SmartSys

WILEY

有科出版 YOUKE PUBLISHING

REVIEW ARTICLE OPEN ACCESS

Skin-Integrated Wearable Electronics: A Dual-Interface Perspective

Fuying Dong[1] | Chi Han[1] | Sheling T. Cai[1,2] | Ju-Hyuck Lee[3] | Simiao Niu[1]

[1]Department of Biomedical Engineering, Rutgers University, Piscataway, New Jersey, USA | [2]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA | [3]Department of Energy Science and Engineering, Daegu Gyeongbuk Institute of Science and Technology (DGIST), Daegu, Republic of Korea

Correspondence: Simiao Niu (simiao.niu@rutgers.edu)

Received: 21 November 2025 | **Revised:** 11 December 2025 | **Accepted:** 11 December 2025

Keywords: epidermal electronics | sensor–receiver interface | sensor-skin interface | wearable electronics | wireless communication

ABSTRACT

Skin-integrated wearable electronics enable continuous, medical-grade monitoring and therapy in daily life, but must balance conflicting needs related to mechanics, power, and communication. This review uses a dual-interface approach that separates the sensor–receiver interface, which handles wireless data and energy transfer, from the sensor–skin interface, where physiological signals are converted and mechanical and biological integration occur. We first reviewed wireless connections designed for skin electronics, focusing on Bluetooth Low Energy (BLE), Radio Frequency Identification (RFID)/Near-Field Communication (NFC) systems, and hybrid systems. Next, we examine sensor–skin interfaces ranging from mediated contact layers such as hydrogels for wearable ultrasound and soft conductive electrodes, to skin-conformal direct-contact methods based on structural mechanics, and ultrathin epidermal devices. Finally, we discuss cross-interface coupling, emphasizing how antenna layouts, power budgets, and body-induced RF effects limit mechanical design, and how skin mechanics influence link reliability. We conclude by exploring opportunities in battery-free and energy-autonomous systems, body-coupled communication, and integration with artificial intelligence (AI)-enabled digital health, positioning future electronic skins as soft, networked platforms that are comfortable and reliable.

1 | Introduction

Wearable electronics that intimately integrate with the human body are driving a paradigm shift in personalized healthcare. Skin-integrated devices are increasingly deployed for continuous cardiovascular and metabolic monitoring, motion and gait analysis, rehabilitation tracking, and human–computer interaction in virtual or augmented reality environments [1, 2]. Across these scenarios, they are expected to capture physiological signals over extended periods while remaining unobtrusive, comfortable, and compatible with natural daily activities. At the same time, they must also support reliable wireless communication to external receivers and, in many cases, operate under stringent power budgets or even in battery-free modes. However, incorporating components such as batteries, displays, or high-performance processors can add bulk and stiffness, undermining the thin, flexible, and lightweight characteristics essential for skin-compatible wearables and making it difficult to simultaneously satisfy requirements on mechanics, energy, and communication. To reconcile this conflict, many systems offload tasks such as data processing, storage, and user interaction to external platforms, such as smartphones or nearby receivers, via wireless communication links, allowing the on-body module to remain minimal, soft, and discreet. This architectural decoupling allows the on-body module to remain minimal, soft, and discreet. Fundamentally, such designs hinge on two critical interfaces: (1) the sensor–receiver Interface, which governs wireless transmission and, in some cases, energy exchange between the wearable sensor and external receiver; and (2) the sensor–skin interface, which forms the physical and functional contact with the body where biosignals are transduced. This article reviews recent advances across both interfaces, organized within this dual-interface framework. We highlight representative technologies and application examples in healthcare, motion monitoring, and human–computer interaction, identify key engineering challenges in jointly optimizing mechanics, power, and communication, and discuss how their convergence can enable seamless, long-term health monitoring and therapeutic interventions.

2 | Sensor–Receiver Interface

The sensor–receiver interface governs how a skin-mounted device communicates with external receivers (e.g., smartphones, base stations) and how it may harvest energy. The ideal link supports stable, long-range data transmission and adequate power delivery, while also minimizing on-body hardware, such as batteries. Several wireless technologies have been adopted in skin electronics, each with unique design considerations and trade-offs.

2.1 | Bluetooth Low Energy (BLE)

BLE has emerged as a foundational wireless communication protocol in wearable electronics, prized for its robust data transfer capabilities, extended range, and energy efficiency. Recent versions, including Bluetooth 5.0 and later, support multi-device connections and enable reliable transmission over distances ranging from tens to hundreds of meters [3–6]. These features make BLE especially suitable for continuous, body-distributed health monitoring with sensor networks to accomplish goals such as thermal and fever mapping, full-body movement analysis, and multilocation respiratory sounds tracking [7–9] (Figure 1A–C).

One of BLE's key advantages is its ability to maintain persistent, automatic synchronization with external receivers—typically smartphones—without requiring user intervention or repeated pairing over a relatively larger range. Additionally, because of pairing, BLE offers privacy. This makes it particularly attractive for home-based, multi-signal health monitoring scenarios where continuous sensing, automatic data processing, real-time alerts, and cloud storage are essential. Ma et al. [10] Present a wearable textile wristband for real-time, wireless monitoring of potassium in sweat (Figure 1D). Similarly, a smart maternal health patch used BLE to stream Electrocardiogram (ECG) and Photoplethysmogram (PPG) data from postpartum women to the cloud, supporting remote clinical monitoring and early detection of complications [11] (Figure 1F). The Rogers group has also implemented BLE in multiple neonatal monitoring systems to noninvasively track vital signs, cardiopulmonary sounds, and full-body movement in infants across hospital and home settings [8, 9] (Figure 1E). Kwon et al. [12] Leveraged these features in a BLE-enabled epidermal patch designed for sleep apnea screening, which wirelessly transmitted Electroencephalography (EEG) and Electrooculography (EOG) data to a mobile device for real-time sleep-stage classification (Figure 1G).

BLE modules typically require dedicated power sources, such as batteries or supercapacitors, which increase device thickness and stiffness and add maintenance requirements. Even with state-of-the-art low-power chipsets and aggressive duty cycling, typical BLE links still operate in the sub-milliwatt to milliwatt power range during active transmission, making them nontrivial loads for fully battery-free or ultrathin energy-harvesting systems. Although enabling long-range, continuous monitoring, the battery increases in size and weight, limiting skin conformity and lifespan. Advances in ultrathin batteries, flexible storage, and wireless power are addressing these issues [13–15]. BLE remains key for wearables due to its ecosystem, connectivity, and efficiency. The future involves integrating BLE into skin-like, soft platforms that do not require bulky batteries, necessitating co-engineering of electronics, materials, and power.

2.2 | Radio Frequency Identification (RFID) and Near-Field Communication (NFC)

RFID encompasses a broad range of technologies where tags communicate with readers via modulated radio waves. Tags can be passive, harvesting energy entirely from the reader's field, or active/battery-assisted, in which an onboard battery enhances communication range and supports more power-intensive sensing or processing functions. NFC is a specific subset of high-frequency (13.56 MHz) RFID that operates over very short distances through inductive (near-field) coupling, with standardized protocols supported directly by smartphones and many consumer devices. Besides NFC, low-frequency RFID (typically 125–134 kHz) also relies on inductive coupling and provides good penetration through lossy media, but the relatively large coil antennas and discrete components required make it less suitable for thin, skin-conformal wearable formats, so it is used less often in epidermal devices. In contrast, far-field Ultra-High Frequency (UHF) RFID, usually operating between 860 and 960 MHz, can read tags from several meters using backscatter, but often requires dedicated readers, and on-body UHF antennas are affected by tissue detuning and absorption [16]; therefore, the necessary reader setup can make deployment in daily environments more complex [17].

Beyond these basic frequency-dependent trade-offs, thin, patterned radio frequency (RF) antennas can be fabricated from soft, biocompatible materials that add negligible bending stiffness, they can be integrated on highly compliant tissues—including ocular surfaces in smart contact lenses [18]—without significantly perturbing native mechanics, and are therefore widely adopted in wearable and skin electronics [19] (Figure 2A). In such systems, RFID/NFC links usually play three tightly coupled roles: the RF field provides an energy source for battery-free operation; the tag integrates a sensing element and load-modulates signal, which is backscattered to serve as the data channel to external readers. The balance among these three roles largely determines the form factor, range, and usability of the system, and guides design choices

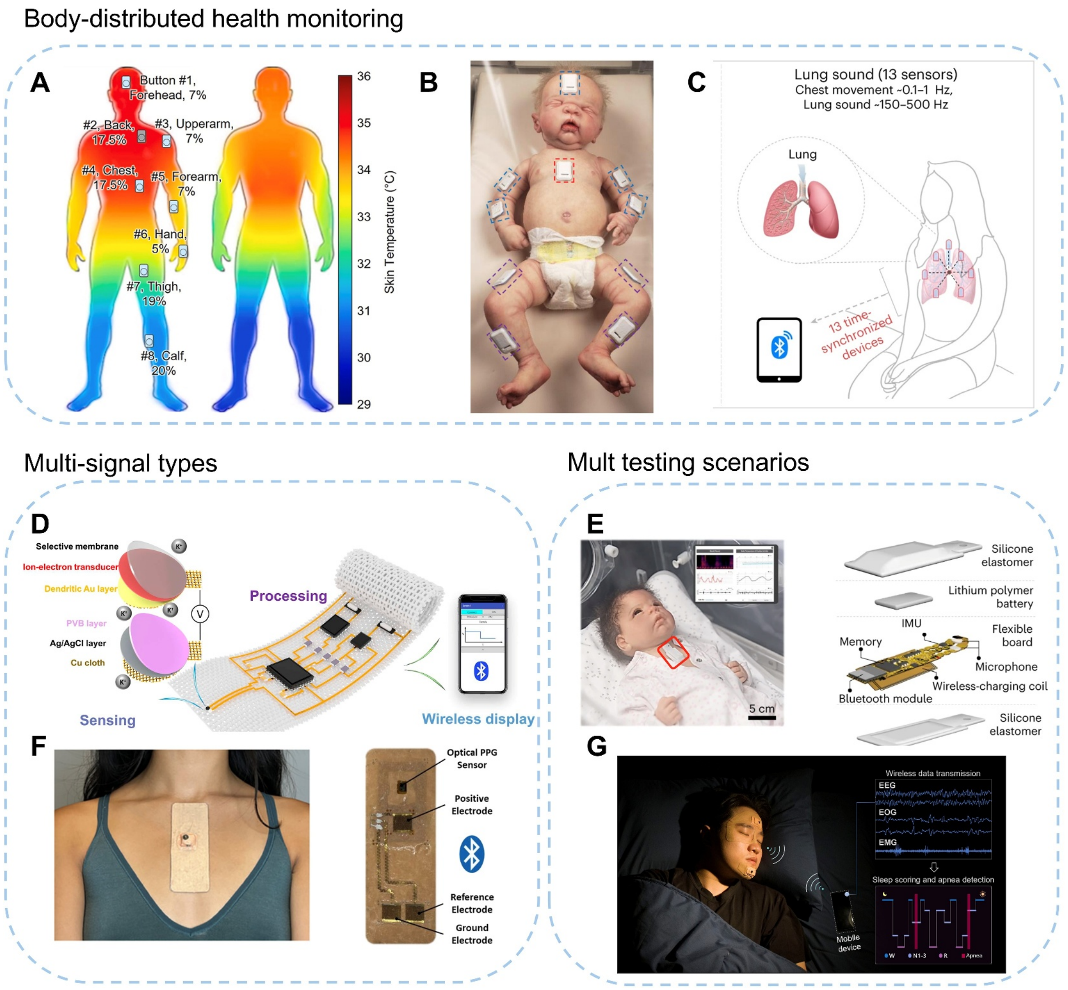

FIGURE 1 | Representative BLE-enabled wearable health monitoring system. (A) Miniaturized wireless sensor for mapping thermoregulatory responses on the skin. Reproduced with permission from Ref. [7]. Copyright 2023, Elsevier. (B) Skin-integrated sensor network for quantifying full-body movement behaviors and vital signs in infants. Reproduced with permission from Ref. [8]. Copyright 2021, The Author(s). (C) Wireless acousto-mechanical sensor patches for multilocation respiratory and cardiopulmonary sounds monitoring. Reproduced with permission from Ref. [9]. Copyright 2023, Springer Nature. (D) Monolithically integrated in-textile wristband for real-time, wireless sweat potassium monitoring. Reproduced with permission from Ref. [10]. Copyright 2023, The Author(s). (E) Broadband acousto-mechanical epidermal patch capable of detecting body motion and voice. Reproduced with permission from Ref. [9]. Copyright 2023, Springer Nature. (F) Cloud-integrated smart nanomembrane patch for continuous ECG and PPG monitoring in postpartum women. Reproduced with permission from Ref. [11]. Copyright 2024, The Author(s). (G) Soft at-home sleep monitoring patch that wirelessly records EEG and EOG for sleep-stage classification and sleep apnea assessment. Reproduced with permission from Ref. [12]. Copyright 2023, The Author(s).

such as antenna geometry, matching networks, and whether to introduce local energy storage or additional sensing circuitry.

