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REVIEW

Electronic Skin Empowered by Structural Design

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ABSTRACT

Inspired by human skin, electronic skin (e-skin) integrates multidisciplinary technologies from materials engineering to microelectronics. It aims to replicate the skin's ability to perceive pressure, temperature, and humidity while also exhibiting excellent biocompatibility. As an emerging technology, e-skin holds significant promise across diverse fields, including industry, medicine, the military, and robotics. This review summarizes recent progress in the structural design of e-skin, which is a pivotal factor enabling breakthroughs in its functionality and performance. The e-skin structural design strategies are classified into three categories: skin-like perception regulation and performance enhancement, conformal interface stabilization design, and beyond-skin functionality design. These strategies facilitate skin-like multimodal sensing, stable human–machine interfaces, and capabilities exceeding those of biological skin, respectively. Current challenges and future prospects for e-skin development are also discussed.

1 | Introduction

As the largest multifunctional organ of the human body, biological skin has the ability to perceive the external environment. It integrates a multimodal sensing network including tactile sensation, thermosensation, and nociception, and can detect a large amount of information from the external environment, such as pressure, temperature, friction, the shape and texture of objects, as well as other physical/chemical signals [1–3]. Inspired by human skin, e-skin, a revolutionary technological integration of materials engineering, microelectronics, and sensory biomimicry, has evolved to possess capabilities that even surpass those of human skin. It has numerous applications, ranging from digital healthcare and intelligent robotics to virtual reality (VR)/augmented reality (AR) and health monitoring [2, 4–13].

As a typical application field of flexible electronics technology, e-skin has emerged as a research hotspot at the intersection of materials science, microelectronics, biomedical engineering, and artificial intelligence since its proposal in the early 21st century [14]. Over the past decade, researchers have made remarkable progress in functional simulation, performance enhancement, and system integration through the synergy between material innovation and structural design [15–17]. Advanced materials provide novel methods for signal transmission and transformation. Beyond material design, structural design plays a pivotal role in enhancing performance and expanding functionality. For example, through structural designs such as microstructures and bioinspired interface structures, signal sensing can be effectively amplified and stabilized [18]. The synergistic integration of both offers an effective strategy for innovation in the design and fabrication of electronic skin. Furthermore, with continuous

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Yufan Wu, Jiangtao Xue, and Lihua Chen contributed equally to this work.

advances in manufacturing technologies and processes, advanced techniques, including micro-nanofabrication, transfer printing, laser cutting, flexible printing, and heterogeneous encapsulation, enable the efficient integration of sophisticated structural designs with high-performance materials, thereby significantly improving the core performance of e-skin in signal sensing, interfacial stability, and functional integration [19]. In recent years, researchers have increasingly focused on integrating novel structural designs with advanced materials through the design of macro/micro structures, achieving remarkable progress in enhancing key performances of e-skin, such as multimodal sensing capability and stretchability. Combined with advances in material and fabrication, novel structural design represents a key optimization pathway for the future evolution of e-skins. Three major development strategies for e-skin have been established: skin-like function simulation and performance enhancement, conformal interface stabilization design, and beyond-skin functional structural design (Figure 1).

The structural designs for skin function simulation aim to mimic the perceptual capabilities of human skin. Inspired by the multimodal sensory network of human skin, materials that are highly sensitive to mechanical, thermal, or chemical stimuli are often combined with microstructures or three-dimensional structures to achieve structural amplification of weak signals, such as micro-pyramids [20–25], cantilevers [26–31], micro-pillars [32–36], micro-spheres [37–41], cavities [42], and wrinkles [43–48] have been introduced. This enables the perception and processing of information including mechanical stimuli, temperature changes, and chemical signals, thereby completing the functional simulation of human skin. For example, the three-dimensional strain gauge structural design bends planar structures into three-dimensional geometric shapes, forming pyramid-like or columnar protrusions [49]. This structure enables simultaneous sensing of normal force, shear force, and temperature, achieving collaborative processing of multi-dimensional information, analogous to the multimodal perception capability of human skin. The structural designs for performance enhancement aim to optimize core performance such as the sensitivity and detection range of sensors through structural improvements. The introduction of bioinspired structures and microstructural designs achieves breakthroughs in the performance of e-skin. For example, a spiral-shaped sensing layer designed to mimic human fingerprints significantly enhances the sensitivity of pressure sensing via geometric deformation amplification, enabling better perception of forces in all directions [50].

The structural design for conformal interface stabilization design aims to not only enhance human comfort experience but also ensure the stability between e-skin and biological skin in practical applications [51]. Most e-skin is an integrated system comprising two main components: the functional part and the interface. Beyond the functional components, an e-skin system requires an interface that not only maintains adhesion between the e-skin and human skin but also serves as a bridge for energy transfer (mechanical, thermal, electrical) and mass transfer (e.g., sweat) between the human skin and e-skin [52]. The design of the skin–device interface directly governs the efficiency of information interaction in e-skin systems [53, 54]. Accordingly, soft and stretchable materials achieve stable adhesion, conformal contact, and efficient energy transport through microstructural designs [2, 18]. For instance, micropillar structures facilitate sweat evaporation, alleviating skin occlusion and discomfort while ensuring stable mechanical and electrical coupling between the skin and the sensing system [55].

Beyond-skin functional structural design aims to achieve functions beyond biological skin. Advanced materials form the foundation for the realization of beyond-skin functionalities, directly determining whether capabilities surpassing those of biological skin can be achieved. For example, biodegradable polymers provide a basis for environmentally benign and transient implantable devices [56–58]; thermoelectric and triboelectric materials enable continuous conversion of environmental thermal or mechanical energy into electricity [59]; ionic hydrogels and conductive polymers impart tissue-like softness and bio-signal compatibility to the devices [60]; while stimuli-responsive materials further endow e-skin with dynamic adaptive capabilities. These materials not only expand the functional boundaries but also, through their unique electrical, mechanical, and chemical properties, establish the groundwork for stable device operation in complex environments. Structural design enhances material responses through micro-/nanoscale structures and three-dimensional layouts, while providing an integrated framework for the spatial arrangement, mechanical matching, and signal coordination of multifunctional modules. For instance, a graded porous structure with gradually decreasing pore size from the surface inward not only facilitates efficient mass exchange but also enhances responsiveness to ambient humidity. This structural characteristic allows the outer layer of the skin to adjust its surface properties according to humidity levels that exceed the regulatory range of biological skin [61]. Rather than being simply additive, the two are synergistically optimized through material-structure co-design: materials grant the possibility of functionality, while structures transform that possibility into stable, efficient, and integrable performance. Together, they propel e-skin from biomimetic simulation toward functional transcendence.

Therefore, in-depth research on the structural design of e-skin holds significant theoretical and practical value for advancing the development and application of e-skin technology. In this review, we summarize the latest research progress in e-skin structural design and forecast its future development. Based on design strategies, the structural design of e-skin is classified into three categories. Finally, the current challenges and prospects of e-skin structural design are also discussed.

2 | Skin-Like Perception Regulation Function Simulation and Sensing Performance Enhancement Design

Human skin is a highly complex and sophisticated organ that not only provides a physical protective barrier for the human body but also possesses multiple essential functions such as sensing external stimuli (e.g., pressure, temperature, humidity), regulating body temperature, and metabolism [71, 72]. One of the development goals of e-skin is to mimic these functions of human skin as closely as possible, enabling it to interact with the external environment like real skin in applications and to exhibit excellent performance meeting the needs of diverse scenarios. Structural design plays a decisive role in this process [73–75].

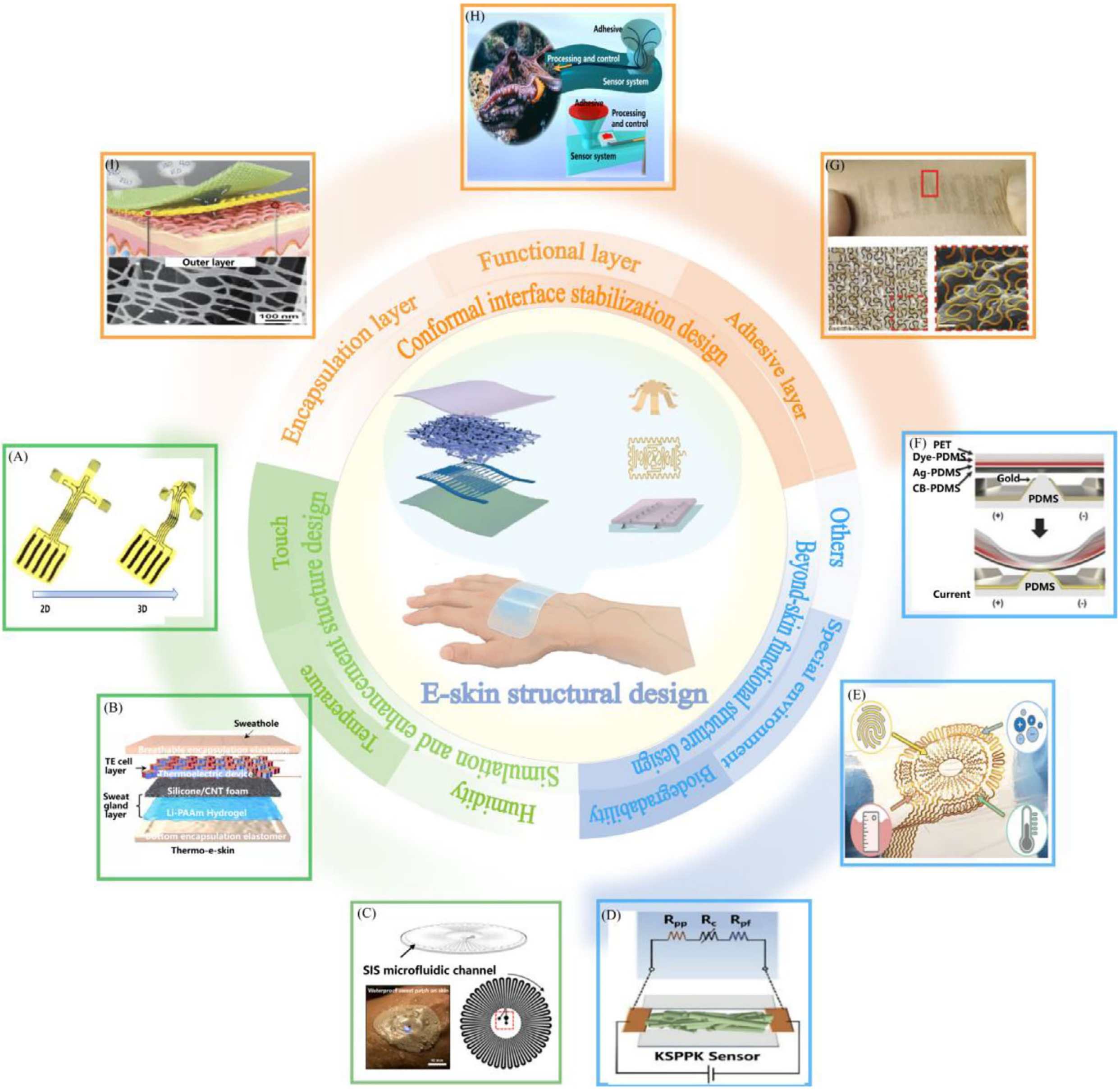

FIGURE 1 | Structural design strategies for e-skin. The schematic illustrates nine typical function-oriented structural designs for e-skin, encompassing structures for pressure sensing, temperature sensing, humidity sensing, biodegradability, resistance to harsh environments, as well as the adhesive, functional, and encapsulation layers design within the e-skin interface. (A) Multimodal sensing with a three-dimensional piezoresistive structure. Reproduced with permission [62]. Copyright 2019, American Chemical Society. (B) Electronic skin with biomimetic structures realizes excellent isothermal regulation. Reproduced with permission [63]. Copyright 2024, Elsevier. (C) Skin-interfaced microfluidic systems with spatially engineered 3D fluidics for sweat capture and analysis. Reproduced with permission [64]. Copyright 2023, AAAS. (D) Breathable, degradable piezoresistive skin sensor based on a sandwich structure for high-performance pressure detection. Reproduced with permission [65]. Copyright 2021, Wiley-VCH. (E) Aquatic skin enabled by multi-modality iontronic sensing. Reproduced with permission [66]. Copyright 2022, Wiley-VCH. (F) Spatially pressure-mapped thermochromic interactive sensor. Reproduced with permission [67]. Copyright 2017, Wiley-VCH. (G) Fractal design concepts for stretchable electronics. Reproduced with permission [68]. Copyright 2014, Springer Nature. (H) Octopus-inspired adhesive skins for intelligent and rapidly switchable underwater adhesion. Reproduced with permission [69]. Copyright 2022, AAAS. (I) Moisture-wicking, breathable, and intrinsically antibacterial electronic skin based on dual-gradient poly (ionic liquid) nanofiber membranes. Reproduced with permission [70]. Copyright 2021, Wiley-VCH.

Functional structural design endows e-skin with functions such as tactile perception, temperature management, and humidity management through bionic thinking. It disassembles the complex functions of biological skin into different structural units. For example, it designs tactile sensing arrays by simulating the mechanoreceptors in the dermis, and constructs humidity-sensitive microchannel structures by drawing inspiration from human sweat gland ducts [23, 76]. Furthermore, performance-enhanced structural design is built upon function-mimetic structural design, and it addresses the bottlenecks of e-skin in core performance metrics such as sensitivity, detection range, and response time [26, 34, 39]. For example, by mimicking the fundamental mechanisms of tactile perception, biomimetic synaptic structures are introduced to amplify signal transduction. This approach not only significantly enhances tactile sensitivity but also breaks through the intrinsic performance limitations of conventional planar e-skin systems [50]. These structural designs are typically realized through fabrication techniques such as soft lithography, micro-molding, laser cutting, and additive manufacturing, which enable precise control over feature size, geometry, and spatial arrangement at micro- and mesoscales [1, 19, 77–81].

2.1 | Functional Simulation of Sensing Regulation

Biological skin's tactile, temperature, and humidity perception rely on intricate mechanisms. Tactile sensing involves specialized mechanoreceptors: Merkel cells detect static pressure and textures; Meissner corpuscles sense light touch and low-frequency vibrations; Pacinian corpuscles perceive high-frequency vibrations and rapid pressure changes; Ruffini corpuscles respond to sustained stretch [82–85]. Their integrated signals enable comprehensive tactile awareness [86–91]. Temperature perception uses thermosensitive neurons: TRPV1 channels and TRPM8 channels activate with temperature changes [92–94]. Humidity perception arises from synergies between stratum corneum moisture changes, ion channel activation, and Merkel cells, generating signals transmitted to the central nervous system [95, 96]. These intricate, multi-dimensional sensory mechanisms of biological skin serve as the biological blueprint for the functional bionics of e-skin, which aims to replicate such sensory capabilities in e-skin.

2.1.1 | Three-Dimensional Tactile Perception

Most current e-skins with tactile perception capabilities mostly adopt planar piezoresistive or capacitive sensing methods. Such technologies detect normal pressure by laying a two-dimensional sensing array on a flexible substrate, featuring simple structures and low preparation costs [97–99]. For example, Guo et al. [100] designed a mechanoreceptor-inspired e-skin based on a 2D sensor array. Through a biomimetic layout strategy, this design realizes multimodal force sensing while simplifying system complexity. However, they have significant limitations in practical applications. Due to the inherent defects of two-dimensional planar sensing structures, they can only perceive normal forces perpendicular to the surface, but cannot decouple and detect the three-dimensional components of force (such as normal pressure, tangential friction force, torque, etc.), making it difficult to accurately restore the spatial distribution and directional characteristics of force in complex interaction scenario.

