Vol. 20 (2026): Proceedings of 2026 International Conference on Materials Science, Energy Engineering and Automation Control (ICMSEAC 2026)
E-ISSN: 3105-0522 P-ISSN: 3105-0514
DOI: https://doi.org/10.70267/mseac.2026173180

Flexible Conductive Composites for Electronic Skin Applications: A Review

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Abstract

Research into electronic skin, or e-skin, has evolved into a fast-moving field. Researchers aim to build artificial systems with sensing performance matching human skin. Robotics, wearable electronics, and healthcare monitoring tools are all seeing rapid progress. This has generated strong demand for flexible sensors that fit curved surfaces and detect signals such as pressure, strain, and temperature. Many material systems are currently being tested for e-skin devices, among which flexible conductive composites deliver clear advantages. These materials combine conductive properties, stretchability, and sound mechanical resilience, making them highly practical for e-skin construction. This review surveys the latest progress in conductive composite materials for e-skin across five dimensions—material systems, conduction mechanisms, sensing principles, structural design strategies, and practical deployment hurdles. It examines representative conductive fillers (carbon nanotubes, graphene, MXene, silver nanowires, and conductive hydrogels) alongside their polymer hosts, compares charge-transport behaviors and sensing modalities across different composite families, and analyzes how micro- and nano-scale structural engineering boosts sensitivity, flexibility, and durability. Mainstream fabrication routes, real-world application scenarios, and persistent technical obstacles are also discussed, along with emerging directions such as self-healing materials and self-powered e-skin architectures. By tracing the links among material choice, sensing mechanism, device architecture, and application requirements, this paper clarifies what existing conductive composite systems can and cannot deliver, and offers a forward-looking perspective on where intelligent e-skin sensing systems may head next.

Keywords

electronic skin, flexible conductive composites, tactile sensing, conductive hydrogels, wearable electronics

1. Introduction

Human skin is far more than a protective covering. It serves as a densely integrated sensory system that captures pressure, strain, temperature, and various external stimuli, while remaining soft and highly deformable.

Inspired by this natural design, researchers have spent the past two decades developing artificial devices to replicate these sensing functions for use in robotics, wearable electronics, health monitoring, and human–machine interfaces. The concept of electronic skin—an elastically compliant platform that integrates flexible materials, sensing technologies, and electronic systems to enable tactile perception and environmental awareness—has consequently become a focal point of interdisciplinary research [1].

The push for more intelligent robots and advanced wearable devices has brought new urgency to the development of electronic skin. High-end prosthetic limbs, for example, increasingly rely on tactile feedback to enhance movement control precision and the quality of the user experience. Robotic manipulators require tactile sensing skins to safely grip and manipulate objects of varying shapes, textures, and hardness. In healthcare applications, flexible sensing patches enable continuous monitoring of limb motion, pulse waves, breathing, and other physiological signals, supporting personalized health evaluation and early disease detection systems. These applications all demand high sensitivity, stable performance, and long-term compatibility, characteristics that traditional rigid electronic sensors cannot easily meet.

The fundamental problem with rigid sensors is straightforward: they do not deform easily, and their mechanical mismatch with soft biological tissues and flexible robot surfaces leads to signal drift under repeated bending, stretching, or compression, and sometimes outright device failure. Flexible conductive composites have emerged as the most compelling answer to this limitation. By dispersing conductive fillers within an elastic polymer matrix, these materials retain stable electrical pathways even under large mechanical strains.

A diverse set of conductive fillers has now been explored in the e-skin context—carbon nanotubes (CNTs), graphene, MXenes, silver nanowires (AgNWs), and conductive hydrogels. Each brings distinct trade-offs in conductivity, stretchability, sensitivity, biocompatibility, and processing compatibility [2]. In parallel, advances in micro- and nanostructuring, fabrication, and sensor architecture have considerably advanced device-level performance.

That said, the field remains far from mature. An ideal e-skin platform would simultaneously deliver high conductivity, large stretchability, extreme sensitivity, long-term operational stability, biocompatibility, and scalability to mass production—and these metrics frequently conflict. Simply increasing filler content to improve conductivity often comes at the cost of flexibility and stretchability. Materials with excellent stretchability often exhibit unstable conductivity under repeated bending and stretching.

Long-term durability in real environments, self-healing capabilities after mechanical damage, built-in power supply solutions, and large-scale manufacturing constraints all add layers of difficulty to the commercial translation of electronic skin technologies. Disentangling the relationships among material composition, conductive network architecture, sensing mechanism, and structural design is therefore an essential step toward the next generation of electronic skin.