First, the flexible RFID/NFC antenna can act as a sensor. Changes in geometry, strain, pressure, tissue proximity, or surrounding permittivity perturb the antenna's resonant frequency, quality factor, and backscattered amplitude. By tracking these RF signatures, one can infer mechanical or physiological variables without adding separate sensing elements. This strategy has been widely explored in textile RFID strain and compression sensors, where knitted or embroidered antennas on garments monitor motion, posture, or joint kinematics in a fully passive, battery-free manner [20, 24, 25] (Figure 2B). Such antenna-as-sensor designs are attractive for wearables because they minimize component count and can be seamlessly integrated into clothing, bandages, or soft substrates.

Second, RFID/NFC tags can harvest energy from the incident RF field. In NFC-based epidermal systems, inductive coupling between a powered reader coil and a thin, flexible sensor antenna generates an alternating current voltage that is rectified to supply the on-tag electronics. This mechanism has enabled fully battery-free, skin-like platforms for microfluidic sweat patches that perform on-demand biochemical analysis of lactate, pH, and glucose [21], full-body pressure and temperature mapping [22], and stretchable optoelectronic skins for cardiovascular monitoring and ultraviolet exposure assessment using NFC-driven LEDs and photodetectors [23] (Figure 2C–E). These examples illustrate how NFC's short-range, inductively powered architecture is well matched to applications where the user or caregiver can bring a smartphone or dedicated reader into close proximity for intermittent readout.

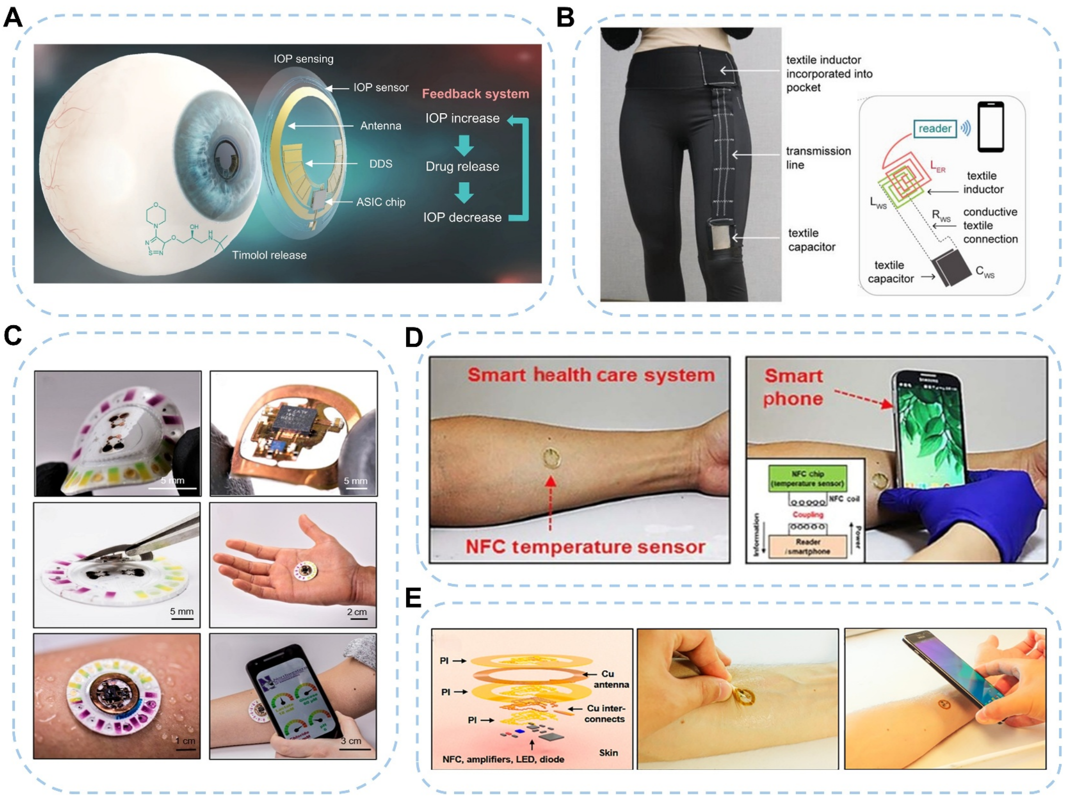

FIGURE 2 | NFC/RFID-enabled wearable platforms for sensing and power/data transfer. (A) Wireless theranostic smart contact lens for monitoring and controlling intraocular pressure in glaucoma. Reproduced with permission from Ref. [18]. Copyright 2022, The Author(s). (B) Passive and wireless all-textile wearable sensor system for motion monitoring. Reproduced with permission from Ref. [20]. Copyright 2023, The Author(s). (C) Battery-free, skin-interfaced microfluidic/electronic platform for simultaneous electrochemical, colorimetric, and volumetric sweat analysis. Reproduced with permission from Ref. [21]. Copyright 2023, The Author(s). (D) Battery-free, wireless sensor array for full-body pressure and temperature mapping. Reproduced with permission from Ref. [22]. Copyright 2018, AAAS. (E) Stretchable, battery-free optoelectronic skin for wireless optical characterization of the skin using NFC-powered LEDs and photodetectors. Reproduced with permission from Ref. [23]. Copyright 2016, The Author(s).

Third, the RFID/NFC link acts as the communication channel [26]. In fully passive tags, sensor outputs modulate the load on the antenna, which then influences the amplitude, phase, or frequency of the backscattered signal received by the reader. For NFC, the data rates are sufficient for low-bandwidth physiological variables and configuration commands, and the ability to use consumer smartphones as readers greatly simplifies system deployment. In the NFC-based skin platforms mentioned earlier, pressure, temperature, sweat analyte levels, or optical biometrics are encoded into the backscattered or load-modulated signal and read through tap-to-scan interactions with a phone or simple handheld reader. Conversely, UHF RFID-based wearable systems can target many tags over a meter-scale distance [27], but they usually require specialized readers and must contend with body absorption and orientation sensitivity.

Most skin-like RFID/NFC wearables have been designed as fully passive, battery-free devices to maximize softness, thinness, and long-term safety. Eliminating the battery removes a major source of mechanical stiffness and potential failure, and it also avoids concerns about leakage or overheating. At the same time, some tags deliberately incorporate small batteries. These battery-assisted designs can support higher instantaneous power, longer read range, local signal preprocessing, and buffered data logging between interrogations. The trade-off is an increase in thickness, reduced mechanical compliance, finite battery lifetime, and the need for recharging or replacement. Choosing between purely passive NFC/RFID and battery-assisted architectures is therefore application dependent: passive tags are ideal for lightweight, disposable, or spot-check sensing, whereas battery-assisted tags are better suited for high-duty-cycle sensing, on-board computation, or more continuous connectivity.

Across these RFID/NFC architectures, antenna layout and power budget must be co-optimized with mechanics and skin coupling. Planar coils and meandered traces are typically routed along low-strain directions or placed near neutral mechanical planes so that bending and stretching do not fracture conductors or strongly detune the resonance, whereas worst-case on-body detuning and posture-dependent shadowing are explicitly accounted for in the link budget. Full-wave electromagnetic simulations on realistic body phantoms, coupled electro–mechanical modeling, and the use of soft decoupling layers or ground planes, together with antenna diversity and adaptive transmit-power control, are increasingly used to mitigate human-induced RF loading and maintain stable read range and link reliability during daily motion [28–30].

2.3 | Hybrid RFID–BLE System

To merge the benefits of passive RFID with BLE's connectivity and ecosystem support, hybrid architectures have been proposed [31]. These systems feature chip-free, battery-free tags on the skin, however a separate reader module—often integrated into clothing or accessories—collects signals and transmits data via a standard radio link. In such setups, the on-skin tags are optimized for stretchability, conformability, and passive operation, while the reader manages tasks that are more difficult on soft, ultrathin substrates, such as high-power transmission, complex modulation, and multi-sensor coordination.

An example is the BodyNET concept, where stretchable, skin-conforming RF sensor stickers wirelessly connect to flexible readout circuits on clothes [32] (Figure 3A). The on-skin tags are chip-free and battery-free, acting as passive sensors for signals such as respiration, pulse, and body movement. The reader aggregates these data and transmits them wirelessly to external devices for storage and analysis. By physically separating the soft, skin-mounted sensors from the more rigid, power-demanding communication hardware, systems such as BodyNet maintain high comfort and mechanical robustness while enabling reliable, long-range data transfer through standard radios such as BLE.

Major challenges include co-designing multiple RF links (tag-to-reader and reader-to-gateway), managing power and heat in the reader, ensuring robustness during clothing deformation and daily activities, and controlling costs. Despite these challenges, hybrid RFID–BLE architectures present a promising path toward scalable body-area networks that combine the advantages of battery-free, stretchable sensors with seamless connectivity to consumer devices and cloud systems.

2.4 | Other Wireless Communication Technologies for Sensor–Receiver Interfaces

Beyond BLE and RFID/NFC-based systems, other wireless technologies have also been adapted as sensor–receiver interfaces in wearable electronics [35]. For short-range applications, Zigbee and related low-power mesh protocols (e.g., Thread) offer moderate data rates with multi-hop networking, enabling coverage across a room or building with numerous nodes and offering benefits for body sensor networks [36, 37]; however, they typically require dedicated gateways and have a smaller consumer ecosystem compared to BLE. As a further-range method, Wi-Fi offers high data rates and seamless integration with existing network infrastructure, making it attractive for applications that require continuous streaming of large datasets (e.g., high-density EEG [38] or ultrasound signal acquisition [33] [Figure 3B]), but its comparatively high power consumption and rigid radio modules limit suitability for thin, battery-constrained skins [39]. Low-power wide-area network (LPWAN) technologies such as Long Range (LoRa)/Long Range Wide Area Network (LoRaWAN), Narrowband Internet of Things (NB-IoT), and Long-Term Evolution for Machines (LTE-M) extend communication ranges to kilometers at the expense of lower data rates, making them suitable for sparse physiological measurements or environmental/context sensing in remote monitoring scenarios, especially when wearables are used outdoors and away from a receiver [34] (Figure 3C). Their dependence on operator infrastructure or dedicated gateways and relatively bulky radio front-ends currently limits their use in ultrathin, skin-like devices, but they are promising for long-range, low-duty-cycle health monitoring. Overall, these additional protocols occupy distinct niches in terms of range, data rate, power consumption, and ecosystem support, and are typically used when applications demand capabilities (e.g., high bandwidth or kilometer-scale coverage) that go beyond what BLE or RFID/NFC alone can provide.

In practice, these wireless options occupy different regions of the range, data rate, and power space, and therefore suit various wearable applications. BLE offers meter-scale range and moderate data rates while leveraging the smartphone ecosystem, making it attractive for frequent, moderate-volume streaming of signals such as ECG, PPG, and motion in home-monitoring scenarios. RFID/NFC links, on the other hand, provide very low power operation and can be implemented as fully battery-free tags, with centimeter- to meter-scale read ranges and relatively low data rates, making them better suited for intermittent, on-demand readouts of slowly changing variables such as sweat biomarkers, tissue pressure distributions, or hydration levels. High-throughput radios such as Wi-Fi enable continuous transmission of large data streams (e.g., high-density EEG or ultrasound imaging), but at the cost of increased power consumption and bulkier, more rigid radio modules, which are difficult to integrate into ultrathin, skin-like form factors. LPWAN technologies trade off data rate for kilometer-scale coverage and multi-day or multi-week operation, making them suitable for sparse vital-sign or context logging in outdoor or resource-limited environments where fixed receivers are unavailable. Choosing the right sensor–receiver technology depends on factors such as payload size and duty cycle, acceptable latency, whether a smartphone or local gateway can act as the receiver, and whether the on-skin node can remain battery-free or needs to support a rechargeable power source. These trade-offs can be further clarified by summarizing representative protocols and applications in Table 1.