In contrast, biological skin achieves excellent 3D force perception capabilities by virtue of the three-dimensional distribution of multi-layer mechanoreceptors. Therefore, it is necessary to incorporate 3D structures, multi-layered sensing arrays, or other specialized structures, so as to achieve the decoupled detection of the spatial distribution and direction of forces. Inspired by this, Liu et al. [23] developed a biomimetic three-dimensional e-skin (Figure 2A) that emulates the 3D distribution of Merkel cells and Ruffini endings in human skin, enabling decoupled sensing of normal force, shear force, and strain. Researchers have achieved three-dimensional force perception through an eight-armed cage microstructure combined with a hierarchical encapsulation design. Force sensors are arranged on the eight-armed cage structure close to the surface. The normal force and tangential force components are decoupled by using the sum of resistance changes of the eight arms under normal force and the cosine/sine components of resistance changes of each arm under tangential force. Strain sensors are located on the arch structure at a lower height, achieving spatial decoupling from the force sensors by sensing skin tensile strain. This manufacturing approach, which involves creating multilayer planar devices via micro-nanofabrication, transforming them into a bioinspired three-dimensional layout through mechanically guided assembly, and finally achieving skin-like mechanical properties via heterogeneous multi-material encapsulation, provides a crucial pathway for the functional simulation of bioinspired e-skin.

On this basis, researchers have further expanded the bio-inspired design direction and explored the strategy of 3D integration of multiple types of sensors to more flexibly construct e-skin systems with comprehensive tactile perception capabilities. Zeng et al. [101] proposed a bio-inspired 3D integrated e-skin (Figure 2B), in which three types of micro-/nanostructured flexible sensors based on template replication and soft lithography were incorporated into a three-dimensional layout, thereby enabling tactile perception. This e-skin integrates strain sensors, shear force sensors, and pressure sensors in a layered, non-overlapping, and suspended 3D layout. A mechanical isolation design ensures each sensor only responds to specific mechanical stimuli, effectively avoiding signal crosstalk.

Besides the above-mentioned ones, in the exploration of structural innovation for 3D force perception, researchers have further drawn inspiration from the fine structures of biological organs or functional structures with special mechanical responses. By optimizing the mechanical-electrical conversion efficiency of the structure, they have opened up another technical route to achieve high-performance 3D tactile perception. Inspired by human fingertips, Li et al. [102] developed an anisotropic sensing liquid metal sensor (Figure 2C). By combining three layers of high-density liquid metal coils with an elastic substrate, they constructed a sensor with a unique three-dimensional structure, enabling the natural discrimination between normal pressure and lateral pressure. The inductance signal increases under normal pressure and decreases under lateral pressure, allowing for preliminary identification of multi-axial forces without relying on complex arrays or algorithms. This biomimetic design provides a new structural approach for improving sensor performance. Notably, the sensor also adopts an innovative unsealed port design: liquid metal can overflow under pressure and flow back automatically after pressure release, which breaks through the range limitation of traditional sealed structures, further demonstrating the value of structural innovation in optimizing sensor performance. Besides the above fingertip-inspired anisotropic structural design, the dome structure has also been recognized as an effective structure for achieving high-performance three-dimensional tactile perception—especially in sensitive force detection scenarios. Building on this, Kim et al. [103] developed an all-soft multi-axial force sensor based on liquid metal microchannel arrays (Figure 2D). Liquid metal microchannel arrays were fabricated via multilayer 3D printing and arranged

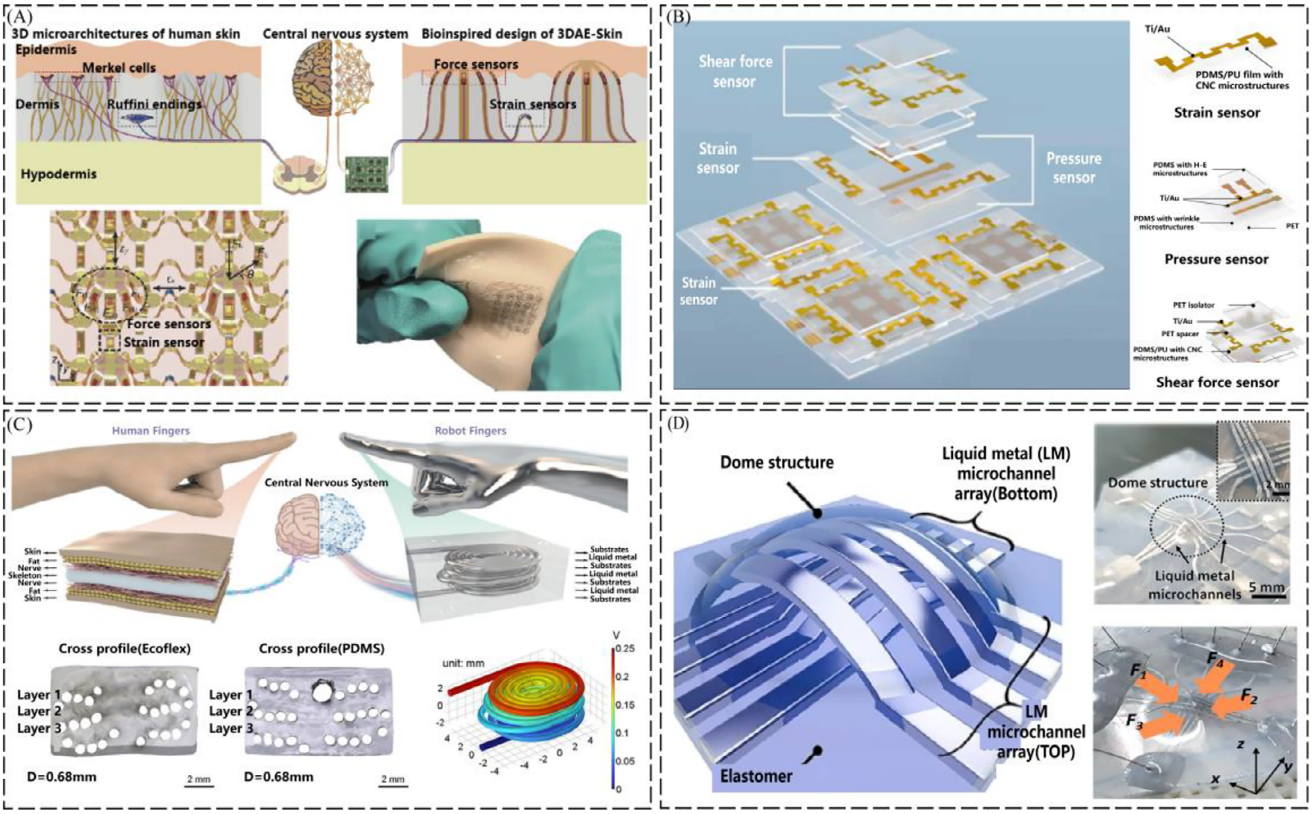

FIGURE 2 | Three-dimensional tactile perception design. (A) A three-dimensionally architected electronic skin mimicking human mechanosensation. Reproduced with permission [23]. Copyright 2024, AAAS. (B) A bioinspired three-dimensional integrated e-skin for multiple mechanical stimuli recognition. Reproduced with permission [101]. Copyright 2022, Elsevier. (C) Fingertip-inspired spatially anisotropic inductive liquid metal sensors with ultra-wide range, high linearity, and exceptional stability. Reproduced with permission [102]. Copyright 2025, Wiley-VCH. (D) All-soft multiaxial force sensor based on liquid metal for electronic skin. Reproduced with permission [103]. Copyright 2021, Springer Nature.

along dome-like structures to enable multidirectional force detection. The core of this design lies in the dome structure: when external pressure is applied, the dome deforms, which in turn induces changes in electrical properties (such as resistance or capacitance) within the liquid metal microchannels. This mechanical deformation-electrical signal conversion mechanism can translate minute external forces into significant electrical signal variations, ultimately enabling highly sensitive perception of weak forces.

2.1.2 | Thermoregulation

Most current e-skins with temperature management capabilities mainly adopt planar resistive or thermoelectric sensing structures, which detect temperature variations by embedding temperature-sensitive arrays in flexible substrates. Such designs feature straightforward configurations and low fabrication costs [104–106]. However, they present significant limitations in practical applications. Owing to the inherent flaws of two-dimensional planar structures, these technologies can only sense surface temperature uniformly, thus making it difficult to maintain optimal thermal balance in complex environmental scenarios.

In contrast, biological skin achieves efficient temperature management through the spatial distribution of multi-layer thermoreceptors. This highlights the significance of structural design in e-skin temperature regulation: innovative structure design can mimic biological mechanisms to enhance thermal management and improve human comfort [107–109]. Inspired by this, Neto et al. [110] developed a biomimetic thermal management e-skin (Figure 3A) that emulates the hierarchical thermal regulation mechanism of human skin, enabling decoupled sensing and control of temperature gradients and thermal feedback. Researchers have achieved a biomimetic thermal-sensing e-skin with high sensitivity, fast response, and mechanical robustness by incorporating directional vanadium pentoxide nanowire arrays and hierarchical encapsulation design, which integrates nanomaterial assembly, printed electronics, and flexible packaging technologies, thereby enabling three-dimensional thermal management. Thermal sensors are arranged on the surface of the nanowire array, which is close to the skin-like surface. The normal heat flux and tangential heat flow components are decoupled by using the temperature gradient difference across the nanowire array under normal heat flux and the cosine/sine components of temperature-induced resistance changes of each nanowire under tangential heat flow. Another representative case of bioinspired structural design for thermal control in e-skin takes its cue from the distinctive "skin-spine" structure of hedgehogs. Wu et al. [111] proposed a mechanically stable bioinspired wearable thermoelectric devices based on the hedgehog's "skin-spine" structure (Figure 3B). Through a bioinspired-driven soft–hard integration strategy, the thermo–mechanical coupling performance has been optimized by structural design, thereby

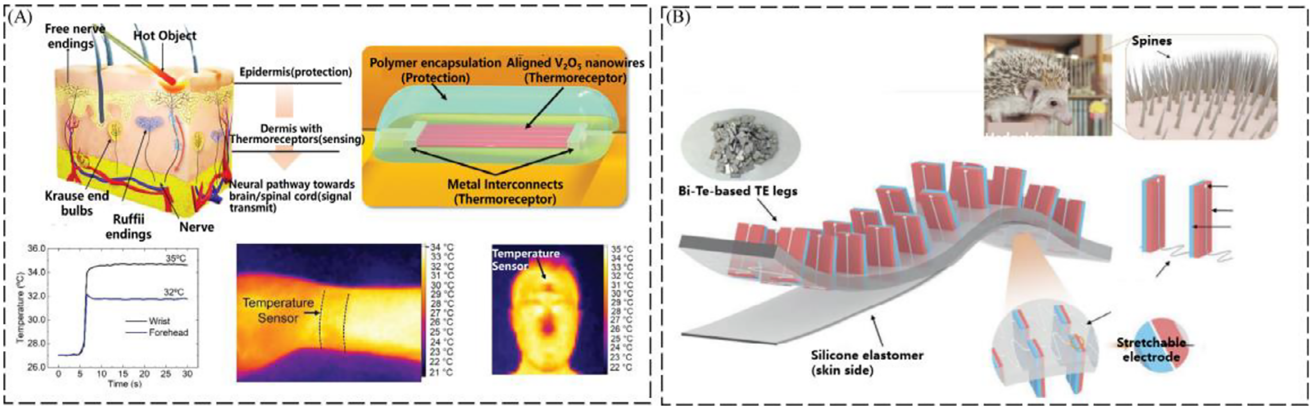

FIGURE 3 | Thermoregulation design. (A) Skin-inspired thermoreceptors-based electronic skin for biomimicking thermal pain reflexes. Reproduced with permission [110]. Copyright 2022, Wiley-VCH. (B) Bioinspired wearable thermoelectric device constructed with soft-rigid assembly for personal thermal management. Reproduced with permission [111]. Copyright 2024, Wiley-VCH.

enabling efficient thermal regulation capability. Inspired by the mechanism where rigid spines in hedgehog skin are embedded in the flexible epidermis, the device uses Bi-Te-based thermoelectric units as rigid "spines" vertically anchored in an Ecoflex silicone elastomer "skin" substrate. This design not only retains the material's excellent thermoelectric conversion properties at room temperature but also enhances energy conduction efficiency along the thermal gradient direction through vertical layout. The Ecoflex substrate mimics the flexible characteristics of skin, ensuring the device maintains structural stability under deformation, while the island-bridge serpentine electrode network absorbs mechanical stress. Based on the above structure, the device realizes active temperature control through the Peltier effect: it can efficiently utilize human body heat for power generation or reversely drive skin cooling.

In addition, many thermally responsive materials have also been integrated with structural design to enhance temperature-sensing capabilities. Examples include conductive hydrogel materials, thermoelectric materials, and phase-change materials, among others. Building on this, Luo et al. [112] developed a strain-insensitive multimodal e-skin based on ionic hydrogel, which further demonstrates the critical role of structural design in achieving stable temperature perception. By employing a chemically anchored "island-bridge" heterostructure, the hydrogel temperature sensor maintains highly consistent resistive responses under tensile strain, with strain interference as low as 0.2%, thereby enabling reliable and highly linear temperature monitoring even during dynamic deformation.

2.1.3 | Humidity Detection

Microfluidic channels are widely utilized in the humidity management of e-skin, as they play a core role in facilitating moisture transport, sweat wicking, and localized humidity regulation—key functions for maintaining the device's stability and human comfort during long-term wear [76, 113, 114]. However, conventional microfluidic channel designs suffer from notable limitations: first, their simple linear or planar structures are prone to clogging by sweat residues, environmental dust, or skin exudates, which disrupts continuous moisture circulation; second, the lack of optimized spatial structure leads to low moisture diffusion efficiency, failing to match the rapid and uniform humidity adjustment capability of biological skin [115]. These drawbacks underscore the critical significance of structural design in microfluidic channel development: by integrating innovative structural features, researchers can effectively alleviate clogging, enhance moisture diffusion uniformity, and improve skin conformality, thus overcoming the bottlenecks of traditional designs and elevating the overall performance of e-skins in humidity management.

Recently, innovative microfluidic structural designs have emerged as a core strategy to address the limitations of traditional systems [116]. For instance, inspired by the hierarchical structure of cactus spines, Son et al. [117] developed wedge-shaped wettability channels with conical asymmetric surfaces (Figure 4A). Leveraging the synergistic effect of superhydrophobic and superhydrophilic surfaces, these channels achieve directional sweat transport via Laplace pressure difference, maintaining high-efficiency collection even under vertical tilting. Compared to conventional microfluidic channels, the wedge-shaped wettability-patterned channels exhibit doubled sweat collection speed and enhanced efficiency, offering an innovative solution to the challenge of sweat drainage. Building on this cactus-inspired design logic and further expanding its functional boundaries, Liao et al. [118] proposed a dual-biomimetic microfluidic patch (Figure 4B) that integrates not only wedge microstructures but also superhydrophobic valves. This upgraded design not only retains the advantage of directional sweat transport driven by capillary pressure difference but also solves the critical issue of old and new sweat mixing that plagued previous single-biomimetic systems, enabling time-sequential sweat collection.

