

PVDF-Based Electronic Skin: Mimicking Life for Enhanced Human-Machine Interfaces

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Abstract- Electronic skin (e-skin)- elastic, flexible materials that replicate the sensory capabilities of human skin- has emerged as a transformative field of research. This review paper critically examines the role of Polyvinylidene fluoride (PVDF) and its composites in enabling next-generation e-skin sensors. Unlike prior surveys, this review (i)compiles a unified fabrication checklist for PVDF/MoS₂/ BaTiO₃ – based devices, (ii)presents a normalized benchmark table for recent PVDF and PVDF-composite e-skins, and (iii)introduces a standardize nomenclature of device parameters. We analyze how advanced fillers (e.g., MoS₂, BaTiO₃) and fabrication protocols improve piezoelectric, piezoresistive, and durability metrics, while also mapping PVDF-based e-skins to Internet of Things (IOT) applications. Key challenges- such a large-scale fabrication, long-term stability, and signal processing- are critically discussed, and future directions including AI-driven adaptive sensing, self-healing materials, and biocompatible integration are highlighted. The study positions PVDF nanocomposites as a central pillar in the advancement of robust, self-powered, and IoT-ready e-skin systems.

Keywords: E-Skin, PVDF, Nanocomposite, IOT, Robotics.

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1. Introduction

The human skin, an astonishing feat of natural engineering, has inspired the creation of electronic skin (e-skin)—flexible[1], elastic materials designed to duplicate its sensory capabilities for advanced human-machine interaction. Biological skin features networks of mechanoreceptors, thermoreceptors, and nociceptors, which provide complex awareness of touch[2],

temperature, and pain[3], setting a benchmark for e-skin innovation.

This review article focuses on the crucial role of polyvinylidene fluoride (PVDF) nanocomposites in advancing e-skin technology, particularly their use in fabricating durable, sensitive[4], and flexible piezoelectric sensors. Unlike earlier reviews that broadly covered stretchable electronics, this work concentrates on PVDF and PVDF-composite e-skins, presenting fabrication pathways, normalized device-level comparisons, and clear nomenclature to guide reproducibility[5].

Nomenclature Box

E-Skin	Electronic Skin
PVDF	Polyvinylidene
MoS ₂	Molybdenum Disulfide
BaTiO ₃	Barium Titanate
PDMS	Polydimethylsiloxane
PET	Polyethylene Terephthalate
PI	Polyimide
PU	Polyurethane
IOT	Internet of Things
Eco-Flex	Silicone Rubber
Piezoelectricity	Electric charge generated by mechanical stress
Piezo resistivity	Resistance changes due to mechanical strain
LOD	Limit of Detection

1.1 Introduction to Work Done

Table 1. provides a comparative overview of the major flexible sensing mechanisms including piezoresistive, capacitive, piezoelectric, triboelectric, and optical approaches. Each mechanism is summarized in terms of the materials typically employed, their key

performance advantages, and the most common applications in wearable and electronic skin devices. This comparison highlights how PVDF-based piezoelectric sensors stand out for their self-powered capability and wide dynamic range, making them highly suitable for real-time physiological monitoring.

Table 1. Comparative table of Flexible Sensing Technologies

Sensing Mechanism	Material Used	Key Advantages	Typical Application
Piezoresistive	CNTs[6], Graphene[7], Conductive Polymers	High sensitivity, Simple fabrication, Low cost	Strain, Pressure, and Motion sensing[8]
Capacitive	Elastomers, PDMS[9] with conductive layers	Excellent stability, High sensitivity to pressure, less affected by temperature changes	Pressure sensing, Tactile sensing, Proximity detection
Piezoelectric	PVDF, ZnO nanowires[10]	Self-powered, High dynamic range	Vibration, Pulse monitoring and Acoustic sensing[11]
Triboelectric	Various polymers (e.g. PET, Kapton)	High efficiency for converting mechanical energy, Self-powered, Versatile	Pressure sensing, Motion detection[12], Energy harvesting
Optical	Optical fibers, Photodiodes	Immunity to electromagnetic interference, Good for in vivo sensing	Blood oxygen saturation and Heart rate monitoring[13]

1.1.1 Overview

Electronic skin (e-skin) refers to flexible, stretchable electronic systems designed to replicate the sensory and responsive functions of human skin[14]. By integrating sensors and actuators onto flexible substrates[15], e-skin can detect external stimuli and respond in ways similar to physiological reactions[16].