3 | Sensor–Skin Interface

Equally vital to a successful wearable is the sensor–skin interface: how the device physically contacts the body to obtain signals or interact, and how it maintains that contact through various movements and conditions. A high-quality skin interface maximizes signal fidelity (electrical, thermal, mechanical, or chemical) and minimizes irritation or discomfort. Two broad design strategies have emerged: mediated contact, where an intermediate layer or structure aids the coupling between sensor and skin (often to improve signal or comfort), and intrinsic contact, where the device itself is made mechanically compliant and skin-like so that it can interface directly without needing additional coupling materials. In practice, many advanced wearables use a combination of both strategies. Below, we discuss representative approaches under each category. A summary of representative sensor–skin coupling strategies and

FIGURE 3 | Hybrid and other wireless communication technologies. (A) Wireless body-area sensor network based on stretchable passive RF tags and a BLE-enabled reader module. Reproduced from our previous work. [32]. Copyright 2019, Springer Nature. (B) Fully integrated wearable ultrasound system that uses wireless phased arrays on the skin and Wi-Fi for high-bandwidth deep-tissue monitoring in freely moving subjects. Reproduced with permission from Ref. [33]. Copyright 2023, Springer Nature. (C) Biosymbiotic platform for chronic, long-range monitoring of biosignals in limited-resource settings using low-power wide-area network connectivity. Reproduced with permission from Ref. [34]. Copyright 2023, The Author(s).

their typical trade-offs in signal quality, wear time, and comfort is also provided in Table 2.

3.1 | Adhesive-Mediated Contact Interfaces

Mediated interfaces utilize gels, coatings, adhesives, or other interstitial layers to improve contact between a device and the skin. The goals include lowering interfacial impedance (for bioelectric sensors), enhancing acoustic or ionic coupling, accommodating movement to prevent slippage, and even enabling functions such as drug delivery or skin protection. For long-term wear, these interfacial materials must also be biocompatible and hypoallergenic, with adhesive formulations that minimize disruption of the stratum corneum and irritation during repeated application and removal.

3.1.1 | Acoustic Coupling—Stretchable Ultrasound Patch

In conventional medical ultrasound, a liquid gel is applied to the skin to eliminate air gaps and facilitate the transmission of high-frequency sound into the body. For wearable ultrasound

TABLE 1 | Representative wireless protocols for sensor–receiver interfaces in skin-integrated electronics and their typical operating regimes.

Protocol	Frequency band	Typical range	Typical data rate	Power consumption	Ecosystem/typical application
Bluetooth low energy (BLE)	2.4 GHz ISM	< 100 m	Up to ~1 Mbps	Milliwatt-level active power; low average power with aggressive duty cycling	Strong smartphone and tablet ecosystem; continuous streaming of ECG, PPG, motion, and multimodal vital signs in home and clinical monitoring
NFC	13.56 MHz	Very short (centimeter level, ~0–0.1 m)	Up to 424 kbps	Fully passive or microwatt-level harvested power; battery-free operation	Smartphone-readable epidermal patches and microfluidic sweat systems for on-demand biochemical sensing, pressure mapping, and temperature monitoring
UHF RFID (far-field backscatter)	860–960 MHz	Meter-scale (~1–5 m) with dedicated reader	Tens to hundreds of kbps	Passive tags without batteries; reader-side power dominates	Battery-free textile or sticker tags for motion, pressure, and temperature sensing in body-area networks with dedicated readers
Zigbee/Thread (mesh protocols)	Typically 2.4 GHz (also sub-GHz variants)	Room-scale coverage via multi-hop networking	Up to 250 kbps at 2.4 GHz	Low-power radios with modest duty cycle; requires always-on or periodically active mesh nodes	Dense body or room sensor networks where multi-hop connectivity is needed, and a smartphone alone is not sufficient
Wi-Fi	2.4 GHz/5 GHz ISM	Tens of meters within the existing Wi-Fi infrastructure	Multi-Mbps to hundreds of Mbps	Tens to hundreds of milliwatts; continuous connection can significantly increase power and thermal load	High-throughput streaming of large datasets, such as high-density EEG or wearable ultrasound imaging, where thicker, more rigid modules are acceptable
LPWAN (LoRa, NB-IoT, LTE-M)	Sub-GHz ISM or licensed cellular bands	Up to kilometers (outdoors, line-of-sight)	Approximately 0.3–50 kbps	Tens of milliwatts during brief transmission bursts; very low average power with long sleep intervals	Sparse logging of vital signs, activity, or environmental context in remote and resource-limited settings, where fixed gateways or cellular base stations act as the receiver

devices, a built-in soft coupling layer is essential. Researchers have developed stretchable ultrasonic arrays embedded in soft polymers that can continuously image internal organs when attached to the skin, monitor central blood pressure waveforms from major arteries, and provide real-time tracking of deep tissue vessels and cardiac dynamics [58, 59] (Figure 4A,B). In a 2022 study, Wang et al. [60] introduced a bioadhesive ultrasound device that can be worn for over 48 h, enabling continuous imaging of organs during daily activities. They designed a hybrid hydrogel–elastomer layer that adheres strongly to skin and maintains contact even during movement, eliminating the need for gel reapplication, a key step toward long-term ultrasound monitoring (Figure 4C). This demonstrates how an engineered intermediary, like a viscoelastic layer, can transform traditionally cumbersome ultrasound imaging into a wearable modality. Challenges include ensuring skin adhesion, biocompatibility, and hydration; ideally, the material should be breathable and non-irritating. Ongoing improvements focus on providing strong skin adhesion and painless removal, using durable, skin-safe adhesives or switchable hydrogels.

3.1.2 | Conductive Electrodes for Bioelectric Signal Acquisition

The evolution of electrodes for physiological signal acquisition—whether ECG, EMG (Electromyography), or EEG—has been largely driven by two primary goals: reducing skin–electrode contact impedance to improve signal fidelity and maintaining stable attachment during motion to minimize artifacts. Early systems relied on hard, dry metal electrodes connected via wires; although simple, their poor ionic coupling with skin produced noisy signals and made them highly

TABLE 2 | Representative sensor–skin coupling strategies and their trade-offs in signal quality, wear time, and comfort.

Interface type	Typical signals/ modalities	Coupling quality/ contact impedance	Wear time and comfort	Breathability/ irritation risk	Representative examples
Conventional Ag/ AgCl gel electrodes	ECG, EMG, EEG	Low impedance and high signal quality initially; impedance increases as gel dries	Hours to one day; gel drying and skin maceration limit long-term use	Limited breathability; potential irritation or allergy due to gel and strong adhesives	Traditional clinical monitoring electrodes used in hospital ECG/EMG/ EEG systems
Soft conductive hydrogels/porous sponge electrodes	ECG, EMG, EOG, impedance sensing	Very low and stable impedance; mimics wet-gel contact	Multi-day wear with sustained signal quality; soft mechanics reduce pressure points and motion artifacts	Generally good breathability for porous designs; long-term hydration must be controlled to avoid maceration	Porous PDMS–hydrogel sponge electrodes and freeze-resistant hydrogels used for long-term ECG/ EMG recording [40–43]
Medical adhesive tapes	ECG/EMG electrodes, temperature patches, strain and pressure sensors	Moderate to good coupling;	Hours to days; comfort governed by adhesive strength, stiffness, and skin sensitivity	Breathability and irritation risk vary widely	Commercial wearable patches
Microneedle-based or minimally invasive interfaces	Interstitial fluid biomarkers, impedance, localized stimulation, and drug delivery	Very strong ionic or electrical coupling with minimal motion artifacts once inserted	Hours to possibly days; local discomfort or safety constraints can limit duration and application sites	Localized disruption of the skin barrier requires careful biocompatibility, sterilization, and infection control	Microneedle-based smart bandages [44]
Skin-conformal structural interfaces (stretchable circuits on elastomers)	Distributed strain, pressure, temperature, multimodal sensor arrays	Good mechanical conformity and stable contact over large areas; electrical contact quality depends on local electrode design	Designed for day-long or multi-day wear, low bending stiffness and softness improve perceived comfort	Elastomeric substrates may limit breathability	Serpentine and island–bridge layouts enabling stretchable circuits [45–52]
Ultrathin epidermal electronic tattoos (5–10 µm)	ECG, EMG, EEG, temperature, strain, optical, and multimodal sensing	Excellent conformal contact with minimal interfacial layers; high-fidelity signals with low motion artifacts	Highly comfortable and almost imperceptible; wear time limited by mechanical durability and sweat	Very low added stiffness; breathability governed by the base film and any adhesive layers used	Electronic tattoo systems that laminate directly onto the skin surface [53–57]

sensitive to motion [61, 62]. Traditional gel electrodes addressed these issues by incorporating a salt-infused, water-rich gel that hydrates the stratum corneum and provides a low-impedance ionic bridge between skin and electrode, enabling cleaner biopotential recordings. However, liquid gels dry out over time, can irritate skin, and are not well-suited for long-term wear or repeated attachment [63, 64].

Advances in soft materials have led to hydrogels and other compliant ionic conductors that replicate the electrical performance of wet gels while offering superior comfort, mechanical conformity, and long-wear stability. These hydrogels—composed predominantly of water with polymer networks engineered for stretchability and biocompatibility—maintain low impedance and contact even under deformation, capable of collecting multiple bioelectric signals with high signal quality [40, 41]. For instance, freeze-resistant hydrogel electrodes capable of reliable ECG monitoring down to −40°C maintain both softness and conductivity where conventional gels stiffen or fail [42] (Figure 5A,B). Beyond hydrogels, porous, moisture-retaining interfaces—such as polydimethylsiloxane (PDMS) infused with conductive polymers—can sustain a "wet-like" ionic interface for days by capturing sweat or saline within pores, producing stable, high-signal-to-noise ECG and EMG recordings during daily motion [41, 43] (Figure 5C,D). More recently, spider cuticular pad–inspired viscoelastic gelatin–chitosan hydrogel dampers

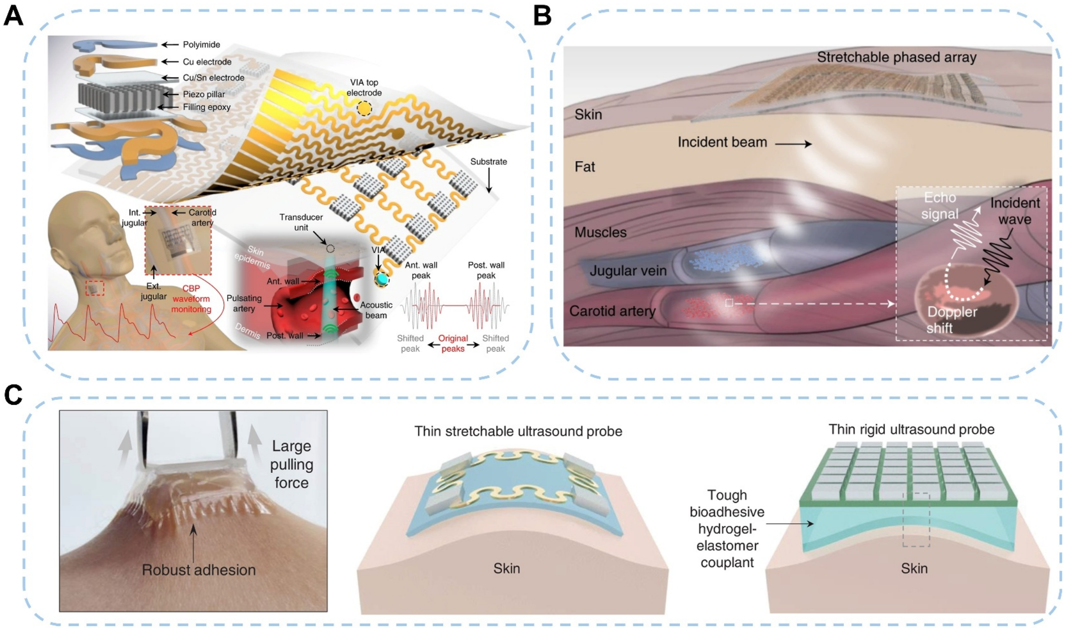

FIGURE 4 | Wearable ultrasound devices enabled by engineered acoustic coupling layers. (A) Conformal ultrasonic device for noninvasive monitoring of central blood pressure waveforms at the body surface. Reproduced with permission from Ref. [59]. Copyright 2018, Springer Nature. (B) Stretchable ultrasonic phased-array system for continuous monitoring of deep-tissue hemodynamics. Reproduced with permission from Ref. [58]. Copyright 2021, Springer Nature. (C) Bioadhesive ultrasound patch for long-term continuous imaging of diverse organs during daily life activities. Reproduced with permission from Ref. [60]. Copyright 2022, AAAS.

have been introduced as a material-level bandpass filter: their frequency-dependent transition from rubbery to glassy state dampens low-frequency mechanical noise (tens of hertz) while transmitting higher-frequency biosignals [65] (Figure 5E). Laminating this hydrogel between skin and sensors suppresses motion artifacts from breathing, walking, or tapping in real time, enabling nearly noise–free recordings of neck vibration, ECG, and EEG without digital filtering, with damping tunable via temperature. These developments show how ionically conductive, mechanically compliant, and sometimes frequency-selective interfaces extend wet-electrode performance into long-term, skin-conformal wearables while filtering motion noise at the material level rather than through signal processing.