However, despite these breakthroughs in sweat transport and temporal sampling, traditional planar microfluidic systems still suffer from inherent limitations due to their 2D structure and low collection efficiency at low rates. To address these unresolved issues, Yang et al. [114] proposed a soft, skin-interfaced 3D microfluidic system (Figure 4C), which achieves a substantial leap in low-rate sweat collection efficiency through synergistic optimization of surface chemistry and structural design.

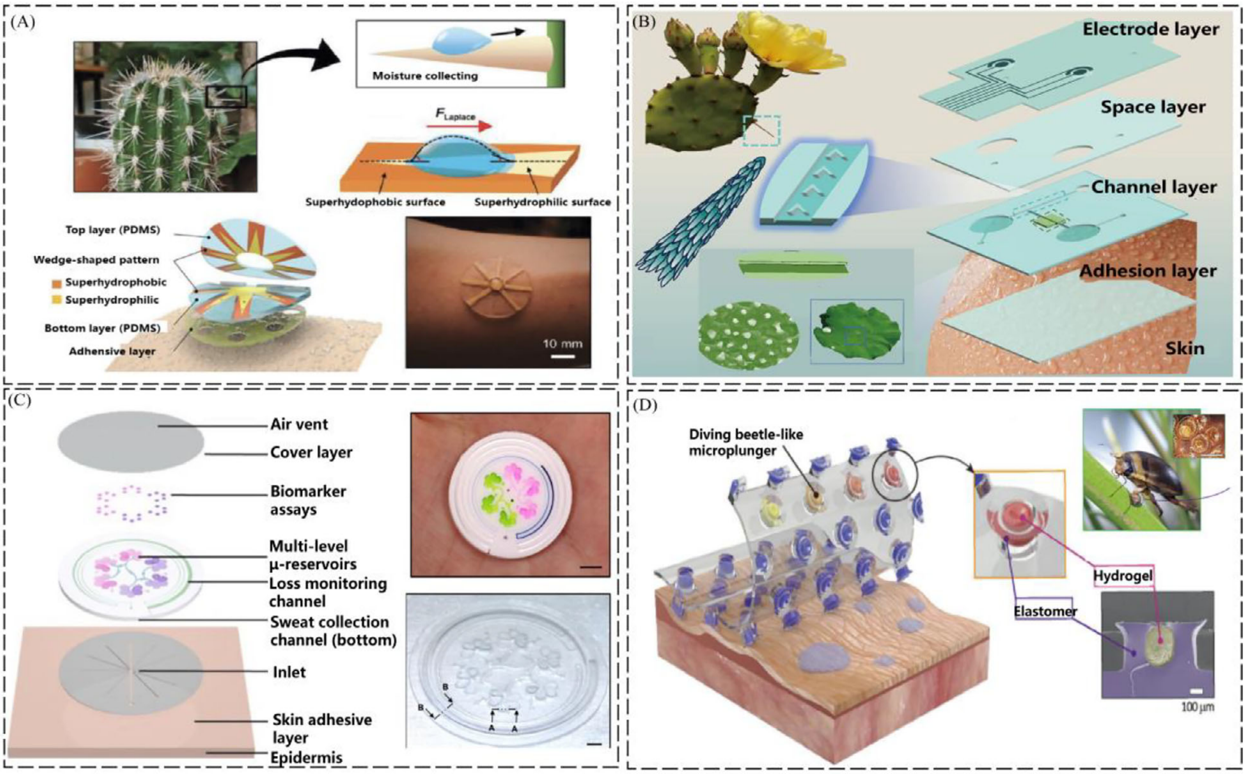

FIGURE 4 | Humidity detection design. (A) Cactus-spine-inspired sweat-collecting patch for fast and continuous monitoring of sweat. Reproduced with permission [117]. Copyright 2021, Wiley-VCH. (B) Coupled biomimetic microfluidic sensors with fast time-sequenced collection for sweat detection. Reproduced with permission [118]. Copyright 2025, Elsevier. (C) Soft, skin-interfaced 3D microfluidic systems for high-performance assessment of sweat rate, cumulative loss, and biochemical content. Reproduced with permission [114]. Copyright 2025, Wiley-VCH. (D) Diving beetle–like miniaturized plungers with reversible, rapid biofluid capturing for machine learning–based care of skin disease. Reproduced with permission [119]. Copyright 2021, AAAS.

Specifically, they developed a 3D variable-cross-section sweat loss monitoring channel: the channel features a small cross-section of 125 × 125 µm at the inlet and expands continuously in an exponential fashion along the flow path, ultimately reaching a large cross-section of 1.5 × 1.5 mm at the outlet. By leveraging the dimensional size gradient in the spatial dimension to balance the hydraulic resistance under different sweat rates, this design addresses the problem of traditional planar channels: inaccurate measurement at low sweat rates and easy filling at high sweat rates. Meanwhile, multi-branch transport channels are integrated around the inlet to expand the effective sweat collection area, enabling capture of sweat from regions adjacent to the inlet that are otherwise inaccessible to planar channels. While these designs effectively overcome the bottlenecks of traditional planar microfluidics in sweat rate adaptation and low-rate collection efficiency, two key issues still affect the reliability of sweat analysis results: the long-term conformal stability of the skin interface and the non-specific evaporation of captured sweat. To address these technical pain points not fully covered, Baik et al. [119] proposed another innovative approach from a biomimetic perspective: drawing inspiration from the spatula setae structure of male diving beetles, they designed a bionic microplunger array (Figure 4D), which achieves both bidirectionally stable adhesion to the skin and instantaneous capture of biofluids through the synergy of structural and material properties. They prepared perforated pillars with cavity-like suction chambers by using developed methods such as photolithography, partial-filling techniques, and replica molding. By rapidly trapping sweat droplets and adsorbing trace skin moisture via its hydrophilic inner cavities, it provides high-quality, undistorted samples for humidity sensing.

2.2 | Enhancement of Sensing Performance

In the design of e-skin, core performance parameters such as sensitivity, detection range, and response time must be prioritized to accurately acquire sensing information from the e-skin and interactive interfaces. Performance requirements are closely tied to specific application scenarios. However, human skin possesses multimodal perception capabilities, rooted in the hierarchical, spatially distributed structural arrangement of its mechanoreceptors, thermoreceptors, and humidity-sensitive components and this provides important references for the development of e-skin (Table 1). The core goal of e-skin is precisely to mimic such sensory functions of human skin [120–125]. This section deeply explores the above key performance indicators, with a particular focus on the significance of structural design; through material compounding, bionic shape optimization, and functional layering, it has systematically enhanced flexibility, sensitivity, durability, and multimodal sensing capabilities, thus becoming a core means to break through the performance bottlenecks of traditional sensors. (e.g., balancing high sensitivity with a broad detection range).

TABLE 1 | Sensing properties of human skin.

Parameter	Human skin		
	Pressure	**Temperature**	**Humidity**
Sensitivity	1 mN [120]	0.02°C [120]	≥0.5% change [122]
Detection range	>10 kPa [121]	∼5°C to 48°C [120]	from 10% to 100% (relative humidity) [124]
Response time	≈15 ms [120]	100–300 ms [125]	50–200 ms [123]

2.2.1 | High Sensitivity

Biological skin's high sensitivity to pressure, temperature, and humidity comes from the synergy of multi-level tissues, sensory receptors, neural systems, and physiological regulation. Mechanoreceptors turn mechanical stimuli into electrical signals even via micro-deformations [120]. Humans can identify temperature changes as small as 0.02°C [120]. Humidity is sensed via stratum corneum hydration and moisture evaporation, with signals amplified and sent to the central nervous system [122].

For improving the sensitivity of electronic devices, sensitivity refers to the device's ability to respond to input signals (such as physical quantities, chemical quantities, etc.). It is specifically expressed as the ratio of the change in output signal to the change in input signal—the larger the ratio, the stronger the device's ability to perceive and convert tiny input signals [126, 127]. For example, the sensitivity of piezoresistive pressure sensors is commonly expressed by $(\Delta R/R_0)/P$, where ΔR, R_0, and P represent the change in resistance, the initial resistance, and the input pressure, respectively [128]. Achieving high sensitivity to multi-physical field signals thus relies on the collaborative optimization of material innovation and structural design.

In terms of pressure perception, a widely used strategy to improve sensitivity is to engineer microstructures, such as micro-pyramids, micro-cracks, micro-hemispheres, etc., which enhance the change in electrical signals under unit pressure through stress concentration and deformation amplification [32, 35, 39, 50]. For example, inspired by the hierarchical microstructure of banana leaf surfaces, Nie et al. [129] fabricated an e-skin employing soft lithography, which features bioinspired hierarchical microstructures and microcrack structures. (Figure 5A). This hierarchical structure will sequentially make contact and deform at different levels when subjected to pressure. Due to the fact that small-sized structures are more sensitive to pressure, a small pressure stimulus can cause a large change in current, thus significantly improving the sensitivity of the sensor. In addition, designing significant changes in the contact area between sensing materials is another possible approach to improve the sensitivity of pressure perception, especially for resistive sensors that use changes in contact resistance [38, 130]. For example, Yao et al. [131] designed an e-skin with a conical array microstructure(Figure 5B). By imitating the conical array microstructure on the surface of natural plants, an interlocking microstructure was constructed on the friction layer. When subjected to pressure, the conical microstructures of the upper and lower friction layers will form interlocking contact, greatly increasing the friction contact area. The increase in contact area enhances the triboelectric effect, resulting in a larger electrical signal output and improving the sensitivity to pressure perception.

In e-skin systems, enhancing sensitivity to temperature and humidity relies on structural design strategies that amplify material deformations or electrical signal changes induced by environmental stimuli [132]. Micro-nanostructures, porous structures, and multilayer configurations, for example, can effectively magnify subtle thermal or hygroscopic expansions, thereby improving sensing efficiency. Such structural-oriented signal amplification approaches can be applied across a variety of sensing materials. For example, Hong et al. [133] developed a flexible wearable thermoelectric device by sandwiching rigid inorganic high thermoelectric figure of merit (ZT) thermoelectric pillars between stretchable elastomer plates (Figure 5C). By adopting an innovative dual elastic body design concept, an air gap insulating layer was embedded between two stretchable plates and a high ZT inorganic thermoelectric column, achieving the optimal aspect ratio and space density. This design not only maximized the flexibility of the equipment but also minimized the heat leakage through TED to the greatest extent, ultimately achieving high cooling performance. This device integrates heterogeneous materials by using a laminated-assisted embedding process, combining high-ZT inorganic thermoelectric columns, flexible stretchable polymer substrates, and flexible metal electrodes together. This improves the thermoelectric conversion efficiency and significantly enhances the sensitivity of temperature sensing. Beyond thermoelectric structures, structural design has also been extended to modulate interfacial charge transport for humidity sensing. For instance, Zhao et al. [134] designed an e-skin (Figure 5D) based on graphene and MoS_2, selecting single-layer molybdenum disulfide as the humidity-sensitive material, forming a heterojunction structure with nanographene, and integrating it into an active-matrix circuit. Multimodal sensors are ingeniously integrated into the multi-layered geometric structures through a series of micro-manufacturing processes such as lithography and etching. When the humidity changes, water molecules are adsorbed on the surface of MoS_2, causing changes in the charge distribution on the material surface. Due to the high specific surface area and layered structure of MoS_2, the amount of water molecule adsorption is significantly positively correlated with the humidity, which in turn leads to significant changes in its electrical conductivity.

However, although low-dimensional functional materials possess high sensitivity, their limited stretchability has restricted the development of e-skin. To overcome these limitations, signal amplification strategies guided by structure design have increasingly been extended to soft and highly deformable materials,

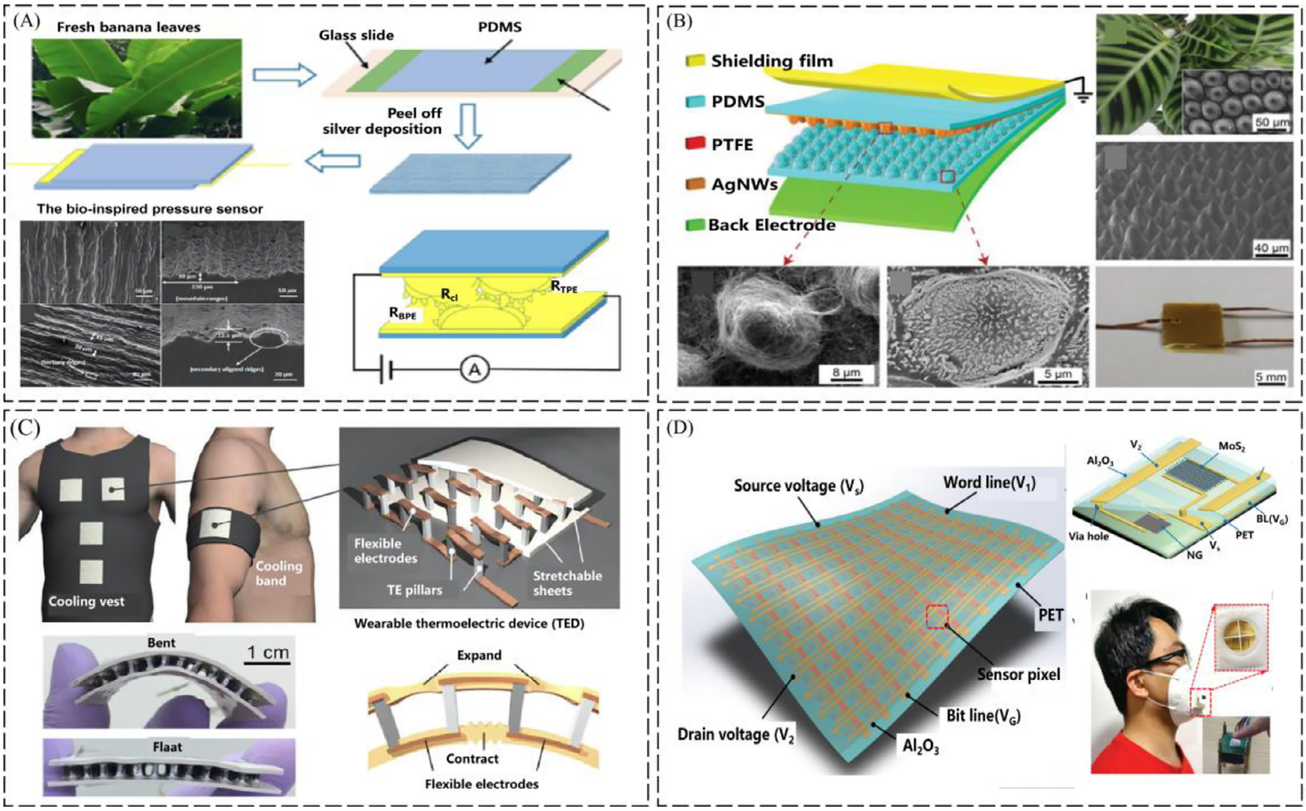

FIGURE 5 | High sensitivity design. (A) High-performance piezoresistive electronic skin with bionic hierarchical microstructure and microcracks. Reproduced with permission [129]. Copyright 2017, American Chemical Society. (B) Bioinspired triboelectric nanogenerators as self-powered electronic skin for robotic tactile sensing. Reproduced with permission [131]. Copyright 2019, Wiley-VCH. (C) Wearable thermoelectrics for personalized thermoregulation. Reproduced with permission [133]. Copyright 2019, AAAS. (D) Skin-inspired high-performance active-matrix circuitry for multimodal user-interaction. Reproduced with permission [134]. Copyright 2021, Wiley-VCH.

such as polymer conductors and ionic hydrogels [112, 135, 136]. Ding et al. [136] reported a flexible hydrogel chemical sensor based on an intelligent adaptive hydrogel, which can dynamically respond to gas and humidity stimuli. This work designs a state-switchable smart hydrogel through ion engineering and uses it as an electrolyte, ingeniously combining it with a classic metal–air battery electrochemical system. Its inherent ionic conductivity and adaptive network structure enable it to switch between gas and humidity sensing modes without an external power source, and its porous and tunable structure amplifies the ionic transport changes caused by environmental variations. Moreover, it can directly adhere two different electrodes to both sides of the hydrogel electrolyte without additional adhesives, thus possessing flexibility, leak-proofness, and non-flammability.

