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

Yatin Kohli[1], Mrinmoy Misra[2]
[1]SRM Institute of Science and Technology
Kattankulathur, Chennai, Tamil Nadu- 603203
[1]yk9618@srmist.edu.in; [2]mrinmoy.mishra@jaipur.manipal.edu
[2]Manipal University Jaipur
Dehmi Kalan, Jaipur, Rajasthan- 303007

Abstract
Human skin represents an extraordinary example of biological engineering, inspiring intensive research into electronic skin (e-skin)—flexible, elastic electronic materials that mimic its sensory capabilities. This review focuses on the pivotal role of polyvinylidene fluoride (PVDF) nanocomposites in advancing e-skin technology. The study critically explores the development of highly sensitive, durable, and flexible piezoelectric materials essential for next-generation e-skin sensors, particularly in the context of their integration within the rapidly expanding Internet of Things (IoT) ecosystem. At the heart of e-skin functionality is **piezoelectricity**, a property in which certain materials generate electric charges under mechanical stress. The review examines the theoretical principles behind piezoelectricity. It highlights PVDF's inherent advantages—its semi-crystalline structure and strong dipole moments—which make it an excellent material for converting mechanical stimuli into electrical signals. The work delves into the incorporation of advanced fillers like two-dimensional (2D) materials (e.g., MoS_2) and ceramics (e.g., $BaTiO_3$) into PVDF matrices. These additions enhance the piezoelectric, piezoresistive, and hydrophilic properties of the material, critical for creating sensitive and flexible e-skin systems. Biocompatible polymers such as silicone rubber (Eco-Flex) are also explored for improving elasticity, stretchability, and physiological compatibility. Furthermore, the study reviews innovative manufacturing techniques, including precision layering and encapsulation methods, to address engineering challenges in developing reliable sensor systems. Beyond material science, the paper highlights e-skin's transformative role in IoT, including applications in gesture control interfaces, environmental monitoring, smart textiles, personalized healthcare, and industrial automation. Challenges such as long-term stability, self-healing, scalable production, and advanced signal processing are discussed. Finally, the review envisions future e-skin developments featuring AI-driven adaptive sensing, predictive analytics, self-sustainability, and seamless biological integration. Overall, this comprehensive study underscores the immense potential of PVDF-based e-skins in shaping the future of intelligent, responsive, and interconnected electronic systems.

Keywords**:** E-Skin, PVDF, Nanocomposite, Sensors, IOT, Human-Machine Interactions, Robotics Healthcare

1. *Introduction*
The human skin, an astonishing feat of natural engineering, has inspired the creation of electronic skin (e-skin)—flexible, elastic materials designed to duplicate its sophisticated sensory capabilities for advanced human-machine interaction. Featuring networks of mechanoreceptors, thermoreceptors, and nociceptors, biological skin offers sophisticated awareness of touch, temperature, and pain, setting a benchmark for e-skin innovation [1]. This paper focuses on the crucial role of polyvinylidene fluoride (PVDF) nanocomposites in advancing e-skin technology, notably in generating durable, sensitive, and flexible piezoelectric materials. These materials are vital for constructing next-generation e-skin sensors, with seamless integration into the rapidly growing Internet of Things (IoT) ecosystem, ultimately altering how humans interact with intelligent digital environments [2].

1.1 Introduction to Work Done

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. By integrating sensors and actuators onto flexible substrates, e-skin can detect external stimuli and respond in ways like physiological reactions. This technology has transformative potential across fields like advanced prosthetics, robotics, wearable tech, and healthcare monitoring, enabling intuitive human-computer interaction and continuous, non-invasive health tracking. With applications ranging from sensitive(Kim et al., 2009; Vosgueritchian et al., 2012) robotic touch to environmental sensing and personalized medical diagnostics, e-skin bridges the gap between humans and machines. The use of PVDF nanocomposites combined with IoT technologies promises a future of seamless, intelligent connectivity, making electronic systems an almost natural extension of the human body.

1.1.2 Potential Applications

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

- **Robotics**: E-skin enhances robotic systems by providing them with a feeling of touch, 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(Moon et al., 2013) interactions with people and objects. Using materials like PDMS polymer nanocomposites with carbon nanotubes, flexible sensors can measure 3D contact forces with high precision, making robots more sensitive and adaptable(Lipomi et al., 2011).

