Multimodal Sensing Integration in Electronic Skin: The Synergistic Evolution of Materials, Structures, and Algorithms

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Abstract: Electronic skin (e-skin) serves as a crucial sensory interface linking intelligent systems with the external environment. Recent progress has shifted its development from single-modality sensors toward integrated multimodal systems capable of perceiving complex stimuli with high sensitivity and adaptability. This review highlights advances across three core dimensions—materials, structures, and fusion mechanisms. Material innovations have evolved from simple conductive layers to multifunctional and recyclable composites; structural designs have progressed from planar arrays to biomimetic microstructures and 3D interlocking architectures; and multimodal fusion has advanced from signal stacking to intelligent decoupling and in-sensor computing. Despite these advances, challenges remain in stability, scalability, and low-power integration. Future efforts should focus on synergizing materials, structures, and algorithms to develop self-healing, energy-efficient, and adaptive e-skin systems capable of evolving from passive sensors to intelligent, human-like perceptual interfaces.

1. Introduction

Tactile sensing is one of the primary modalities through which humans acquire information from the external world, and it plays a crucial role in enabling natural interaction between intelligent robots and their environment[1]. Traditional tactile sensors predominantly rely on a single working principle—such as piezoresistive, capacitive, or piezoelectric mechanisms. While they have achieved widespread application in specific scenarios, their limitations are becoming increasingly apparent. Firstly, their unimodal sensing capability is insufficient to meet the demands of multi-information fusion required in complex environments[2]. For instance, when a robot performs delicate manipulation tasks, it often requires the simultaneous perception of pressure, temperature, and material properties, which traditional unimodal sensors cannot provide comprehensively. Secondly, these single-modality sensors are susceptible to crosstalk in multi-stimuli environments—for example, the influence of temperature variations on pressure signals—which compromises the system's reliability and accuracy. Furthermore, traditional sensors are typically fabricated from rigid, inorganic materials, resulting in a lack of flexibility and conformability. This makes it difficult to meet the requirements for comfort and structural adaptability in applications like wearable electronics and soft robotics. Although integrating multiple discrete sensors can achieve multimodal functionality, this approach suffers from drawbacks such as device complexity, high cost, and significant power consumption, thereby limiting its potential for large-scale application[3]. Therefore, there is an urgent need for an innovative sensing system built on a flexible platform that can achieve both multimodal perception and effective signal decoupling.

To address the aforementioned limitations of traditional sensors, bio-inspired electronic skin (e-

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skin) sensors offer an effective solution by emulating the multimodal sensing characteristics of human skin[3]. These bio-inspired sensors can integrate various sensing units on a flexible substrate, enabling the synchronous acquisition and decoupling of multimodal information—such as pressure, temperature, friction, and humidity—thereby significantly enhancing the completeness and reliability of environmental perception[4]. Novel designs based on nanomaterials, conductive polymers, and flexible hydrogels not only endow the devices with excellent mechanical flexibility and stretchability but also ensure high sensitivity and stability in sensing. Concurrently, biomimetic designs that draw inspiration from the hierarchical structure and neural encoding mechanisms of skin enable these devices to exhibit distinct advantages in anti-interference, signal decoupling, and integration[5][6]. Compared to conventional sensors, multimodal bio-inspired sensors are better aligned with the future demand of intelligent robots for human-like tactile sensation.

The study of multimodal bio-inspired sensors is of great significance for advancing intelligent robotics and human-machine interaction. On one hand, it can endow robots with perception capabilities more akin to those of humans, thereby enhancing their safety and fine manipulation skills in complex operational environments. On the other hand, these sensors also exhibit immense application potential in fields such as medical rehabilitation, prosthetic feedback, virtual reality, and wearable electronics. Concurrently, this research direction integrates state-of-the-art advancements from materials science, device engineering, and bionics, providing new impetus for the development of flexible electronics and intelligent sensing technologies. Therefore, this paper aims to systematically review the research progress of bio-inspired electronic skin for multimodal integrated sensing, focusing on three core dimensions: innovations in materials, structures, and multimodal fusion mechanisms. The goal is to provide a theoretical reference and to outline future directions for research in intelligent e-skin sensing.

2. Key Technological Advances in Multimodal Sensing Integration for Electronic Skin

To fully reveal the formation mechanism and developmental logic of its multimodal sensing capabilities, this paper presents a review from three core dimensions: innovations in materials, structures, and multimodal fusion mechanisms. Material innovation serves as the foundation for functionality, determining the sensor's sensitivity, flexibility, and environmental adaptability. Structural innovation is the core of performance optimization, imparting higher stability and spatial resolution to the device through geometric design and hierarchical construction. Finally, the multimodal fusion mechanism is the key element for realizing intelligent perception, enabling the electronic skin to integrate information and perform synergistic recognition in response to complex stimuli[3][5][7].