2.2.2 | Wide Detection Range

The broad detection range of biological skin for pressure, temperature, and humidity stems from its full-scale response to environmental stimuli, it can achieve continuous perception through multi-level structures and dynamic regulatory capabilities, ranging from micro-newton-level pressure from a light fingertip touch to kilo-newton-level loads borne by limbs [121], from sub-freezing cold to above-body-temperature heat [120], and from low humidity in dry air to high humidity from sweat infiltration [124].

For e-skin, its detection range can be defined as the interval of physical stimulus intensities to which it can stably and accurately respond [137]. However, the detection range of traditional e-skin is often restricted by material properties or the singularity of sensing mechanisms, making it difficult to achieve high sensitivity over a wide range and potentially leading to highly non-linear and unstable responses. To achieve this goal, it is necessary to break through the inherent limitations of traditional e-skin in terms of material properties and sensing mechanisms through structural design, thereby enabling high sensitivity of e-skin over a broad detection range.

For pressure perception, an effective strategy is to use multi-layered geometries, which increase the contact area and the variation of stress distribution in each layer [40, 138]. For example, Chen et al. [139] proposed a flexible sensing array based on programmable multi-stage dome structures (Figure 6A). In this study, the conductive layer of silver nanowires was embedded into the microstructure layer of the PDMS dome by a spraying and molding process, and the flexible pressure-sensitive conductive film of the microstructure was controllably manufactured. The interdigital electrodes were manufactured by electron beam evaporation coating technology, and the pressure-sensitive film and interdigital electrode were bonded and packaged by a hot-pressing process. Under small pressures, only the small-diameter domes make contact with the electrodes, ensuring high sensitivity. As the pressure increases, the large-diameter domes

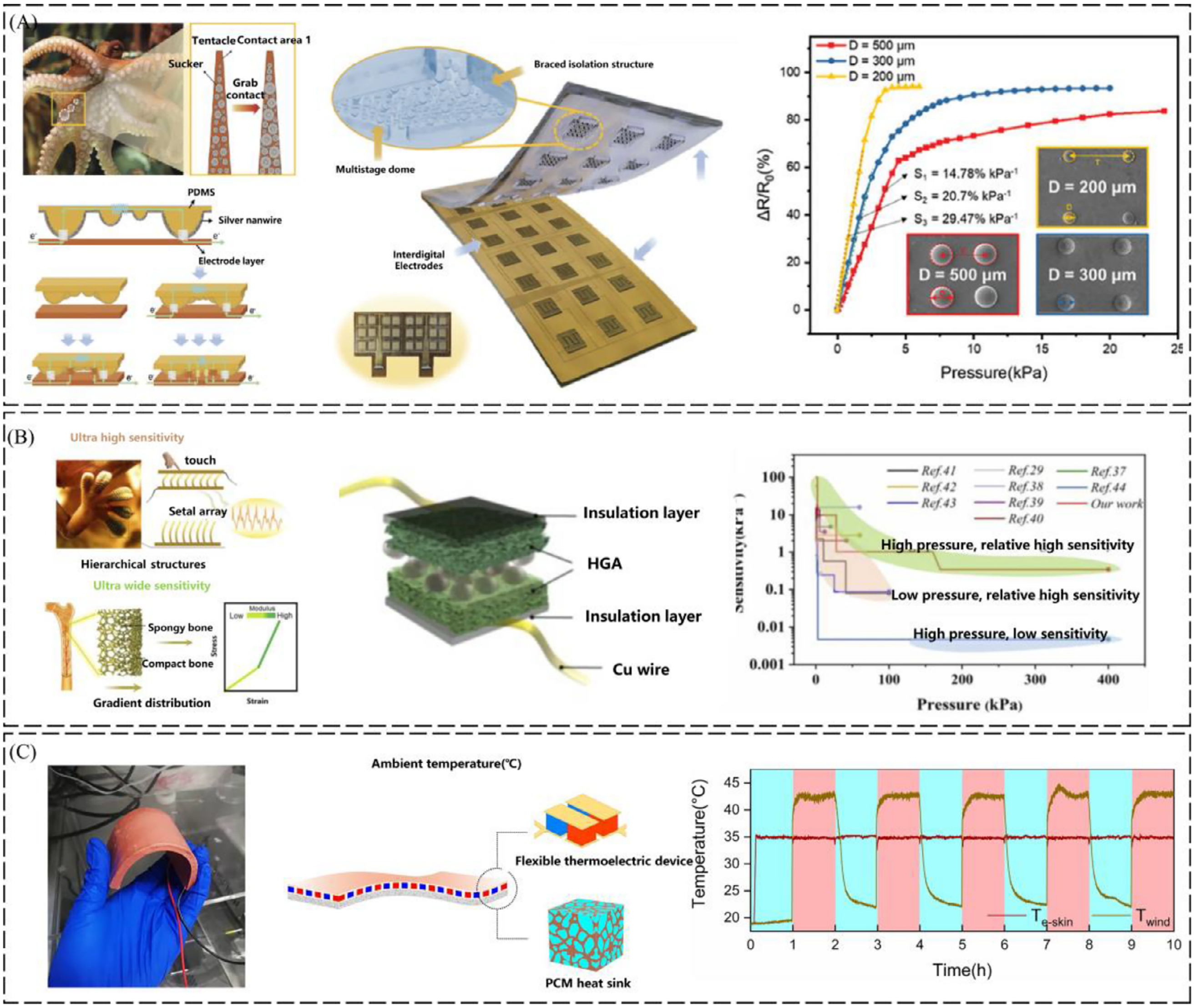

FIGURE 6 | Wide detection range design. (A) Biomimetic contact behavior inspired a tactile sensing array with programmable microdomes patterned by scalable and consistent fabrication. Reproduced with permission [139]. Copyright 2024, Wiley-VCH. (B) Bioinspired engineering of gradient and hierarchical structure into pressure sensors toward high sensitivity within an ultra-broad working range. Reproduced with permission [142]. Copyright 2022, Elsevier. (C) Wide-temperature range thermoregulating e-skin design through a hybrid structure of flexible thermoelectric devices and phase change materials heat sink [106]. Copyright 2022, Elsevier.

gradually participate in the contact, increasing the contact area, thus expanding the pressure detection range while maintaining high sensitivity. This structure enables the sensor to maintain good response within the pressure range of 0–100 kPa. Moreover, by adjusting parameters such as the diameter of the multi-stage dome structure and the array period, programmable control of the sensor performance can be achieved. Another approach to maintaining high sensitivity over a wide pressure range is to use structured materials that gradually increase contact or deformation under applied stimuli [140, 141]. Inspired by this, Song et al. [142] proposed a design of pressure sensors that achieves high sensitivity over a wide pressure range through a bioinspired hierarchical and gradient structure (Figure 6B). This structure integrates hemispherical arrays and gradient pores, with its inspiration derived from the hierarchical structure of gecko setae and the gradient porous structure of bones, respectively. Its core maintains high sensitivity over a wide pressure range through a progressive contact/deformation mechanism, thus achieving a highly sensitive response over the full pressure range from an ultra-low pressure of 0.4 Pa to a high pressure of 400 kPa.

In terms of temperature and humidity perception, the main approach to enhance the detection range is to break through material limitations, so as to achieve a wide temperature range/full humidity detection [143]. Zhang et al. [106] realized an e-skin with wide temperature range regulation through a hybrid structure of flexible thermoelectric devices and phase-change material radiators (Figure 6C). They selected paraffin with a phase-change temperature of 37°C as the phase-change material (PCM), and combined it with a thermally conductive potting adhesive to fabricate a PCM radiator. The paraffin was encapsulated in a high thermal conductivity foam framework with a porosity of 65%, which improves the heat dissipation and heat storage capacity of the paraffin. When the hot-end

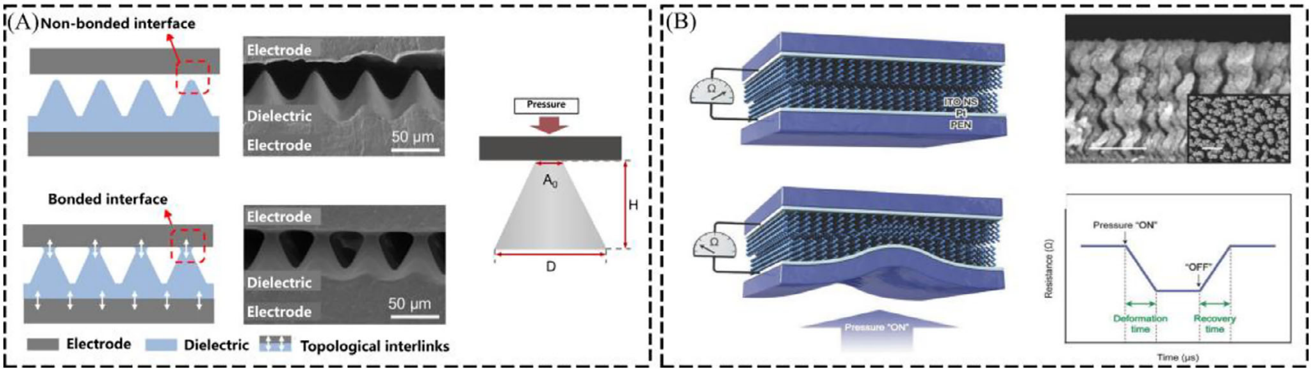

FIGURE 7 | Fast response time design. (A) Ultrafast piezocapacitive soft pressure sensors with over 10 kHz bandwidth via bonded microstructured interfaces. Reproduced with permission [148]. Copyright 2024, Springer Nature. (B) A highly sensitive force sensor with fast response based on interlocked arrays of indium tin oxide nanosprings toward human tactile perception. Reproduced with permission [149]. Copyright 2018, Wiley-VCH.

temperature of the thermoelectric device approaches the phase-change point, the PCM absorbs a large amount of heat and maintains a constant temperature, extending the effective cooling time of the thermoelectric device and breaking through the limitation of low heat dissipation efficiency of single paraffin materials in a wide temperature range.

2.2.3 | Fast Response Time

As one of the core performance indicators of sensors, response time directly defines the duration from the application of an external stimulus to the stabilization of the output signal, and its value is of decisive significance in real-time dynamic scenarios. For example, in pressure mapping displays, an excessively long response time can cause lag and blurring in the pressure distribution images of the contact surface, making it impossible to accurately reflect instantaneous pressure changes [144, 145]. For e-skin, optimizing response time requires balancing sensitivity and stability: an overly short response time may introduce high-frequency noise, while an excessively long one will result in the loss of dynamic tracking capability. To achieve rapid response of e-skin to stimuli in real-time dynamic scenarios, it is necessary to break the limitations of the inherent response rate of materials through structural design.

For resistive and capacitive sensors based on polymeric materials, the viscoelasticity of polymers is the main cause of slow response, as the deformation and recovery of polymer chains require time [146, 147]. To improve response time, a common strategy is to design dielectric layers with microstructured surfaces. This strategy works through two principles. First, the microstructures reduce the bulk viscoelasticity of the dielectric by storing more elastic energy with smaller deformations. Second, they reduce the contact area between the dielectric and the electrodes, thereby lowering energy dissipation caused by interfacial friction and adhesion [40, 77]. For example, Zhang et al. [148] designed a capacitive flexible pressure sensor with an adhesive microstructured interface (Figure 7A), reducing the response and relaxation time to 0.04 ms. This interface can effectively reduce interfacial friction and energy dissipation. The limitation was addressed by incorporating 2 wt.% CNTs into the PDMS dielectric layer to reduce its viscosity. In addition, the authors designed the adhesion between the microcone structures and the electrodes. By engineering microcones with moderate height and adhesive head size, the response recovery time was effectively reduced to approximately 0.04 ms, achieving an optimal balance that ensures fast response-recovery time, high mechanical stability, and enhanced sensitivity. Similarly, tactile sensors with sub-millisecond responses were developed based on interlocked arrays of ITO nanospring structures [149]. Owing to the enhanced elasticity and self-recovery from the spring-like structures, the sensors could respond to a pressure of 10 kPa within 2 ms, and recover to the initial state in less than 1 ms (Figure 7B). With the sub-millisecond response times, the sensor was capable of measuring vibrating pressures ranging from 1 to 1000 Hz, with a signal-to-noise ratio of over 20 dB.

3 | Conformal Interface Stabilization Design

Traditional electronic devices, primarily constructed from semiconductors like silicon and conductors such as copper, exhibit excellent electrical performance but suffer from rigid physical forms. This rigidity restricts their ability to undergo tensile, bending, or torsional deformations, limiting integration with complex curved surfaces—particularly the soft substrates of biological tissues [18]. The development of e-skin interfaces from humanity's long-standing pursuit of skin-like intelligent interface systems, with the core objective of overcoming the physical barrier between conventional electronics and biological organisms through material and structural innovations [150].

Notably, structural design emerges as a pivotal bridge in this pursuit, serving as a critical strategy to reconcile the inherent contradictions between the functional requirements of electronic components and the mechanical demands of bionic systems. Particularly, the stability of conformal interfaces highly depends on the synergy between advanced manufacturing strategies and structural design. Techniques such as 4D-printed shape-adaptive interfaces, mechanically metamaterial-structured patches, and in situ crosslinked bio-integration enable the direct fabrication of micro/nanostructured interfaces on complex curvatures. These interfaces exhibit multifunctional characteristics, including gradient modulus, dynamic adhesion, and moisture permeability, thereby ensuring long-term mechanical compatibility and signal stability of e-skin during dynamic wear [18, 30, 151, 152]. Unlike rigid electronics that rely on fixed, planar structures, e-skin necessitates structural configurations capable of mimicking the hierarchical complexity of biological skin, from macroscopic flexibility to microscopic adaptability. For instance, bioinspired designs such as wrinkled structures and serpentine interconnects have been engineered to effectively dissipate mechanical stress under deformation, enabling the integration of brittle conductive materials into stretchable matrices without compromising electrical conductivity.

3.1 | Adhesive Layer Design

Most e-skin devices require flexibility to conform to complex curved surfaces, yet excessive flexibility often compromises interfacial adhesive force. The degree of interfacial adhesion between e-skin and substrates significantly affects long-term stability and functional reliability [1, 52, 153–155]. Material and structural design innovations are essential to balance flexibility and adhesion, ensuring maintenance of stable interfacial bonding during dynamic deformations. Adhesion optimization is a critical factor in achieving reliable interfaces between e-skin and diverse substrates, which is inherently linked to the device's practical viability—the ability to withstand repeated deformation and external disturbances. This directly influences operational stability and functional persistence in real-world applications.

