

Flexible Electronic Skin Sensors: Review

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Received: 5 Nov. 2024 / Revised: 20 Jan. 2025 / Accepted: 5 March 2025 / Published: 30 April 2025

Abstract: Traditional rigid electronics face critical challenges of non-conformability to multiple shapes. Flexible and stretchable electronics offer unique solutions to such critical challenges by allowing conformability to various shapes. Electronic skin (E-skin) sensors have emerged from the field of flexible electronics to mimic human skin's functional properties. By mimicking such properties, e-skin sensors have potential applications in several fields ranging from healthcare to robotics. This paper provides a comprehensive review of advancements in e-skin sensor technologies, highlighting sensing mechanisms used to convert external stimuli to electric signals, various sensor structures for effectively elevating sensing capabilities, and the materials utilized to achieve flexible and stretchable e-skins. We also discuss the potential application areas of e-skin sensor technologies and the challenges affecting e-skin sensor technologies. Achieving multi-functional e-skin sensors capable of simultaneously detecting various stimuli while maintaining mechanical properties like the human skin presents unique opportunities for future innovations in diverse fields.

Keywords: Flexible electronics, E-skin sensors, Substrates, Electrodes, Sensing mechanisms.

1. Introduction

The field of flexible electronics is an emerging research area where electronic circuits are mounted on flexible substrates to enable their application on curvilinear surfaces. Current electronic devices are mainly realized by mounting electronic components on rigid substrates [1]. Flexible and stretchable electronic devices provide an alternative to their rigid counterparts as they conform to curvilinear surfaces and detect signals more accurately and precisely. Work towards these uniquely structured electronic devices began approximately three decades ago and has seen significant progress over recent years [2].

Electronic skin (E-skin) sensors evolved from flexible electronics mainly due to the need for flexible, sensitive, and stable sensors that could be applied in various areas. These sensors are designed to satisfy several requirements for conformable pressure sensing on curvilinear surfaces. Their functional requirements

demand that they achieve high-performance sensing even under different deformation modes, including bending, twisting, and stretching. Due to their flexibility and stretchability, e-skins have potential applications in wearable electronics, human health monitoring, robotics, and medical devices [2].

Despite the promise these sensors show in diverse fields, they are still plagued by challenges in fulfilling design requirements of high performance and reliability while being subjected to various modes of deformation [2]. The drive towards adapting e-skins in healthcare monitoring and robotics poses further challenges for these sensors to achieve multimodal sensing capabilities, thus sensing more than a single source of stimuli [3]. However, there have been growing efforts to reduce the limitations of e-skin sensors, as will be discussed later in this paper. Addressing these challenges requires interdisciplinary collaboration across several fields.

2. Sensing Mechanisms for E-skins

The mode of signal transduction is an essential consideration for developing e-skin sensors. By studying human skin composition, sensing mechanisms for e-skins have advanced. Some sensing mechanisms widely employed for developing e-skins with good sensing capabilities generally include piezoresistive, capacitive, piezoelectric, and triboelectric sensing [4]. Other sensing mechanisms also utilized for signal transduction include iontronic [5], magnetoresistive [6], optical [7], thermal [8], and hybrid [9] mechanisms. These mechanisms have demonstrated promise in achieving sensors with good sensing capabilities, as will be further discussed.

2.1. Piezoresistive Sensing

Piezoresistive sensing relies on a change in a material's resistance to achieve signal transduction. When mechanical stress is exerted on the material, the material deforms, and a change in its resistance is observed. The deformation is mapped to the corresponding applied force or pressure. Thus, a proportional relationship is established between the change in resistance and applied deformation [10]. This sensing mechanism is illustrated in Fig. 1. The variation in resistance could be attributed to the natural resistivity of material under variable pressure [11]. The resistance of the material is fundamentally governed by the following equation.

$$R = \frac{\rho l}{A} \quad (1)$$

where R is the material resistance, ρ is its resistivity, A is the cross-sectional area and l is the length of the material [11].

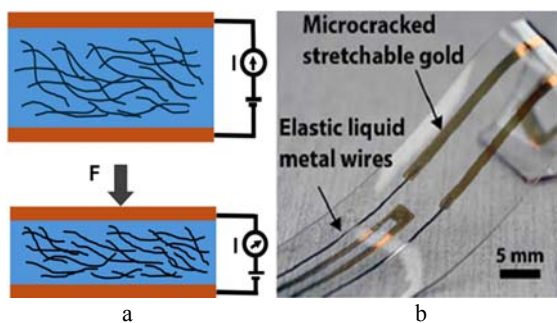


Fig. 1. a. Illustration of piezoresistive sensing. b. Magnified image of sample piezoresistive e-skin. Reproduced with permission. [16] Copyright 2015 John Wiley & Sons, Inc.