This technology has transformative potential across fields like advanced prosthetics, robotics, wearable technology[17], and healthcare monitoring, enabling intuitive human-computer interaction and continuous, non-invasive health tracking[18]. With applications ranging from sensitive robotic touch to environmental sensing[19] and personalized medical diagnostics, e-skin bridges the gap between humans and machines[20]. The use of PVDF nanocomposites combined with IoT technologies promises a future of seamless, intelligent connectivity[21], making electronic systems an almost natural extension of the human body[22].

1.1.2 Potential Applications

PVDF nanocomposite-based electronic skin, with its inherent flexibility, sensitivity, and adaptability, finds a broad spectrum[23] of potential applications across various industries, each poised for significant transformation[24].

- **Robotics:** E-skin enhances robotic systems by providing them with a sense of touch[25], enabling safer and more precise interactions with their surroundings. This allows robots to handle delicate objects, overcome obstacles, and interact intuitively with humans, supporting advanced tasks including surface recognition, soft robotics, and adaptive control.
- **Tactile Sensing:** E-skin enhances robotic systems by enabling them to sense tactile data like temperature, vibration, and pressure, allowing more accurate and responsive interactions[26] with people and objects.

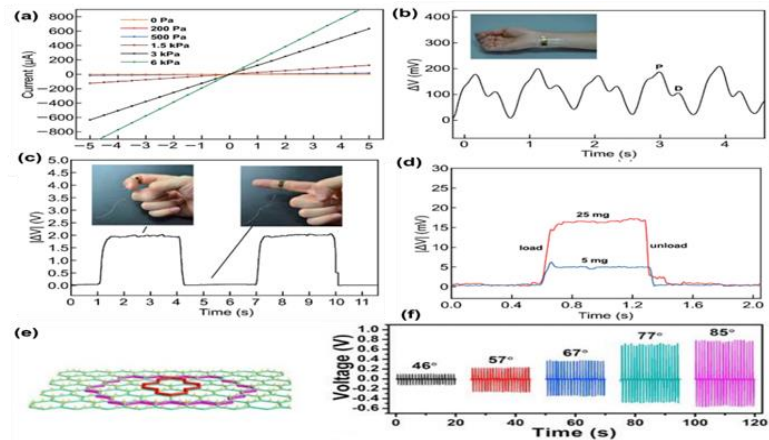


Figure 1. PVDF/MoS₂-based e-skin performance: (a) Current-voltage response under applied pressure (linear up to 100kPa, sensitivity $\approx 0.32V/kPa$); (b) real-time detection of

wrist pulse signals (~ 72 bpm); (c) piezoelectric voltage output under finger bending at 30° , stable over 105 cycles; (d) micro-pressure detection down to ~ 5 Pa; (e) schematic illustration of bending deformation; and (f) voltage response at different bending angles (0° – 60°).

- **E-skin for Object Manipulation and Robotics:**

The integration of tactile feedback from e-skin significantly enhances the dexterity and precision with which robots can handle objects[27]. By sensing the forces applied during grasping, robots can intelligently adapt their grip, which allows them to firmly and securely hold objects of widely varying sizes, textures, and shapes[28], reducing the risk of slippage or

human-machine interfaces that respond intuitively to touch and gestures. By embedding tactile sensors into interactive surfaces, e-skin can dramatically enhance[31] usability and unlock novel interaction modalities, moving beyond simple button presses to more nuanced and expressive gestural controls.