Biomimetic design represents a pivotal strategy in e-skin adhesion, drawing inspiration from biological organism–environment interactions. By emulating natural adhesion mechanisms—such as van der Waals adhesion in gecko toes [156, 157], microstructural adhesion in insect feet [158–161], and capillary adhesion in plant seeds [162]—researchers have unlocked breakthroughs in reversible dry adhesion. For example, the setal microstructure of gecko feet inspired Kwak et al. [163] to develop a novel medical skin patch (Figure 8A) featuring high-density mushroom-shaped micropillars. Constructed from soft PDMS, these micropillars mimic gecko foot microstructures to explore adhesive performance on human skin, which has unique hierarchical topographical features. The study tested two types of broad-headed micropillars, revealing that adhesion strength is significantly influenced by parameters like aspect ratio (AR), with optimal performance achieved at $AR = 3$. Theoretically, models derived from thin-film elastic bending confirm that micropillar height must exceed a critical value to form stable contacts. Additionally, Choi et al. [164] developed cephalopod-inspired dry adhesives (Figure 8B), integrating ultrathin, stretchable structures with physiological sensors, drug-delivery actuators, and therapeutic nanoparticles. The micro-suction cup structure design enhances adhesion and comfort, with adhesion approximately 3 times higher than traditional gecko-inspired micro-column structures, limiting tissue damage and inflammation. More notably, Guo et al. [165] applied biomimicry of web-droplet spider silk to design a web-droplet e-skin (Figure 8C), composed of Ecoflex film and polyborosiloxane distributed at network intersections to mimic silk mucus for adhesion, with semi-liquid metal Cu-EGaIn providing high conductivity and stretchability. This e-skin exhibits strong adhesion, stable performance under diverse conditions, and excellent breathability—pioneering new design paradigms for e-skin adhesion.

Skin deformations during movement including stretching, bending, and twisting, induce stress concentrations at adhesive interfaces, causing edge delamination in traditional patches. Conventional adhesion designs, lacking adaptability to dynamic skin deformations, often lead to detachment, signal distortion, or tissue damage. In recent years, researchers have developed dynamic conformality technologies through biomimetic structural design, smart material responses, and multi-physics coupling optimization. Inspired by barnacle and armadillo structures, Choi et al. [166] proposed a motion-adaptive mosaic skin patch (Figure 8D), arranging rigid and compliant shape memory polymers (SMPs) in a mosaic array. SMP nanocomposites adapt to rough skin surfaces when heated, harden upon cooling to achieve strong adhesion, and restore shape via reheating to reduce adhesion for on-demand detachment. The patch exhibits exceptional adhesion in both dry and wet conditions, resolving the conflict between skin adhesion and motion adaptability while enabling seamless integration of large electronic components, pioneering innovative adhesion designs for wearable electronics. Similarly, Kim et al. [167] developed a reversible, multifunctional skin-adhesive tactile interface platform (Figure 8E). Through the molding and transfer technology based on soft materials, multi-microscopic-scale structural control is achieved. The adhesive patch integrates frog toe pad-inspired drainage hexagonal arrays with snail pedal muscle-inspired energy-dissipating matrix structures, generating significant adhesive force in both tensile and shear directions under dry/wet conditions. Hexagonal microchannels efficiently drain water to enhance skin conformality, while the patch demonstrates excellent vibration resistance, maintaining stable adhesion across 1–150 Hz frequencies—marking a breakthrough in tactile interface adhesion design.

3.2 | Functional Layer Design

Most e-skin devices remain two-dimensional planar structures, while biological tissues exhibit three-dimensional topographies. The degree of interfacial conformality between these two significantly affects the quality of signal transmission and reception [51, 151, 168–170]. Implementing high-performance inorganic electronic materials in e-skin while maintaining electrical properties requires flexible structural designs to expand device ductility and enable conformal interfaces [171, 172].

The combination of fundamental mechanical deformation modes, including stretching, rigid-body rotation, and out-of-plane buckling, enables the design of inorganic electronic materials into diverse flexible structural units, serving as the basis for conformal interface structures. Inspired by corrugated pipes, introducing buckling in inorganic thin film–flexible substrate systems has emerged as an effective approach to achieve stretchable structures. When a silicon strip is bonded to a pre-stretched flexible substrate, and the pre-strain is released, the silicon strip undergoes compressive buckling, leading to out-of-plane deformation that detaches from the substrate. The resulting wavy structure allows the silicon strip to withstand tensile deformation by leveraging its geometric compliance [173–175]. This configuration mitigates strain through out-of-plane deformation, offering a reliable approach for integrating inorganic thin films into flexible systems.

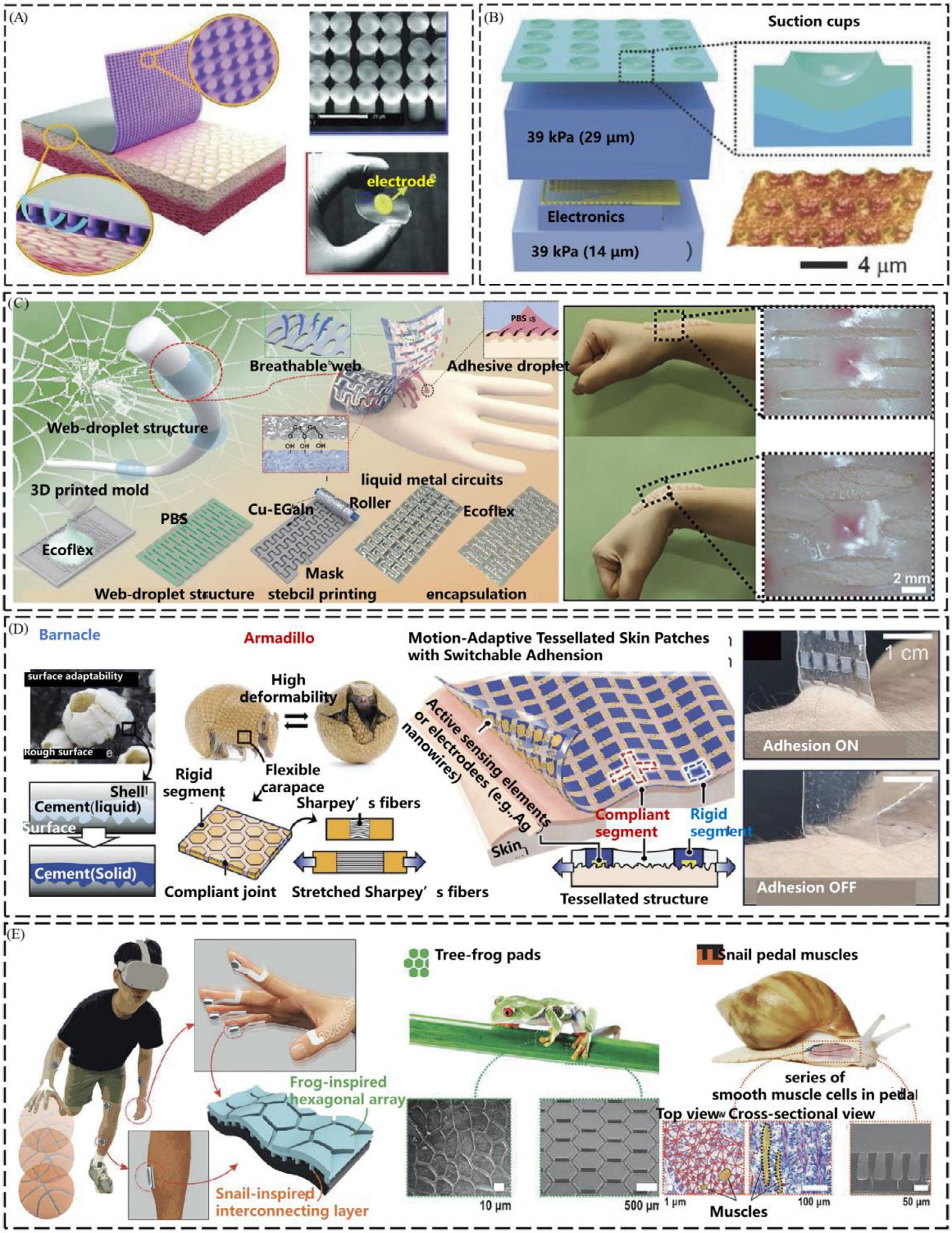

FIGURE 8 | Adhesive layer design. (A) Rational design and enhanced biocompatibility of a dry adhesive medical skin patch. Reproduced with permission [163]. Copyright 2011, Wiley-VCH. (B) Cephalopod-inspired miniaturized suction cups for smart medical skin. Reproduced with permission [164]. Copyright 2015, Wiley-VCH. (C) Semi-liquid metal-based highly permeable and adhesive electronic skin inspired by a spider web. Reproduced with permission [165]. Copyright 2024, Elsevier. (D) Motion-adaptive tessellated skin patches with switchable adhesion for wearable electronics. Reproduced with permission [166]. Copyright 2024, Wiley-VCH. (E) A reversible, versatile skin-attached haptic interface platform with bioinspired interconnection structures capable of resisting sweat and vibration. Reproduced with permission [167]. Copyright 2023, Wiley-VCH.

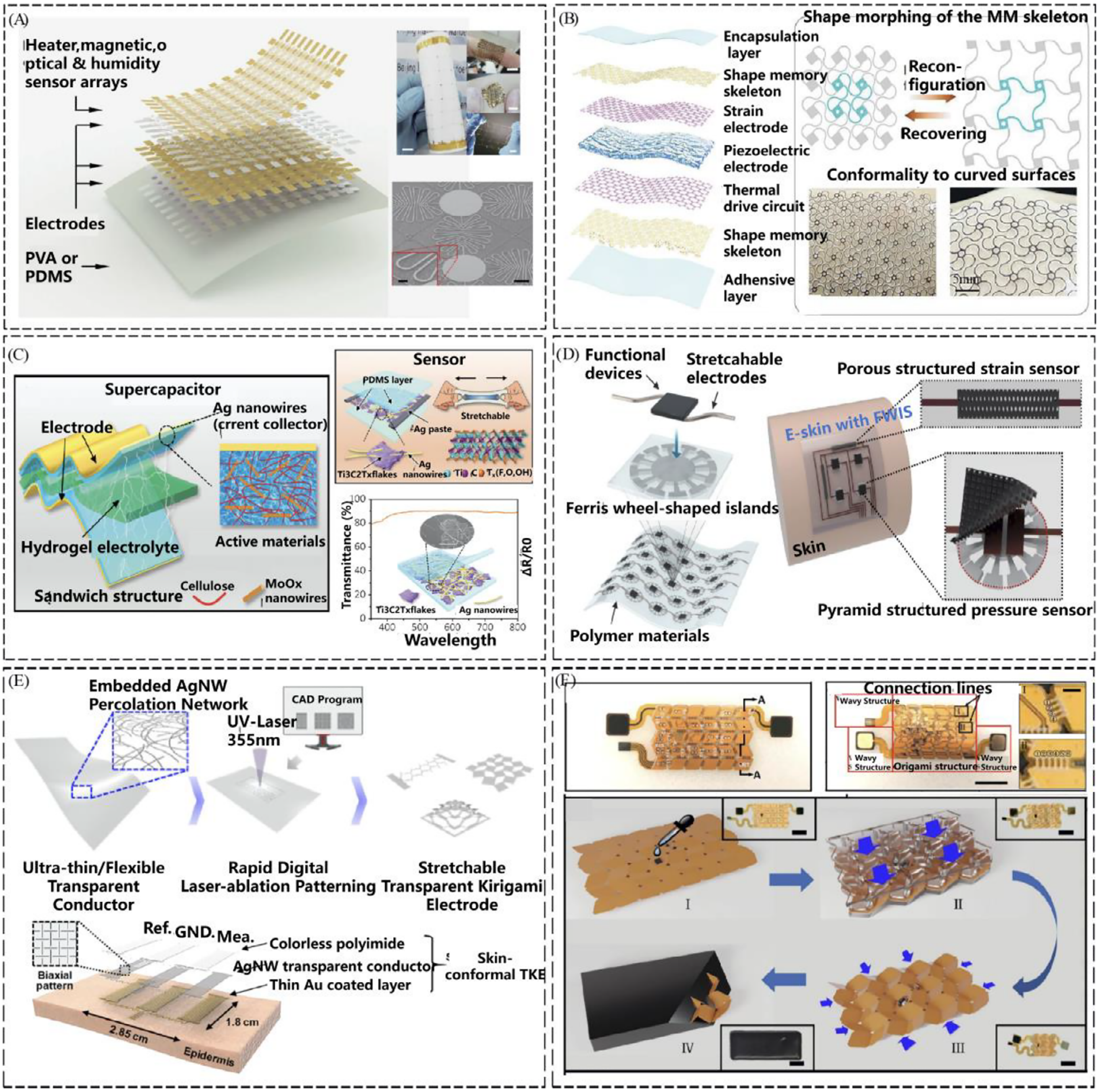

FIGURE 9 | Functional layer design. (A) Skin-inspired highly stretchable and conformable matrix networks for multifunctional sensing. Reproduced with permission [180]. Copyright 2016, Springer Nature. (B) Metamaterial-based electronic skin with conformality and multisensory integration. Reproduced with permission [181]. Copyright 2024, Wiley-VCH. (C) Transparent electronic skin from the integration of strain sensors and supercapacitors. Reproduced with permission [184]. Copyright 2022, Wiley-VCH. (D) Geometrically engineered rigid island array for stretchable electronics capable of withstanding various deformation modes. Reproduced with permission [185]. Copyright 2022, AAAS. (E) Stretchable and transparent kirigami conductor of a nanowire percolation network for electronic skin applications. Reproduced with permission [188]. Copyright 2019, American Chemical Society. (F) Miura-ori enabled stretchable circuit boards. Reproduced with permission. Reproduced with permission [189]. Copyright 2021, Springer Nature.

Serpentine wire structures offer a novel paradigm for improving the stretchability of inorganic electronic materials, achieving elongation through in-plane rotation and out-of-plane buckling to enable large deformations in minimal spaces [176–179]. Hua et al. [180] emulated the neural distribution network of human skin, using wavy meandering wires to connect sensor nodes and form a scalable matrix network (Figure 9A). Experiments show that serpentine structures maintain stable electrical performance under 800% tensile deformation, with only 2.6% resistance variation, and exhibit no significant degradation after 54 000 cyclic stretching cycles. This structure not only allows sensor networks to remain tightly conformable to complex curved surfaces but also adjusts node spacing via pre-stretching to adapt to skin deformation requirements across different body parts, significantly enhancing the mechanical adaptability and long-term stability of the sensor-skin interface. Additionally, Li et al. [181] proposed a self-powered e-skin based on metamaterials (Figure 9B), providing innovative insights for conformal interface stabilization design, particularly through the distinct advantages of its serpentine wire configuration. It employs a hybrid integration of 4D printing technology and multifunctional materials, aimed at achieving shape-adaptive, multimodal sensing, and self-powering capabilities. The device features a multilayer structure integrating a sensing system and substrate system, where the substrate employs a 4D-printed mechanical metamaterial (MM) skeleton. This MM skeleton incorporates two representative topological arrangements (tetra/hexa-MMs) with horseshoe-shaped ligaments, enabling the e-skin to excel in conformal interfacing by better adapting to tissue deformations and maintaining interface stability. In summary, serpentine structures embody a systematic design philosophy that goes beyond geometric innovation. They address the core challenges of mechanical compatibility, electrical stability, and long-term durability, providing a crucial material-structural foundation for reliable multimodal sensing on dynamic biological surfaces.