With these challenges in mind, this paper provides a systematic overview of the state of the art in flexible conductive composites for electronic skin, organized around five core themes: material systems, conduction mechanisms, sensing principles, structural design strategies, and practical application bottlenecks. It compares mainstream conductive fillers—CNTs, graphene, MXene, AgNWs, and conductive hydrogels—and their compatible polymer matrices, reviews fabrication methods and strategies for optimizing sensor performance, and highlights emerging technologies such as self-healing materials.

This work focuses specifically on self-powered intelligent electronic skin. By linking material choices, conductive behavior, sensing performance, and practical application needs, it provides a comprehensive overview of the current state of intelligent e-skin sensing systems and highlights key areas for future breakthroughs.

2. Flexible Conductive Composites

2.1 Conductive Material Systems

At the heart of any flexible conductive composite is the pairing of an elastic polymer matrix with one or more conductive fillers. The matrix—most often polydimethylsiloxane (PDMS), Ecoflex, or polyurethane (PU)—provides the mechanical backbone and deformability; the filler constructs the percolating network through which electrical signals travel. Each type of matrix material carries distinct characteristics. PDMS stands out for good processability and high transparency; Ecoflex provides exceptional stretchability; and PU allows broad adjustment of hardness.

Carbon nanotubes were among the first nanoscale fillers to be seriously pursued for e-skin. Their high aspect ratio means that only modest quantities are needed to knit a continuous conductive network, so the composite can stay flexible without trading away too much conductivity. Graphene entered the picture somewhat later and generated considerable excitement thanks to its exceptional conductivity, enormous specific surface area, and outstanding in-plane stiffness—attributes that translate well to pressure and strain sensing. A persistent difficulty, however, is that graphene sheets tend to restack during solution processing or composite curing, which can degrade the reproducibility of the sensing response [2].

MXenes represent a more recent addition to the toolbox. These two-dimensional transition-metal carbides and nitrides combine near-metallic conductivity with a surface rich in hydrophilic functional groups, giving them excellent compatibility with aqueous polymer processing routes. Sensors built around MXenes routinely report high sensitivity and fast response times. Their Achilles' heel is environmental stability: MXene flakes oxidize gradually under ambient conditions, and preserving their performance over months remains an active area of investigation [2].

Silver nanowires sit at the high-conductivity extreme of the filler spectrum. Because silver is an outstanding intrinsic conductor, AgNW-based composites can achieve very low sheet resistances and rapid electrical responses to deformation. On the downside, silver is prone to oxidation and electrochemical corrosion, and maintaining stable performance through thousands of stretch–release cycles is not trivial.

Conductive hydrogels occupy a special niche. With water contents that can exceed 90%, they feel soft and tissue-like, and their ionic or mixed ionic–electronic conduction mechanisms make them naturally compatible with biological environments. These features have made hydrogels the material of choice for many wearable healthcare and bioelectronic demonstrations [3]. Their long-term reliability, however, is tightly coupled to water retention—once the gel dries out, conductivity plummets.

Taken together, no single filler family ticks every box. CNTs and graphene deliver a workable compromise between conduction and mechanics; MXenes push sensitivity to impressive levels; AgNWs offer the highest raw conductivity; and hydrogels win on biocompatibility and stretchability. Unsurprisingly, much of the current research effort is directed at hybrid systems that blend two or more filler types to pool their strengths while canceling out individual weaknesses [4].

2.2 Electrical Conductivity Mechanisms

The electrical conductivity of such composites depends largely on whether filler particles can form interconnected networks within insulating polymer matrices. At low filler loading, particles stay separated from one another, and the composite acts as a typical dielectric. Once filler content reaches a critical level, particles come into direct contact or enable electron tunneling across thin polymer interlayers, forming the first continuous pathways for electrical conduction.

This transition is described by percolation theory, and the critical volume fraction at which it occurs—the percolation threshold—is one of the most practically important parameters in composite design.

Filler geometry matters enormously for the location of that threshold. CNTs and silver nanowires, with their long, slender shapes, can bridge large distances within the matrix and therefore percolate at relatively low volume fractions. Spherical or flaky particles generally require higher loadings to achieve the same effect. Apart from particle geometry, filler dispersion quality also plays a decisive role. Poorly dispersed fillers tend to aggregate, which not only causes material waste but also generates unstable conductive hotspots. In contrast, uniformly dispersed fillers can form homogeneous, mechanically stable conductive networks. Interfacial chemical properties between fillers and polymer matrices also regulate electron-transfer efficiency between adjacent particles, including polymer wetting behavior on filler surfaces and interfacial functional groups that enhance interfacial adhesion.