Beyond mechanical conformability and low impedance, interfaces for long-term electrophysiology must also address moisture management and skin breathability [66, 67]. Breathable, water-vapor-permeable adhesive matrices and porous hydrogel–elastomer composites enable transepidermal water loss and sweat evaporation, which helps prevent maceration, rash, and discomfort during multi-day use. Designing coupling layers with controlled water-vapor transmission rates and sweat-wicking microstructures is therefore essential to maintaining stable ionic conduction while preserving skin health under high-sweat conditions.

3.1.3 | Multifunctional Layers

Mediated Sensor–Skin interfaces have evolved from basic couplants into multifunctional, flexible layers combining sensing, actuation, and therapeutic delivery. In chronic wound care, "smart bandages" exemplify how integrating sensors and actuators enables closed-loop strategies. For example, Jiang et al. [68] developed a battery-free, wireless bandage with a hydrogel electrode for sensing and electrical stimulation. Changes in impedance and temperature detect early signs of infection, with data processed internally and used to adjust stimulation (Figure 6A). Other designs include Mostafalu et al.'s [69] pH and temperature sensors with a microheater and drug carriers, and Derakhshandeh et al.'s programmable bandage with microneedles and pumps delivering growth factors [44] (Figure 6B,C). Recently, the ABLE platform by Shi et al. [70] Embeds skin bacteria in a hydrogel on electronic mesh, enabling stable sensing of EMG, impedance, temperature, and humidity (Figure 6D). Bacteria modulate immune responses in psoriasis, whereas electrical stimulation manages safety and tissue environment, integrating monitoring and treatment.

Overall, these develop from simple couplants to multifunctional, bioactive layers that sense native physiology and actively intervene—using drugs, electrical stimulation, or living cells—at the interface, enabling robust closed-loop tissue control. In many of these systems, mechanically soft coupling layers also function as impedance-matching media, isolating rigid components from the skin. Low-modulus foams, hydrogels, or graded encapsulation stacks can redistribute stress and reduce motion-induced strain transfer, thereby minimizing motion artifacts in both electrical and optical readouts. Combining such engineered coupling layers with chemical sensing and therapeutic functions will be crucial for maintaining signal integrity during realistic, ambulatory use.

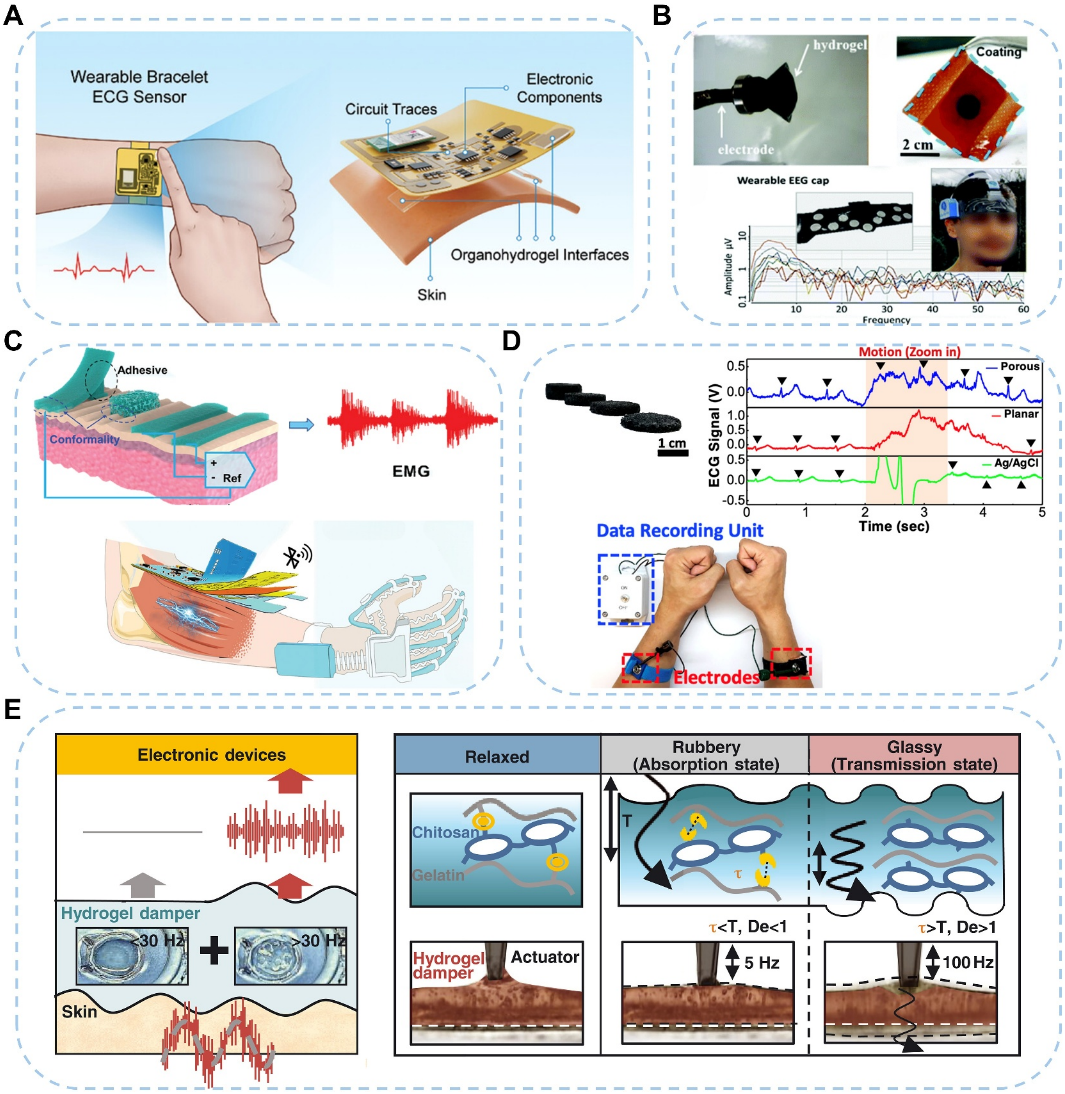

FIGURE 5 | Skin interfaces that enhance bioelectric signal quality and suppress motion artifacts. (A) Freeze-resistant, highly stretchable organohydrogel electrodes enabling reliable ECG monitoring at ultralow temperatures. Reproduced with permission from Ref. [42]. Copyright 2024, Wiley-VCH. (B) High-performance ionic-conducting hydrogel electrodes that maintain low impedance and support multimodal biopotential sensing (including EEG) with high signal quality. Reproduced with permission from Ref. [40]. Copyright 2022, Royal Society of Chemistry. (C) Hydrogel-based wearable EEG electrodes designed for medical applications and long-term recording. Reproduced with permission from Ref. [41]. Copyright 2024, Wiley-VCH. (D) Stretchable sponge electrodes with moisture-retaining porous structures for motion-artifact-tolerant, long-term electrophysiologic recordings (e.g., ECG/EMG). Reproduced with permission from Ref. [43]. Copyright 2022, The Author(s). (E) Spider cuticular pad–inspired viscoelastic gelatin–chitosan hydrogel dampers that act as material-level bandpass filters to selectively suppress low-frequency mechanical noise while transmitting physiological signals. Reproduced with permission from Ref. [65]. Copyright 2022, AAAS.

3.2 | Skin-Conformal Direct Contact Interfaces

Skin-conformal direct contact interfaces are designed to mimic the mechanical properties of skin, allowing the device to bond directly to the body without the need for significant intermediate couplants. These devices can stretch, bend, and twist along with the body, maintaining close contact even during movement. The key goal is to reduce the device's thickness and stiffness, ensuring it does not hinder natural skin mobility and can sometimes adhere through van der Waals forces alone. Achieving this involves innovations in materials—such as stretchable conductors, plastics, and gels—and in structural design, including serpentine interconnects and island–bridge configurations.

3.2.1 | Structural Engineering for Stretchability

One major approach is to construct devices from conventional electronic materials (which are often rigid or brittle) but in shapes and layouts that allow large deformations. Island–bridge configurations, filamentary serpentine traces, and buckled or wavy interconnects are used to mechanically decouple local strain in the soft substrate from strain in the hard chips, thus allowing silicon devices and packaged components to ride on an elastomeric matrix while maintaining low strain in the active regions [45–52] (Figure 7A–E). Building upon these principles, three-dimensional architectures that embed pre-designed stretchable circuits within elastomers further increase integration density and functional complexity compared with single-