In traditional rigid circuit boards, semiconductor devices of various functionalities are connected by wires embedded in the circuit board, which solely serve the purpose of electrical connection. In fact, the fabrication of e-skin does not require every component made of inorganic electronic materials to be stretchable. Therefore, structural segmentation can be implemented: parts responsible for complex computation and communication functions are designed as non-deformable islands, while interconnection wires act as stretchable bridges for ductility. The islands and bridges are connected to form an island-bridge structure [176, 182, 183]. For instance, Liang et al. [184] reported a self-powered integrated transparent e-skin by integrating flexible transparent supercapacitors and transparent strain sensors (Figure 9C). The stretchable transparent strain sensor with an island-bridge structure is constructed via spray coating of transition metal carbide/carbonitride (MXene) nanosheets and silver nanowire (Ag NWs) networks. The integration of 2D conductive $Ti_3C_2T_x$ MXene nanosheets as islands significantly enhances the interconnectivity and integrity of 1D AgNWs networks as bridges by welding nanowire junctions and increasing their interaction with soft PDMS substrates. This island-bridge structure endows strain sensors with high Gage Factor under low strain, high signal-to-noise ratio, fast millisecond response time, and excellent stability. However, in traditional island-bridge structures, the modulus mismatch between rigid islands and flexible substrates often leads to interface crack propagation, limiting the stability of e-skin. Inspired by this, Yang et al. [185] proposed geometrically engineered rigid island arrays for stretchable electronics (Figure 9D). The fabrication involved 3D-printing PLA rigid islands of various shapes and embedding them into an elastic Ecoflex polymer matrix, followed by integration of stretchable Ag flake composite electrodes to ultimately assemble a complete e-skin system. This approach enables interfacial crack suppression through geometrical engineering. This structure utilizes periodic toothed interlocking structures, increasing the interfacial failure strain between rigid islands and Ecoflex substrates from 75% (circular islands) to 175%, while maintaining stability after 1000 cycles at 120% strain. The island-bridge structure and its derived configurations constitute a versatile design principle for harmonizing rigid and soft elements in flexible electronic systems. By systematically mitigating integration-related issues of stability and reliability.

Discontinuous structures like kirigami reduce device stiffness, enabling large tensile and bending deformations that facilitate conformal contact between small-area devices and large-area target surfaces. Furthermore, cutting patterns in the structure allow planar devices to be reconstructed into developable surfaces, achieving changes in Gaussian curvature [172, 186, 187]. Won et al. [188] constructed micro-nano grids on composite materials via laser etching (Figure 9E), achieving strain dispersion through periodic slits in kirigami structures. Experiments show that kirigami electrodes exhibit only 3% resistance variation under 400% tensile strain and maintain stability after 10 000 cyclic stretches. The curved contact structures formed by laser etching enable the electrodes to remain tightly adhered to skin during dynamic deformation, with a contact resistance of only 28.9 kΩ—significantly enhancing interfacial mechanical stability and electrical reliability. Additionally, Li et al. [189] proposed integrating kirigami reinforcement into Miura-ori origami structures (Figure 9F), achieving stretchability through geometric design rather than material modification. By introducing micro-slits at the vertex regions, they effectively reduced stress concentration, decreasing interfacial strain by over 50%. This approach not only enables high stretchability but also increases interfacial contact area by 40% via optimized slit distribution, remarkably improving signal acquisition quality. Kirigami and its hybrid configurations offer a distinct structural strategy that overcomes inherent material constraints in electronics. Through deliberate cutting and folding patterns, these designs confer exceptional stretchability, robustness, and conformal compatibility to conventional electronic materials.

3.3 | Encapsulation Layer Design

As the interactive interface between wearable devices and biological systems, the long-term adhesion stability of e-skin is profoundly influenced by breathability. Traditional flexible electronics often adopt hermetic encapsulation to ensure component reliability, yet this design obstructs moisture and gas exchange on the skin surface. This barrier not only causes thermophysiological discomfort (e.g., skin irritation, overheating) but also deteriorates signal quality and adhesion performance—ultimately hindering prolonged accurate signal monitoring [190–192]. Thus, achieving efficient breathability through innovative mechanical and material design has emerged as a core challenge for enhancing the interface stability of e-skin [193–198].

Although traditional flexible devices improve conformality by reducing thickness, their dense structures lead to insufficient breathability—posing a dual challenge for breathable design: maintaining mechanical robustness in ultrathin forms while enabling efficient gas and moisture exchange. Hydrogels offer an excellent paradigm. They are cross-linked polymer networks immersed in water, exhibiting soft properties similar to biological tissues, and have been widely used in tissue engineering and biomedical applications [199]. For example, Cheng et al. [200] developed a hypoallergenic ultrathin hydrogel interface with high water vapor permeability, allowing unimpeded transdermal

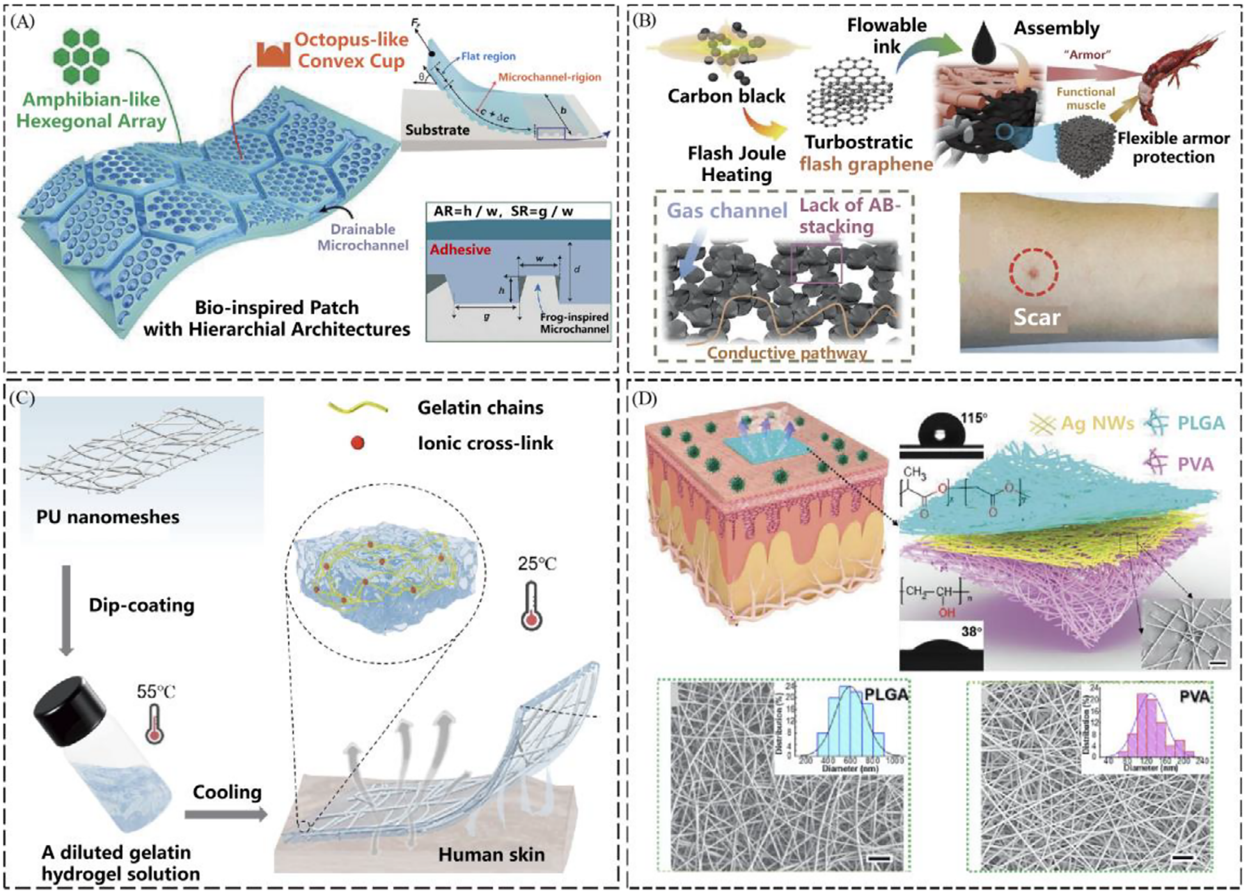

FIGURE 10 | Protective layer design. (A) Highly permeable skin patch with conductive hierarchical architectures inspired by amphibians and octopi for omnidirectionally enhanced wet adhesion. Reproduced with permission [201]. Copyright 2019, Wiley-VCH. (B) Bioinspired robust gas-permeable on-skin electronics: armor-designed nanoporous flash graphene assembly enhancing mechanical resilience. Reproduced with permission [202]. Copyright 2024, Wiley-VCH. (C) A 10-micrometer-thick nanomesh-reinforced gas-permeable hydrogel skin sensor for long-term electrophysiological monitoring. Reproduced with permission [203]. Copyright 2024, AAAS. (D) A breathable, biodegradable, antibacterial, and self-powered electronic skin based on all-nanofiber triboelectric nanogenerators. Reproduced with permission [204]. Copyright 2024, AAAS.

water loss and free skin respiration. This enables thin-film devices to adhere to skin for over a week without restricting natural motion, causing irritation, or accelerating performance degradation.

One of the design strategies for breathable interfaces in e-skin is the construction of airflow channels. The micro-pillar array inspired by geckos not only endows e-skin with strong adhesion but also provides breathable channels for its air permeability [163, 201]. Kim et al. [201] have adopted the same strategy, using micro-channels inspired by tree frogs to enhance breathability (Figure 10A). The regular hexagonal epithelial cells and the network of microchannels on the tree frog skin enable efficient gas exchange and liquid drainage under both dry and wet conditions. The biomimetically designed microchannels not only improve the adhesive stability of the patch on dynamic skin surfaces but also achieve directional liquid drainage through structural optimization, thereby effectively preventing adhesion failure caused by sweat accumulation.

In addition to the method of directly constructing air channels at the contact interface, an ultrathin breathable design is central to achieving invisible adhesion and long-term stability in e-skin. Over the past few years, nanoporous, fibrous, and grid structures have emerged as representative solutions for ultra-thin and breathable designs. For instance, Chen et al. [202] proposed a biologically inspired armor design strategy, integrating nanoporous flash graphene components into a polypropylene melt-blown non-woven fabric framework to prepare skin electrodes with high interfacial stability and breathability (Figure 10B). This not only achieves low surface resistance but also ensures high breathability. The 10-micron-thick polyurethane nanomesh-reinforced breathable hydrogel sensor developed by Zhang et al. [203] realizes a robust thin structure through nanomesh reinforcement (Figure 10C), which not only significantly improves skin compliance but also allows rapid gas diffusion, effectively ensuring breathability and solving skin problems caused by insufficient breathability of traditional e-skin. Simultaneously achieving mechanical robustness, this approach constructs an ultrathin yet porous gel network. This innovation exemplifies how, through microstructural modulation, ionic hydrogels can retain their electrical advantages while attaining superior mechanical, breathable, and long-term stable performance. Similarly, the e-skin based on all-nanofiber triboelectric nanogenerators designed by Peng et al. [204] forms multiple inter-fiber capillary channels by constructing a multi-layer interlaced nanofiber network and hierarchical pore structure (Figure 10D), which not only provides a high specific surface area for contact electrification and pressure sensing but also greatly enhances breathability.

4 | Beyond-Skin Functional Structural Design

Current e-skin has made significant strides in mimicking biological skin, with most of the latter's core functionalities now effectively replicated [205]. It can serve as a reliable mechanical barrier against external impacts and contaminants; meanwhile, it can achieve multimodal sensing of pressure, temperature, and humidity; furthermore, it can dynamically adapt to the stretching or bending of human tissues; these characteristics enable it to basically cover the essential performance of natural biological skin. However, two key factors drive the need to develop beyond-skin functionality: on one hand, biological skin itself has inherent limitations; on the other hand, emerging application scenarios demand capabilities that go beyond biological skin's natural scope. Structural design plays a pivotal role in bridging this gap and enabling super-skin functionality: for example, to surpass biological skin's poor environmental interference resistance and adapt to complex outdoor application scenarios, an e-skin with a gradient hydrophobic-conductive structure has been proposed. This gradient structural design ensures that the e-skin maintains stable electrical conductivity and pressure sensing performance even in high-humidity environments [206].

4.1 | Enhanced Biodegradability Design

The design for enhancing biodegradability in e-skin represents an inevitable choice to drive technological innovation. Traditional e-skin predominantly employs non-degradable materials such as polyimide and silicone rubber, which take decades to naturally decompose after disposal. Among the over 50 million tons of electronic waste generated globally each year, these materials release heavy metals and organic pollutants that continuously damage the ecological chain [56, 96, 207]. In the process of optimizing the biodegradability of e-skin, structural design is no longer a mere auxiliary supplement to materials, but instead serves as a key hub playing a pivotal role. Its fundamental purpose lies in overcoming the inherent limitations of materials through innovations in structural design, thereby meeting the requirements of a broader range of application scenarios.

In the biodegradable design of e-skin, the selection of appropriate materials is indispensable, as the chosen materials should possess biocompatibility, conformability, non-toxicity, and biodegradability, while also exhibiting enhanced mechanical, electrical, and optical properties. Flexibility, stretchability, and specific mechanical properties that enable minimal stress and close connection with biological skin are key aspects of biodegradable e-skin [57, 58, 96, 208–211]. The cost and abundance of renewable and biodegradable natural materials, including animal-derived polymers (such as collagen [212], silk [213–215], and chitosan [216]) and plant-based polysaccharides (such as cellulose [217–219], alginate, and dextran), are also important considerations. However, single materials or simple composite structures struggle to balance rapid degradation and long-term functionality. For example, pure polylactic acid (PLA) is biodegradable but has low mechanical strength, and its degradation rate is affected by crystallinity (semi-crystalline PLA requires 6–12 months to degrade in soil), failing to meet short-term monitoring needs [220]. In contrast, the dense structure of traditional e-skin (such as polyimide substrates) ensures mechanical performance, but enzymes and water molecules have difficulty penetrating, resulting in a degradation cycle of up to several years.

Structural design enables directional regulation of the contact area between materials and biological fluids, penetration pathways, and stress distribution, thereby controlling degradation. For instance, Luo et al. [221] employed digital light processing 3D printing technology to fabricate Conductive ionoelastomers skin with biomimetic microstructures (Figure 11A). This structure emulates the interlocking microstructure between the epidermis and dermis of human skin, forming interlocking microdome structures. It increases the specific surface area of the material, providing more action sites for degradation media, thereby potentially accelerating the degradation process. Meanwhile, the design of the microstructure enables the material to decompose more uniformly during degradation, avoiding the problem of uneven degradation of bulk materials. Experiments show that the porosity is increased to more than 80%, the contact area between enzymes and the material is tripled, and the degradation time is shortened to 7 days. In addition, the design of multi-layer composite structures can achieve gradient control of degradation rates. For example, Peng et al. [204] combined PLGA (slow degradation, 6 months) and PVA (fast degradation, 1 week), and adjusted the thickness ratio to enable the e-skin to gradually degrade within 3 months, matching the fracture healing cycle. Xu et al. [65] developed a degradable piezoresistive skin sensor based on a sandwich structure (Figure 11B). The sandwich structure facilitates overall degradation: when the outer KC layer is stirred in 90°C hot water, it first swells and then dissolves, exposing the internal SPP sensing elements to disperse in water. Without this layered structure, material degradation may be hindered, as interactions between different materials can affect the contact between degradation media and the materials. The sandwich structure, however, provides a pathway for degradation media to more easily access each layer of material.