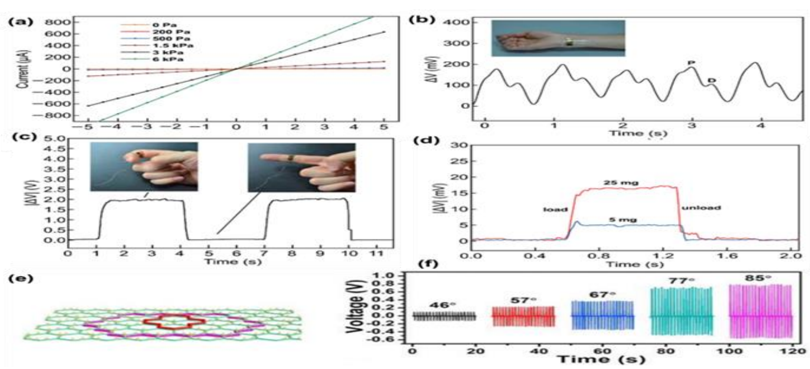

Fig.1. (a) the sensor's current-voltage curves at different pressures; (b) the detection of wrist pulses in humans; and (c) the observation of human finger bending (d) Micro pressure detection (e) Schematic representation of the e-skin's bending deformation; (f) the e-skin's piezoelectric voltage at various bending angles.

- **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. By sensing the forces applied during grasping and manipulation activities, robots can intelligently adapt their grip. This allows them to firmly and securely hold objects of widely varying sizes, textures, and shapes, reducing the risk of slippage or damage, and enabling more complex and delicate tasks.

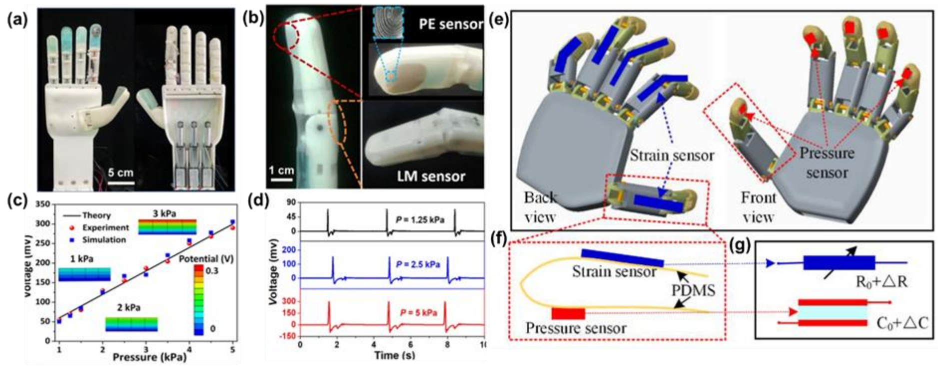

Figure 2. (a) A biomimetic manipulator; (b) Flexible piezoelectric and strain sensors as elements of a cohesive sensing system; (c) Fluctuations in the voltage output generated by applied pressure on the flexible piezoelectric layer (e) A diagram illustrating the incorporation of pressure and strain sensors within the robotic finger; (d) An analysis of the piezoelectric voltage relative to the applied pressure.