Piezoresistive sensing is comparatively a preferable sensing mechanism since changes produced by stimuli such as pressure, temperature, and strain can easily be mapped to a corresponding resistance

change and detected by peripheral circuitry [12]. E-skin sensors with this sensing mechanism have advantages, including low cost of fabrication, low power consumption, good stability, and a simple signal-sensing mechanism [13].

Piezoresistive e-skin sensors made from carbon, metal, and conductive polymer materials have demonstrated excellent mechanical and electrical properties [10]. These sensors have been utilized for applications, including human health monitoring and soft robotics, to advance sensing technology. Liu et al. developed a piezoresistive textile-based pressure sensor using Carbon nanotubes (CNTs) and graphene-polymer nanocomposites, achieving a sensitivity reaching 14.4 kPa^{-1} with a low detection limit of 2 Pa [14].

Various methods have also been explored to enhance the sensing properties of piezoresistive e-skin sensors using new materials and structures. More recently, Zhang et al. developed a piezoresistive e-skin sensor using a PDMS substrate and Waterborne Polyurethane (WPU) and silver nanowire composite, achieving a remarkable sensitivity of $1.04 \times 10^6 \text{ kPa}^{-1}$ in the pressure range from 0 to 27kPa [15]. The performance characteristics of various piezoresistive e-skin sensors are summarized in Table 1. Performance characteristics examined for these sensors generally include determining the sensor's sensitivity, the spatial resolution of the sensor, how fast it responds to a stimulus, how easily it recovers after it deforms, as well as the life cycle of the sensor based on cyclic tests. The kinds of materials used to fabricate the sensor were also considered. These performance characteristics of e-skin sensors combine to give an idea of how close they are to the sensing capabilities of human skin.

2.2. Capacitive Sensing

This sensing mechanism relies on the capacitance change in a material under mechanical deformation. Capacitive e-skin sensors rely on the principle of capacitance, thus the ability of a system to store electric charge. They comprise a dielectric layer sandwiched between two flexible electrodes and enclosed by a substrate [20]. When pressure is applied to the sensor, it changes the material's area and reduces the distance between the electrodes, causing a variation in the capacitance of the sensor [11]. This relationship is shown in the following equation and illustrated in Fig. 2.

$$C = \frac{\epsilon A}{d}, \quad (2)$$

where the capacitance has a direct relationship with area and an inverse relationship with distance. A is the area of the electrode material, whereas d is the gap distance between the electrodes, and ϵ is the permittivity of the dielectric material.

Table 1. Summary of results of piezoresistive sensing for e-skin applications.

Reference	Materials	Sensitivity	Spatial Resolution	Response Time	Recovery Time	Stability
[14]	Polyester/Nylon/ Ni/CNT ^e /VHB ^f	14.4 kPa ⁻¹ @ < 3.5 kPa	n/a	24 ms @ 2.9 kPa	30 ms @ 2.9 kPa	1000 cycles
[15]	PDMS ^a /WPU ^b / AgNWs ^c	1.04 x 10 ⁶ kPa ⁻¹ @ 0-27 kPa, 9.5 x 10 ⁴ kPa ⁻¹ @ 27 -33 kPa	n/a ^d	160 ms	160 ms	> 1000 cycles
[17]	PDMS/MWCNTs ^g	15.1 kPa ⁻¹ @ < 0.5 kPa	1 cm × 1.5 cm sensile, 10 × 10 array	~ 0.04 s	~ 0.04 s	> 1000 cycles
[18]	PDMS/GNPs ^h / PEO ⁱ /MWCNTs	6.56 MPa ⁻¹ @ < 66 kPa, 0.335 kPa ⁻¹ @ 100 kPa	n/a	171 ms	110 ms	1000 cycles
[19]	PDMS/PPy ^j /Au	1907.2 kPa ⁻¹ @ 0-100 Pa	5 × 5 array	50 μs	6 ms	> 15 000 cycles

a. Polydimethyl Siloxane b. Water-borne Polyurethane c. Silver Nanowires d. Not available e. Carbon Nanotubes f. Very High Bonding g. Multi-walled Carbon Nanotubes h. Graphene Nanoplatelets i. Polyethylene Oxide j. Polypyrrole

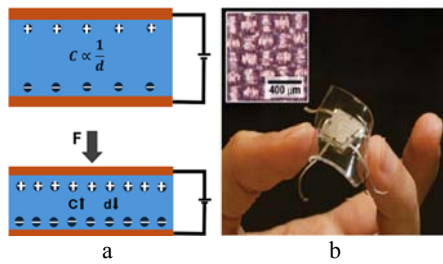


Fig. 2. a) Illustration of capacitive pressure sensing; b) Sample capacitive e-skin with an optical microscope view of a conductive textile electrode. Reproduced with permission. [24] Copyright 2014 John Wiley & Sons, Inc.