4.2 | Special Environment Adaptability Design

It is well-known that robots and machines are required to operate in harsh environmental conditions, including complex scenarios with wide temperature ranges and corrosive chemicals. However, current e-skin cannot withstand such complex environments. Therefore, the lack of broad environmental adaptability has become a major obstacle restricting the application of e-skin in extreme environments, such as polar low temperatures, desert high temperatures, deep-sea high pressure, and industrial corrosion. These environmental challenges impose strict requirements on the material stability, interfacial adhesion, signal reliability, and long-term durability of e-skin, thus limiting the research community from making more breakthroughs [222–225].

Harsh environments, especially high-temperature or high-pressure conditions, are among the most common scenarios in practical applications. For example, real-time physiological monitoring of firefighters during fire suppression can be

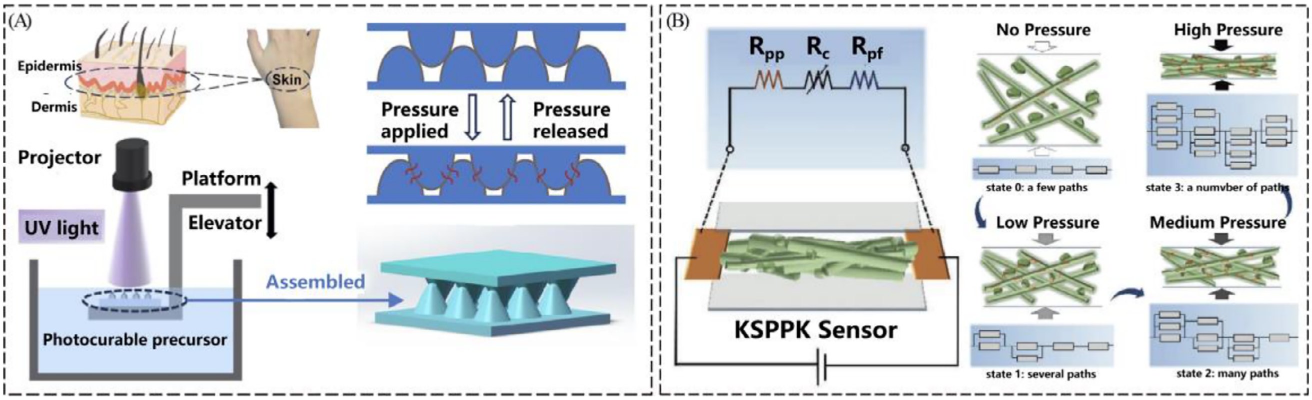

FIGURE 11 | Enhanced biodegradability design. (A) 3D printing of self-healing and degradable conductive ionoelastomers for customized flexible sensors. Reproduced with permission [221]. Copyright 2024, Elsevier. (B) Breathable, degradable piezoresistive skin sensor based on a sandwich structure for high-performance pressure detection. Reproduced with permission [65]. Copyright 2021, Wiley-VCH.

used to assess critical situations and assist in making optimal decisions based on collected data (such as heart rate, respiratory rate, body temperature, and electrocardiogram) to protect firefighters [226, 227]. Therefore, Xu et al. [228] prepared a composite aerogel pressure sensor (Figure 12A), which exhibits excellent high-temperature resistance due to its unique honeycomb structure. The honeycomb structure itself endows the material with unique performance advantages. On the one hand, its concave–convex and porous structure gives the fabric good air permeability. In high-temperature environments, this characteristic helps the e-skin dissipate heat, avoiding performance degradation or component damage caused by heat accumulation. Inspired by the Sahara silver ant, an insect that maintains multisensory perception in high-temperature environments [229], Liu et al. [59] developed an extreme environment-adaptive multimodal triboelectric sensor (Figure 12B). Based on triboelectric nanogenerator technology, an asymmetric structure capable of independently outputting dual signals was designed, which can achieve adaptive tactile sensing under extreme high temperatures, exceeding the human tactile limit. It can work in an environment up to 200°C, far exceeding the high-temperature sensing limit of 60°C for human skin, providing new ideas for the design of e-skin in special environments.

To enable e-skin to function normally in humid or even underwater environments, waterproofing is typically achieved as an additional feature during experiments by using waterproof materials to seal internal circuits. This isolates the device's interior from the humid environment, allowing the sensor to operate underwater [230–233]. Zou et al. [234] proposed a biomimetic stretchable nanogenerator (Figure 12C), which imitates the ionic channel structure of electric eel cell membranes. It can harvest mechanical energy from human underwater movements, outputting an open-circuit voltage exceeding 10 V underwater. The device exhibits excellent flexibility, stretchability, and resistance to tensile fatigue.

In addition to high-temperature or high-pressure environments, e-skin may also be affected by other extreme environments in practical applications, such as acid-base environments. The three-layer sandwich woven e-skin (TSW e-skin) proposed by Tao et al. [235] constructs an environmentally adaptive structure (Figure 12D) through a core-filled packaging strategy, integrating ultra-high molecular weight polyethylene (UPE)/polyimide (PI) fibers with carbon fibers (CF). The multi-layer woven structure endows TSW e-skin with excellent mechanical toughness. The high elasticity of UPE fibers and the high strength of PI fibers form a complement through the weaving process, enabling the material to maintain structural integrity under mechanical stresses such as stretching, bending, and twisting. As the core layer, CF bundles not only provide conductivity but also enhance the tear resistance of the overall structure like a skeleton.

4.3 | Others

E-skin, as a key technology in the field of wearable devices, has always been a research hotspot for innovative and optimized functional designs. In addition to enhancing degradable and environmental resistance designs, remarkable progress has also been made in other functional designs of super-skin functionality, which are often closely linked to unique structural designs. These aim to achieve high performance, multifunctionality, and intelligence of e-skin in different scenarios.

Biological systems in nature, such as cephalopods [236] and chameleons [237, 238], possess the remarkable ability to rapidly perceive external stimuli and adapt their behaviors to complex environments, achieving changes in skin color or fluorescence through various micro/nanostructures, chromatophores, and muscle-controlled surface structures [60, 239, 240]. Inspired by the responsive color-changing properties of these biological skins, various e-skins that output electrical signals through visual feedback have been developed. Among them, chameleon-inspired structural color materials constructed by periodic micro/nanostructures exhibit unique advantages, such as high contrast, fast response, and excellent stability [241–245]. Inspired by this, Shang et al. [246] proposed a bionic structural color e-skin, which is composed of a structural color layer and a conductive double-network hydrogel layer (Figure 13A). The structural color layer forms an ordered colloidal crystal array by assembling monodisperse polystyrene nanoparticles, serving as the basis for generating structural colors. The ordered structure

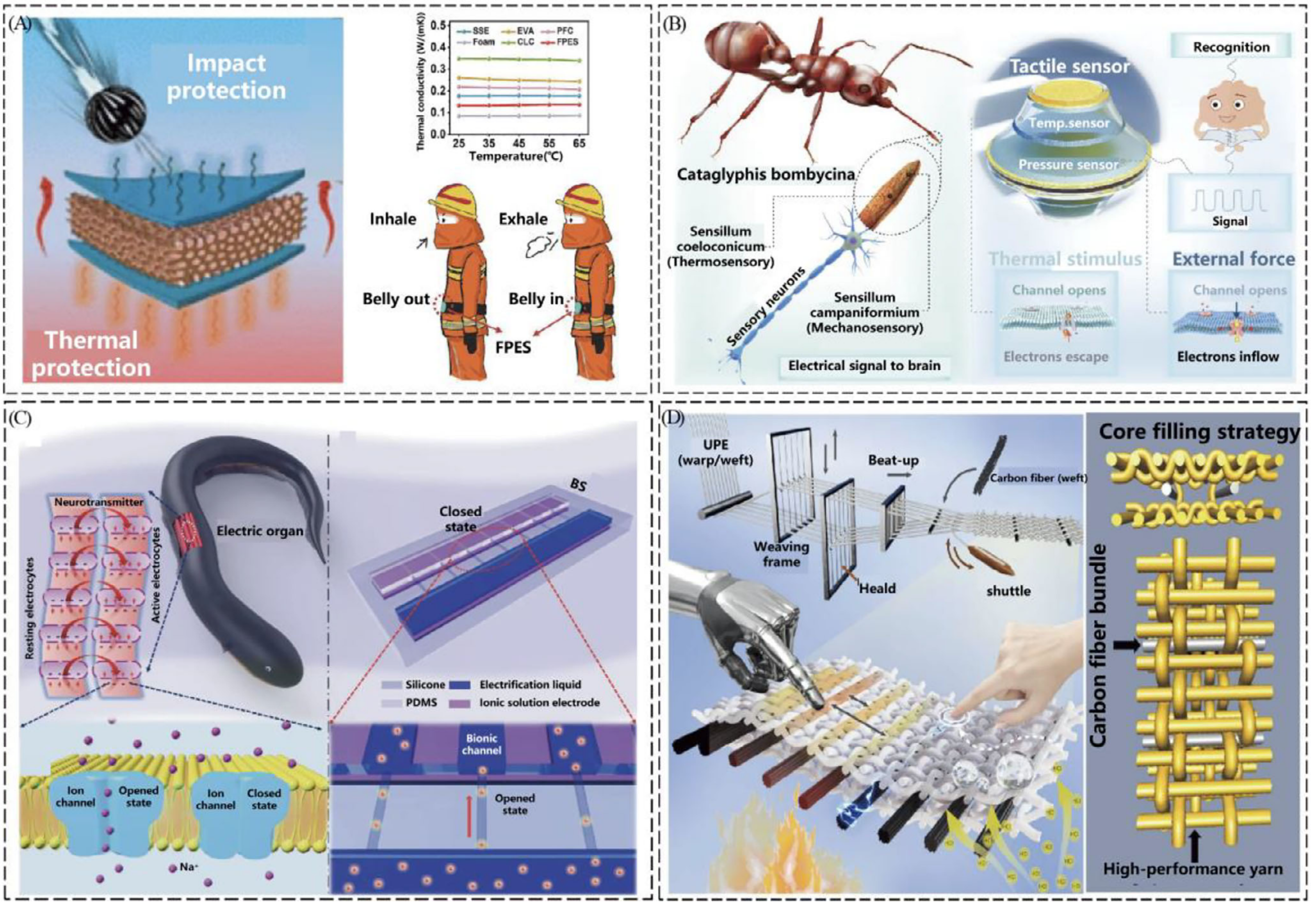

FIGURE 12 | Special environment adaptability design. (A) Flexible pressure sensors with high pressure sensitivity and low detection limit using a unique honeycomb-designed polyimide/reduced graphene oxide composite aerogel. Reproduced with permission [228]. Copyright 2021, Royal Society of Chemistry. (B) Triboelectric tactile sensor for pressure and temperature sensing in high-temperature applications. Reproduced with permission [59]. Copyright 2025, Springer Nature. (C) A bionic stretchable nanogenerator for underwater sensing and energy harvesting. Reproduced with permission [234]. Copyright 2019, Springer Nature. (D) Robust all-fabric e-skin with high-temperature and corrosion tolerance for self-powered tactile sensing. Reproduced with permission [235]. Copyright 2024, Elsevier.

scatters and interferes with light, enabling the e-skin to exhibit different colors under varying strains or pressures, providing a visual basis for optical sensing. The hydrogel is composed of a polyacrylamide/sodium alginate double-network and embedded with liquid metal particles. Ionic hydrogels serve not only as a highly conductive, stretchable sensing layer but also form a functionally complementary hetero-integrated system with the overlying structural-color optical layer. This bilayer structural design integrates the optical properties of the structural color layer with the electrical and mechanical properties of the conductive double-network hydrogel layer, endowing synergistic electro-optical sensing and excellent mechanical performance.

Similarly, inspired by the biosensing mechanisms of chameleons and spiders, Zhang et al. [247] designed a multilayered flexible optical/electrical skin, integrating structural color with microcrack conductive technology in a multilayer flexible device (Figure 13B). The multilayer structure integrates functions of sensing, visualization, conductivity, and encapsulation. The middle mechanical color-changing layer is composed of Fe_3O_4@C magnetic photonic crystal arrays embedded in a gelatin/PAM hydrogel. Under the induction of an external magnetic field, the nanoparticles self-assemble into an ordered array, with the center-to-center distance adjustable, corresponding to a reflection spectrum covering 435–680 nm (purple to deep red). When subjected to strain or pressure, deformation of the matrix causes changes in d, thus achieving color visualization mapping.

With the continuous development of humanoid robots and human–machine interfaces, the traditional five sensory perceptions can no longer meet the needs. Remote sensing provides a new way to unlock innovative dimensions of human perception and cognition. It realizes non-contact sensing and precise spatial positioning by amplifying human sensory organs. Biological systems provide a large number of demonstration templates, especially in the fields related to perception and tactile discrimination. Various animals have many charming abilities. Inspired by the ordered mechanoreceptors and electroreceptors on the beak of the platypus, Du et al. [248] designed a bionic multi-receptor skin (Figure 13C) with electro-mechanical bimodal sensing capabilities. They transformed the distributed receptor array of the platypus into a structured nanoparticle-doped and micro-nano pore array of artificial skin, realizing a synergistic response to electric field changes and mechanical stimuli. Through a hierarchical design, the two sensing modes do not interfere with each other. Electric field perception depends