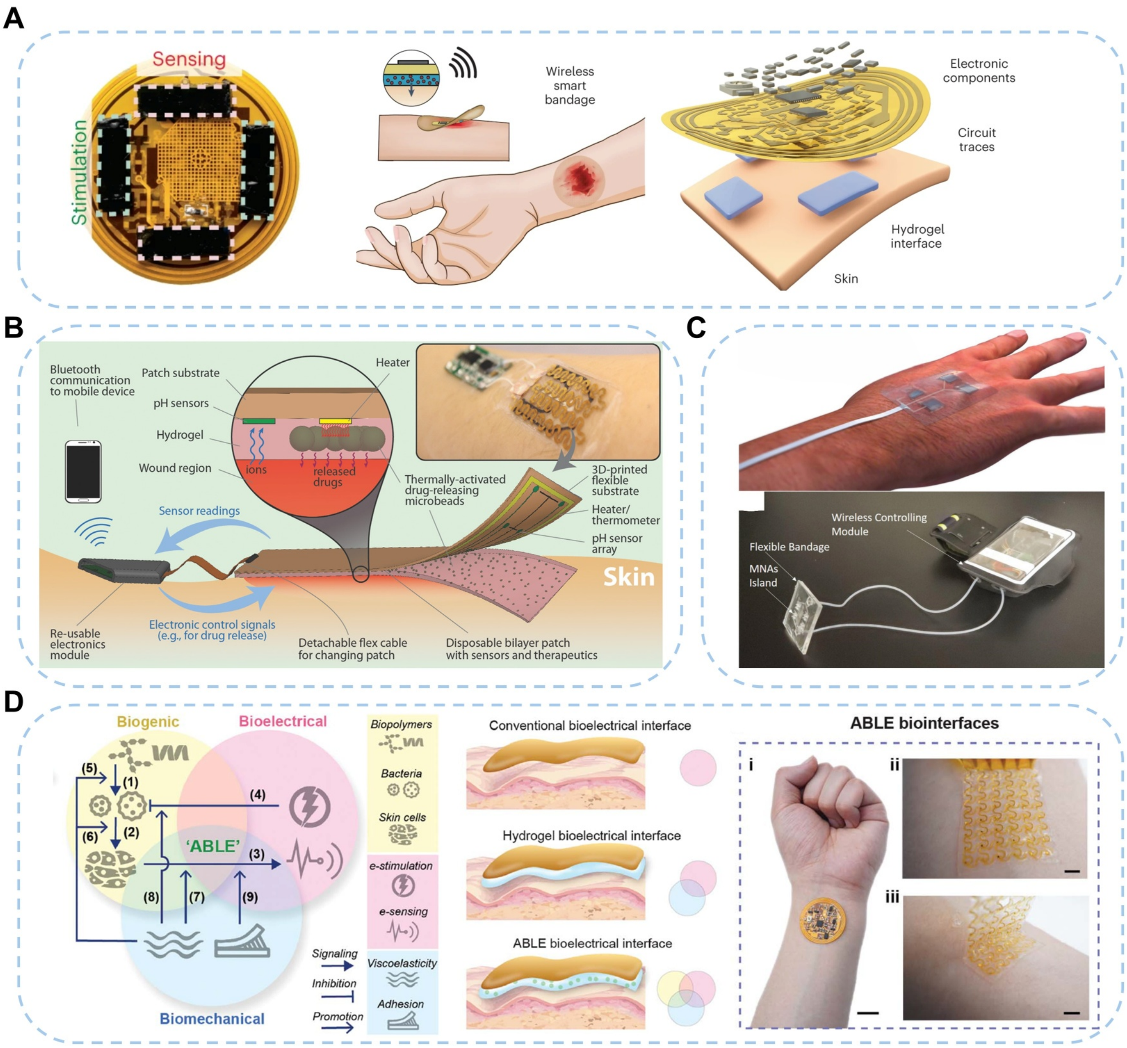

FIGURE 6 | Multifunctional mediated sensor–skin interfaces for closed-loop wound care and inflammation management. (A) Wireless, closed-loop smart bandage integrating impedance and temperature sensing with electrical stimulation for accelerated wound healing. Reproduced from our previous work. [68]. Copyright 2023, Springer Nature. (B) Smart bandage that combines pH and temperature sensing with a microheater and drug reservoirs for on-demand treatment of chronic wounds. Reproduced with permission from Ref. [69]. Copyright 2018, Wiley-VCH. (C) Wirelessly controlled smart bandage with 3D-printed miniaturized needle arrays for active and programmable drug delivery. Reproduced with permission from Ref. [44]. Copyright 2020, Wiley-VCH. (D) An active biointegrated living electronics platform that embeds engineered bacteria in a hydrogel on an electronic mesh for multimodal sensing and electrical stimulation to manage inflammation. Reproduced with permission from Ref. [70]. Copyright 2024, AAAS.

layer designs, while still enabling conformal contact over curved skin surfaces [71] (Figure 7F). Through such structural engineering schemes, large-area systems can follow skin motion and maintain stable contact quality or electrical performance at the skin–device interface, even though the underlying materials are not intrinsically stretchable. These structural strategies support recent epidermal demonstration platforms where large-area skin-conformal systems combine sensing, power, and wireless modules while maintaining strong contact and signal quality during daily activities.

3.2.2 | Emerging Stretchable Materials

Another strategy realizes skin-conformal direct contact by exploiting intrinsically stretchable electronic materials so that both the substrate and electronic components share tissue-like softness and stretchability. Stretchable conductors, dielectrics, and semiconductors have been assembled into large-area arrays of field-effect transistors, optoelectronic elements (LEDs, photodetectors), electronic skin, and energy-harvesting modules that can withstand substantial tensile strain while preserving electrical performance [72–82]. Representative examples include nanocomposite conductors formed by metal nanowires, carbon nanotubes, or graphene embedded in elastomeric matrices, "twining spring" fiber–nanowire architectures that maintain high conductivity up to several hundred percent strain, and elastic printed circuit boards based on liquid-metal particle networks that retain robust percolation pathways under extreme deformation [77, 83–86] (Figure 8A–D). In parallel, semiconducting polymer systems have been engineered to combine mixed electron–ion conduction with tissue-like mechanics. Recent work on immune-

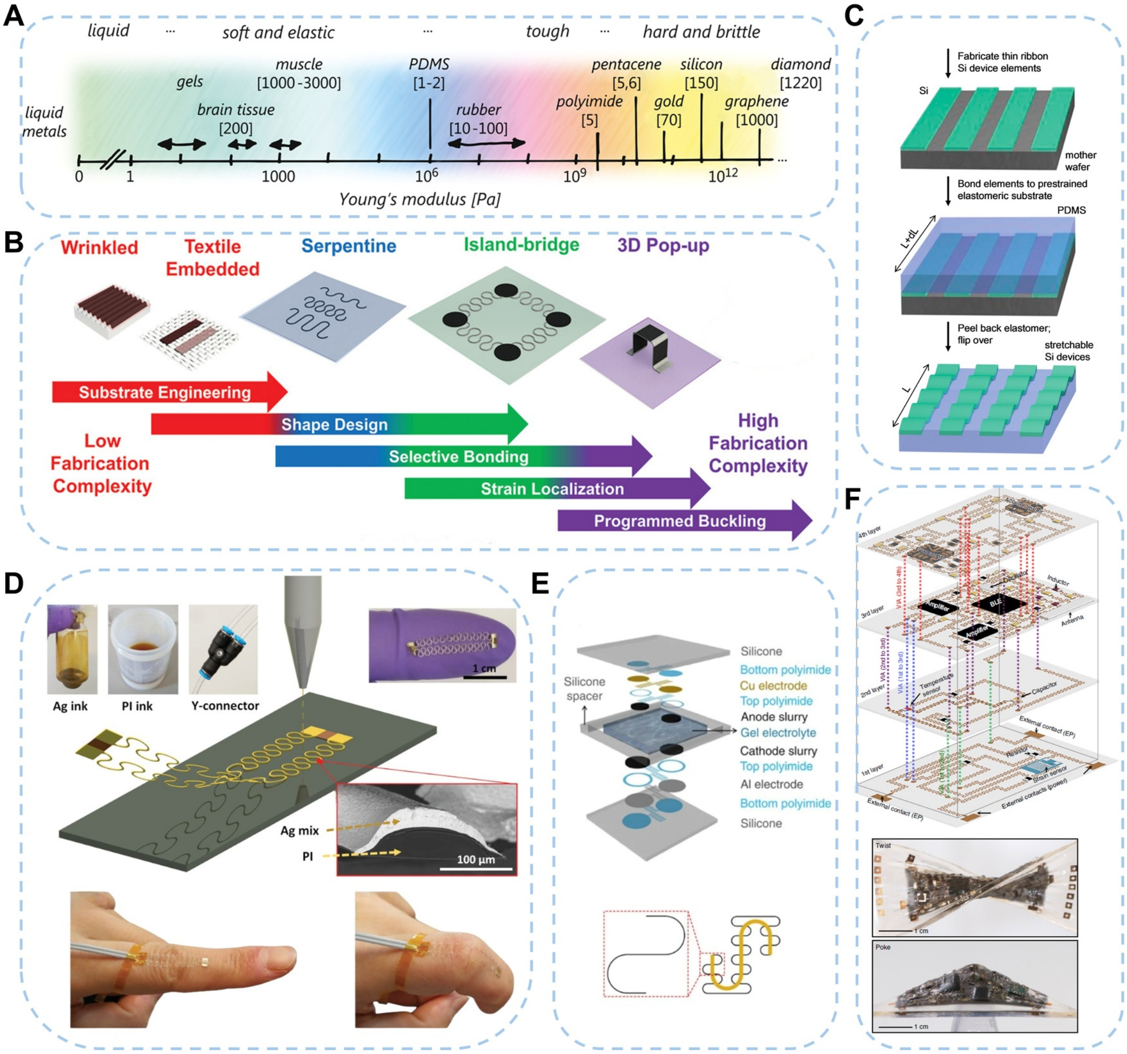

FIGURE 7 | Structural engineering strategies for stretchable electronic systems. (A) Stretchable electronic surfaces that integrate viscoelastic, plastic, and brittle materials spanning many orders of magnitude in Young's modulus. Reproduced with permission from Ref. [49]. Copyright 2012, Springer Nature. (B) Schematic illustration of innovative structural engineering concepts for printed, flexible, and stretchable electronics (e.g., serpentines, island–bridge layouts, buckled structures). Reproduced with permission from Ref. [48]. Copyright 2020, Wiley-VCH. (C) Process for building stretchable single-crystal silicon devices on elastomeric substrates to achieve high-performance stretchable electronics. Reproduced with permission from Ref. [47]. Copyright 2006, AAAS. (D) Fabrication scheme and on-finger bending demonstration of aerosol-jet printed freestanding stretchable conductive wires for sensing applications. Reproduced with permission from Ref. [46]. Copyright 2019, The Author(s). (E) Exploded-view layout of a stretchable battery system and self-similar serpentine interconnect geometries for mechanically robust, wireless-rechargeable stretchable power modules. Reproduced with permission from Ref. [45]. Copyright 2013, Springer Nature. (F) Design and characterization of a three-dimensional, four-layer integrated stretchable electronic system with high device density and mechanical compliance. Reproduced with permission from Ref. [71]. Copyright 2018, Springer Nature.

compatible semiconducting polymers shows that molecular design at the backbone and side-chain level can endow these stretchable components with additional non-electrical functionalities—such as reactive oxygen species scavenging and immunomodulation—while maintaining high charge-carrier mobility and softness, thereby simultaneously supporting signal transduction and active suppression of foreign-body responses at the biointerface [87] (Figure 8E). These material-level innovations are enabling skin-conformal circuits whose direct contact with tissue can improve both mechanical integration and long-term biological compatibility.

3.2.3 | Ultrathin Epidermal Electronics

Ultrathin and flexible electronic systems, often referred to as epidermal electronic devices, can conform to skin microtexture. These ultrathin electronics blend into the epidermis, with low bending stiffness, making them barely felt. The 2011 epidermal electronics by Kim et al. [53] exemplify this: a 50-µm-thick sensor and interconnects that measure ECG, EMG, and temperature, adhering via van der Waals forces without conventional adhesives and surviving daily motions (Figure 9A). Their elastic modulus and curvature matched skin, allowing

FIGURE 8 | Emerging intrinsically stretchable materials and elastic circuit platforms for skin-like electronics. (A) Intrinsically stretchable nanowire–polymer composite photodetector array on an elastomeric substrate, showing maintained conduction and photodetection under large strain. Reproduced with permission from Ref. [77]. Copyright 2013, Wiley-VCH. (B) Three-dimensional network morphology of nanoscale polymer semiconductor domains engineered to achieve highly stretchable semiconducting films with preserved charge transport. Reproduced with permission from Ref. [85]. Copyright 2017, AAAS. (C) Elastic multilayer printed circuit board based on a liquid metal particle network that maintains electrical connectivity under large deformation. Reproduced with permission from Ref. [86]. Copyright 2022, AAAS. (D) Monolithically integrated soft electronic skin patch showing the constituent components and its excellent conformability to human skin for neuromorphic sensorimotor functions. Reproduced with permission from Ref. [74]. Copyright 2023, AAAS. (E) Immune-compatible semiconducting polymer designs for bioelectronics that combine high charge-carrier mobility with suppressed foreign-body response and tissue-like mechanics. Reproduced with permission from Ref. [87]. Copyright 2025, Springer Nature.

movement with the body for comfort and quality signals. Subsequent devices use polymer nanosheets or tattoo decal techniques to make devices thinner (down to 5-10 μm), further enhancing invisibility [54–57] (Figure 9B). For example, Gogurla et al. [55] reported a carbon nanotube/silk nanofiber electronic tattoo with an overall membrane thickness of approximately 2 μm and a mass of about 0.4 mg for a 1.2 cm × 1.2 cm patch, which conforms to fingerprint-level skin texture while remaining mechanically robust under repeated bending, stretching, and twisting (Figure 9C). In that system, the ultrathin on-skin membrane is still connected to off-skin power and readout electronics, highlighting a common trade-off between on-skin imperceptibility and reliance on external modules.