The three dimensions—materials, structural design, and multimodal fusion mechanisms—are interrelated and build upon one another in a progressive manner. Advanced materials provide the physical support for structural optimization. Structural design, in turn, influences the effectiveness of signal acquisition and decoupling. And the multimodal fusion mechanism integrates the former two at the system level, achieving the leap from physical response to information cognition. Therefore, approaching the topic from these three dimensions not only helps to systematically map the developmental trajectory of e-skin technology but also helps to reveal its intrinsic trend toward becoming more intelligent, adaptive, and sustainable in the future.

2.1. Materials Innovation: From Conductive Platforms to Intelligent Adaptive Systems

The development of electronic skin is inseparable from continuous advancements in materials science. The evolution of material systems—from initial single conductive materials to composite and functionalized systems, and subsequently to a new generation of flexible materials possessing self-healing, recyclable, and intelligently responsive properties—demonstrates a progressive path from enabling perception to optimizing performance and enhancing intelligence.

In the early research stage, electronic skin primarily relied on single conductive materials to achieve flexible sensing. In 2011, Chen et al. reported in Nature Nanotechnology a stretchable strain sensor based on a carbon nanotube network, demonstrating the feasibility of carbon-based materials in stretchable electronic devices[8]. This research addressed the challenge of metal electrodes being prone to fracture upon stretching, providing electronic skin with a preliminary deformable conductive capability. Subsequently, Hu et al. further demonstrated a carbon nanotube/polydimethylsiloxane (PDMS) hybrid sensor with an adjustable percolation pathway, which exhibited improved linearity and durability compared to the early carbon nanotube thin-film sensors[9]. In 2012, another study reported a capacitive strain gauge based on carbon nanotubes with a strain capacity of up to approximately 300% and excellent durability, further demonstrating the practicality of carbon nanotubes as stretchable conductors in electronic skin[10]. In 2015, based on carbon allotropes, laser-scribed graphene (LSG) achieved record-high pressure sensitivity, further validating the pure graphene piezoresistive network as a robust single-material sensing skin[11]. Researchers are also committed to the study of single-material, embedded single-walled carbon nanotube stretchable conductors to form transparent electrodes for pressure/strain/touch sensing[12]. Although these works laid the foundation for flexible and stretchable electronics, systems based on single conductive materials possess inherent physical limitations: it is difficult to reconcile their electrical performance with mechanical flexibility, they can only achieve unimodal signal output, and they exhibit insufficient environmental stability and response diversity.

As the limitations of single-component materials became increasingly evident—particularly the trade-off between electrical conductivity and mechanical flexibility—research began to shift toward the design of composite and hybrid material systems. Through the synergistic effects between materials, scientists aimed to strike a balance between conductivity, stability, and manufacturability. In 2016, Bai et al. constructed a composite electrode system of silver nanowires and PDMS, embedding a highly conductive metal network into an elastomer, thus combining high conductivity, transparency, and flexibility[13]. Subsequently, Yin et al. developed a stretchable electronic skin using pre-cracked silver nanowire (AgNW) composite fiber electrodes, in which the pre-cracked AgNW fibers were embedded in an elastomer, enabling simultaneous pressure sensing and multi-directional strain detection, highlighting the value of microstructural design in composite materials[14]. Similarly, studies embedding AgNW networks into PDMS matrices have demonstrated enhanced electrical conductivity and acceptable mechanical compliance[15] .In 2019, Guo et al. further proposed a composite system utilizing an ionogel and biomimetic nanofibers, which enabled the material to possess both pressure-sensitive and temperature-sensitive properties, thereby achieving the leap from unimodal to bimodal sensing[16]. Around the same period, Hua et al. reported a skin-inspired matrix network that responded simultaneously to pressure and temperature through an adaptable microstructural layout, representing another approach to achieving multimodal coupling[17]. In addition to the aforementioned work, Luo et al. explored the use of printable PEDOT:PSS/PDMS composite conductors as stretchable electrodes for soft sensors, aiming to balance processability and conductivity[18]. At the interface material level, designs such as wavy PDMS and interfacial AgNW deposition can be employed to enhance mechanical robustness while maintaining electrical pathways[19]. Notably, Sun et al., in their review, summarized the composite applications of a wide range of functional fillers (such as carbon nanotubes, graphene, MXene, and metal nanoparticles) in electronic skin and thoroughly discussed the challenges these systems face in terms of manufacturability, interfacial stability, and performance consistency[20]. Nevertheless, despite the remarkable improvement in multifunctionality and mechanical robustness, composite systems introduced new constraints—such as mismatched thermal and electrical response rates and interfacial incompatibility—which ultimately limited signal stability and repeatability, highlighting the need for more intrinsically integrated material architectures.