2.3 Sensing Mechanisms

Piezoresistivity is the workhorse transduction mechanism in e-skin. The idea is simple: apply pressure or stretch, and the internal arrangement of conductive filler particles shifts, changing the contact resistance between neighboring particles and thus the overall resistance of the composite. Because resistance is easy to measure with simple circuitry, piezoresistive sensors have been the most widely adopted in wearable prototypes.

Capacitive sensing takes a different route. Here, the device is built as a parallel-plate capacitor—typically a soft dielectric layer sandwiched between two compliant electrodes. External pressure compresses the dielectric layer, reducing electrode spacing and boosting capacitance, while tensile deformation alters the overlap area between paired electrodes. Capacitive sensors feature ultra-low power consumption and favorable long-term drift resistance. Such merits make them ideal for long-duration monitoring scenarios that cannot support regular recalibration.

Piezoelectric sensing offers yet another option. Certain materials generate a voltage directly in response to mechanical deformation, enabling sensors that respond almost instantaneously to dynamic pressure changes. The catch is that the generated charge leaks away under static load, so piezoelectric devices are poorly suited to measuring sustained pressure.

Triboelectric sensing has surged in popularity largely because it opens a door to self-powered operation. Based on contact electrification coupled with electrostatic induction, triboelectric nanogenerators (TENGs) convert mechanical motion into measurable electrical pulses without requiring an external battery [5]. For wearable scenarios specifically, it is promising to harvest mechanical energy from human body motion while simultaneously detecting tactile or pressure signals. Nevertheless, TENG output performance is susceptible to ambient humidity, surface contaminants, and contact material properties, posing challenges for device calibration.

Temperature and humidity detection add further dimensions to e-skin functionality. Temperature sensing usually relies on a thermally induced change in resistance of a sensing layer. This strategy works well with many of the same composite materials already used for pressure sensing. Humidity sensing relies on variations in ionic conductivity, dielectric permittivity, or volumetric swelling when materials adsorb or desorb water vapor. Combining humidity detection with mechanical sensing can substantially broaden application boundaries, yet it poses a critical issue. Multiple external stimuli frequently generate superimposed electrical responses, and decoupling these signals to distinguish them remains a core research challenge.

Current solutions span multi-layered sensor architectures that physically separate different sensing channels, materials engineered to respond selectively to a single stimulus, and machine-learning pipelines trained to disentangle mixed signals [6].

2.4 Micro- and Nano-Structural Design

Material formulation alone does not determine how sensitive a sensor will be. The geometry of the sensing layer—its surface topography and internal architecture—can amplify small mechanical inputs into large electrical outputs, sometimes by orders of magnitude.

Borrowing from biology has been a fruitful strategy. Human skin is not flat; its epidermis is sculpted into intricate micro-ridge patterns that enhance tactile discrimination. Drawing on this natural design, researchers have fabricated sensing layers embedded with microscale pyramids, domes, and ridge-shaped protrusions. Applied pressure triggers stress concentration at protrusion tips, inducing substantial local deformation and thereby generating distinct electrical signals. Pyramid arrays deliver optimal performance under low-pressure ranges. Tip-concentrated stress can induce obvious resistance or capacitance variation in response to extremely gentle tactile stimuli.

Dome-shaped microstructures, because they distribute stress more evenly, tend to widen the usable pressure range and resist mechanical fatigue better over repeated cycles [7]. Furthermore, fingerprint-mimicked linear patterns and multilayered epidermal structures can improve sensor spatial resolution, enabling precise discrimination of subtle surface textures.

Porous and foam-like internal structures offer a complementary approach. A highly compressible conductive network riddled with voids can collapse significantly under tiny external loads, making porous composites especially adept at capturing faint physiological signals—pulse waves, subtle joint movements, breathing rhythms. Beyond sensitivity, porosity reduces weight and can shorten the mechanical response time by allowing air or fluid to escape during compression. More sophisticated hierarchical designs now stack multiple structural features (e.g., micro-pyramids on a porous substrate) to simultaneously push sensitivity, detection range, durability, and multimodal discrimination. The takeaway is clear: sensor performance is as much an architectural problem as a materials one.