In the context of our dual-interface framework, the skin–device contact in these tattoo-like systems still forms the sensor–skin interface; however, unlike mediated interfaces that rely on a distinct gel, tape, or hydrogel layer between the device and skin, the ultrathin electronic stack itself functions as a quasi-epidermal layer that laminates directly onto the skin surface, sometimes supported only by van der Waals forces or a nanometer-scale adhesive coating. As a result, adhesion energy, moisture transport, and surface chemistry remain critical design parameters, even though no thick "interface layer" exists. Careful engineering of these factors is necessary to sustain long-term contact and signal fidelity. This direct, skin-like interface enhances mechanical conformability, signal accuracy, and wearer comfort but also increases the devices'

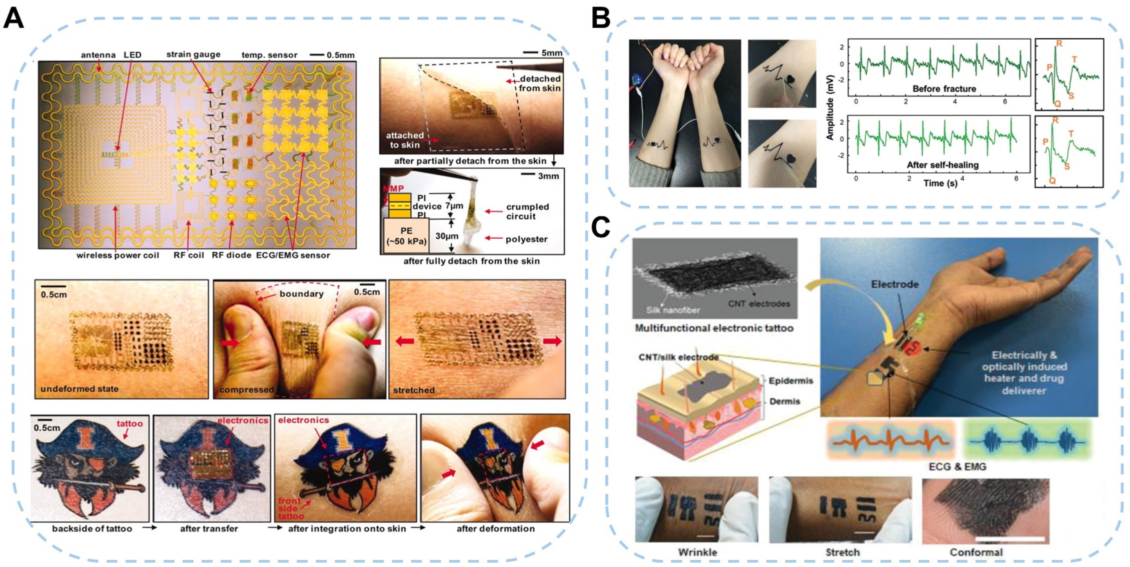

FIGURE 9 | Ultrathin epidermal electronic systems that mechanically blend with the skin. (A) Demonstration platform for multifunctional epidermal electronics with thickness, bending stiffness, and mechanics matched to the epidermis. Reproduced with permission from Ref. [53]. Copyright 2011, AAAS. (B) Self-healable multifunctional electronic tattoos based on silk and graphene that provide ultrathin, skin-like electronic interfaces. Reproduced with permission from Ref. [54]. Copyright 2019, Wiley-VCH. (C) Ultraflexible multifunctional electronic tattoo placed on the forearm, enabling on-skin diagnostic and therapeutic functions while conforming to skin microtexture. Reproduced with permission from Ref. [55]. Copyright 2021, Wiley-VCH.

vulnerability to mechanical damage and sweat-induced delamination if encapsulation and adhesion strategies are not properly optimized. In addition, they often need external modules. In most reported systems, the ultrathin on-skin membrane is tethered (by thin wires or short-range wireless links) to external modules that host the battery, higher-power RF radios, data-processing and storage circuitry, and sometimes user-interface components [28, 53–57, 88]. Fully integrating these elements into the same ultrathin, stretchable form factors is still constrained by the thickness, heat generation, and packaging requirements of energy storage and high-speed communication hardware.

The "thin is better" approach guides skin electronics development. Combining ultrathin designs with stretchable materials allows devices to be both compliant and functional. Even though very thin functional films can be prone to cracking or delamination under large tensile strain, highly compliant substrates can introduce non-uniform strain fields that perturb electrical performance. Recent work mitigates this tension by embedding kirigami/serpentine networks and by using liquid-metal, or nanocomposite interconnects that confine large strains to elastomeric regions while keeping the active layers in a low-strain state [53, 85, 86].

Intrinsic contact approaches aim to conceal devices within the skin by employing smart layouts, soft materials, and ultra-thin designs, ensuring electronics mimic skin's properties. The main goal is to develop skin-like electronics that share similar mechanical characteristics while providing reliable electrical performance, although challenges in power supply, durability, and scalable manufacturing persist. Advances have been achieved with stretchable circuits and epidermal sensors, yet further innovations are necessary for widespread adoption.

4 | Cross-Interface Coupling and Outlook

Designing for sensor–receiver and sensor–skin interfaces together is essential because improvements in one can create challenges for the other. For example, adding high-frequency antennas to skin-based devices for NFC, RFID, or BLE can increase size and stiffness, reducing conformability. Researchers need to optimize antenna and mechanical designs simultaneously, such as using stretchable serpentine traces to maintain resonance during deformation. Removing rigid electronics from the skin in the bodynet hybrid system requires a flexible reader on clothing, showing how enhancing one interface (comfort) depends on solutions for the other (wireless connection). Using BLE for long-range data transfer requires batteries or rechargers, leading to thicker patches or textile formats. Integrating stretchable power sources, such as batteries and harvesters, is an emerging field, aiming for fully untethered e-skin with solar or kinetic energy, stretchable antennas, and breathable sensors.

Another cross-interface issue is how the body influences communication. The body attenuates RF signals, so on-body antennas must be designed to either compensate for this attenuation or use the body as part of the system, for example, through capacitive coupling or surface wave transmission to connect sensors, or by exploiting reflections for intra-body networks. Such hybrid schemes blur boundaries, potentially enabling networks of sensors that use the human body as data infrastructure, known as "body-coupled communication" [89].

Looking ahead, skin-integrated electronics are promising. Innovations in soft, biodegradable, or self-healing materials could make devices more compatible with the body, reducing barriers. 5G/6G and Internet of Things (IoT) enable more real-time data transfer, supporting artificial intelligence (AI)-driven health analysis [90, 91]. Recent demonstrations of AI-powered electronic skins that combine conformal multimodal sensor arrays with deep-learning models for health-state recognition show how such integration can identify clinically relevant patterns directly on or near the skin surface [92]. Simultaneously, advances in transient bioelectronics and bioresorbable materials suggest epidermal platforms that safely degrade or resorb after use, reducing long-term material buildup while still providing high-performance sensing and therapy [93]. Powering options include wireless transfer, ambient energy harvesting, and high-density, flexible batteries [94, 95]. Closed-loop systems that monitor and intervene—like smart bandages or drug patches—will need seamless integration of sensing, stimulation, and communication interfaces.

Ultimately, future e-skin will likely comprise networked sensor arrays that measure various health parameters, thereby creating comprehensive health monitors connected to the cloud [96, 97]. Ensuring reliable contact and wireless links for each node, while minimizing interference and avoiding skin irritation, will be critical. Collaboration across disciplines among scientists and engineers will be crucial.

In conclusion, separating concerns into sensor–skin and sensor–receiver interfaces facilitates the design of advanced wearables. Comfort and connectivity can coexist. Innovations are making devices high-performance and human-friendly, paving the way for invisible, effortless wearables that provide continuous, meaningful data or therapy. Properly engineered dual interfaces will help electronic skins become a natural extension of our bodies.

Author Contributions

Simiao Niu supervised the work. Fuying Dong, Chi Han, Sheling T. Cai, Ju-Hyuck Lee, and Simiao Niu jointly contributed to the conception and overall development of the review. Fuying Dong and Chi Han wrote the manuscript. Sheling T. Cai, Ju-Hyuck Lee, and Simiao Niu revised the manuscript. All the authors commented on the manuscript.

Acknowledgments

This research was financially supported by the Rutgers Startup Package, NJ Health Foundation (Grant No. PC 221-25), Rutgers–New Brunswick OVPR Behavioral Health and Equity Pilot Seed Funding Award, MIT Lincoln Lab Collaboration Award, NJ Commission on Brain Injury Research (Grant No. CBIR25IRG024), and the National Research Foundation (Grant No. RS-2024-00406674) funded by the Ministry of Science and ICT of Korea.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. C. Yiu, Y. Liu, W. Park, et al., "Skin-Interfaced Multimodal Sensing and Tactile Feedback System as Enhanced Human-Machine Interface for Closed-Loop Drone Control," *Science Advances* 11, no. 13 (2025): eadt6041, https://doi.org/10.1126/sciadv.adt6041.

2. G. Xu, H. Wang, G. Zhao, et al., "Self-Powered Electrotactile Textile Haptic Glove for Enhanced Human-Machine Interface," *Science Advances* 11, no. 12 (2025): eadt0318, https://doi.org/10.1126/sciadv.adt0318.

3. T. Zhang, J. Lu, F. Hu, and Q. Hao, "Bluetooth Low Energy for Wearable Sensor-Based Healthcare Systems," in *2014 IEEE Healthcare Innovation Conference (HIC)* (2014), 251–254.

4. X. Tao, T.-H. Huang, C.-L. Shen, Y.-C. Ko, G.-T. Jou, and V. Koncar, "Bluetooth Low Energy-Based Washable Wearable Activity Motion and Electrocardiogram Textronic Monitoring and Communicating System," *Advanced Materials Technologies* 3, no. 10 (2018): 1700309, https://doi.org/10.1002/admt.201700309.

5. H. Ozkan, O. Ozhan, Y. Karadana, M. Gulcu, S. Macit, and F. Husain, "A Portable Wearable Tele-ECG Monitoring System," *IEEE Transactions on Instrumentation and Measurement* 69, no. 1 (2020): 173–182, https://doi.org/10.1109/TIM.2019.2895484.

6. F. D. Rienzo, A. Virdis, C. Vallati, N. Carbonaro, and A. Tognetti, "Evaluation of NFC-Enabled Devices for Heterogeneous Wearable Biomedical Application," *IEEE Journal of Radio Frequency Identification* 4, no. 4 (2020): 373–383, https://doi.org/10.1109/JRFID.2020.3003986.

7. S. Oh, J.-Y. Yoo, W.-Y. Maeng, et al., "Simple, Miniaturized Biosensors for Wireless Mapping of Thermoregulatory Responses," *Biosensors and Bioelectronics* 237 (2023): 115545, https://doi.org/10.1016/j.bios.2023.115545.

8. H. Jeong, S. S. Kwak, S. Sohn, et al., "Miniaturized Wireless, Skin-Integrated Sensor Networks for Quantifying Full-Body Movement Behaviors and Vital Signs in Infants," *Proceedings of the National Academy of Sciences of the United States of America* 118, no. 43 (2021): e2104925118, https://doi.org/10.1073/pnas.2104925118.

9. J.-Y. Yoo, S. Oh, W. Shalish, et al., "Wireless Broadband Acousto-Mechanical Sensing System for Continuous Physiological Monitoring," *Nature Medicine* 29, no. 12 (2023): 3137–3148, https://doi.org/10.1038/s41591-023-02637-5.

10. X. Ma, P. Wang, L. Huang, et al., "A Monolithically Integrated in-Textile Wristband for Wireless Epidermal Biosensing," *Science Advances* 9, no. 45 (2023): eadj2763, https://doi.org/10.1126/sciadv.adj2763.

11. J. Matthews, I. Soltis, M. Villegas-Downs, et al., "Cloud-Integrated Smart Nanomembrane Wearables for Remote Wireless Continuous Health Monitoring of Postpartum Women," *Advanced Science* 11, no. 13 (2024): 2307609, https://doi.org/10.1002/advs.202307609.

12. S. Kwon, H. S. Kim, K. Kwon, et al., "At-Home Wireless Sleep Monitoring Patches for the Clinical Assessment of Sleep Quality and Sleep Apnea," *Science Advances* 9, no. 21 (2023): eadg9671, https://doi.org/10.1126/sciadv.adg9671.