- **Environmental Monitoring:** E-skin can be deployed in sophisticated environmental monitoring systems to accurately detect minute changes in pressure, humidity, and temperature[32]. When integrated into smart surfaces, tactile sensors facilitate real-time monitoring of critical infrastructure and sensitive ecosystems, providing early warnings for potential issues[3].

- **Industrial Automation and Quality Control:** In industrial settings, e-skin serves as a vital tactile sensor for highly precise robots and automation systems[33]. The tactile feedback helps to ensure consistent product quality, facilitates the immediate detection of defects, and allows for the continuous optimization of complex manufacturing processes[34].

- **Smart Textiles and Fabrics:** Integrating e-skin into smart textiles enables interactive clothing and advanced wearable health monitors[35] that can track body movements, posture, and provide real-time feedback for rehabilitation or sports training[34].

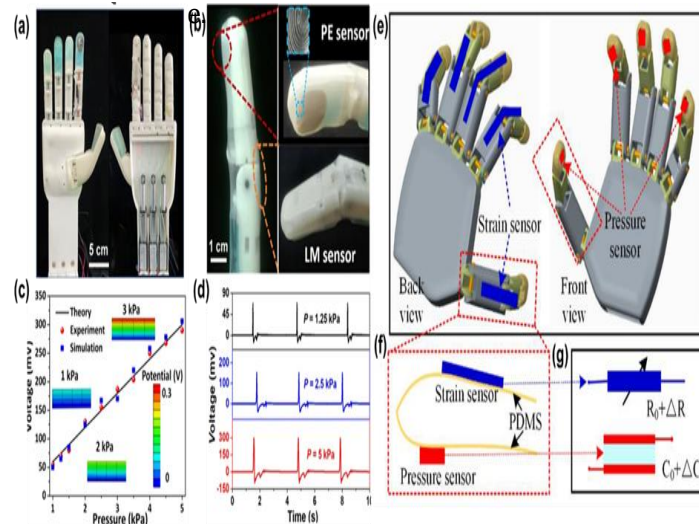


Figure 2. Integration of PVDF-based piezoelectric and strain sensor in robotics: (a) Biomimetic manipulator with conformal e-skin; (b) flexible piezoelectric and strain sensors as elements of an integral tactile system; (c) piezoelectric voltage fluctuations under applied pressure (up to ~ 50 kPa); (d) incorporation of pressure and strain sensors into a robotic finger; and (e) voltage-pressure relationships showing sensitivity of ~ 0.25 V/kPa.

- **E-skin for Prosthetic Devices:** E-skin integrated into prosthetics and wearable devices enhances sensory feedback, allowing users to experience sensations like natural touch[29]. In healthcare, it enables continuous vital sign monitoring, improves surgical precision through real-time tactile feedback[28], and supports rehabilitation by providing responsive, adaptive feedback[30].
- **Human-Machine Interfaces:** E-skin is a critical enabler for the development of highly advanced

1.1.3 Advantages

The inherent design and material properties of e-skin confer several compelling advantages, making it an indispensable tool for future technological advancements.

- **Sensitivity:** E-skin sensors can detect a wide array of physical stimuli, including delicate touch, varying levels of pressure, temperature fluctuations, and even subtle changes in humidity[36]. This makes them incredibly versatile and adaptable for deployment in diverse and complex environments.
- **Durability:** Despite their thin and flexible form factor, e-skin designs prioritize robustness and are engineered to withstand significant wear and

tear[37]. This durability is a critical differentiator compared to more rigid and fragile traditional sensors.