- **E-skin for Prosthetic Devices**: E-skin integrated into prosthetics and wearable devices enhances sensory feedback, allowing users to experience sensations like natural touch. In healthcare, it enables continuous vital sign monitoring, improves surgical precision through real-time tactile feedback, and supports rehabilitation by providing responsive, adaptive feedback(Dargahi & Najarian, 2004; Sabry & Hussein, 2019).
- **Human-Machine Interfaces**: E-skin is a critical enabler for the development of highly advanced human-machine interfaces that respond intuitively to touch and gestures. By embedding tactile sensors into touchscreens, touchpads, and other interactive surfaces, e-skin can dramatically enhance usability. Furthermore, it unlocks novel interaction modalities, moving beyond simple button presses to more nuanced and expressive gestural controls, making digital interactions feel more natural and responsive.
- **Environmental Monitoring**: The versatile nature of e-skin allows for its effective deployment in sophisticated environmental monitoring systems. These systems can accurately detect minute changes in various physical parameters such as pressure, humidity, and temperature within a given space. Tactile sensors, when seamlessly integrated into smart surfaces or structures, facilitate real-time monitoring of critical infrastructure (like bridges or buildings), sensitive ecosystems, and natural habitats, providing early warnings for potential issues(Dong et al., 2017).
- **Industrial Automation and Quality Control**: In demanding industrial settings, e-skin serves as a vital tactile sensor for highly precise robots and advanced automation systems. This enables exceptionally precise manipulation of objects and rigorous quality control inspections. The tactile feedback provided by e-skin helps to ensure consistent product quality, facilitates the immediate detection of defects, and allows for the continuous optimization of complex manufacturing processes, leading to increased efficiency and reduced waste.
- **Smart Textiles and Fabrics**: Integrating e-skin into smart textiles enables interactive clothing and advanced wearable health monitors that can track body movements, posture, and provide real-time feedback for rehabilitation or sports training. This innovation opens new possibilities across industries like healthcare, robotics, and consumer electronics, transforming how we interact with technology(Seminara et al., 2014).

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**: A paramount advantage of e-skin sensors is their exceptional sensitivity. They can detect a wide array of physical stimuli, including delicate touch, varying levels of pressure, temperature fluctuations, and even subtle changes in humidity. This multifaceted sensitivity makes them incredibly versatile and adaptable for deployment in diverse and complex environments, from medical diagnostics to industrial inspection(Seminara et al., 2014).

- **Durability**: Despite their often thin and flexible form factor, electronic skin designs prioritize robustness. They are engineered to withstand significant wear and tear, ensuring long-lasting performance even under continuous mechanical stress or repeated deformation. This durability is a critical differentiator when compared to more rigid and fragile traditional sensors, making e-skin suitable for prolonged use in dynamic applications(Pan et al., 2024).
- **Biocompatibility**: A critical consideration for applications requiring direct human contact is biocompatibility. Specific varieties of electronic skin are meticulously designed for biocompatibility, allowing safe utilization in medical applications 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, or immersing users fully in virtual reality environments through responsive tactile sensations.
- **Customization**: Electronic skin technologies offer a high degree of customization. They can be precisely tailored to suit vastly different needs, whether it's configuring specific sensor types, arranging sensors in bespoke patterns for localized sensing, or integrating unique functionalities. This adaptability significantly enhances its versatility across a multitude of applications(Kulkarni & Kumari, 2023).
- **Energy Efficiency**: Many electronic skin technologies are designed with energy efficiency as a core principle. They often require minimal power consumption for continuous operation, which is a significant advantage for battery-powered wearable devices and long-term monitoring systems where frequent recharging is impractical(Kulkarni & Kumari, 2023).
- **Integration**: E-skin is engineered for seamless integration into existing systems and device architectures. This ease of integration positions it as a cost-effective and efficient solution for upgrading conventional devices with advanced sensing capabilities, streamlining the adoption of new functionalities.
- **Remote Monitoring**: The inherent connectivity potential of electronic skin enables robust remote monitoring of various parameters. This includes critical data such as vital signs in healthcare or environmental conditions in industrial or ecological settings. 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. Its multidisciplinary nature fosters advancements in healthcare, robotics, human-computer interaction, and materials science, pushing the boundaries of what is technologically achievable(Zhang et al., 2023).

2. Background Material

2.1 Conceptual Overview

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, 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 and revolutionizes healthcare through continuous, real-time health monitoring and tailored feedback, facilitating superior health management.

- **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. 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.

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 [15].

- **General Fabrication Procedure**

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

- **Initial Mixture Preparation:** This phase commences with the precise measurement of selected active components, including Polyvinylidene Fluoride (PVDF), Molybdenum Disulphide (MoS2), and Barium Titanite (BaTiO3), 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 [16].
- **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 (Optional but Recommended):** In many fabrication protocols, an 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(Luo et al., 2021).

- **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. 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.