To overcome the issues of interfacial effects and modal coupling, research has progressed to the stage of functionalized and self-decoupling materials. In 2021, Li et al. reported a MOF film that, through the in-situ growth of $Ni_3(HiTP)_2$ on microstructured cellulose, output independent pressure and temperature signals while maintaining strain suppression, achieving interference-free pressure-temperature sensing and material-level decoupling without the need for complex circuits[21]. In 2023, Hu et al. reported in the Chemical Engineering Journal a dual-functional flexible material that achieves signal separation through the differential response of heterogeneous fillers, effectively reducing the crosstalk between temperature and pressure signals[22]. In the same year, Liang et al. employed a gradient dielectric constant composite strategy, enabling different layers to respond distinctively to external stimuli and thus achieving signal decoupling at the material level[22]. This stage represents a transition from physical superposition to intrinsic functional differentiation within the material, endowing electronic skin with higher recognition accuracy and anti-interference capabilities. However, the fabrication of such functionalized materials is complex and costly, and their stability in extreme environments still requires improvement.

Recent advances in multimodal electronic skin have transitioned toward the integration of sustainability, recyclability, and intelligence—seeking not only higher sensing performance but also environmentally responsible and energy-autonomous operation. As early as 2018, Zhou et al. introduced a dynamically covalent thermoset (polyimide) doped with silver nanoparticles, achieving a self-healing, fully recyclable, and stretchable electronic skin capable of sensing touch, temperature, flow, and humidity[23]. In 2022, Chen et al. reported a stretchable, transparent multimodal electronic skin based on PVA, cellulose acetate, and AgNP composites, achieving simultaneous detection of strain, temperature, and humidity while maintaining full recyclability and optical transparency[24]. In 2023, an environmentally friendly graphene-coated piezoresistive foam material manufactured via water-based and solvent-free methods demonstrated high motion sensitivity and sustainable processing routes for flexible sensors[25]. In 2024, Liang et al. developed an environmentally friendly multifunctional pressure and temperature sensor based on wood sponge, where the pressure and temperature channels operated independently through different piezoresistive and thermoelectric mechanisms, demonstrating the potential of sustainable materials in high-performance multimodal sensing[26]. In the same year, Yuan et al. employed an inkjet printing process to fabricate a fully flexible dual-modal sensing layer, achieving a unification of structural continuity and sensitive multimodal perception, which significantly improved manufacturability and consistency[27]. In the same year, Zhao et al. reviewed soft bioelectronic materials, emphasizing eco-friendly synthesis routes and low-power operation principles, and highlighted the necessity for sustainable material-system co-design[28]. In 2025, Mi et al. developed a recyclable PVA–ethylene glycol composite system capable of simultaneously sensing pressure, temperature, and humidity, and which allows for material recycling through dissolution and reprocessing after its service life[29]. Subsequently, Gong et al. developed a CNFs/Al_2O_3--SiC composite Schottky device that achieved independent pressure-temperature responses with excellent repeatability, demonstrating how heterogeneous interfaces can enhance multimodal recognition capabilities[30]. Collectively, these studies mark a critical transition in the evolution of electronic skin—from performance-oriented multimodal integration toward sustainable, recyclable, and self-powered intelligent systems—reflecting a convergence of materials science, environmental consciousness, and functional design.

Overall, material innovation for electronic skin has undergone a systematic evolution from single conductive materials to multi-component composite systems, and finally to functionally self-differentiating and sustainable materials. Early research focused on overcoming the conflict between flexibility and conductivity, enabling electronic skin to possess basic deformation sensing capabilities. The intermediate stage achieved coupled responses for multimodal sensing of force, temperature, and humidity through composite and hybrid materials. In recent years, functionalized and recyclable systems have begun to concentrate on environmental adaptability and intelligent response, marking a transition from being performance-driven to intelligence-driven. This evolutionary path indicates that material innovation has gradually shifted from the mere pursuit of enhanced physical properties toward a comprehensive optimization of structure-function-environment compatibility.