3. Applications and Future Perspectives

3.1 Tactile and Pressure Sensing

Pressure sensing is the most fundamental thing an electronic skin must do. Flexible conductive composites translate tactile stimuli, pressure distribution, and mechanical deformation into electrical signals. Arranging sensing units in dense arrays also enables e-skin systems to achieve high-resolution spatial mapping of in-plane pressure distributions.

This capability matters enormously for robotic manipulation: real-time force feedback lets a gripper sense whether an object is slipping, adjust its grip accordingly, and handle delicate or irregular items without crushing them [1].

Outside robotics, pressure-sensitive e-skin has found a growing role in wearable health monitoring. Sensors with sufficiently low detection floors can resolve subtle signals—the pulsatile waveform at the wrist, the expansion of the chest during breathing, the twitch of a facial muscle, the flexion of a knee joint. For real-world deployment, such sensors must juggle several demanding metrics: high sensitivity, fast response and recovery, a wide dynamic range, low hysteresis, and stable performance through thousands of deformation cycles. When flexible composites are paired with thoughtfully designed sensor architectures, these requirements become achievable while preserving the comfort and conformal skin contact that rigid devices cannot offer [8].

3.2 Multi-Modal Sensing Systems

Natural skin does not sense pressure in isolation—it simultaneously registers texture, temperature, wetness, and pain through distinct but coordinated sensory channels. Modern e-skin platforms increasingly attempt something analogous, packing multiple sensing modalities into a single device to deliver richer environmental awareness. A wearable health patch might, for example, track body motion, skin temperature, and heart rate concurrently, giving a fuller picture of the wearer's physiological state.

Building such multimodal systems, however, involves more than simply assembling discrete sensors. Different external stimuli can trigger highly similar electrical responses in the same active material, an effect known as cross-sensitivity. A single resistance variation may stem from changes in pressure, temperature, or humidity. Inability to isolate these individual signal components will degrade measurement accuracy. Accordingly, signal decoupling has emerged as a hotspot research topic in multimodal sensing. The main strategies on the table include designing sensor arrays with physically separated sensing layers so that each channel responds predominantly to one stimulus, engineering materials whose response functions are inherently selective, and applying machine-learning classifiers that learn to assign signal features to their correct physical origins [6]. Getting decoupling right is widely seen as a prerequisite for making multimodal e-skin practically useful rather than a laboratory curiosity.

3.3 Wearable Healthcare and Robotics

Health monitoring represents the fastest-growing application domain for electronic skin. Flexible sensors can be worn directly on the skin to continuously capture body motion, joint angles, pulse, breathing rate, and skin temperature, all with minimal disruption to the wearer's daily routine. Because they conform to the body's irregular contours and remain in place during movement, e-skin devices are well-suited to prolonged monitoring, rehabilitation tracking, and the early detection of abnormal physiological patterns [8].

Robotics and intelligent prosthetics form a second pillar of e-skin application. Pressure-sensitive sensor arrays mounted on robot grippers provide real-time tactile feedback to assess contact forces and surface properties, enabling manipulation that is both safer around humans and more dexterous with fragile or unpredictable objects. In prosthetic hands, tactile sensing can restore a degree of sensory awareness to the user, improving grip control and making interactions with the physical world feel more natural. These inherent sensing capabilities also support safe physical human–robot collaboration, since robotic equipment requires real-time contact perception and adaptive responses during human interaction.

4. Challenges and Future Perspectives

4.1 Material Stability and Biocompatibility

Despite promising laboratory performance, long-term durability under practical operating conditions remains a major bottleneck. Cyclic mechanical loading, including stretching, compression, and bending, inevitably causes mechanical fatigue in polymer matrices and conductive filler networks, which manifests as baseline drift, sensitivity degradation, or complete electrical malfunction. Conductive hydrogels face an additional, more fundamental issue: they dry out. Water evaporation gradually increases the internal ionic concentration, alters mechanical properties, and eventually reduces conductivity. Environmental factors such as UV exposure, oxygen, and humidity fluctuations further conspire against long-term stability, with MXenes being particularly prone to oxidative degradation and AgNWs to corrosion [2,3]. Biocompatibility adds yet another layer of constraint for skin-worn or implantable devices: the materials must not provoke immune responses, and any leachable components must be demonstrably harmless during extended contact.