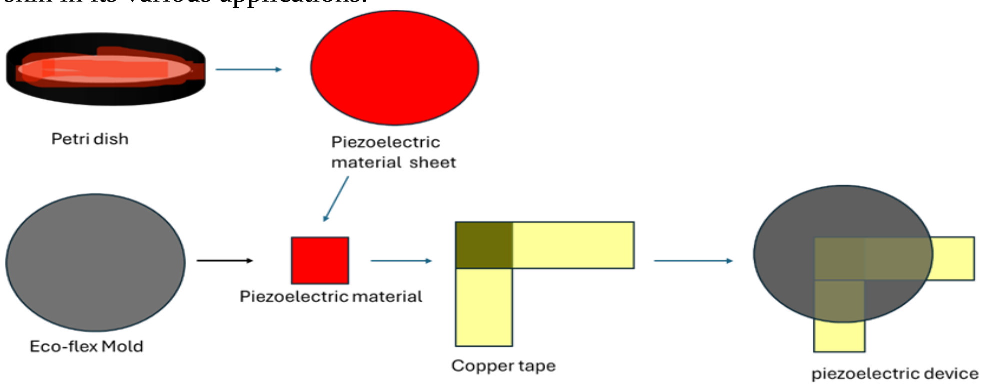

Fig. 3. Making of the Device

4. Results and Discussion

This study demonstrates that PVDF nanocomposites enhanced with MoS_2 and $BaTiO_3$ exhibit superior piezoelectric, piezoresistive, and mechanical properties, making them highly suitable for advanced tactile sensing in electronic skin applications. The integration of a flexible Eco-Flex silicone matrix ensures mechanical durability(Ai et al., 2017; T. Lv et al., 2018) and long-term stability under repeated deformation. These sensors display high sensitivity, 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(Deng et al., 2019; He et al., 2017).

5. Conclusion

This extensive study highlights the crucial importance of PVDF-based nanocomposites in the progression of electronic skin technology. By adeptly integrating the intrinsic piezoelectric characteristics of PVDF with sophisticated fillers like MoS_2 and $BaTiO_3$, the resultant materials exhibit improved sensitivity, mechanical flexibility, and durability, meeting essential criteria for next-generation e-skin sensors. The effective fabrication processes, encompassing meticulous mixture preparation and encapsulation, produce devices that enable stable, real-time sensing under varying mechanical circumstances. The incorporation of these e-skin systems into IoT ecosystems presents revolutionary opportunities in robotics, prosthetics, healthcare monitoring, and industrial automation. Nonetheless, the path to mainstream adoption necessitates addressing persistent issues associated with scalability, durability, and sophisticated signal processing. Future advancements in AI-driven adaptive sensing and enhanced biocompatibility are poised to actualize the concept of genuinely intelligent, responsive, and sustainable electronic skin. PVDF nanocomposite e-skins represent a significant advancement in human-machine interfaces and wearable technology, with exceptional potential for improving tactile perception, environmental awareness, and tailored healthcare in a connected environment.

6. Future Scope

The trajectory of PVDF-based electronic skin technology is marked by continuous innovation, with its future applications holding immense promise across various critical domains. The ongoing research and development efforts are focused on expanding its functionalities and integrating it more deeply into human-centric technologies(Wang et al., 2021).

- **Wound Monitoring**: E-skin can revolutionize wound care by embedding sensitive sensors that continuously monitor temperature, humidity, and pH at the wound site. This real-time, non-invasive data enables early detection of complications and remote communication with healthcare providers for timely, personalized treatment.
- **Vital Signs Monitoring**: E-skin enables continuous, non-invasive monitoring of vital signs like heart rate, blood pressure, and respiration, eliminating the need for bulky medical devices. This allows healthcare providers to remotely track patients' health, (Ibrahim & Valle, 2018; X. Lv et al., 2023)especially those with chronic conditions, improving safety, comfort, and reducing hospital visits.
- **Drug Delivery**: An exciting future direction for e-skin lies in its potential for precise, controlled drug delivery. E-skin could be developed to release specific amounts of medication into the human body based on predetermined requirements or real-time physiological feedback. This offers a revolutionary approach, especially beneficial for patients who struggle with swallowing pills or require sustained, controlled drug release over time, ensuring optimal therapeutic effects with minimal patient effort.
- **Robotics and Prosthetics**: E-skin enhances robots' interaction by providing tactile sensing for delicate handling, safer human-robot collaboration, and intuitive responses to their surroundings. In prosthetics, it offers sensory feedback, making artificial limbs feel more natural and improving the user's perception of objects.

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