- **Biocompatibility:** Specific varieties of electronic skin are meticulously designed for biocompatibility, allowing safe utilization in medical applications[38] without provoking unpleasant reactions or inflicting harm on the human body. This facilitates the development of implanted devices and prolonged wearable health monitors.
- **Real-time Feedback:** The capacity of e-skin to deliver instantaneous feedback is revolutionary. This quick reaction capability is vital for applications where instantaneous information is required, such as enabling prosthetic limbs to "feel" their surroundings and react intuitively[21].
- **Customization:** Electronic skin technologies offer a high degree of customization and can be precisely tailored to suit vastly different needs.
- **Energy Efficiency:** Many electronic skin technologies are designed with energy efficiency as a core principle[39], often requiring minimal power consumption for continuous operation.
- **Integration:** E-skin is engineered for seamless integration into existing systems and device architectures[40], positioning it as a cost-effective and efficient solution for upgrading conventional devices.
- **Remote Monitoring:** The inherent connectivity potential of electronic skin enables robust remote monitoring of various parameters[41], including vital signs in healthcare or environmental conditions. Remote monitoring enhances safety, convenience, and provides crucial data for proactive decision-making.
- **Innovation:** The ongoing development and refinement of electronic skin technology are continuously opening new possibilities and driving innovation across diverse fields, fostering advancements in healthcare, robotics, and materials science[42].

2. Background Material

PVDF-based electronic skin relies on the piezoelectric properties of PVDF, which convert mechanical stress into electrical signals. This capability

enables sensitive detection of touch, pressure, and other stimuli, making it ideal for applications in sensing, actuation, and energy harvesting across various industries. Its flexibility and lightweight nature allow seamless integration onto curved surfaces, mimicking human skin for advanced robotic and wearable applications. The material's robustness and responsiveness make it suitable for both dynamic and static sensing environments.

2.1 Conceptual Overview

By integrating flexible e-skin with IoT, real-time data collection, remote monitoring, and intelligent control become possible. This combination enhances human-robot interaction, enables continuous health monitoring, and supports automation, creating smarter and more responsive systems. IoT connectivity allows large-scale deployment of e-skin-enabled devices, facilitating data-driven decision-making and predictive maintenance. Additionally, this synergy opens opportunities for personalized healthcare, adaptive robotics, and interactive smart environments.

2.1.1 Theory Used

The foundational principles underpinning the functionality of PVDF-based electronic skin are rooted in advanced material science and engineering concepts, primarily focusing on piezoelectricity and its synergistic integration with e-skin design and the Internet of Things (IoT).

- **Piezoelectricity:** Piezoelectricity, present in materials such as PVDF, facilitates the creation of electric charges upon the application of mechanical stress, and conversely. This feature renders PVDF optimal for e-skin applications[43], as it effectively transforms touch or pressure into electrical signals, facilitating applications in sensing, energy harvesting, and precise actuation across diverse industries.
- **E-Skin:** Electronic skin (e-skin) simulates the sensory properties of human skin utilizing flexible sensors and actuators to sense inputs like pressure, temperature, and humidity. It improves human-robot interaction for safer, more accurate operations[44] and revolutionizes healthcare through continuous, real-time health monitoring and tailored

feedback, facilitating superior health management[45].

- **Internet of Things (IoT):** The Internet of Things (IoT) interlinks various physical objects equipped with sensors and software, facilitating remote monitoring, control, and data sharing to enhance efficiency and convenience[46]. The collection of real-time data via IoT improves decision-making and automation in various industries, yet it also presents significant security and privacy challenges that necessitate robust safeguards[47].

3. Fabrication of E-skin

The production of diverse e-skin devices, especially those utilizing PVDF, adheres to a systematic and rigorous general protocol. This procedure incorporates meticulous material preparation, deliberate mixing, and systematic assembly to attain flexible, sensitive, and resilient properties vital for sophisticated electronic skin. The process is consistent across many e-skin types, with differences mainly in the active ingredients and their concentrations.