13. K. Kwon, J. U. Kim, S. M. Won, et al., "A Battery-Less Wireless Implant for the Continuous Monitoring of Vascular Pressure, Flow Rate and Temperature," *Nature Biomedical Engineering* 7, no. 10 (2023): 1215–1228, https://doi.org/10.1038/s41551-023-01022-4.

14. W. Ouyang, W. Lu, Y. Zhang, et al., "A Wireless and Battery-Less Implant for Multimodal Closed-Loop Neuromodulation in Small Animals," *Nature Biomedical Engineering* 7, no. 10 (2023): 1252–1269, https://doi.org/10.1038/s41551-023-01029-x.

15. K. Kwon, H. Wang, J. Lim, et al., "Wireless, Soft Electronics for Rapid, Multisensor Measurements of Hydration Levels in Healthy and Diseased Skin," *Proceedings of the National Academy of Sciences of the United States of America* 118, no. 5 (2021): e2020398118, https://doi.org/10.1073/pnas.2020398118.

16. D. D. L. Chung, "Pitfalls in Electromagnetic Skin-Depth Determination," *Journal of Electronic Materials* 51, no. 5 (2022): 1893–1899, https://doi.org/10.1007/s11664-022-09488-9.

17. H. Zou, Z. Zhou, M. Huang, et al., "NFC/RFID-Enabled Wearables and Implants for Biomedical Applications," *Microsystems & Nanoengineering* 11, no. 1 (2025): 191, https://doi.org/10.1038/s41378-025-01010-5.

18. T. Y. Kim, J. W. Mok, S. H. Hong, et al., "Wireless Theranostic Smart Contact Lens for Monitoring and Control of Intraocular Pressure in Glaucoma," *Nature Communications* 13, no. 1 (2022): 6801, https://doi.org/10.1038/s41467-022-34597-8.

19. J. W. Song, H. Ryu, W. Bai, et al., "Bioresorbable, Wireless, and Battery-Fee System for Electrotherapy and Impedance Sensing at Wound Sites," *Science Advances* 9, no. 8 (2023): eade4687, https://doi.org/10.1126/sciadv.ade4687.

20. V. Galli, S. K. Sailapu, T. J. Cuthbert, C. Ahmadizadeh, B. C. Hannigan, and C. Menon, "Passive and Wireless All-Textile Wearable Sensor System," *Advanced Science* 10, no. 22 (2023): 2206665, https://doi.org/10.1002/advs.202206665.

21. A. J. Bandodkar, P. Gutruf, J. Choi, et al., "Battery-Free, Skin-Interfaced Microfluidic/Electronic Systems for Simultaneous Electrochemical, Colorimetric, and Volumetric Analysis of Sweat," *Science Advances* 5, no. 1 (2019): eaav3294, https://doi.org/10.1126/sciadv.aav3294.

22. S. Han, J. Kim, S. M. Won, et al., "Battery-Free, Wireless Sensors for Full-Body Pressure and Temperature Mapping," *Science Translational Medicine* 10, no. 435 (2018): eaan4950, https://doi.org/10.1126/scitranslmed.aan4950.

23. J. Kim, G. A. Salvatore, H. Araki, et al., "Battery-Free, Stretchable Optoelectronic Systems for Wireless Optical Characterization of the Skin," *Science Advances* 2, no. 8 (2016): e1600418, https://doi.org/10.1126/sciadv.1600418.

24. M. A. S. Tajin, C. E. Amanatides, G. Dion, and K. R. Dandekar, "Passive UHF RFID-Based Knitted Wearable Compression Sensor," *IEEE Internet of Things Journal* 8, no. 17 (2021): 13763–13773, https://doi.org/10.1109/JIOT.2021.3068198.

25. J. Lee, M. Lee, J. Kim, et al., "All-Textile, Chip-Less, Battery-Free Body Sensor Networks Enabled by a Concentric Multi-Node Hub Antenna Architecture," *npj Flexible Electron* 9, no. 1 (2025): 109, https://doi.org/10.1038/s41528-025-00486-5.

26. S. Kananian, J. Rho, C. Chen, et al., "A Disposable Reader-Sensor Solution for Wireless Temperature Logging," *Device* 1, no. 6 (2023): 100183, https://doi.org/10.1016/j.device.2023.100183.

27. R. Colella and L. Catarinucci, "Wearable UHF RFID Sensor-Tag Based on Customized 3D-Printed Antenna Substrates," *IEEE Sensors Journal* 18, no. 21 (2018): 8789–8795, https://doi.org/10.1109/jsen.2018.2867597.

28. J. Kim, A. Banks, H. Cheng, et al., "Epidermal Electronics With Advanced Capabilities in Near-Field Communication," *Small* 11, no. 8 (2015): 906–912, https://doi.org/10.1002/smll.201402495.

29. J. Kim, A. Banks, Z. Xie, et al., "Miniaturized Flexible Electronic Systems With Wireless Power and Near-Field Communication Capabilities," *Advanced Functional Materials* 25, no. 30 (2015): 4761–4767, https://doi.org/10.1002/adfm.201501590.

30. G. A. Casula, F. Lestini, F. P. Chietera, et al., "Design of on-Body Epidermal Antenna on Amc Substrate for UHF RFID in Healthcare," *IEEE Transactions on Antennas and Propagation* 72, no. 5 (2024): 4023–4035, https://doi.org/10.1109/TAP.2024.3383214.

31. J. W. Kwak, M. Han, Z. Xie, et al., "Wireless Sensors for Continuous, Multimodal Measurements at the Skin Interface With Lower Limb Prostheses," *Science Translational Medicine* 12, no. 574 (2020): eabc4327, https://doi.org/10.1126/scitranslmed.abc4327.

32. S. Niu, N. Matsuhisa, L. Beker, et al., "A Wireless Body Area Sensor Network Based on Stretchable Passive Tags," *Nature Electronics* 2, no. 8 (2019): 361–368, https://doi.org/10.1038/s41928-019-0286-2.

33. M. Lin, Z. Zhang, X. Gao, et al., "A Fully Integrated Wearable Ultrasound System to Monitor Deep Tissues in Moving Subjects," *Nature Biotechnology* 42, no. 3 (2024): 448–457, https://doi.org/10.1038/s41587-023-01800-0.

34. T. Stuart, M. Farley, J. Amato, et al., "Biosymbiotic Platform for Chronic Long-Range Monitoring of Biosignals in Limited Resource Settings," *Proceedings of the National Academy of Sciences of the United States of America* 120, no. 50 (2023): e2307952120, https://doi.org/10.1073/pnas.2307952120.

35. C. Y. Kim, J. Lee, E. Y. Jeong, et al., "Wireless Technologies for Wearable Electronics: A Review," *Advanced Electronic Materials* 11, no. 10 (2025): 2400884, https://doi.org/10.1002/aelm.202400884.

36. K. Malhi, S. C. Mukhopadhyay, J. Schnepper, M. Haefke, and H. Ewald, "A Zigbee-Based Wearable Physiological Parameters Monitoring System," *IEEE Sensors Journal* 12, no. 3 (2012): 423–430, https://doi.org/10.1109/JSEN.2010.2091719.

37. L. Kong, W. Li, T. Zhang, et al., "Wireless Technologies in Flexible and Wearable Sensing: From Materials Design, System Integration to Applications," *Advanced Materials* 36, no. 27 (2024): 2400333, https://doi.org/10.1002/adma.202400333.

38. U. Topalovic, S. Barclay, C. Ling, et al., "A Wearable Platform for Closed-Loop Stimulation and Recording of Single-Neuron and Local Field Potential Activity in Freely Moving Humans," *Nature Neuroscience* 26, no. 3 (2023): 517–527, https://doi.org/10.1038/s41593-023-01260-4.

39. S. Tan, Y. Ren, J. Yang, and Y. Chen, "Commodity WiFi Sensing in Ten Years: Status, Challenges, and Opportunities," *IEEE Internet of Things Journal* 9, no. 18 (2022): 17832–17843, https://doi.org/10.1109/JIOT.2022.3164569.

40. J.-C. Hsieh, Y. Li, H. Wang, et al., "Design of Hydrogel-Based Wearable EEG Electrodes for Medical Applications," *Journal of Materials Chemistry B* 10, no. 37 (2022): 7260–7280, https://doi.org/10.1039/D2TB00618A.

41. H. Wang, Q. Ding, Y. Luo, et al., "High-Performance Hydrogel Sensors Enabled Multimodal and Accurate Human–Machine Interaction System for Active Rehabilitation," *Advanced Materials* 36, no. 11 (2024): 2309868, https://doi.org/10.1002/adma.202309868.

42. X. Huang, Z. Zheng, H. Wang, et al., "A Freeze-Resistant, Highly Stretchable and Biocompatible Organohydrogel for Non-Delayed Wearable Sensing at Ultralow-Temperatures," *Advanced Functional Materials* 34, no. 16 (2024): 2312149, https://doi.org/10.1002/adfm.202312149.

43. L.-W. Lo, J. Zhao, K. Aono, et al., "Stretchable Sponge Electrodes for Long-Term and Motion-Artifact-Tolerant Recording of High-Quality Electrophysiologic Signals," *ACS Nano* 16, no. 8 (2022): 11792–11801, https://doi.org/10.1021/acsnano.2c04962.

44. H. Derakhshandeh, F. Aghabaglou, A. Mccarthy, et al., "A Wirelessly Controlled Smart Bandage With 3D-Printed Miniaturized Needle Arrays," *Advanced Functional Materials* 30, no. 13 (2020): 1905544, https://doi.org/10.1002/adfm.201905544.

45. S. Xu, Y. Zhang, J. Cho, et al., "Stretchable Batteries With Self-Similar Serpentine Interconnects and Integrated Wireless Recharging Systems," *Nature Communications* 4, no. 1 (2013): 1543, https://doi.org/10.1038/ncomms2553.

46. Q. Jing, Y. S. Choi, M. Smith, C. Ou, T. Busolo, and S. Kar-Narayan, "Freestanding Functional Structures by Aaerosol-Jet Printing for Stretchable Electronics and Sensing Applications," *Advanced Materials Technologies* 4, no. 7 (2019): 1900048, https://doi.org/10.1002/admt.201900048.

47. D.-Y. Khang, H. Jiang, Y. Huang, and J. A. Rogers, "A Stretchable Form of Single-Crystal Silicon for High-Performance Electronics on Rubber Substrates," *Science* 311, no. 5758 (2006): 208–212, https://doi.org/10.1126/science.1121401.

48. L. Yin, J. Lv, and J. Wang, "Structural Innovations in Printed, Flexible, and Stretchable Electronics," *Advanced Materials Technologies* 5, no. 11 (2020): 2000694, https://doi.org/10.1002/admt.202000694.

49. S. Wagner and S. Bauer, "Materials for Stretchable Electronics," *MRS Bulletin* 37, no. 3 (2012): 207–213, https://doi.org/10.1557/mrs.2012.37.

50. C. A. Silva, J. Lv, L. Yin, et al., "Liquid Metal Based Island-Bridge Architectures for all Printed Stretchable Electrochemical Devices," *Advanced Functional Materials* 30, no. 30 (2020): 2002041, https://doi.org/10.1002/adfm.202002041.

51. D.-H. Kim, J.-H. Ahn, W. M. Choi, et al., "Stretchable and Foldable Silicon Integrated Circuits," *Science* 320, no. 5875 (2008): 507–511, https://doi.org/10.1126/science.1154367.

52. R. C. Webb, A. P. Bonifas, A. Behnaz, et al., "Ultrathin Conformal Devices for Precise and Continuous Thermal Characterization of Human Skin," *Nature Materials* 12, no. 10 (2013): 938–944, https://doi.org/10.1038/nmat3755.

53. D.-H. Kim, N. Lu, R. Ma, et al., "Epidermal Electronics," *Science* 333, no. 6044 (2011): 838–843, https://doi.org/10.1126/science.1206157.

54. Q. Wang, S. Ling, X. Liang, H. Wang, H. Lu, and Y. Zhang, "Self-Healable Multifunctional Electronic Tattoos Based on Silk and Graphene," *Advanced Functional Materials* 29, no. 16 (2019): 1808695, https://doi.org/10.1002/adfm.201808695.

55. N. Gogurla, Y. Kim, S. Cho, J. Kim, and S. Kim, "Multifunctional and Ultrathin Electronic Tattoo for on-Skin Diagnostic and Therapeutic Applications," *Advanced Materials* 33, no. 24 (2021): 2008308, https://doi.org/10.1002/adma.202008308.