Despite significant progress, current material systems still face several bottlenecks. Firstly, the mismatched thermal, mechanical, and electrical responses at the multiphase interfaces in composite structures lead to signal drift and insufficient long-term stability. Secondly, the synthesis of self-decoupling and multimodal responsive materials still relies on complex compositional control, making them difficult to manufacture on a large scale. Some systems also exhibit performance degradation in extreme temperature and humidity environments. Furthermore, the synergistic design between materials, structures, and electronic circuits remains inadequate, with the modulus mismatch between the sensing layer and the support layer causing coupling errors. In addition, although green and recyclable materials offer environmental advantages, their conductivity, durability, and performance after recycling can hardly match those of traditional systems. Overall, an ideal balance among high performance, high stability, and high manufacturability has not yet been achieved in electronic skin materials.

To address the issues mentioned above, future materials research is likely to evolve toward higher levels of integration and intelligence. Firstly, in terms of multi-scale synergistic design, future work could involve constructing flexible composite systems with dynamically tunable conductive networks through molecular-level interface engineering and macroscopic structural control, thereby maintaining electrical stability under large strain conditions. Secondly, it is noteworthy that materials such as self-healing and recyclable systems are receiving increasing attention in the field of electronic skin, as they offer potential for long-term stable and environmentally friendly devices[31][32][33]. Furthermore, intelligent response and adaptive regulation may become new research focal points. For example, ionic conductors, phase-change materials, and neuromorphic polymers are considered candidate systems for achieving material-level information memory and self-learning behaviors. In the long term, the multi-level synergy of materials, structures, and algorithms can become a key driving force for the further evolution of electronic skin. Through this cross-scale design philosophy, e-skin is expected to evolve from passive sensing units into systems possessing a certain sense-regulate closed-loop capability, laying a solid material foundation for the construction of truly bio-like intelligent sensory interfaces.

2.2. Structural Innovation: From Planar Flexibility to Biomimetic 3D Architectures

Building upon advanced materials, structural design is a critical step for both realizing and optimizing the functionality of electronic skin. The developmental path—from initial planar flexible arrays, to the introduction of bio-inspired microstructures, and subsequently to the emergence of stretchable interconnect networks and three-dimensional interlocking architectures—demonstrates a progressive evolution from achieving deformation compatibility to refined perception and intelligent self-adaptation.

Early electronic skin designs primarily utilized two-dimensional planar structures, which achieved spatial distribution detection of pressure or temperature by integrating sensor arrays onto flexible substrates. In 2005, Someya et al. reported in PNAS the first flexible active-matrix array based on organic transistors, which made the large-area integration of electronic skin possible[34]. In 2008, Someya's team further introduced elastic conductors, enabling the device to maintain stable electrical characteristics under bending and mild stretching[35]. The key breakthrough of this stage was demonstrating the feasibility of flexible arrays, proving that electronic devices could operate in non-planar environments. However, these planar structures still had significant deficiencies in sensitivity, directional resolution, and strain-handling capability, making it difficult to address complex tactile stimuli.

To strike a balance between high sensitivity and high stretchability, the research focus further shifted to stretchable networks and interconnect structures. In 2017, a review mentioned that skin-inspired stretchable matrix networks, through an island-bridge interconnect design, enable sensing units to maintain stable output even under tensile strains of up to several tens of percent, significantly mitigating the signal drift issue under deformation seen in earlier structures[35]. In the same year, Pan et al. systematically investigated the effects of substrate thickness and geometry on the stretchability and fatigue life of serpentine interconnect structures, providing guidance for the design of large-strain interconnect systems[36]. Subsequently, in 2022, Liu et al. proposed an interlocking interface design that achieves stress dispersion and contact stability through micro-scale interlocking between upper and lower layers, significantly improving cyclic durability and signal repeatability[37]. Similarly, Liu et al. designed interconnect interfaces in stretchable pressure sensors, demonstrating that stable micro/nanostructures and the interface between the elastomer matrix are key to long-term mechanical reliability[38]. Parallel to the island-bridge approach, recent hybrid electronic networks also alleviate stress concentration through material-structure synergy. Wen et al. embedded a composite network of hollow MXene spheres/Ag nanowires into PDMS, which can simultaneously achieve proximity, pressure, and strain multimodal sensing and significantly reduce the risk of electrode delamination under stretching[39]. This demonstrates the dual benefit for stability from combining composite fillers plus network geometry. This stage of research marks the transition of electronic skin from two-dimensional flexibility to three-dimensional adaptive structures, achieving a performance balance of being flexible yet stable. However, the complexity and encapsulation precision required for these interconnect networks still limit their large-scale fabrication.