3.1 General Fabrication Procedure

The fabrication process for each e-skin device type generally follows these steps[48]:

- **Initial Mixture Preparation:** This phase commences with the precise measurement of selected active components, including Polyvinylidene Fluoride (PVDF), Molybdenum Disulphide (MoS_2), and Barium Titanite (BaTiO_3), chosen for their distinct contributions to the qualities of the e-skin. The components are carefully blended in a container to guarantee uniform distribution. Two components of a biocompatible binding polymer (e.g., Eco-Flex cure silicone rubber Part A and Part B) are combined in a precise ratio. The produced polymer mixture is subsequently incorporated into the active components within the container, and the amalgamation is meticulously agitated. This procedure is crucial for maintaining uniform material qualities and ensuring the active components are evenly dispersed inside the flexible polymer matrix, which contributes to the e-skin's comfort and longevity.

- **Curing/Drying:** After thorough mixing, the solution-filled container is typically left overnight. This allows the binding polymer to cure, transforming the liquid mixture into a solid yet highly flexible and durable material. The overnight drying also ensures optimal mechanical properties and structural integrity.
- **Device Formation:** Once the material has fully dried and cured, a precisely cut piece of the prepared material, with a specific area (e.g., a square centimetre), forms the core of the e-skin sensor device. This piece is then strategically sandwiched between two pieces of copper tape. These copper tapes serve as crucial electrical contacts or electrodes, facilitating the capture of electrical signals generated by the piezoelectric or piezoresistive effects within the e-skin material when subjected to mechanical stimuli. This selective copper tape electrode placement is a key engineering consideration for reliable sensor systems.
- **Encapsulation:** In many fabrication protocols, an optional yet important additional layer of the mixed binding polymer is poured over the prepared device containing the copper tape. This serves as a final encapsulation step, providing further protection to the active material and electrical contacts from environmental degradation, mechanical damage, and moisture. This resilient encapsulation highlights the engineering challenges and creative ideas for producing dependable and robust sensor systems, contributing to their long-term stability and performance.

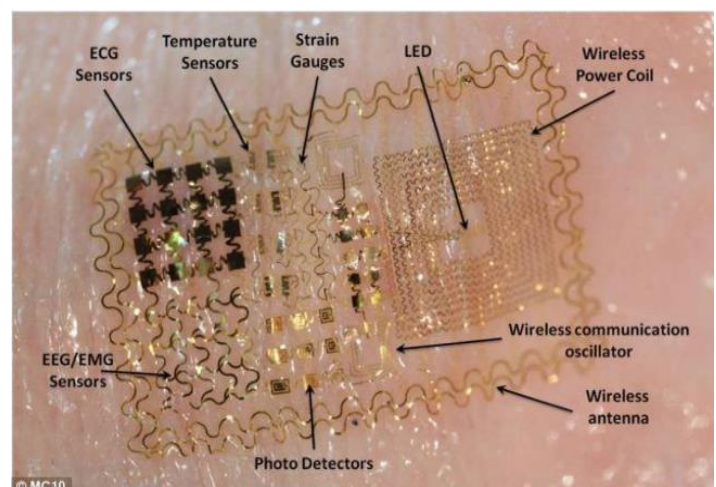


Figure 3. Flexible multifunctional electronic patch for health monitoring: Patch integrates PVDF-based piezoelectric sensors with ECG, EEG/EMG, temperature, and strain sensing units, combined with photodetectors and an LED for multimodal monitoring. Wireless module includes power coil, oscillator, and antenna, enabling continuous, untethered bio-signal acquisition. Demonstrates IoT-ready operation with real-time physiological tracking.

