabrication.

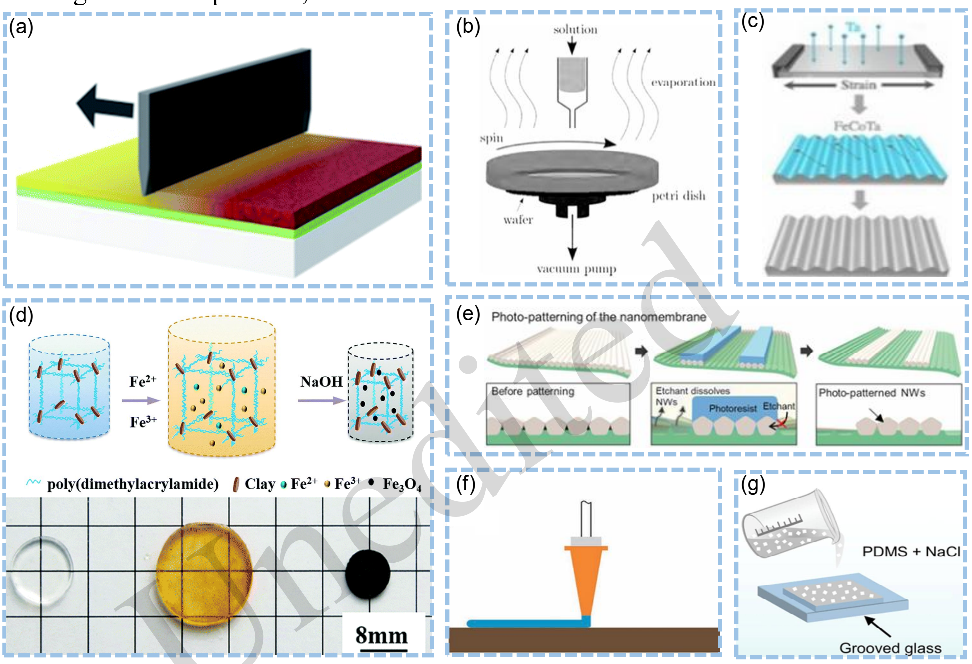



**Fig. 3 Formation method of flexible magnetic film: (a) blade coating (reprinted from(Siegrist et al., 2021), Copyright 2021, with permission from Royal Society of Chemistry); (b) spin coating(reprinted from(Burmann et al., 2014), Copyright 2014, with permission from Elsevier); (c) sputtering(reprinted from(Li et al., 2017), Copyright 2017, with permission from Springer Nature); (d) chemical vapor deposition(reprinted from(Tang et al., 2018), Copyright 2018, with permission from Royal Society of Chemistry); (e) photolithography(reprinted from(Jung et al., 2021), Copyright 2021, with permission from American Association for the Advancement of Science); (f) 3D printing(reprinted from(Mohammed and Kramer, 2017), Copyright 2017, with permission from Wiley-VCH); (g) mold forming(reprinted from(Liu et al., 2025b), Copyright 2025, with permission from Elsevier)**

Coating methods are categorized into blade-coating and spin-coating. As shown in Fig. 3a, doctor blade coating uses a variable-height blade to uniformly apply coating onto substrates, and is suitable for large-area production (Butt, 2022; Siegrist et al., 2021). Spin-coating uses the centrifugal force generated by a high-speed rotating substrate to spread the coating into a uniform thin film (Fig. 3b). This formation method offers better thickness uniformity but tends to cause material waste, making it unsuitable for manufacturing large-area flexible magnetic films (Burmann et al., 2014).

Fig. 3c shows the sputtering method, which involves bombarding a target surface with plasma, causing atoms or molecules to be sputtered and deposited onto the substrate to form a film (Li et al., 2017). Sputtering can deposit various metals, metal alloys, and compounds, yielding high-quality films with excellent uniformity and minimal batch-to-batch variation, making it suitable for large-scale production. However, it requires sophisticated equipment and can easily damage flexible substrates (Phuoc et al., 2012; Fridriksson et al., 2022).

Chemical vapor deposition (CVD) controls chemical reactions in a solution to precipitate the target layer, depositing it uniformly onto the substrate (Stassen et al., 2016). This method can deposit magnetic materials like metals or oxides onto flexible substrates, forming highly uniform coatings even on complex substrate surfaces. (Fig. 3d) Tang et al. (2018) used this method to synthesize soft magnetic films with excellent uniformity. This method is suitable for sensors requiring high manufacturing precision.

Photolithography is a typical subtractive manufacturing process (Jung et al., 2021) (Fig. 3e). In contrast, 3D printing is an additive manufacturing process that builds structures by depositing materials layer by layer onto the flexible substrate (Fig. 3f). 3D printing enables the fabrication of flexible magnetic films with greater design flexibility and rapid prototyping capabilities (Mohammed and Kramer, 2017), though the manufacturing accuracy is significantly lower than that of photolithography. Both photolithography and 3D printing are key technologies for patterning substrate surfaces and are widely used in the preparation of flexible magnetic films for research.

Mold forming is a fabrication technique that involves pouring a mixed solution into a pre-designed mold cavity. Through curing and demolding, it produces flexible magnetic films with specific shapes, dimensions, and surface structures. Its core advantage lies in the ability to manufacture flexible magnetic films with microstructures while enabling high-precision, batch replication. Liu et al. (2025) used mold forming to fabricate flexible magnetic films with porous structures, demonstrating outstanding performance through over 10,000 reuse cycles in sensors (Fig. 3g).

## 2.2 Magnetosensitive elements

In force sensors based on flexible magnetic films, magnetosensitive elements convert collected magnetic information into electrical signals such as resistance or voltage. The performance of magnetosensitive elements directly impacts sensing sensitivity, resolution, and dynamic range (Kwon et al., 2018). Common Hall sensors detect external forces by reading changes in the magnetic field of soft magnetic materials. They are sensitive to magnetic fields perpendicular to the film. Giant magnetoresistance (GMR), anisotropic magnetoresistance (AMR), and tunnel magnetoresistance (TMR) are magnetoresistive sensors that alter the electrical signal in an external circuit by changing internal resistance in response to external magnetic fields (Khan et al., 2021; Gao et al., 2024). Magnetoresistive sensors are sensitive to magnetic fields in the film plane. Hall sensors operate based on the Hall effect. The Lorentz force deflects moving charge carriers in a magnetic field, generating a voltage signal. This type of sensor is suitable for medium-to-low precision magnetic field detection and position sensing. AMR sensors rely on the change in resistivity of ferromagnetic materials with the angle between magnetization and current directions. These sensors are commonly used in geomagnetic measurement and angle sensing. GMR sensors use a multilayer ferromagnetic thin-film structure. A low resistance state appears when the magnetization directions are parallel, and a high resistance state appears when antiparallel. Such sensors are ideal for hard disk read heads and magnetic encoders. TMR sensors are based on the spin-dependent tunneling effect in magnetic tunnel junctions. A parallel magnetization direction results in low resistance, whereas an antiparallel direction results in high resistance. TMR sensors are suitable for high-precision magnetic field measurement.

Fig. 4 summarizes the sensing principles of magnetosensitive elements and Table 3 summarizes their advantages and disadvantages.