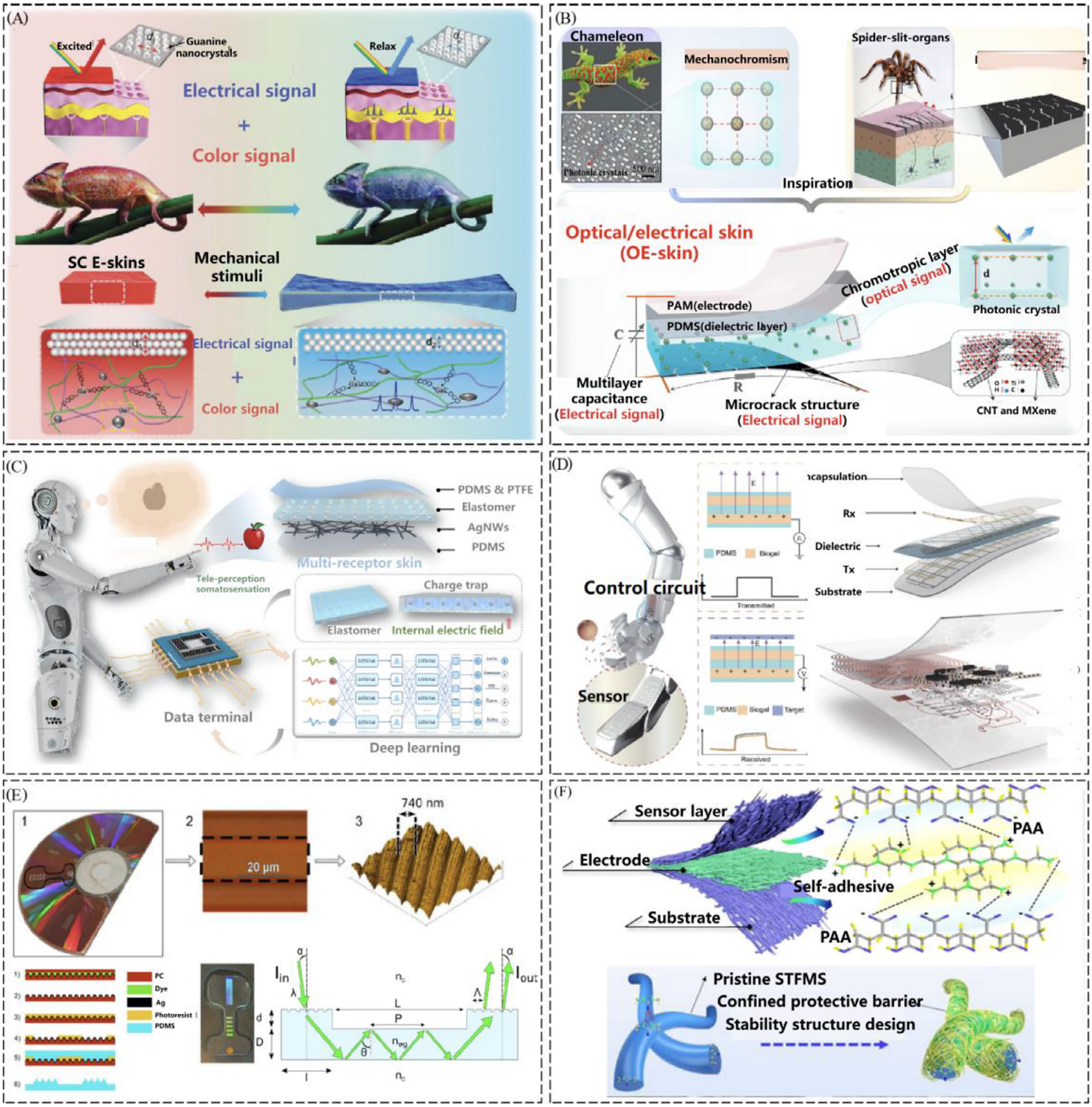

FIGURE 13 | Others design. (A) Bioinspired ultra-stretchable and highly sensitive structural color electronic skins. Reproduced with permission [246]. Copyright 2024, Wiley-VCH. (B) Mechanochromic optical/electrical skin for ultrasensitive dual-signal sensing. Reproduced with permission [247]. Copyright 2023, American Chemical Society. (C) Multi-receptor skin with highly sensitive tele-perception somatosensory. Reproduced with permission [248]. Copyright 2024, AAAS. (D) Mormyroidea-inspired electronic skin for active non-contact three-dimensional tracking and sensing. Reproduced with permission [249]. Copyright 2024, Springer Nature. (E) Design, fabrication, and characterisation of multi-parameter optical sensors dedicated to e-skin applications. Reproduced with permission [250]. Copyright 2022, MDPI. (F) Superstable and intrinsically self-healing fibrous membrane with bionic confined protective structure for breathable electronic skin. Reproduced with permission [251]. Copyright 2022, Wiley-VCH.

on the polarization of nanoparticles, while tactile perception relies on the triboelectric effect, breaking through the limitations of sensitivity and detection range of traditional non-contact sensors. In addition, inspired by Mormyroidea using electric fields to actively detect prey and perceive the surrounding environment through their skin, Zhou et al. [249] designed a non-contact 3D sensing wireless transparent e-skin (Figure 13D). They transformed the electric organ-electroreceptor system of Mormyroidea into a layered structure of transmitting electrodes and receiving electrodes of e-skin, achieving electric field distortion detection and spatial positioning of target objects.

Human skin is constrained by the physical boundaries of biological systems, unable to quantify light intensity at different wavelengths or distinguish differences across the ultraviolet-infrared spectrum, and incapable of maintaining stable light perception in extreme environments. In contrast, flexible photosensitive e-skin can identify light of varying wavelengths (e.g., ultraviolet and infrared) and even sense subtle changes in light intensity—photosensitive capabilities absent in human skin. Thus, Fliegans et al. [250] proposed an artificial skin (Figure 13E) based on PDMS waveguides and grating coupling structures. By leveraging the diffraction and propagation properties of light, this design enables conversion between light perception and mechanical signals, overcoming the dimensional limitations of light sensing in biological skin. Additionally, biological skin has a limited self-healing speed, while e-skin can achieve rapid self-repair through structural and material design. Zhu et al. [251] designed a super-stable self-healing fibrous membrane with biomimetic confinement protection structures (Figure 13F), successfully developing an intrinsically self-healing and thermochromic fibrous membrane with a core–shell structure. The core layer is composed of polydimethylsiloxane-based polyurea. The shell is a polyelectrolyte protective layer constructed via layer-by-layer self-assembly technology, composed of polyacrylic acid and branched polyethyleneimine. This composite coating forms a confinement protection barrier through electrostatic interactions, effectively preventing excessive fusion between core-layer fibers and maintaining the porous morphology of the membrane structure.

Beyond the representative beyond-skin functionalities discussed above, emerging structural designs are increasingly exploring system-level integration, adaptive reconfigurability, and fabrication-aware structures. These structures not only expand the functional boundaries of e-skin but also provide new pathways for mitigating signal crosstalk and mechanical mismatch in multimodal systems. Importantly, the realization of such structural designs is closely linked to advanced manufacturing strategies, including patterning and micro-/nanofabrication techniques, transfer and heterogeneous integration strategies, multilayer and embedded integration manufacturing, as well as related advanced packaging processes. These methods collectively facilitate the implementation of beyond-skin functionalities while achieving outstanding performance.

5 | Challenge and Prospects

E-skin, a frontier technology mimicking human skin's sensing functions, relies heavily on sophisticated structural design for its core performances (sensing sensitivity, range, stability, comfort, and multifunctional integration). Despite significant progress in recent years, the practical application of e-skin remains constrained by multiple challenges. In particular, the increasing structural complexity required for high performance often conflicts with the feasibility and scalability of manufacturing strategies. At the same time, it is still not an easy task to efficiently integrate advanced materials into structures that are manufacturable. These challenges underscore the imperative for structural design in e-skin development, emphasizing the need to synergistically combine structural design with advanced material innovations and manufacturing processes. This section focuses on the structural design of e-skin, examining the current major challenges and future prospects (Figure 14):

1. The comfort-encapsulation conflict in long-term wear: for long-term wearable applications, e-skin must exhibit gas permeability and moisture vapor transmission comparable to human skin, representing a core objective for skin-like functional mimicry and performance enhancement. However, this will lead to a practical application issue, that is, the high-integration packaging enhances the signal sensing performance and mechanical durability of the device, but to some extent, it reduces the comfort during long-term wearing (such as breathability and moisture permeability). This conflict highlights the limitations of conventional encapsulation structures in replicating the physiological functions of natural skin.
2. Flexibility and adaptability in complex dynamic environments: in dynamic application scenarios involving repeated stretching, bending, and twisting, existing e-skin designs often suffer from interface delamination and performance degradation, significantly limiting their long-term reliability. From a structural design perspective, these failures highlight the limitations of current conformal interface designs, where insufficient strain-adaptive structural design undermines mechanical durability. Furthermore, practical wearable applications demand intimate and stable contact with complex curved and non-uniform surfaces, imposing stringent requirements on conformability.
3. Multifunctional integration and signal crosstalk: the design of beyond-skin functional structures aims to extend e-skin toward multimodal sensing and system-level functionalities that surpass natural skin. However, the simultaneous detection of multiple physical stimuli, such as pressure, temperature, and humidity, inevitably introduces signal crosstalk, which arises from mechanical coupling and overlapping deformation responses in high-density structure.

Specifically, e-skin structure design still has much space for advancement, which is summarized as follows:

a. To address the long-standing conflict between comfort and packaging in long-term wearable electronic skin applications, future development will focus on advanced packaging strategies based on process-achievable structural designs to achieve performance breakthroughs. Specifically, the structural design serves as the core, while the manufacturing process provides the supporting foundation. On one hand, the combination of porous structures, layer-like structures inspired by the epidermis, and selective permeable micro-nano structures enables efficient gas and water transmission at the structural level, as well as effective environmental isolation of key functional areas. On the other hand, the successful realization of these complex structures is crucially dependent on their compatibility with advanced manufacturing technologies, including soft lithography, micro-molding, laser cutting, and heterogeneous integration, to ensure signal fidelity, mechanical robustness, and manufacturing scalability [185]. Through the collaborative innovation of structural design and manufacturing paths, the electronic skin system is expected to achieve reliable packaging and signal stability without compromising the comfort of long-term wear.

b. Intelligent and self-adaptive structural systems address this challenge by incorporating geometry-driven and structure adaptability, allowing the structure itself to actively

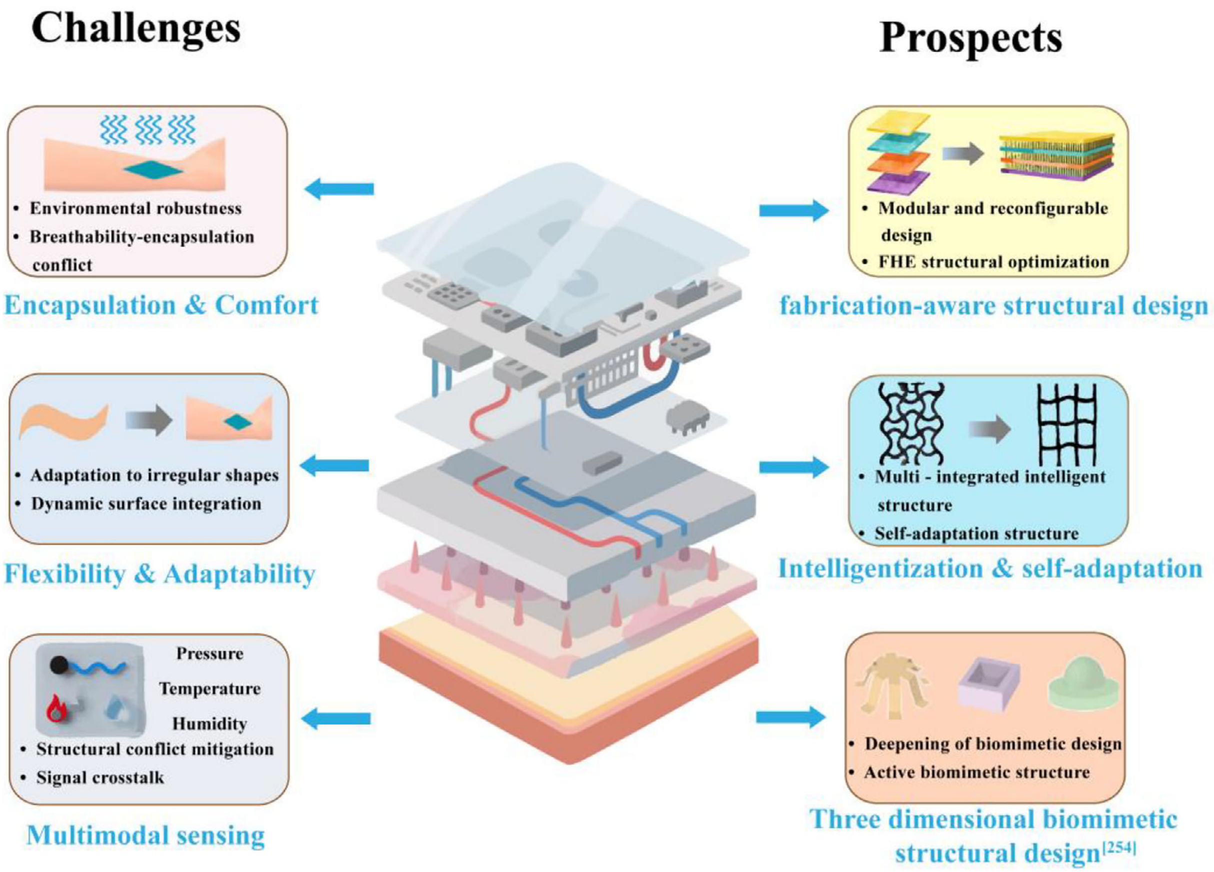

FIGURE 14 | Challenges and prospects of e-skin structure design. Reproduced with permission [254]. Copyright 2025, American Chemical Society.

accommodate and distribute mechanical deformation. For instance, kirigami and origami-inspired structures, gradient stiffness layers, and hierarchical microstructures enable controlled deformation pathways and strain redistribution, thereby mitigating stress concentration under complex loading conditions [166]. Such structures can dynamically adjust their effective mechanical response in response to external stimuli, maintaining stable sensing performance under repeated and multidirectional deformation.

c. The three-dimensional biomimetic structure provides a breakthrough solution to the core challenges of multifunctional integration and signal crosstalk in electronic skin [252]. For instance, inspired by the hierarchical organization of biological skin, advanced three-dimensional structures achieve functional division that is difficult to achieve with traditional two-dimensional designs by spatially separating different functional units along the vertical direction [253, 254]. Specifically, the pressure-sensitive element can be placed in the mechanical active layer close to the skin interface, while the temperature and humidity sensing units are integrated in the mechanical neutral area. Through this vertical layered structure, the stimulus-induced deformation is limited to the designated structural layer, thereby achieving sensing of complex stimulus signals and solving the problem of signal interference in the coupling signal analysis.

In practical applications, effective crosstalk suppression requires the integration of these 3D structural decoupling strategies with fabrication-compatible approaches, such as multilayer stacking, transfer printing, and additive manufacturing. By spatially separating different sensing units and constructing mechanically isolated multilayer structures, stimulus-induced responses can be confined to their corresponding sensing elements, thereby improving the sensing accuracy and operational stability of multimodal e-skin systems.

6 | Conclusion

Structural design is fundamental to advancing e-skin technology, playing a critical role in overcoming challenges associated with functional simulation and performance enhancement. The three types of design strategies reviewed in this paper have achieved remarkable results: The skin-like perception regulation and performance enhancement design realizes multimodal sensing of force, temperature, and humidity through 3D structures, while optimizing sensitivity, detection range, and response speed; The conformal interface stabilization design balances the conformability, stability, and breathability between e-skin and biological skin by means of bioinspired adhesive layers, serpentine wiring functional layers, and porous protective layers; The beyond-skin functionality design endows e-skin with capabilities surpassing biological skin based on structures like gradient porous and multi-layer composites.

Despite significant advancements, key structural design challenges remain for practical implementation. These include ensuring robust adaptability and reliability in complex dynamic environments, mitigating signal crosstalk in tightly integrated multifunctional systems, and resolving the inherent conflict between encapsulating/protecting components and achieving skin-like breathability for long-term wearability. Future research should prioritize the development of intelligent, self-adaptive structural systems integrating sensing, actuation, and computation; the refinement of complex 3D biomimetic structures to efficiently organize multifunctional elements; and the advancement of heterogeneous integration and modular design principles to achieve seamless fusion of diverse rigid/flexible components and reconfigurable functionality. In the future, potentially combining AI-aided structural optimization with heterogeneous integration technology will promote the practical application of e-skin in fields like medical health and human–computer interaction, providing key support for the development of flexible electronics technology.

Author Contributions

Y.W. wrote this paper. J.X. and L.C. participated in the discussion of the paper content and assisted in writing some chapters. Z.L. and Y.D. participated as supervisors in the writing and revision of the paper. All authors have read and approved the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The authors have nothing to report.

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