3.2 Specific Material Preparations

While the general procedure remained consistent, the specific active materials and their combinations varied to optimize properties for diverse applications:

- **MoS₂ Devices:** E-skin devices were prepared primarily using MoS₂ as the active material.
- **BaTiO₃ Devices:** E-skin devices were fabricated using BaTiO₃ as the active material.
- **PVDF Devices:** E-skin devices were made with PVDF as the active material. Additionally, devices with different proportions of PVDF were also prepared to examine concentration-dependent effects.
- **MoS₂+PVDF Devices:** This involved combining MoS₂ and PVDF as active materials. Variations in the amount of MoS₂ were explored while keeping the PVDF content constant to assess their synergistic effects.
- **BaTiO₃+PVDF Devices:** E-skin devices were created using a mixture of BaTiO₃ and PVDF. Different concentrations of BaTiO₃ were investigated while maintaining a consistent amount of PVDF.
- **BaTiO₃+MoS₂ Devices:** E-skin devices were constructed with a mix of BaTiO₃ and MoS₂[49]. The procedure comprised preparing devices with various quantities of BaTiO₃ while keeping the MoS₂ content fixed.
- **MoS₂+BaTiO₃+PVDF Devices:** This involved a more complex ternary mixture of MoS₂, BaTiO₃, and PVDF as the active materials, allowing for the optimization of multiple properties simultaneously.

This multi-step process is precisely tailored for different material combinations and concentrations, with each variation designed to optimize properties such as piezo resistivity (the alteration in electrical resistance due to mechanical strain) and surface characteristics (e.g., hydrophilicity/hydrophobicity), which are essential for the optimal performance of sensitive and flexible electronic skin in its various applications.

To achieve reliable and high-performance e-skin devices, the choice of materials and fabrication methods plays a critical role. Table 2 summarizes the commonly used substrates, conductive traces, encapsulation layers, and active components, along with the key fabrication techniques adopted for each category.

Table 2. Summary of Materials and Fabrication Techniques

Component	Common Materials	Key Fabrication Techniques
Substrate	PDMS, Polyimide (PI), Polyurethane (PU), Polyethylene Terephthalate (PET)	Spin coating, Electrospinning, Spray coating[50]
Conductive Traces	Liquid metal alloys, silver nanowires[51], CNTs	Inkjet printing, Screen printing, Lithography, Roll-to-roll processing
Encapsulation	Parylene, Eco flex, Silicone	Vapour deposition, Lamination
Active Components	Silicon nanomembranes, Organic Semiconductors	Transfer printing, Pick-and-place method

4. Results and Discussion

This study demonstrates that PVDF nanocomposites enhanced with MoS₂ and BaTiO₃ exhibit superior piezoelectric, piezoresistive, and mechanical properties[52], making them highly suitable for advanced tactile sensing in electronic skin applications. The integration of a flexible Eco-Flex silicone matrix ensures mechanical durability and long-term stability under repeated deformation. These sensors display high sensitivity[53], fast response times, and signal stability across various stimuli, supporting their use in real-time prosthetic and robotic interfaces. Additionally, the seamless integration with IoT frameworks opens avenues for remote monitoring, gesture control, and personalized healthcare. While challenges remain in large-scale manufacturing and advanced signal

processing, future developments in AI-driven adaptive sensing and self-powered systems hold promise for fully autonomous, biocompatible, and commercially viable e-skin technologies[54].

Table 3. presents a quantitative comparison of various PVDF-based electronic skin devices, highlighting their key performance metrics such as sensitivity, response time, durability, and output mode. It provides a clear overview of how different material composites and designs influence the sensing capabilities and practical applications of e-skin technologies. This comparison aids in evaluating the suitability of each device for specific real-time monitoring and human-machine interaction scenarios.

Table 3. Quantitative Comparison Table

Device Type	Stimulus	Range	Sensitivity	LOD	Response
PVDF- MoS ₂ composite	Pressure	0-250 Pa	314 kPa ⁻¹	0.5 Pa	40/60 ms
PVDF-HFP	Pressure	0-200 kPa	0.468 pF/Pa	0.065 Pa	0.1mm dielectric layer
PVDF-HFP	Pressure	0-200 kPa	9.51 kPa ⁻¹	Not specified	Not specified
PVDF/ZnO/Graphene Hybrid	Pressure	0-310 kPa	3.2 mV/kPa	Not specified	Not specified
PVDF- based capacitive sensor	Pressure	0-200 kPa	5.734% kPa ⁻¹	Not specified	200ms