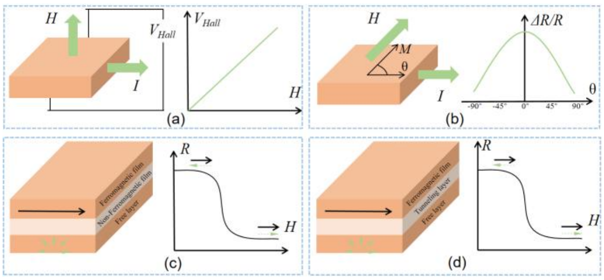


**Fig. 4 Working principles and output characteristic curves of magnetosensitive elements: (a) Hall sensor. (b) AMR sensor. (c) GMR sensor. (d) TMR sensor.**

## 2.3 Structural design of a soft magnetic force sensor body

### 2.3.1 Design based on bionic structures

Human skin functions as a low-power sensor capable of converting environmental stimuli into physiological signals (Chou et al., 2015). Tactile sensors based on flexible magnetic films adopt biomimicry as core design principle, simulating the layered structure and sensory functions of human skin. Drawing inspiration from the synergistic mechanism of the epidermis, dermis, and subcutaneous nerve endings (Maksimovic et al., 2014), the flexible magnetic film serves as the sensory layer, with embedded magnetic particles

**Table 3 Advantages and disadvantages of different magnetosensitive elements**

| Types | Advantages | Disadvantages | References |
|---|---|---|---|
| Hall | ·Simple structure<br>·Low cost<br>·Easy integration with flexible substrates | ·Low sensitivity to low magnetic fields | Heidari et al., 2016 |
| GMR | ·Capable of detecting small magnetic field changes | ·High process complexity | Gawade et al., 2025 |
| TMR | ·Magnetic field sensitivity superior to GMR<br>·Compact size<br>·High response frequency | ·Interface quality significantly impacts performance<br>·High price | Chen et al., 2017 |
| AMR | ·Simple manufacturing process<br>·Low cost<br>·Low impedance<br>·High reliability | ·Narrow linear range | Becker et al., 2022 |



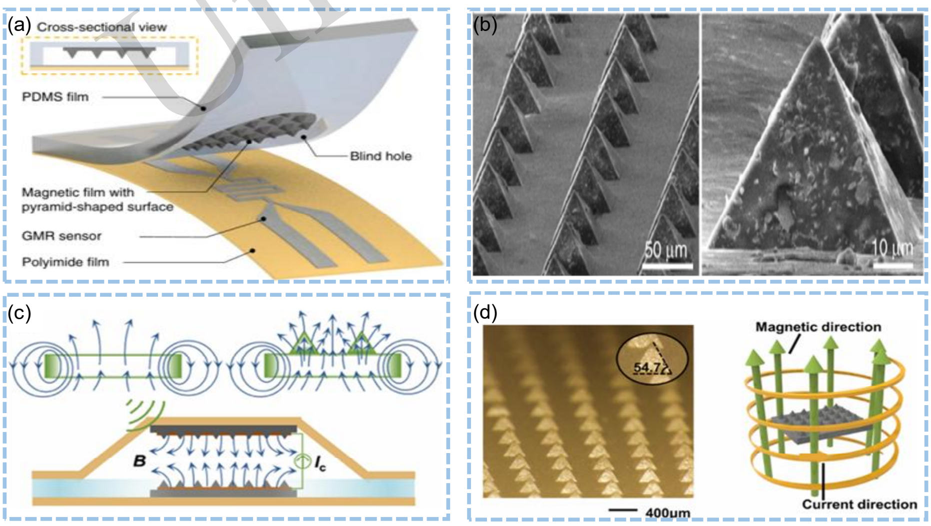


**Fig. 5 Pyramidal microstructured sensors: (a) electronic skin structural diagram; (b) optical microscope image of pyramid structure. Reprinted from (Ge et al., 2019), Copyright 2019, with permission from Springer Nature; (c) principle of a suspended flexible vibration sensor; (d) image of a micro-pyramid array on magnetic film and its magnetization mechanism. Reprinted from (Zhang et al., 2022), Copyright 2022, with permission from American Chemical Society.**

functioning as mechanoreceptors that convert external force signals into quantifiable magnetic information. Flexible magnetic force sensors can self-decouple normal and shear forces and achieve super-resolution localization through machine learning. These capabilities allow the sensors to mimic the functions of human skin. Zhang et al. (2024a) used a biomimetic structure to design a tactile electronic skin. From top to bottom, it consists of a magnetic film, a silicone buffer layer, a TMR element, and a printed circuit board (PCB). The top magnetic film mimics the epidermis, the intermediate silicone buffer layer mimics the dermis enveloping receptor cells, and the TMR element mimics the nerve cells that detect external stimuli in human skin. This multi-layer synergy endows the sensor with high sensitivity, high positional resolution, and large-area scalability. Xia et al. (2022) similarly used biomimetic principles to fabricate a soft magnetic tactile sensor comprising magnetic layers, silicone layers, and a 3D Hall effect sensor array. Under limited sample conditions, it achieved over 80% accuracy in contact shape recognition and over 95% accuracy in contact posture recognition. Building upon conventional biomimetic structures, researchers have pursued further enhancements to optimize sensor performance, leading to diverse improvements in the perceptual capabilities of flexible magnetic sensors. Li et al. (2024a) developed a specialized sensor by connecting a flexible magnetic film to a magnetic sensor plate via four interconnected columns. This design enables the sensor to detect shear forces and normal pressures as the millimeter-scale lever columns in the connecting layer undergo continuous deformation under pressure and shear forces.



### 2.3.2 Microstructure design

Microstructure design constitutes another important aspect of magnetization sensor development. Its core functions include optimizing magnetic coupling efficiency and enhancing stress/strain response sensitivity and dimensionality, while adapting to the bending and stretching deformations inherent in flexible substrates (Tang et al., 2021). Common microstructures in flexible sensor designs include micro-pyramidal (pyramid-shaped) (Boutry et al., 2018), micro-columnar (cilia-like) (Zhou et al.,2020), and micro-porous (Wang et al., 2022) configurations.

The micro-pyramidal structure on the magnetic film surface features a perpendicular magnet with inclined sidewalls that ensure shear force sensing, enabling multi-directional force decoupling capability (Peng et al., 2018). The conical structure concentrates stress at the apex, enabling significant deformation with minimal force input. This high sensitivity makes it suitable for flexible magneticsensors requiring high responsiveness. Ge et al. (2019) developed an electronic skin based on a pyramidal structure on a magnetic film surface,

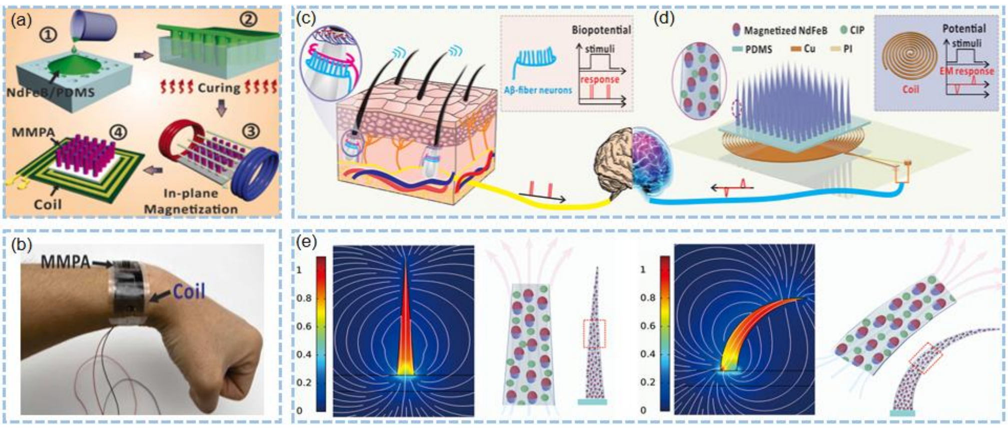


**Fig. 6 Microcolumn array sensors: (a) fabrication process of microcolumn-structured sensors; (b) image of the wearable sensor. Reprinted from (Ding et al., 2022a), Copyright 2022, with permission from Elsevier;(c) schematic diagram of human skin tactile perception mechanism; (d) typical structure of biomimetic skin; (e) schematic diagram and simulation of magnetic field changes during microcolumn bending. Reprinted from (Zhou et al., 2022), Copyright 2022, with permission from Wiley-VCH.**

substantially enhancing the sensor pressure sensitivity and response speed. The sensor structure in Figs. 5a and 5b clearly shows the pyramidal structure observed under the microscope. A vibration sensor was reported with a soft-mechanical motion structure using two parallel magnetic films (Fig. 5c).