56. M. K. Choi, J. Yang, K. Kang, et al., "Wearable Red–Green–Blue Quantum Dot Light-Emitting Diode Array Using High-Resolution Intaglio Transfer Printing," *Nature Communications* 6, no. 1 (2015): 7149, https://doi.org/10.1038/ncomms8149.

57. S. Han, M. K. Kim, B. Wang, D. S. Wie, S. Wang, and C. H. Lee, "Mechanically Reinforced Skin-Electronics With Networked Nanocomposite Elastomer," *Advanced Materials* 28, no. 46 (2016): 10257–10265, https://doi.org/10.1002/adma.201603878.

58. C. Wang, B. Qi, M. Lin, et al., "Continuous Monitoring of Deep-Tissue Haemodynamics With Stretchable Ultrasonic Phased Arrays," *Nature Biomedical Engineering* 5, no. 7 (2021): 749–758, https://doi.org/10.1038/s41551-021-00763-4.

59. C. Wang, X. Li, H. Hu, et al., "Monitoring of the Central Blood Pressure Waveform via a Conformal Ultrasonic Device," *Nature Biomedical Engineering* 2, no. 9 (2018): 687–695, https://doi.org/10.1038/s41551-018-0287-x.

60. C. Wang, X. Chen, L. Wang, et al., "Bioadhesive Ultrasound for Long-Term Continuous Imaging of Diverse Organs," *Science* 377, no. 6605 (2022): 517–523, https://doi.org/10.1126/science.abo2542.

61. Y. M. Chi, T. P. Jung, and G. Cauwenberghs, "Dry-Contact and Noncontact Biopotential Electrodes: Methodological Review," *IEEE Reviews in Biomedical Engineering* 3 (2010): 106–119, https://doi.org/10.1109/RBME.2010.2084078.

62. A. Searle and L. Kirkup, "A Direct Comparison of Wet, Dry and Insulating Bioelectric Recording Electrodes," *Physiological Measurement* 21, no. 2 (2000): 271–283, https://doi.org/10.1088/0967-3334/21/2/307.

63. H. Kim, E. Kim, C. Choi, and W. H. Yeo, "Advances in Soft and Dry Electrodes for Wearable Health Monitoring Devices," *Micromachines (Basel)* 13, no. 4 (2022): 629, https://doi.org/10.3390/mi13040629.

64. P. Tallgren, S. Vanhatalo, K. Kaila, and J. Voipio, "Evaluation of Commercially Available Electrodes and Gels for Recording of Slow EEG Potentials," *Clinical Neurophysiology* 116, no. 4 (2005): 799–806, https://doi.org/10.1016/j.clinph.2004.10.001.

65. B. Park, J. H. Shin, J. Ok, et al., "Cuticular Pad–Inspired Selective Frequency Damper for Nearly Dynamic Noise–Free Bioelectronics," *Science* 376, no. 6593 (2022): 624–629, https://doi.org/10.1126/science.abj9912.

66. Y. Yang, T. Cui, D. Li, et al., "Breathable Electronic Skins for Daily Physiological Signal Monitoring," *Nano-Micro Letters* 14, no. 1 (2022): 161, https://doi.org/10.1007/s40820-022-00911-8.

67. H. Wu, G. Yang, K. Zhu, et al., "Materials, Devices, and Systems of on-Skin Electrodes for Electrophysiological Monitoring and Human–Machine Interfaces," *Advanced Science* 8, no. 2 (2021): 2001938, https://doi.org/10.1002/advs.202001938.

68. Y. Jiang, A. A. Trotsyuk, S. Niu, et al., "Wireless, Closed-Loop, Smart Bandage With Integrated Sensors and Stimulators for Advanced Wound Care and Accelerated Healing," *Nature Biotechnology* 41, no. 5 (2023): 652–662, https://doi.org/10.1038/s41587-022-01528-3.

69. P. Mostafalu, A. Tamayol, R. Rahimi, et al., "Smart Bandage for Monitoring and Treatment of Chronic Wounds," *Small* 14, no. 33 (2018): 1703509, https://doi.org/10.1002/smll.201703509.

70. J. Shi, S. Kim, P. Li, et al., "Active Biointegrated Living Electronics for Managing Inflammation," *Science* 384, no. 6699 (2024): 1023–1030, https://doi.org/10.1126/science.adl1102.

71. Z. Huang, Y. Hao, Y. Li, et al., "Three-Dimensional Integrated Stretchable Electronics," *Nature Electronics* 1, no. 8 (2018): 473–480, https://doi.org/10.1038/s41928-018-0116-y.

72. J. C. Yang, J. Mun, S. Y. Kwon, S. Park, Z. Bao, and S. Park, "Electronic Skin: Recent Progress and Future Prospects for Skin-Attachable Devices for Health Monitoring, Robotics, and Prosthetics," *Advanced Materials* 31, no. 48 (2019): 1904765, https://doi.org/10.1002/adma.201904765.

73. M. Wang, Y. Luo, T. Wang, et al., "Artificial Skin Perception," *Advanced Materials* 33, no. 19 (2021): 2003014, https://doi.org/10.1002/adma.202003014.

74. W. Wang, Y. Jiang, D. Zhong, et al., "Neuromorphic Sensorimotor Loop Embodied by Monolithically Integrated, Low-Voltage, Soft e-Skin," *Science* 380, no. 6646 (2023): 735–742, https://doi.org/10.1126/science.ade0086.

75. S. Wang, J. Xu, W. Wang, et al., "Skin Electronics From Scalable Fabrication of an Intrinsically Stretchable Transistor Array," *Nature* 555, no. 7694 (2018): 83–88, https://doi.org/10.1038/nature25494.

76. W. Wang, S. Wang, R. Rastak, et al., "Strain-Insensitive Intrinsically Stretchable Transistors and Circuits," *Nature Electronics* 4, no. 2 (2021): 143–150, https://doi.org/10.1038/s41928-020-00525-1.

77. C. Yan, J. Wang, X. Wang, et al., "An Intrinsically Stretchable Nanowire Photodetector With a Fully Embedded Structure," *Advanced Materials* 26, no. 6 (2014): 943–950, https://doi.org/10.1002/adma.201304226.

78. Z. Ren, X. Shi, Q. Yang, et al., "An Ultrastretchable Seamlessly Integrated Contactless Charging Microsystem Towards Skin-Attachable Wireless Microelectronics," *Nature Communications* 16, no. 1 (2025): 1642, https://doi.org/10.1038/s41467-025-56881-z.

79. Y. Luo, M. R. Abidian, J. H. Ahn, et al., "Technology Roadmap for Flexible Sensors," *ACS Nano* 17, no. 6 (2023): 5211–5295, https://doi.org/10.1021/acsnano.2c12606.

80. H. Park, G. S. Gbadam, S. Niu, H. Ryu, and J.-H. Lee, "Manufacturing Strategies for Highly Sensitive and Self-Powered Piezoelectric and Triboelectric Tactile Sensors," *International Journal of Extreme Manufacturing* 7, no. 1 (2025): 012006, https://doi.org/10.1088/2631-7990/ad88be.

81. H. Park, Y. Ryu, H. Joo, et al., "High-Output, Thermally Resilient Nano-TiO2 Dielectric Gel Triboelectric Nanogenerator for Energy Harvesting and Reliable Temperature-Independent Pressure Sensing,"

Journal of Materials Chemistry A 13, no. 6 (2025): 4197–4206, https://doi.org/10.1039/D4TA07867E.

82. Y. Chen, H. Lei, Z. Gao, et al., "Energy Autonomous Electronic Skin With Direct Temperature-Pressure Perception," *Nano Energy* 98 (2022): 107273, https://doi.org/10.1016/j.nanoen.2022.107273.

83. H. Jang, Y. J. Park, X. Chen, T. Das, M.-S. Kim, and J.-H. Ahn, "Graphene-Based Flexible and Stretchable Electronics," *Advanced Materials* 28, no. 22 (2016): 4184–4202, https://doi.org/10.1002/adma.201504245.

84. Y. Cheng, R. Wang, J. Sun, and L. Gao, "Highly Conductive and Ultrastretchable Electric Circuits From Covered Yarns and Silver Nanowires," *ACS Nano* 9, no. 4 (2015): 3887–3895, https://doi.org/10.1021/nn5070937.

85. J. Xu, S. Wang, G.-J. N. Wang, et al., "Highly Stretchable Polymer Semiconductor Films Through the Nanoconfinement Effect," *Science* 355, no. 6320 (2017): 59–64, https://doi.org/10.1126/science.aah4496.

86. W. Lee, H. Kim, I. Kang, et al., "Universal Assembly of Liquid Metal Particles in Polymers Enables Elastic Printed Circuit Board," *Science* 378, no. 6620 (2022): 637–641, https://doi.org/10.1126/science.abo6631.

87. N. Li, S. Kang, Z. Liu, et al., "Immune-Compatible Designs of Semiconducting Polymers for Bioelectronics With Suppressed Foreign-Body Response," *Nature Materials* (2025), https://doi.org/10.1038/s41563-025-02213-x.

88. S. R. Krishnan, C.-J. Su, Z. Xie, et al., "Wireless, Battery-Free Epidermal Electronics for Continuous, Quantitative, Multimodal Thermal Characterization of Skin," *Small* 14, no. 47 (2018): 1803192, https://doi.org/10.1002/smll.201803192.

89. W. J. Tomlinson, S. Banou, C. Yu, M. Stojanovic, and K. R. Chowdhury, "Comprehensive Survey of Galvanic Coupling and Alternative Intra-Body Communication Technologies," *IEEE Communications Surveys & Tutorials* 21, no. 2 (2019): 1145–1164, https://doi.org/10.1109/COMST.2018.2879643.

90. N. F. M. Aun, P. J. Soh, A. A. Al-Hadi, M. F. Jamlos, G. a. E. Vandenbosch, and D. Schreurs, "Revolutionizing Wearables for 5G: 5G Technologies: Recent Developments and Future Perspectives for Wearable Devices and Antennas," *IEEE Microwave Magazine* 18, no. 3 (2017): 108–124, https://doi.org/10.1109/MMM.2017.2664019.

91. H. F. Ahmad, W. Rafique, R. U. Rasool, A. Alhumam, Z. Anwar, and J. Qadir, "Leveraging 6G, Extended Reality, and IoT Big Data Analytics for Healthcare: A Review," *Computer Science Review* 48 (2023): 100558, https://doi.org/10.1016/j.cosrev.2023.100558.

92. C. Xu, S. A. Solomon, and W. Gao, "Artificial Intelligence-Powered Electronic Skin," *Nature Machine Intelligence* 5, no. 12 (2023): 1344–1355, https://doi.org/10.1038/s42256-023-00760-z.

93. Y. Wang, C. Wu, Y. Zhang, S. Du, and X. Zhou, "Wearable and Implantable Transient Bioelectronics," *Journal of Materials Chemistry C: Materials for Optical and Electronic Devices* 13, no. 29 (2025): 14682–14696, https://doi.org/10.1039/D5TC01911G.

94. X. Liu, Y. Wang, G. Wang, et al., "An Ultrasound-Driven Implantable Wireless Energy Harvesting System Using a Triboelectric Transducer," *Matter* 5, no. 12 (2022): 4315–4331, https://doi.org/10.1016/j.matt.2022.08.016.

95. C. Han, M. Jin, F. Dong, et al., "Interpretable Machine Learning for Evaluating Nanogenerators' Structural Design," *ACS Nano* 19, no. 14 (2025): 14456–14466, https://doi.org/10.1021/acsnano.5c02525.

96. J. V. Vaghasiya, C. C. Mayorga-Martinez, and M. Pumera, "Wearable Sensors for Telehealth Based on Emerging Materials and Nanoarchitectonics," *npj Flexible Electron* 7, no. 1 (2023): 26, https://doi.org/10.1038/s41528-023-00261-4.

97. X. Yang, W. Chen, Q. Fan, et al., "Electronic Skin for Health Monitoring Systems: Properties, Functions, and Applications," *Advanced Materials* 36, no. 31 (2024): 2402542, https://doi.org/10.1002/adma.202402542.