Capacitive e-skin sensors often present some advantages, including high-performance pressure sensing, low hysteresis, reduced response times, good stability, and a wide detection range [20]. Leveraging

these characteristics, there have been significant efforts to develop capacitive pressure sensors mirroring these features. Kang et al. developed a capacitive e-skin sensor using porous PDMS and Indium Tin Oxide (ITO)/Polyethylene Terephthalate (PET) films which achieved a sensitivity of 0.63 kPa⁻¹ and a low detection limit of 2.42 Pa [21]. Li et al. developed a flexible capacitive pressure sensor using bionic hybrid microstructures, achieving sensitivity reaching 3.17 kPa⁻¹ over a wide detection range [22]. Efforts have also been made to integrate these sensors into proximity detection for robotics and human-machine interfaces. Wu et al. further discuss the piezocapacitive transduction mechanism for proximity sensing and its applications in human-robot collaboration, and human-machine interfaces [23]. A summary of the performance characteristics of various capacitive e-skins sensors is shown in Table 2.

Table 2. Summary of results of capacitive sensing for e-skin applications.

Reference	Materials	Sensitivity	Spatial Resolution	Response Time	Recovery Time	Stability
[21]	PDMS/ITO ^a / PET ^b	0.63 kPa ⁻¹ , 0.009 kPa ⁻¹ @ > 90 kPa	0.9 × 0.9 cm sensile, 15 × 15 array (42 × 42 mm)	40 ms	< 1 s	> 10 000 cycles
[22]	PDMS/Ionic gel	3.17 kPa ⁻¹ @ 0-90 kPa	n/a	n/a	n/a	n/a
[24]	PDMS/FVMQe/ Cu/Sn	0.91 kPa ⁻¹ @ 0.5 kPa	n/a	< 40 ms	n/a	n/a
[25]	PDMS/AgNPs ^c / SBS ^d	0.21 kPa ⁻¹ @ < 2 kPa	0.16 mm ² pixel, 6 × 6 array (2 × 1.5 cm ²)	~ 40 ms	~ 10 ms	10 000 cycles
[26]	PDMS/Ag/Ni	0.159 kPa ⁻¹ @ 0-1 kPa	n/a	n/a	n/a	9200 cycles

a) Indium Tin Oxide; b) Polyethylene Terephthalate; c) Silver Nanoparticles; d) Poly(styrene-butadiene-styrene); e) Fluorosilicone.

2.3. Piezoelectric Sensing

Piezoelectric sensing generally utilizes the piezoelectric effect principle, where certain materials can generate electric charges when subjected to mechanical stress. When pressure or strain is exerted

on the material, it creates a deformation that causes the positions of opposite charges within the material to shift, thus producing an electric charge. The electric charge is proportional to the applied mechanical deformation. Table 3 highlights the performance characteristics of various e-skin sensors with

piezoelectric sensing. The operating principle for piezoelectric sensing is illustrated in Fig. 3.

Piezoelectric sensors generally comprise piezoelectric material as the active layer, conductive layers that transmit charges, and a substrate to encapsulate the structure and provide flexibility. Sensors developed using this mechanism have shown some advantages, including self-powering capabilities, high sensitivity, and detection of dynamic pressure in real-time, making them ideal for applications in robotics and prosthetics [27, 28].

By leveraging these advantages, Guan et al. developed a piezoelectric elastomer sensor that achieved an electrical signal output of 253 mV with applied pressure and a response time of 15 ms, demonstrating its ability to detect signals quickly [27]. Sultana et al. also developed a flexible piezoelectric e-skin using an electrospun poly(l-lactic acid) PLLA nanofiber membrane, achieving a sensitivity reaching 22 VN^{-1} , stable over 37500 cycles [29].

Table 3. Summary of results of piezoelectric sensing for e-skin applications.

Reference	Materials	Sensitivity	Power Density	Open Circuit Voltage	Spatial Resolution	Stability
[27]	PVDF ^a /PAN ^b	5.6503 kPa^{-1} @ 40.59 kPa	n/a	253 mV	$10 \text{ mm} \times 10 \text{ mm} \times 1 \text{ mm}$	10 000 cycles
[29]	PLLA ^c /Cu/Ni	22 V N^{-1}	0.07 mW cm^{-2}	1 V @ 15 Hz	n/a	375 000 cycles
[31]	PDMS/Ecoflex/PVDF	$0.33 \text{ mV } \mu \text{ } \epsilon^{-1}$	n/a	n/a	$3.5 \text{ cm} \times 1.5 \text{ cm}$	n/a
[32]	SiO ₂ ^d /PVDF	5.6503 kPa^{-1} @ $150\text{-}510 \text{ kPa}$	39.24 mW m^{-2}	n/a	n/a	n/a

a) Poly(vinylidene fluoride); b) Polyacrylonitrile; c) Poly(l-lactic acid); d) Silicon dioxide