A micro-pyramid array on a magnetic film surface (Fig. 5d) substantially enhances magnetism, enabling force and displacement sensing for medical and industrial monitoring (Zhang et al., 2022). Due to high sensitivity and strong sensing capabilities, micro-cone structures have become the most extensively researched and applied microstructures in the field of flexible magnetic sensors.

The sensing principle of microcolumn structures lies in their tendency to tilt and compress when force is applied to the tops. By detecting changes in the magnetic field of the microcolumns, the magnetic sensor array determines the magnitude and direction of external forces (Man et al., 2024), while also having the capability to decouple force direction. The manufacturing process involves mainly mixing magnetic particles with PDMS, injecting the mixture into molds for shaping and curing, and subsequently magnetizing it using an external magnetic field. A planar flexible microcolumn structure applied to magnetic film surfaces was proposed, which demonstrates excellent magnetic signal response performance (Ding et al., 2022a). Following the fabrication process shown in Fig. 6a, a wearable sensor was produced (Fig. 6b). Microcolumn structures often use arrayed designs to ensure response uniformity and prevent single-point failures. Drawing inspiration from human skin hair biomimicry, Zhou et al. (2022) proposed a flexible, whisker-like magnetized micropillar array (Figs 6c and 6d). This array was applied to high-performance sensors, enabling its use in wearable devices for monitoring respiratory status and body movements, while also featuring self-powered characteristics. Fig. 6e illustrates the spatial variation of the magnetic field after the structure is subjected to bending.

Porous structures exist in nature, such as sponges and diatoms, and are commonly used in sensing applications (Yuan et al., 2024). A flexible magnetic sensor with porous structures developed by Nie et al. (2025) enhances flexibility and compressibility by reducing Young's modulus, demonstrating highly sensitive pressure capture capabilities for tactile sensing (Fig. 7a and 7b). Peng et al. (2024) incorporated porous structures into magnetic film designs to create a flexible magnetic force sensor (Fig. 7c), essentially creating magnetoelastic materials filled with numerous micropores. Flexible magnetic films with microporous structures exhibit extremely low elastic moduli during initial loading stages. Even under minimal pressure, flexible magnetic films with microporous structures deform effectively and generate magnetic field changes, demonstrating sensitivity far surpassing that of magnetic films of other structures. In 2021, Chen's team at the California Institute of Technology observed super-giant magnetoelastic phenomena in porous soft magnetoelastic films, exhibiting a magneto-mechanical coupling coefficient five times higher than conventional rigid magnetic materials (Fig. 7d). This discovery shows potential for significant applications in wearable biomonitoring sensors (Zhou et al., 2021). The team has now developed a comprehensive theoretical framework for studying porous magneto-magnetoelastic materials (Zhou et al., 2025), providing constructive guidance for the future development of high-performance porous magnetoelastic devices. Researchers designed a soft magnetoelastic generator that efficiently converts externally applied mechanical pressure into electrical energy through the synergistic interaction between an induction coil layer and a magnetoelastic layer (Fig. 7e). This innovation overcomes the physical constraints of traditional rigid power-generating materials, realizing highly efficient and comfortable integration between the human body and electronic devices.

In summary, the three microstructures each have several advantages. Pyramid structures are sensitive to weak pressure and offer a wider linear response range and lower hysteresis due to progressive contact. Microcolumn structures convert small normal forces into large lateral magnetic field changes, also achieving high sensitivity. However, when bending exceeds a certain angle, plastic deformation or fracture may occur, limiting effective range. Microcolumns with a high aspect ratio are prone to breakage and have low fabrication yield. Thus, their preparation is the most challenging among the three. Porous structures rely mainly on overall compressive deformation, and provide the widest linear detection range but are prone to plastic deformation or collapse under long-term cycling, leading to hysteresis. Researchers should choose the appropriate microstructure based on application needs.

The microstructure of magnetic films can enhance sensor performance in multiple ways. With future advancements in nanoscale manufacturing technology, the surface microstructures of flexible magnetic films will be fabricated and used with greater precision, meeting the functional demands of flexible magnetic films across diverse fields.

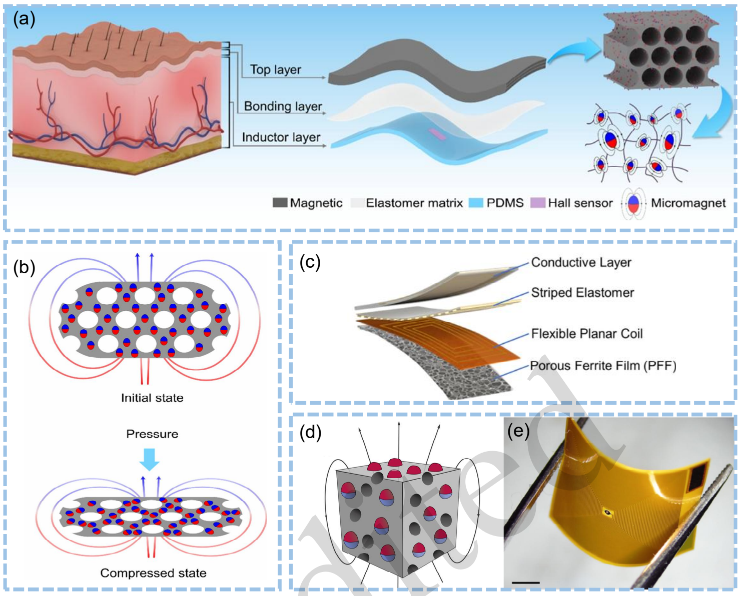


**Fig. 7 Porous microstructured sensors: (a) schematic diagram of human skin structure and porous magnetic force sensor structure; (b) schematic diagram of magnetic flux density changes in porous flexible magnetic films under pressure. Reprinted from (Nie et al., 2025), Copyright 2025, with permission from American Chemical Society; (c) schematic layup of a soft inductive bimodal sensor; (reprinted from (Peng et al., 2024), Copyright 2024, with permission from Mary Ann Liebert, Inc). (d) sketch of a porous soft system generating a magnetic flux; (e) a flexible electronic skin based on porous magnetic film. Reprinted from (Zhou et al., 2025), Copyright 2025, with permission from the American Association for the Advancement of Science.**



## 2.4 Development trends in manufacturing engineering

Innovations in materials, formation methods, and microstructures have improved the performance of flexible magnetic force sensors. However, the performance of flexible magnetic films is highly sensitive to fabrication processes. During spin coating, casting, or 3D printing, small fluctuations in temperature, air pressure, or uniformity can cause random variations in grain size, crystal orientation, and doping concentration. These variations lead to significant fluctuations in magnetic properties. Meanwhile, on polymer substrates commonly used in flexible electronics, the dispersion uniformity of magnetic particles and the curing shrinkage of the substrate are difficult to control precisely. This can cause deviations in elastomer thickness and hardness. These issues seriously hinder the batch production of flexible magnetic force sensors. In practice, a planetary mixer generates high-speed rotation to fully mix and degas the materials. High-precision 3D printed molds are used for forming. These measures ensure the uniformity and consistency of flexible magnetic films as much as possible (Dai et al., 2025). A dynamic magnetic field-assisted digital light processing method has also been proposed (Sun et al., 2026). This method solves the problem in traditional approaches where magnetized particle agglomeration prevents particles from rotating fully to the desired direction under an external magnetic field, thereby improving film consistency.