Meanwhile, to overcome the limitations of planar structures, researchers have developed bio-inspired structures with micro-protrusions and textures, drawing inspiration from the hierarchical surface morphology of natural skin. Earlier, Mannsfeld et al. introduced the now-classic concept of microstructured PDMS dielectrics to enhance the sensitivity of flexible capacitive sensors, demonstrating that elastic dielectric structures can significantly improve sensitivity while maintaining compatibility with soft substrates[40]. In 2019, Choi et al. demonstrated a bilayer fingerprint-ridge tactile sensor capable of resolving surface features smaller than 100 micrometers by mimicking the human epidermal ridge/papilla structure[41]. In 2020, Kim et al. developed a hybrid ridge-structured sensor, combining two different fingerprint pattern motifs, and confirmed enhanced surface texture classification performance compared to single-pattern devices[42]. In 2022, Lee et al. constructed a micro-ridged flexible surface layer[43]. This design enabled differential responses to normal and tangential loads at the micro-scale, significantly improving mechanical sensitivity and directional recognition capability. In 2022, Zhang et al. conducted a more comprehensive review, outlining the evolution of biomimetic microstructural designs in artificial tactile systems and linking design principles (ridges, pillars, domes) to functional outcomes (sensitivity, texture recognition, durability)[44]. In 2023, Wei et al. introduced a flexible, conformal, and multi-directional tactile sensor entirely fabricated via 3D printing. Its layered micro-protrusions enabled simultaneous detection of shear and normal forces, further enhancing the multi-axis discrimination capability of electronic skin[45]. Meanwhile, Geng et al. summarized strategies for wearable touch sensors that mimic natural surfaces (such as skin grooves and plant epidermal textures), demonstrating how micro-patterned surfaces enhance durability and reduce hysteresis in long-term use[46]. Fu et al. reviewed biomimetic micro/nanostructured tactile sensors, emphasizing that dome-shaped, ridge-shaped, and pillar-shaped micro-textures significantly improve the linearity, sensitivity, and mechanical durability of flexible tactile interfaces[47]. This stage of research marked a transition from being able to detect to being able to distinguish, representing a leap for electronic skin from macroscopic perception to microscopic structural control. However, these bio-inspired microstructures are prone to wear and fatigue during long-term operation, their morphological consistency is difficult to ensure, and their stability in high-strain environments is limited.

With advancements in manufacturing technology, structural innovation has further progressed toward three-dimensional interlocking. Previously, a bio-inspired 3D integrated electronic skin achieved independent recognition of stretching, shearing, and pressure by mechanically segmenting the sensor modules in a sophisticated manner, pioneering the development of separable multi-directional structural e-skin[48]. In 2024, a 3D interlocking micro-ridge structure designed by Zhang et al. enables the sensing layer to achieve self-decoupling and signal amplification under multi-directional loading by means of spatial interpenetration between upper and lower layers and a self-regulating contact area[49]. In the same year, researchers developed an electronic skin with an interlocking micro-ridge structure, which enhanced the stability of mechanical contact and sensing capabilities, further validating the effectiveness of the three-dimensional interwoven pattern[48]. In 2025, Zhang et al. proposed an interlocking micro-spherical cap structure to optimize the change in contact area and enhance sensitivity, and also demonstrated the integrated photothermal response as a multifunctional extended application[50]. This series of studies indicates that three-dimensional interlocking structures have not only achieved a balance between sensitivity and stability but have also gradually become an important platform for multimodal integration and functional expansion. They herald the transition of electronic skin design from single-sensing functionality to an integrated development of structure-performance-intelligent response.

Based on the research reviewed above, a clear evolutionary trajectory for structural innovation in electronic skin can be identified. It began with early planar array structures, which solved the feasibility issues of flexibility and spatial dotting. This was followed by the stage of bio-inspired microstructures, which achieved enhanced sensitivity and directional recognition capabilities through geometric augmentation. The next phase involved stretchable meshes and interlocking structures, which enabled stable adaptation to large strains and complex deformations while maintaining high sensitivity. Finally, it has evolved to three-dimensional interlocking, which have begun to achieve a balance among sensitivity, stability, and functional diversity. This evolutionary process indicates that the structural design of electronic skin has shifted from deformation tolerance to functional synergy. The structure is no longer merely a carrier for the material but has gradually become a crucial medium for optimizing sensing performance and enabling multimodal fusion.