Device Type	Cycles	Output Mode	Thickness	Test Conditions
PVDF- MoS ₂ composite	10 ⁵ cycles	Piezoelectric	200μm	Ambient lab
PVDF-HFP	Not specified	Capacitive	Not specified	Not specified
PVDF-HFP	Not specified	Capacitive	Not specified	Not specified
PVDF/ZnO/Graphene Hybrid	Not specified	Piezoelectric and Thermoresistive	80μm	Not specified
PVDF- based capacitive sensor	>10 ⁵ cycles	Capacitive	Not specified	Not specified

5. Conclusion

This review paper highlights the crucial role of PVDF-based nanocomposites in the evolution of the e-skin technology. By systematically integrating advanced filler such as MoS₂ and BaTiO₃ into PVDF matrices, researchers have demonstrated remarkable improvements in sensitivity, flexibility, and durability, thereby meeting the stringent requirements of next-generation e-skin devices[55]. Unlike previous surveys, this review contributes three distinct elements: (i) a unified fabrication checklist for PVDF/MoS₂/BaTiO₃ e-skins, (ii) a normalized benchmark table consolidating device-level performance metrics, and (iii) a standardized nomenclature for key parameters used.

The analysis underscores that PVDF nanocomposite e-skins exhibit fast response/recovery times, robustness across 10⁴-10⁵ cycles, and inherent self-powered operation- making them particularly suited for integration into IoT. Furthermore, the normalized comparison reveals that device performance is highly dependent on filler type, substrate selection, and test conditions, offering valuable guidelines for reproducibility and optimization.

Overall, PVDF-based e-skins represent a significant leap toward intelligent, biocompatible, and energy-efficient human-machine interfaces. The findings of this review provide both a practical roadmap and a reference baseline for researchers aiming to design scalable, robust, and IoT-ready e-skin technologies.

6. Future Scope

The future trajectory of PVDF-based e-skin research is poised to expand across materials, device engineering, and system-level integration. Building upon the fabrication checklist and benchmark data compile in this review, several opportunities emerge:

- **Advances Materials:** Development of ternary and quaternary PVDF composites (e.g., PVDF/MoS₂/BaTiO₃/Graphene)[56] will allow researchers to exploit synergistic effects of multiple fillers, leading to simultaneous improvements in piezoelectric output, flexibility, and durability. Such hybrid systems may also open avenues for multifunctional sensing, including pressure, strain, and temperature in a single platform.
- **Scalable Manufacturing:** Future work should focus on scaling lab-level fabrication techniques into cost-effective roll-to-roll processing[57],

screen printing, and 3D printing. These scalable methods will ensure reproducibility, enable large-area e-skin production, and accelerate industrial adoption in robotics, healthcare, and consumer electronics.

- **AI and IoT Integration:** Embedding PVDF-based e-skin into IoT networks and pairing them with AI-driven analytics will allow predictive health monitoring, real-time adaptive calibration, and intelligent signal interpretation. Such integration will push e-skins beyond simple sensors toward fully autonomous smart interfaces for human-machine interaction.
- **Healthcare Applications:** PVDF nanocomposite e-skins hold promise in wound healing patches, prosthetic limb feedback systems, and drug delivery platforms. Clinical translation will require extensive biocompatibility validation, long-term reliability testing, and integration to wearable or implantable medical systems for real-world healthcare applications.
- **Self-Healing and Sustainability:** Incorporation of self-healing elastomers and biodegradable polymers will significantly extend device lifetimes[58] while addressing environmental concerns. Sustainable PVDF composites will reduce electronic waste and contribute to the development of eco-friendly, next-generation e-skins.

By addressing scalability, durability, and system integration challenges, future PVDF nanocomposite e-skins are expected to evolve from proof-of-concept devices to commercially viable smart interfaces that bridge biology and technology.

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