However, even small differences can accumulate in sensor arrays. In practical applications, this requires extensive data for repeated calibration and training, which significantly reduces development efficiency. Therefore, researchers should further optimize production processes to reduce performance variation between batches. This will pave the way for mass production.

## 3 Force-Magnetic field decoupling methods

In force sensing based on flexible magnetic films, the mapping accuracy between force and magnetic field information directly determines the sensor's measurement precision. However, current research remains unclear on the response mechanism of magnetic materials, as illustrated in the basic response mechanism diagram. Researchers use two main approaches to establish the force-magnetic mapping relationship (Fig. 8): the first involves constructing corresponding physical models, combining boundary conditions and analytical modeling to describe the force-magnetic field relationship; the second relies on extensive experimental samples to build complex nonlinear mappings through data-driven methods. Here, we describe how researchers use these two approaches to solve nonlinear magnetic inverse problems.

### 3.1 Analytical Modeling

Modeling analysis constitutes an interpretable response methodology grounded in established physical laws and material properties. Force-magnetic response models derived from modeling analysis typically require only minimal data for calibrating model parameters, enabling the construction of reliable response models with high efficiency and stability (Li et al., 2024a). Accurate magnetic field response models systematically reveal the relationship between force and magnetic field responses (Liu et al., 2025). Researchers can

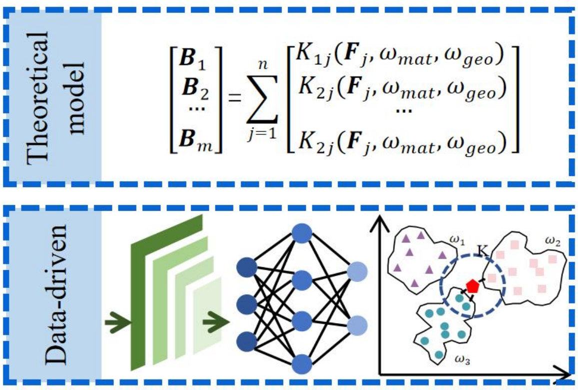


**Fig.8 Force-Magnetic decoupling mechanism**

optimize the structural design of flexible magnetic film sensors through such models, enhancing sensor reliability and precision. Li et al. (2024c) optimized magnetic film and sensor structures via theoretical calculations, reducing signal processing complexity and increasing sensor sensitivity by an order of magnitude.

Following fabrication, flexible magnetic films require magnetization treatment, with directional magnetization and multi-level magnetization being the two common methods (Dai et al., 2024a). Theoretical models constructed for different magnetization methods often differ. The following sections discuss the distinct theoretical models associated with these magnetization approaches.

#### 3.1.1 Directional magnetization model

Directional magnetization involves aligning magnetic moments within a material along a specific orientation by controlling the direction and magnitude of the applied magnetic field, thereby achieving a desired magnetic field direction (Li et al., 2024a). This technique finds extensive application in the fabrication and utilization of flexible magnetic films, and its theoretical modeling is relatively straightforward. Zhou et al. (2024) designed a soft magnetic sensor based on an oriented magnetic core film, and optimized the elastomer thickness, magnetic powder doping ratio, and sensitive element layout through a simplified theoretical model. The nonlinear theoretical model based on finite deformation theory and magnetoelastic interaction proposed by Hu et al. (2022b), along with the finite element modeling method for flexible magnetic films proposed by Jayaneththi et al. (2019), provide theoretical foundations for force sensing research and broaden applications. Chen et al. (2021) proposed a theoretical model relating the perpendicular magnetic field $H_{\perp}$ and principal tensile strain $\lambda$ for porous soft magnetoelastic films (Eq. (1)). External loading induces internal compression of the chain structure, which alters the interactions between magnetic dipoles within the chains and leads to changes in magnetic flux density.

$$H_{\perp} \approx -\frac{1}{(2a+1)\lambda^{1.5k}}M + \frac{r^3 M}{3\lambda^3 h^3}\left(0.3006 - f\left(\frac{b}{h\lambda^{1.5}}\right)\right) \quad (1)$$

Eq. (1) establishes a mapping relationship between external pressure and variation in magnetic flux, where *r* is the particle radius, *a* is the aspect ratio of the wavy chain structure, *λ* is the stretch in the compress direction, M is the magnetization of the micromagnets, *k* is a constant characterizing the influence of nonideality, neighboring chain-chain interaction, and macroscopic shape effect on the demagnetizing factor under compressive deformation, and *b* and *h* are the horizontal and vertical distances respectively, between the neighboring micromagnets. Based on the above study, the researchers developed a universal, accurate theoretical framework that does not require large training datasets. This framework explains and predicts the giant magnetoelastic effect in soft systems (Zhou et al., 2025). Fig. 9 illustrates its core decoupling strategy: first compute rotation, then update magnetization, and finally obtain the magnetic field. The principle uses the deformation gradient from the reference configuration to calculate the rotation of magnetization. This yields the magnetic field distribution in the current state. This approach avoids directly solving complex magnetic constitutive relations in the reference configuration. It also clearly reveals the physical origin of the giant magnetoelastic effect in soft systems: magnetic field changes arise mainly from geometric rotation of the magnetization direction, not from changes in magnitude of the magnetic moment. Thus, it provides a solid theoretical foundation for calculating magnetic field changes in the directional magnetization model.

### 3.1.2 Multipole magnetization model

Sinusoidal magnetization is a specialized magnetization technique that involves applying an alternating magnetic field to the material surface, causing the magnetic moments within the material to vary sinusoidally with spatial position. This results in a periodically distributed magnetic field on the magnetic film surface. Sinusoidally magnetized magnetic films can generate multidimensional magnetic information, enabling sensors to perceive forces in multiple dimensions. Yan et al. (2021) proposed a soft tactile sensor based on a sinusoidally magnetized flexible film. By constructing a mathematical model between force components and the magnetic field, they theoretically achieved natural decoupling of normal and tangential forces, successfully overcoming the strong cross-coupling effects commonly observed in conventional magnetic-based tactile sensors.

The Halbach array, a specially arranged

$$\begin{aligned}\vec{B} &= \int_0^{2\pi}\int_0^{\arccos\left(\frac{R-d}{R}\right)}\int_0^{R} \mathrm{d}\vec{B}\rho^2 \sin(\theta)\mathrm{d}\rho\mathrm{d}\theta\mathrm{d}a \\ &\quad -\int_0^{a_0}\int_0^{1}\int_0^{2\pi} \mathrm{d}\vec{B}\left(R-d\right)a\lambda^2\mathrm{d}\varphi\mathrm{d}\lambda\mathrm{d}a\end{aligned} \quad (2)$$

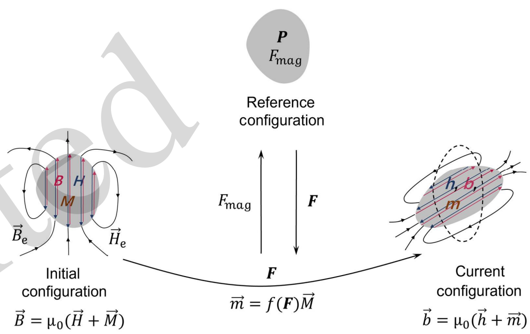


**Fig. 9 Scheme of the decoupled approach to calculate the giant magnetoelastic effect in soft systems (reprinted from (Zhou et al., 2025), Copyright 2025, with permission from the American Association for the Advancement of Science).**