However, despite the significant progress made in recent years, current structural systems still face several common issues. Firstly, multi-scale matching and interlayer synergy remain bottlenecks. The mismatch in mechanical properties and thermal expansion among layers with different moduli, conductive layers, and elastic layers under cyclic strain can easily lead to interfacial delamination and signal drift. Secondly, the conflict between structural complexity and fabrication precision is still prominent. Microstructures and three-dimensional interlocking systems often require high-precision molds or multi-step alignment processes, which limit large-area uniformity and mass production feasibility. Thirdly, long-term stability and reliability have not yet been fully validated. Most research focuses on initial performance enhancement, while structural integrity and signal repeatability under conditions such as long-term fatigue, humid-heat environments, and chemical corrosion remain uncertain. Furthermore, the structure-signal crosstalk under multimodal coupling has not been completely resolved. Although complex geometric designs enhance sensitivity, they may introduce unintended coupling effects, thereby reducing recognition accuracy. Lastly, the system-level coupling among structure, circuits, and algorithms is still weak. Current structural optimization is mostly confined to the physical level, lacking a holistic framework for synergistic co-design with signal decoupling and data processing.

To address these issues, future structural innovations can be explored in the following directions. Firstly, multi-scale synergistic structural design warrants in-depth investigation. By introducing functionally graded structures or controlling the mechanical neutral plane at the micro-scale, while adopting layered and partitioned flexible architectures at the macro-scale, it is possible to achieve stable and reversible responses of the structure under large deformations. Secondly, adaptive and dynamically reconfigurable structures are likely to become a significant trend. Bio-inspired reconfigurable geometries, shape memory units, and programmable microstructures can achieve self-regulation and shape recovery in response to external stimuli, endowing electronic skin with features of active adaptation and self-learning.

Overall, structural innovation in electronic skin is exhibiting a trend of transitioning from being geometry-driven to system-synergy-driven. Future structural design will no longer be confined to enhancing sensitivity or flexibility. Instead, it will take multimodal synergy, manufacturability, self-healing capability, and intelligence as its core objectives, aiming to construct three-dimensional bio-inspired systems that possess the integrated capabilities of perception, response, and learning. The continued advancement in this direction is expected to lay the structural foundation for the leap of electronic skin from sensing hardware to an intelligent interface.

2.3. Multimodal Fusion Mechanisms: From Signal Stacking to Intelligent Cooperative Perception

Through the synergistic design of materials and structures, electronic skin has acquired the capability for efficient multimodal information acquisition. However, the decisive step in making the leap from multi-stimuli sensing to intelligent perception is how to extract effective information from complex and coupled raw signals. This challenge has catalyzed research into multimodal fusion mechanisms. The development of these mechanisms has undergone a continuous evolution—from discrete and parallel arrangements to heterogeneous fusion, and then to structural decoupling and intelligent synergy—reflecting a progressive logic from functional stacking to synergistic recognition.

Early multimodal electronic skin primarily relied on the parallel integration of discrete sensing units on the same flexible substrate. In 2018, Xu et al. demonstrated a bimodal electronic skin that integrates capacitive and piezoelectric mechanisms, capable of detecting pressure and acoustic vibrations through a laminated dielectric piezoelectric structure. In 2019, Zhang et al. reported a stretchable dual-modal sensing array that achieved both capacitive and triboelectric dual-mode sensing through the synergistic action of crossed liquid metal electrodes and a microstructured dielectric layer[51]. Similarly, in 2019, Jeon et al. comprehensively reviewed the integration architectures of multimodal sensors, highlighting the vertical stacking, active matrix arrays, and hybrid transduction mechanisms of electronic skin[52]. In 2021, a bimodal electronic skin textile using a flexible textile substrate achieved simultaneous environmental temperature monitoring and dynamic pressure/tactile mapping[53]. This stage of research validated the feasibility of multimodal coexistence, laying the foundation for complex stimuli recognition. However, due to signal crosstalk and response differences between the modalities, the device suffered from insufficient stability in large-area applications and complex wiring, which limited further development toward integration. Subsequent reviews have pointed out that, although stacking or array designs integrate modalities together, mismatches in mechanisms, crosstalk between sensing channels, and manufacturing yields remain significant barriers[3].

To solve the problems of spatial occupation and modal coupling, researchers gradually shifted to heterogeneous and vertical integration designs. In 2023, Ye et al. proposed a layered, nested structure in which pressure, temperature, and physiological signal sensing units were vertically stacked within the same flexible substrate, achieving physical separation between modalities through an interfacial isolation layer[54]. Concurrently, Heo et al. further integrated optical and pressure sensing into a single system, realizing cross-modal fusion that spanned from proximity sensing to physiological monitoring[55]. In addition, in 2024, it was reported that a multilayer dual-mode flexible sensor had been developed, integrating independent films for pressure and temperature sensing. This highlighted the effectiveness of vertical separation techniques in reducing signal interference in stacked electronic skin configurations[56]. This stage significantly improved the device's integration density and multifunctionality, but interlayer alignment precision and stiffness matching became new technical bottlenecks, leading to complex encapsulation processes and limited fabrication yields.