4.2 Device Integration and Signal Processing

A functional e-skin platform is considerably more than a carefully engineered sensing material. It requires signal-acquisition circuitry, analog-to-digital conversion, on-board processing, and often wireless data transmission—all of which must coexist on a flexible, repeatedly deformed substrate. The interconnects that link sensing elements to readout electronics are especially vulnerable: repeated stretching or bending can crack solder joints, delaminate printed traces, or fatigue flexible cables, causing intermittent failures that are hard to diagnose. On the manufacturing side, moving from a single benchtop device to batch production introduces its own set of headaches—chiefly how to maintain consistent filler dispersion, film thickness, and electrical performance across hundreds or thousands of units. These integration and scalability challenges are less glamorous than inventing a new material, but they are just as critical for translating e-skin from the lab to the market.

4.3 Emerging Research Directions

Several forward-looking research themes are beginning to reshape what electronic skin can be.

Self-healing. The idea that a damaged sensor could repair its own conductive pathways and restore function without external intervention is intuitively appealing —and for good reason: wearable and robotic devices inevitably accumulate microcracks and localized failures during service. Self-healing conductive composites employ dynamic chemical bonds (hydrogen bonding, metal–ligand coordination, Diels–Alder linkages, disulfide exchange) that can reform after cleavage, enabling recovery of both mechanical integrity and electrical continuity [9]. While most current systems still need some combination of heat, moisture, or time to heal effectively, the trajectory of improvement suggests practical, room-temperature self-healing may be within reach.

Artificial intelligence provides feasible solutions to address the above issues. Denser sensor arrays and multimodal systems produce massive volumes of sensing data, which render conventional threshold-based and model-driven analytical methods ineffective. Machine learning, especially deep learning, enables researchers to extract hidden patterns and characteristics from such complex datasets for advanced signal processing.

Neural networks have been trained to classify tactile textures, recognize hand gestures from strain-sensor arrays, and separate mixed pressure–temperature signals into their constituent stimuli [6]. Looking further ahead, the concept of neuromorphic perception—processing tactile information using organic electrochemical devices that emulate the spiking behavior of biological neurons—hints at a future in which the sensor itself performs some of the computation, reducing the data deluge at the source [6].

Self-powered operation. Cutting the cord to bulky batteries or wired power supplies would dramatically expand where and how e-skin can be used. Energy-autonomous e-skin harvests power from ambient sources—most commonly the wearer's own movements via triboelectric or piezoelectric generators—and uses it to drive both sensing and signal transmission [5]. Triboelectric nanogenerators have been a particularly hot topic because they combine energy harvesting with active self-powered sensing in a single material system, eliminating the need for a separate power module.

While the power densities achieved so far are modest, they are often sufficient for low-duty-cycle monitoring tasks, and the vision of a maintenance-free sensing patch that runs indefinitely on body motion alone continues to drive intense research activity.

5. Conclusion

Flexible conductive composites constitute the key material basis for electronic skin fabrication. Among the families of fillers now in the research mainstream—carbon nanotubes, graphene, MXenes, silver nanowires, and conductive hydrogels—each brings a distinctive profile of strengths. MXene-based systems, with their metallic conductivity and versatile surface chemistry, have delivered some of the highest reported sensitivities. At the same time, conductive hydrogels, by virtue of their tissue-mimicking softness and ionic conduction, have carved out a leading position in wearable healthcare [3]. Meanwhile, advances in microstructural engineering and biomimetic surface design have enhanced sensor sensitivity, broadened detection ranges, and enabled multifunctional sensing in ways that bring e-skin closer to the benchmark set by natural skin [7].

Important obstacles stand between the current state of the art and large-scale commercial deployment. Environmental stability—especially for MXenes, AgNWs, and hydrogel-based systems—remains an unsolved problem that directly limits operational lifetime and reliability. Reproducible large-area manufacturing with tight batch-to-batch consistency is still difficult to achieve. And the push toward multimodal integration, while exciting, brings with it a tangle of signal interference, cross-sensitivity, and data-processing complications that cannot be wished away. A single discipline cannot settle these challenges, and solid progress hinges on ongoing collaboration among materials science, electrical engineering, mechanical design, and artificial intelligence.

Promising future research paths fall into three categories: materials with multi-year stability rather than short-term, monthly stability; multimodal systems with intrinsically reliable signal decoupling; and intelligent data workflows to draw valid conclusions from noisy, high-dimensional sensor datasets. Self-healing composites [9], self-powered platforms based on triboelectric and piezoelectric energy harvesting [5], and AI-augmented sensing systems [6] are poised to become central research themes in the coming years. Addressing these challenges systematically will move electronic skin beyond impressive laboratory demonstrations toward real-world impact in healthcare, robotics, prosthetics, and human–machine interaction.

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Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgment

This paper is an output of the science project.