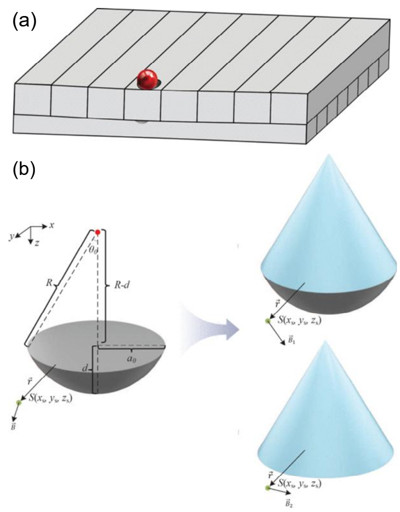


**Fig. 10 Schematic representation of deformation and magnetic field decomposition: (a) a spherical object making contact with an orthogonal Halbach bilayer; (b) decomposition of the magnetic field from the spherical cap into two components (reprinted from (Gui et al., 2025), Copyright 2025, with permission from the Institute of Electrical and Electronics Engineers).**

permanent magnet array, is often used in the sinusoidal magnetization of magnetic films. Based on an orthogonalized double-layer Halbach magnetization method (Fig. 10a), Gui et al. (2025) proposed an accurate analytical formula Eq. (2). Fig. 10b illustrates the geometric deformation of the contact region and its magnetic field decomposition method when a spherical object contacts an orthogonal Halbach bilayer magnetic film. A sphere of radius $R$ presses into the surface of the magnetic film with a compression depth $d$. $\lambda$ is the scaling factor that adjusts the position within the cone segment. The magnetic field variation caused by the deformation is skillfully decomposed into two directional components by the authors. This converts the original calculation of the magnetic field of the spherical cap with variable integration limits into two simple integrals with constant limits, greatly reducing computational complexity. This theoretical model enables super-resolution perception without training data. It improves localization accuracy from the sensor spacing of 20 mm to about 3.89 mm, achieving a five-fold enhancement.



### 3.2 Data-driven decoupling

Flexible magnetic films are the core components of flexible magnetic sensors. These sensors exhibit a highly nonlinear response to external forces, which complicates accurate physical modeling. Data-driven approaches, which do not require explicit model equations, are well-suited for systems with complex and unknown mechanisms (Thuruthel et al., 2019; Wang et al., 2023a). Machine learning is widely used to decode signals and reconstruct underlying physical quantities. Data-driven machine learning approaches offer a solution pathway for continuous sensing analysis tasks (Pires et al., 2018; Ouyang et al., 2024), achieving remarkable results in recent years. By learning from acquired data, these methods predict the relationship between magnetic field information and force. The core of data-driven decoupling lies in establishing nonlinear mapping relationships between inputs and outputs through network training. Increasingly, researchers are applying machine learning to flexible magnetic sensor design. Many data-driven decoupling algorithms, such as LSTM and SVM, have also been explored in related studies. This review focuses on three representative methods: convolutional neural networks (CNN), multi-layer perceptron (MLP), and K-nearest neighbors (KNN). These algorithms cover traditional machine learning, shallow neural networks, and deep learning, respectively, and collectively reflect the current landscape of data-driven methods in this field (Hellebrekers et al., 2019; Hu et al., 2022a; Hu et al., 2024).

#### 3.2.1 CNN

CNN is a deep learning architecture capable of processing grid-like topological data structures, commonly used to handle nonlinear mapping data from flexible magnetic sensors (Liu et al., 2021). Han et al. (2018) used a CNN model to address nonlinearity and response lag issues in flexible sensors. With the rapid expansion of CNN model depth and breadth, researchers are increasingly applying deeper neural networks to obtain more abstract and robust response features for flexible magnetic sensors. A lip-reading system based on a flexible magnetic film using a CNN model was proposed, which achieved high-accuracy translation with excellent scalability from the wearable framework to the neural network model (Angel et al., 2025). Zhou et al. (2024b) proposed a soft magnetic skin featuring multimodality, waterproofing, stackable architecture, and reconfigurability using a one-dimensional CNN. However, CNN models demand substantial sensor data and involve relatively complex training processes, rendering them unsuitable in certain scenarios.

#### 3.2.2 MLP

MLP is a deep learning model based on stacked fully connected structures and nonlinear transformations (Zhang et al., 2018). Sun et al. (2022) achieved an SR factor of $10^6$ using an MLP model for tactile sensors. Compared to CNN, MLP requires only moderate amounts of data for training and exhibits fast prediction speeds post-training. Hellebrekers et al. (2020) used MLP to perceive pressure magnitude and location. Yan et al. (2021)

proposed a soft tactile sensor with 60-fold super-resolution accuracy. A robotic hand equipped with this sensor could stably grasp fragile objects and perform threading tasks despite external disturbances.

However, the MLP model requires input data to be flattened into one-dimensional vectors. When processing data with high spatial element requirements, this approach disrupts spatial proximity relationships, making it difficult to learn certain local features. Consequently, it is suitable only for processing flexible magnetic sensor signals with low to medium dimensions and well-defined features. For high-dimensional complex signals, MLP becomes less effective.

#### 3.2.3 KNN

KNN is a lazy learning algorithm. Unlike CNN and MLP, KNN requires no training phase and can perform inference directly on raw data (Taunk et al., 2019). Its straightforward yet efficient computational process is widely applied in the classification prediction of flexible magnetic film sensing force. Hellebrekers et al. (2019) used KNN regression to estimate force with an average error of only 0.44 N. In 2022, Hu et al. (2022a) combined the Linear Universal Kriging Equation with KNN to achieve super-resolution force position sensing across an entire multi-directional magnetized magnetic film region. Building upon this, Hu et al. (2024) further integrated these methods to enable high-resolution force distribution mapping across the entire magnetic film. Fang et al. (2023) fabricated fingertips using flexible magnetic films, using KNN classification for force position estimation and neural networks for force magnitude estimation. Their approach demonstrated robust grasping performance in experiments, offering novel insights for interactive perception in flexible robotic hands. The KNN algorithm, with distinctive simplicity, has consistently held a prominent position in classification prediction. However, the limitation of handling high-dimensional complex data constrains its application. Researchers have combined KNN with other machine learning methods, effectively advancing the performance of flexible magnetic film sensors.

### 3.3 Development trends in decoupling methods

Using analytical modeling and data-driven methods, researchers have achieved force decoupling from magnetic signals. Developing theoretical models to analyze the force-magnetic field mapping has several advantages: it simplifies the model for easier computation, improves efficiency while maintaining accuracy, and helps describe the relationship between magnetic fields and forces. Such models also allow optimization of relevant parameters. However, this approach often relies on strict assumptions. It is not suitable for complex coupling or highly nonlinear interactions. Data-driven methods address complex, mathematically intractable systems and black-box problems, significantly reducing modeling and testing efforts while cutting costs. This accelerates the development and application of flexible magnetic sensors. Currently, data-driven methods are expanding in this field and show strong predictive capability. Updates with new data also improve adaptability to environmental changes. However, the training process must rely on accurate, high-quality experimental data. Obtaining such data is often challenging. Moreover, the black-box nature leads to poor interpretability during prediction. This poses potential risks, hindering the practical implementation of flexible magnetic sensors in high-risk fields such as healthcare. Researchers should organically integrate the two decoupling methods, using physical laws as constraints and leveraging data to compensate for nonlinear errors, thereby constructing interpretable, high-performance flexible magnetic sensors.

## 4 Sensor Performance

The sensing performance of flexible magnetic sensors is determined by two main properties: magnetic and mechanical. Magnetic properties reflect the sensor's ability to detect magnetic fields, covering metrics such as sensitivity, multi-dimensional sensing capability, linearity, and response speed. Mechanical properties represent the core characteristics that distinguish flexible sensors from traditional rigid sensors, including mainly deformability, fatigue resistance, and biocompatibility. Performance priorities vary across application scenarios. In wearable devices, excellent conformability and high sensitivity form the basis for practical use, while in robotic interaction, multi-dimensional sensing capability and fast response speed are more critical. This chapter focuses on three core performance factors that play a significant role in driving practical applications: super-resolution perception to push the limits of spatial resolution, multi-dimensional force sensing to achieve complete force decoupling, and deformability to ensure physical morphological adaptability. Through a systematic discussion of these three performance aspects, we aim to provide theoretical foundations and practical references for optimizing the performance and expanding the application of flexible magnetic sensors.