As multimodal fusion mechanisms continued to evolve, the research focus gradually shifted from structural superposition to intrinsic physical and algorithmic synergy. In 2024, Guo et al. utilized an LSTM algorithm to achieve real-time separation of pressure and temperature signals[57]. In the same year, Fang et al. achieved synergistic detection of pulse and ion concentration through the fusion of mechanical and electrochemical dual channels[58]. Similarly, the dual-dielectric layer strategy endows capacitive sensors with pressure dependence while maintaining temperature insensitivity, achieving direct physical decoupling of pressure and temperature responses[59]. Moreover, incorporating thermoelectric PEDOT:PSS/CNT components into pda-modified PDMS foam has enabled mechanism-based separation of thermal and pressure stimuli, providing independent readings through different transduction pathways[60]. Additionally, a thermoelectric hydrogel system with piezoresistive pathways exhibits self-powered dual-modal sensing and inherent mechanism-level decoupling between temperature and strain[61]. This stage marks a crucial evolution in multimodal fusion—from external signal processing toward intrinsic, mechanism-level coordination—where materials, structures, and algorithms begin to operate synergistically to achieve stable and discriminative multi-stimuli perception.

In recent years, research on multimodal integration has advanced further toward intelligent fusion and embedded perception-driven systems. In 2024, Zhu et al. developed a soft neuromorphic electronic skin that integrates stretchable synaptic transistors with multiple sensors, enabling multimodal perception and synaptic-like information fusion within a flexible system[62]. Concurrently, Xu et al. reported a stretchable neuromorphic transistor device that is capable of simulating pain perception and sensitivity during the deformation process, indicating that neuromorphic hardware components are being integrated into flexible platforms for richer sensory cognitive tasks[63]. In 2025, Patil et al. proposed the introduction of neuromorphic synaptic transistors into flexible systems, enabling preliminary fusion and feature extraction of multimodal signals at the device level[64]. Concurrently, reviews have pointed out that the future of multimodal integration in e-skin is trending toward sensing-computing integration: implementing low-power, reconfigurable multimodal recognition systems at the hardware level through near-sensor computing and adaptive algorithms[7]. This trend signifies that electronic skin is transitioning from passive sensing to active understanding, laying the foundation for realizing bio-like, self-learning, and adaptive tactile systems. Building on this, research integrating intelligent materials with algorithms has also begun to emerge. A study reported in Device (Cell Press) combined Metal-Organic Framework (MOF) thin films with a flexible substrate for the multimodal detection of biomolecules, motion, and electrocardiogram (ECG) signals[65]. It leveraged a Transformer model to achieve automatic feature extraction and classification of these signals. This research showcases a synergistic mechanism of material sensing - algorithmic recognition, providing a new paradigm for achieving multimodal discrimination and near-sensor computing. However, challenges remain in achieving full integration of sensing, neuromorphic processing, and algorithmic learning in large-area, low-power, and robust form factors—thus the journey from concept to practical adaptive e-skin continues.

Reviewing the research progress in recent years, it is evident that multimodal integration technology has gradually formed a complete evolutionary chain, from physical coexistence to structural fusion, and then to signal decoupling and intelligent synergy. Early parallel integration demonstrated the feasibility of sensing multiple physical signals on a single flexible substrate, laying the conceptual foundation for multimodal electronic skin. Subsequently, the emergence of heterogeneous fusion and vertical integration structures significantly improved functional density and system stability through hierarchical design. The structural decoupling stage further enabled the separation and synergistic recognition of multiple signals at both the physical and algorithmic levels, driving the transition of electronic skin from being multi-functional to multi-intelligent. The recent emergence of neuromorphic and near-sensor computing strategies has enabled the coupling of sensing, processing, and feedback within the same system, providing a new direction for constructing bio-like cognitive systems. Overall, research in multimodal integration has shifted its focus from achieving multiple types of sensing to understanding the relationships between them, showing a clear trend of evolution from stacked integration to system intelligence.