### 4.1 Super-resolution perception

High sensitivity is a primary consideration in the design of flexible magnetic sensors. While traditional approaches often increase sensing array density to achieve high precision, this significantly escalates fabrication complexity and cost, particularly when decoupling multi-axis magnetic responses. To overcome these physical limitations, the concept of tactile super-resolution (SR) has emerged as a core design paradigm (Lepora et al., 2015). By leveraging overlapping sensing domains and interpolation algorithms, SR enables detection capabilities that fundamentally transcend the inherent resolution of the hardware, allowing for robust active sensing in unstructured environments (Miao et al., 2024; Ding et al., 2022b).

To quantitatively evaluate this capability, researchers have established specific performance metrics. The super-resolution factor (SR-factor) is a crucial indicator, defined as the ratio of the effective sensing length (or area) per sensor to the sensing accuracy (Hu et al., 2024; Zhou et al., 2024). A higher SR-factor signifies a greater capability to capture and transmit spatial information with enhanced precision. The metrics are generally calculated as follows:

$$SR\text{-radio}=\frac{S}{RMSE\times n_{taxel}} \tag{3}$$

$$SR\text{-factor}=\frac{L}{RMSE} \tag{4}$$

where $S$ means the effective tactile sensing area; RMSE means the root mean square error of contact location; taxel means the number of tactile pixels; $n_{taxel}$ means the number of tactile sensors; and L means the effective sensing length per single sensor.

Table 4 compares the findings of different researchers across four aspects: sensing principles, taxels, sensing area, and the SR factor. Sensing areas range from 15 to 48400 mm², with application scenarios ranging from fingertip force recognition to tracking continuous spherical motion across a plane. Through optimized sensor design and algorithmic improvements, the SR factor has reached as high as 60, driven by advancements in training algorithms.

### 4.2 Multi-dimensional force sensing

Forces on an object are multi-dimensional and coupled, rather than acting in a single direction (Lee et al., 2011). Single-dimensional force sensing limits the application of sensors. In contrast, multi-dimensional force sensing overcomes the limitations of traditional single-dimensional sensing and enables accurate recognition in complex scenarios (Rehan et al., 2022). Flexible magnetic sensors applied to human physiological signal detection and robotic hand interactions must detect forces from multiple directions. For instance, during finger joint flexion, forces include not only normal pressure perpendicular to the joint surface but also shear forces parallel to it. When a robotic gripper handles fragile objects, it must simultaneously sense vertical gripping force to prevent crushing and horizontal shear force to prevent slippage. Flexible magnetic sensors distinguish force perception across multiple dimensions through two approaches: mechanical decoupling and self-decoupling: mechanical decoupling relies on specialized mechanical structures within the sensor, while self-decoupling depends on the magnetic field characteristics and magnetization patterns of flexible magnetic films, enabling the sensor to inherently decouple forces. Table 5 summarizes the achievements of different researchers in the field of multi-dimensional force sensing.

### 4.3 Deformability

Deformability is an important metric for evaluating flexible magnetic sensor performance, and is determined mainly by the type of flexible substrate material and the ratio between substrate material and magnetic particles. This capability dictates the sensor's adaptability to detecting various curved surfaces and complex geometries. For instance, flexible magnetic sensors in wearable devices often conform to human skin, which exhibits intricate deformations. This necessitates magnetic sensors capable of withstanding omnidirectional strain while maintaining stable performance. Meanwhile, controllable deformation is a core capability for soft robots, necessitating flexible magnetic sensors with excellent deformability within sensing-enabled soft robots to enable autonomous operation in complex environments. Table 6 summarizes the strain ranges and maximum number of cycles reported by different researchers for flexible magnetic sensors.

**Table 4 Summary of super-resolution flexible magnetic sensors by different researchers**

| Sensing principle | Taxels | Sensing area($mm^2$) | SR factor | References |
|---|---|---|---|---|
| Specific magnetization arrangement | 1 | 3600 | 29.6 | Hu, et al., 2022a |
| | 16 | 48400 | 45.8 | Hu, et al., 2024 |
| Soft magnetic skin | 1 | 15 | 5 | Hellebrekers, et al., 2019 |
| | 5 | 1600 | 15.5 | Hellebrekers, et al., 2020 |
| Self-decoupling | 9 | 324 | 60 | Yan et al.,2021 |
| | 3 | 324 | 15 | Yan et al., 2022 |
| An orthogonal Halbach bilayer magnetization | 4 | 1600 | 5.1 | Gui, et al., 2025 |
| Intelligent edge | 5 | 400 | 36.8 | Zhou, et al., 2024a |

**Table 5 Summary of 3D force sensing achieved by different researchers**

| Methods for 3D Force Decoupling | Normal force sense Range | Normal force sensitivity | Shear force sense range | Shear force sensitivity | Applications on 3D force sensing |
|---|---|---|---|---|---|
| Self-decoupling (Yan et al.,2021) | 0-120kPa | 0.01$kPa^{-1}$ | 16kPa | 0.1-0.27$kPa^{-1}$ | ·Adaptive grasping slippery objects (glass bottles) and fragile objects (eggs)<br>·A controller for robotic needle threading |
| Self-decoupling (Dai et al., 2024) | 0-5.88N | 0.137N | 0-0.98N | 0.013N | ·Adaptive grasping of slippery objects (glass bottles) and fragile objects (tomatoes) |
| Self-decoupling (Yan et al., 2024) | 0-260N<br>0-28N<br>0-31 N | 0.002 $kPa^{-1}$<br>0.01$kPA^{-1}$<br>0.002$kPA^{-1}$ | ±27N<br>±8N<br>±10N | 0.01 -0.029$kPa^{-1}$<br>0.006-0.042$kPa^{-1}$<br>0.039$kPa^{-1}$ | ·Knee force distribution measurements<br>·Grasping spoons |
| Mechanical decoupling (Zuo et al., 2025) | 0-1.5N | 98.51mV/N | 0-0.16N | 880.52mV/N | ·Robotic object grasping<br>·Evaluate friction characteristics of the surface |
| Mechanical decoupling (Li et al., 2024a) | 0-4kPa<br>0-4kPa<br>0-4kPa | 0.0084$kPa^{-1}$<br>0.0028$kPa^{-1}$<br>0.0027$kPa^{-1}$ | 0-0.05N<br>0-0.05N<br>0-0.05N | 0.2$N^{-1}$<br>0.09$N^{-1}$<br>0.04$N^{-1}$ | ·Joint bending monitoring<br>·Grasping a table tennis ball<br>·Real-time monitor swallowing action |

### 4.4 Development trends in sensor performance

Although existing flexible magnetic force sensors can be used for over 10,000 cycles with high recognition accuracy, repeated bending and stretching still cause mechanical fatigue. This leads to delamination, microcracks, and oxidation of the flexible magnetic film. These issues result in significant reliability problems and signal drift.Zhang et al. (2025) reported that the mechanical properties of flexible magnetic films degrade significantly over time, thereby affecting magnetic performance. Researchers have tried to reduce signal drift through signal processing, Most approaches couple manufacturing variations with long-term drift. The prevailing strategies rely only on periodic calibration to passively mitigate drift. True long-term calibration-free stability has not been achieved due to the lack of decoupled compensation, physical drift models, or time-series prediction models. Moreover, in high-density sensing arrays, the coupling between multi-axis signal crosstalk and external magnetic interference greatly increases the difficulty of data processing. These problems are key bottlenecks and challenges in the development of flexible magnetic force sensors. Future research should focus on improving the long-term stability of materials and microstructures, while also addressing signal crosstalk. Additionally, building signal drift models for flexible magnetic force sensors will help ensure sensor performance after repeated use.

**Table 6 Summary of the deformability of flexible magnetic sensors by different researchers**

| Strain Range (%) | Maximum Number of Stretches | References |
|---|---|---|
| 30 | No reported | (Cao et al., 2023) |
| 50 | ＞9450 | (Yang et al., 2025) |
| 86 | 1000 | (Pan, et al., 2025) |
| 100 | 2000 | (Wang et al., 2018b) |
| 160 | 9000 | (Guo et al., 2023) |
| 180 | 9000 | (Guo et al., 2022) |
| 600 | ＞10000 | (Zhu, et al., 2022) |
| 961 | No reported | (Melzer et al., 2015) |
| 1200 | No reported | (He and Yuan, 2021) |



## 5 Applications

Force sensors based on flexible magnetic films show significant application potential in wearable devices, robotic hand interactions, and soft robotics due to their high sensitivity, multidimensional force sensing, and excellent deformability. Here, we summarize the applications of flexible magnetic film-based pressure sensing technology across various fields.

### 5.1 Wearable devices

Wearable devices have revolutionized real-time physiological signal monitoring due to convenience, non-invasiveness, real-time capability, and continuous operation. Flexible magnetic film-based electronic skin, with its soft conformability and excellent biocompatibility, finds extensive application in wearable devices (Ha et al., 2021b). Researchers design wearable devices with diverse structures to conform to different body regions and monitor various physiological parameters. Current research on wearable soft magnetic force sensors focuses on enhancing wear comfort, reducing power consumption to extend battery life, improving sensitivity, and broadening application scope.

Zhao et al. (2020) developed a fully flexible microelectromechanical system (MEMS) sensor capable of motion detection, speech recognition, biophysical sensing, and machine condition assessment (Fig. 11a). This sensor exhibits high monitoring sensitivity and durability, offering broad application prospects in sports, healthcare, rehabilitation, and industrial fields. An intelligent tactile sensor featuring a wide measurement range and high sensitivity was reported by Wu et al. (2018). By converting force stimuli into neuro-like signal outputs (Fig. 11b), it presents a novel approach for prosthetic research. Angel et al. (2025) developed a magnetic skin that securely adheres to the body, offering excellent wearability and endurance. This innovation converts lip movements into speech, enabling language interaction for individuals with speech impairments (Fig. 11c).

### 5.2 Robotic hand interaction

The human hand has exceptional multimodal perception capabilities, and robotic hands are now advancing toward mimicking human sensory abilities (Bai et al., 2024; Sekine et al., 2021). Traditional robotic hands often feature rigid, non-feedback contact structures that fail to meet safety interaction requirements. Researchers have integrated flexible magnetic sensors with robotic hands to endow them with tactile perception, including micro-force sensing, multi-dimensional

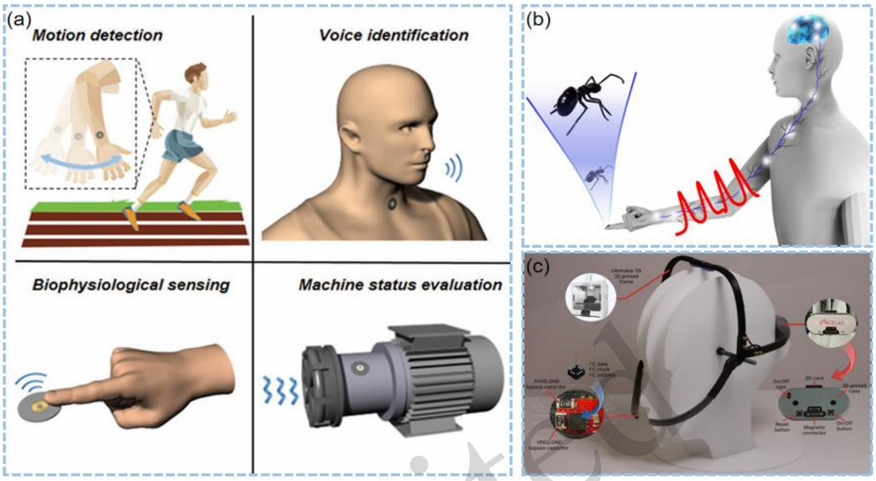


**Fig. 11 Application of flexible magnetic force sensors in wearable devices: (a) soft magnetic sensors for motion detection, voice recognition, biophysical sensing, and machine condition assessment (reprinted from (Zhao et al., 2020), Copyright 2020, with permission from Wiley-VCH). (b) smart tactile sensors for prosthetics (reprinted from (Wu et al., 2018), Copyright 2018, with permission from the American Association for the Advancement of Science); (c) soft magnetic headset system for speech recognition (reprinted from (Angel, et al., 2025), Copyright 2025, with permission from Wiley).**

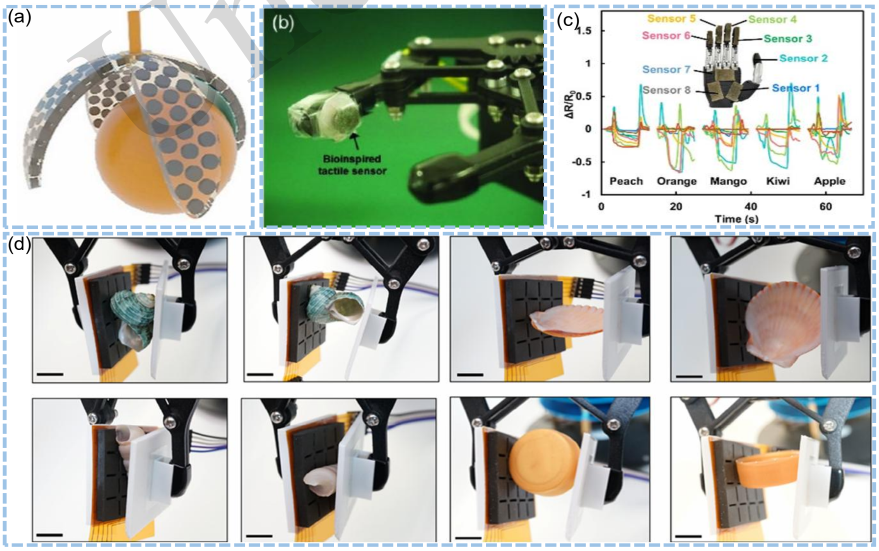


**Fig. 12 Application of flexible magnetic force sensors to robot hand interaction: (a) snatching function of a soft gripper (reprinted from (Qi et al.,2022), Copyright 2022, with permission from Elsevier); (b) a self-powered sensor attached to one tip of a robotic arm，which could feel and respond to diverse objects (reprinted from (Ma et al., 2020), Copyright 2019, with permission from Wiley); (c) a robotic hand integrated with flexible magnetic sensors, and the corresponding resistance variation during the grasping of different fruits (reprinted from (Ren et al.,2025), Copyright 2025, with permission from American Chemical Society); (d) a multimodal magnetoelastic artificial skin for identifying marine creatures and marine litter (reprinted from (Zhou et al.,2024), Copyright 2024, with permission from the American Association for the Advancement of Science)**

force recognition, texture identification, and slip detection (Wei et al., 2016; Bhirangi et al., 2023). Integrated with embedded feedback systems (Liu and Huang, 2018), these enhancements enable adaptive precise physical interactions, such as grasping fragile or slippery objects and performing more intricate manipulations (Huang et al., 2025; Jamone et al. 2015). Qi et al. (2022) proposed a programmable magnetic soft material, which achieves shape changes. A flexible gripping blade is created by 3D printing a set of magnetic structural elements and encapsulating them in silicone, demonstrating adaptive gripping capabilities (Fig. 12a). Ma et al. (2020) developed a flexible, self-powered tactile sensor featuring an inverted conical architecture. Integrated onto a robotic fingertip and combined with a machine learning algorithm, the system effectively distinguished objects of variable stiffness through grasping motions, enabling blind identification of unknown materials (Fig. 12b). Ren et al. (2025) proposed a flexible biomimetic tactile sensor with multimodal perception. Integrated onto a robotic hand and combined with a deep learning algorithm, the sensor achieved high-accuracy performance in tasks such as texture recognition, braille recognition, and fruit identification (Fig. 12c). Zhou et al. (2024) developed a waterproof, multimodal underwater robotic skin for marine object recognition. Capable of identifying seven typical marine organisms and debris with 95% accuracy, it enables deep-sea operations for underwater robots, marking a new milestone in sustainable marine resource development (Fig. 12d).