Despite significant progress, existing research still faces several common issues. Firstly, signal interference and structural coupling between modalities remain difficult to eliminate completely. The differences in sensitivity, response rates, and working principles among various modalities often lead to signal overlap or drift, which is particularly prone to crosstalk under multi-dimensional stimuli. Secondly, the complexity of fabrication and encapsulation constrains the practical application of high-density, multimodal arrays. Although vertical stacking and nested structures enhance integration, they impose higher requirements on interlayer alignment precision, interfacial stability, and mechanical flexibility. Thirdly, there is a lack of synergy between signal decoupling algorithms and hardware systems. Most research is still confined to the back-end data processing level and fails to achieve front-end intelligence at the sensing end during the material or structural design phase. Furthermore, a clear trade-off exists among power consumption, real-time performance, and reliability. This is especially true for neuromorphic or artificial intelligence-driven systems, which, despite improvements in recognition capabilities, often come at the cost of higher power consumption and complex training. Lastly, current multimodal systems still lack unified standardized interfaces and evaluation frameworks, making it difficult to quantify performance comparisons and application migration between different studies.

To address the aforementioned issues, future research on multimodal fusion mechanisms can be further deepened in the following directions. Firstly, the integrated synergistic design from materials to structures is worthy of continuous exploration. By introducing functionally graded materials and programmable interfaces at the material level, combined with structural geometric control, it is possible to achieve preliminary signal filtering and self-decoupling at the physical layer. Secondly, low-power and adaptive computing systems are likely to become a major research hotspot. The introduction of synapse-like neuromorphic components, memristor arrays, or flexible neural networks can achieve local fusion of sensing and computation, thereby reducing redundant signal transmission. Furthermore, the fusion of multimodal and multi-dimensional information will further expand the scope of perception. Future electronic skin may not only sense pressure, temperature, and humidity but also capture chemical signals, physiological data, and contextual information in real-time, enabling multi-level interaction across environment-physiology-emotion. From a longer-term perspective, the developmental trend of multimodal fusion mechanisms may gradually shift toward system intelligence and self-learning evolution. Through the synergistic action of structures and algorithms, electronic skin is expected to gain the ability to dynamically adjust sensing weights and auto-calibrate response thresholds, truly achieving the leap from passive sensing to active cognition.

Overall, research on multimodal fusion mechanisms is moving from a stage of stacking functions to a new phase of understanding and synergizing functions. Future electronic skin systems will likely feature low power consumption, manufacturability, and intelligent response as their core characteristics, forming a closed-loop system that integrates materials, structures, and algorithms. This direction not only provides a new design paradigm for flexible electronic devices but also lays the foundation for constructing bio-like artificial tactile systems capable of learning, perception, and decision-making.

3. Conclusion

The research on integrated multimodal electronic skin is of great significance for advancing the development of intelligent robotics, human-machine interaction, and wearable electronics. It is not only a key technological approach for emulating the human tactile system but also the sensory foundation for achieving the deep integration of artificial intelligence with the physical world. By integrating flexible electronics, bio-inspired design, materials science, and information processing technologies, electronic skin endows machines with perception capabilities approaching those of humans. This enables safe, precise, and natural interaction in complex environments, thereby opening up new application prospects in fields such as medical rehabilitation, virtual reality, and intelligent manufacturing.

From a technical standpoint, existing research has achieved breakthroughs in several areas: advanced composite and functionalized materials have significantly enhanced sensing sensitivity and stability. Multi-level, bio-inspired structural designs have enabled stable responses to large strains and multi-directional stimuli. And the introduction of multimodal fusion mechanisms has allowed electronic skin to simultaneously recognize various physical signals such as pressure, temperature, and humidity, and to achieve signal decoupling and intelligent discrimination by leveraging algorithms. Some cutting-edge research has even realized the synergistic fusion of materials, structures, and algorithms, performing near-sensor computing and feature recognition on flexible hardware and demonstrating a trend toward bio-like intelligent sensing systems.

However, realizing truly intelligent electronic skin still faces several challenges. At the material level, there remains a need to balance performance with manufacturability, and the interfacial stability and long-term reliability of composite systems require further optimization. At the structural level, breakthroughs are still needed in multi-scale synergy and reconfigurability. In terms of multimodal fusion mechanisms, although information integration has been achieved, the synergy between algorithms and hardware remains insufficient, and trade-offs among power consumption, real-time performance, and versatility must still be addressed. Furthermore, standardized testing and evaluation frameworks are not yet well-established, which hinders effective comparison and application migration between different research outcomes.

Future research should continue to advance along the direction of multi-level synergy among materials, structures, and algorithms. On one hand, intelligent material systems with self-healing and self-adaptive properties can be explored to enhance environmental adaptability and sustainability. On the other hand, multi-scale synergistic and dynamically programmable structures should be developed to achieve stable perception under complex deformations. Concurrently, by integrating neuromorphic devices with low-power computing architectures, it is expected to be possible to realize a sense-learnrespond closed-loop system akin to human skin. Through the in-depth analysis presented, this paper puts forward these three recommendations to provide a reference and guidance for subsequent related research.

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