### 5.3 Soft robotics

Advancements in flexible magnetic force sensing technology have driven the development of soft robots that integrate sensing and actuation (Rus and Tolley, 2015). Soft robots based on magnetically responsive soft composites offer non-contact control, rapid response, programmable deformation, and the ability to perform complex tasks such as navigating narrow gaps, suggesting broad application in the biomedical field (Ebrahimi et al., 2020). The fundamental principle involves an externally controllable magnetic field exciting deformation in a magnetic film, driving the soft robot's motion. Integrated sensing modules provide pose feedback, guiding the robot's subsequent actions (Joyee and Pan, 2019). Yue et al. (2022) developed a magnetic soft robot capable of sensing obstacles under an external magnetic field (Fig. 13a). Upon detecting a falling sand signal, it returns to a safe zone, marks the dangerous area, and eventually plans a path to cross the hazardous zone. Wang et al. (2023) developed a magnetic soft robot capable of environmental perception, exhibiting high sensitivity and obstacle avoidance drug dissolution, enabling targeted drug delivery (Fig. 13b). Dong et al. (2022) used a modular assembly strategy to develop soft robotic modules with programmable magnetization curves in 2D or 3D geometries (Fig. 13c). This approach integrates multifunctional modules with diverse material properties and morphologies into soft robots, simplifying the fabrication of multifunctional soft robots. It enhances the multifunctionality and application prospects of small-scale soft robots, offering new insights for their design that integrate sensing and actuation.

### 5.4 Development trends in applications

Flexible magnetic force sensors have achieved initial applications in robotics and wearable devices. However, large-scale adoption in industrial production has not yet been realized. An important reason is that the development of these sensors relies heavily on complex data processing. The high computational demand is expensive and becomes a key bottleneck for deployment on resource-constrained platforms, especially mobile devices. This hinders large-scale production in portable systems. Meanwhile, the development of large AI models has significantly increased computing costs, further raising the development cost of sensors. Yan et al. (2026) developed a fully digital in-memory computing chip. It achieves an operating frequency of up to 12.5 MHz and ultra-low power consumption of only 55.94 μW. The chip enables energy-efficient, high-parallel neural network inference on flexible substrates. It reduces the processing latency of 3D magnetic signals from 20 ms to less than 2 ms with extremely low power consumption. This paves the way for developing integrated, low-power, and portable flexible magnetic tactile sensing systems. Therefore, future research should focus on developing efficient computing models and chips, deeply integrated with AI technologies. This will enable flexible magnetic force sensors with low cost, high reliability, high accuracy, low power consumption, and easy maintenance. It will also promote large-scale applications in embodied intelligent robots, medical monitoring, industrial maintenance, and wearable recognition.

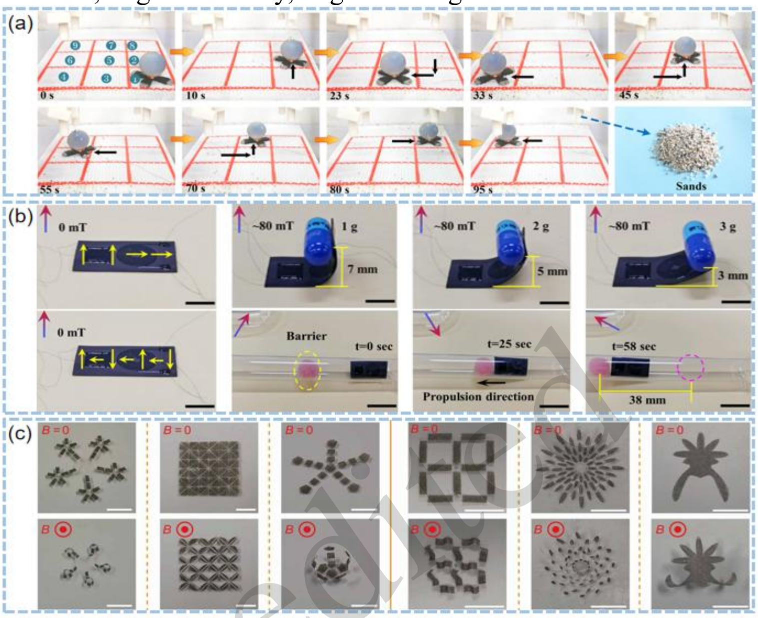


**Fig. 13 Flexible magnetic robots with sensing capabilities: (a) a soft robot with flexible and self-powered electromagnetic sensing that can perceive external obstacles and take corresponding avoidance measures (reprinted from (Yue et al.,2022), Copyright 2022, with permission from Elsevier); (b) soft robots achieve drug delivery under the influence of an external driving field (reprinted from (Wang et al.,2023), Copyright 2023, with permission from Elsevier); (c) soft robots assembled under different magnetization methods (reprinted from (Dong et al.,2022), Copyright 2022, with permission from the American Association for the Advancement of Science)**



## 6 Conclusions and remarks

In recent years, significant progress has been made in the manufacturing processes, decoupling methods, and application of flexible magnetic force sensors. These sensors exhibit unique advantages such as high sensitivity, multi-dimensional force perception, and good deformability. By combining magnetic particles with flexible substrates using different forming processes, high-performance flexible magnetic films with various microstructures can be fabricated. After precisely capturing magnetic field signals using different types of magnetosensitive elements, researchers have combined theoretical models and data-driven methods for signal decoupling. This has established a relatively complete technical roadmap for force-magnetic decoupling. Based on these excellent properties, these sensors have been widely used in wearable devices, robotic hands, and soft robotics. However, batch-to-batch variation and individual inconsistencies of flexible magnetic films require complex calibration procedures, which severely limit large-scale applications. Moreover, signal drift and performance degradation caused by long-term cyclic use remain key research bottlenecks. Bhirangi et al. (2025) proposed the AnySkin scheme, achieving zero-shot policy transfer across sensors. However, this method is currently suitable only for simple recognition scenarios and still lags behind the generalization ability of real skin. Although some studies have explored universal calibration models, stability and consistency remain unsatisfactory, and still far from practical application.

In the future, researchers should integrate AI technologies to develop efficient universal calibration and transfer learning frameworks, thereby simplifying the development process. At the same time, the formation mechanisms of flexible magnetic films should be further investigated. Improvement in consistency from the source, such as through material interface modification, is needed. Robust signal processing algorithms adapted to dynamic environments should also be developed to enhance sensor accuracy and reliability after cyclic use. In the future, it is expected that flexible magnetic force sensors will achieve large-scale application in industrial automation and consumer electronics, promoting intelligent development.


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## Author contributions

Huimin SHEN and Zhexin XIANG wrote the first draft of the manuscript. Shaowen ZHANG helped to organize the manuscript. Huimin SHEN and Geng YANG revised and edited the final version.

## Conflict of interest

Huimin SHEN, Zhexin XIANG, Shaowen ZHANG, Geng YANG declare that they have no conflict of interest.



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