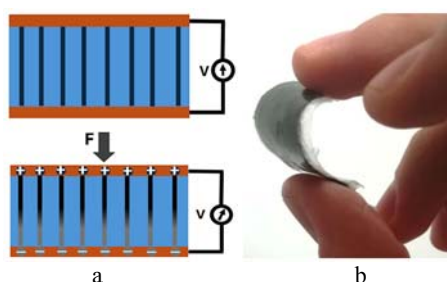


Fig. 3. a. Illustration of piezoelectric pressure sensing. b. Sample piezoelectric e-skin sensor: Reproduced under the terms of the CC BY license. [30] Copyright 2023, The Authors, published by MDPI.

2.4. Triboelectric Sensing

Triboelectric sensing relies on the principle of triboelectric effect where a material becomes electrically charged due to contact and separation from another material. The generated charge is detected as an electrical signal and thus used to detect mechanical stimuli. The operating principle of this sensing mechanism is illustrated in Fig. 4. Electronic skin sensors developed using triboelectric sensing generally comprise a triboelectric layer combined with electrodes and flexible substrates to provide mechanical support. It also offers advantages, including its ability to generate electrical signals without an external power supply, making it suitable for energy-harvesting applications [33].

Triboelectric sensors also exhibit high sensitivity, can detect dynamic pressure, and offer excellent flexibility, making them suitable for robotics and healthcare monitoring [28]. Pu et al. developed a triboelectric e-skin sensor using a hydrogel sealed between two elastomer films of PDMS or Very High Bonding (VHB), achieving remarkable stretchability of up to 1160 % with a peak power density of $35 \text{ mW}\cdot\text{m}^{-2}$ [34]. Arief et al. also developed a Triboelectric e-skin using fluoroelastomer, Laser-Induced Graphene (LIG), and Titanium Dioxide (TiO₂) to achieve a power density of $715 \text{ mW}\cdot\text{m}^{-2}$ and maintained a high electrical output while subjected to 200 % elongation [37]. Table 4 provides a summary of the performance characteristics of various triboelectric e-skin sensors, including the various materials used, the sensitivity of each sensor, the power density, open-circuit voltage, spatial resolution, and stability, which are all crucial parameters.

2.5. Other Sensing Mechanisms

Several other transduction mechanisms, including optical, magnetoresistive, iontronic, and thermal, have been used for e-skin sensors. The optical sensing mechanism uses light to detect various stimuli, including pressure, temperature, and strain. These sensors offer high-precision sensing, low signal interference, and are suited for use in extreme weather conditions [38].

Based on the promising properties of optical sensing, Zhang et al. developed a highly sensitive optical e-skin sensor using glass micro/nanofibers in thin layers of PDMS, which achieved a sensitivity reaching 1870 kPa^{-1} and a low detection limit of 7 mPa [7]. Magnetoresistive sensing measures change in a material's resistance in response to a magnetic field. These sensors can detect objects' position, orientation, and magnetic field properties, thus enhancing tactile perception [6]. This is especially useful in developing magnetoresistive sensors that enable touchless interaction and real-time pressure and temperature detection, as highlighted in Bermúdez and Makarov [39]. Melzer et al. developed a magnetoresistive sensor exhibiting high sensitivity and flexibility reaching strains exceeding 270 % and stable over 1000 cycles [40].

Iontronic sensing generally involves using ions as sensing elements to detect external stimuli. Iontronic sensors detect external stimuli such as pressure, temperature, or humidity by redistributing ions in

response to applied stimuli [41]. They are useful in human-machine interaction and human health monitoring. Guo et al. developed an e-skin sensor based on iontronic sensing using photocurable hydrogel to achieve a sensitivity of 171 kPa^{-1} within the pressure range from 0 to 60 kPa [5].

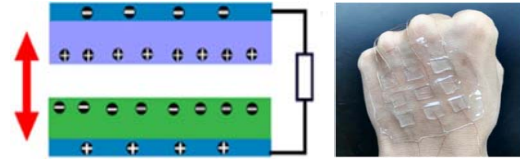


Fig. 4. a. Illustration of triboelectric pressure sensing based on vertical contact separation mode: Reproduced with permission. [11] Copyright 2021 John Wiley & Sons Inc., b. Sample triboelectric e-skin: Reproduced under the terms of the CC BY-NC license. [34] Copyright 2017, The Authors, published by American Association for the Advancement of Science (AAAS).

Table 4. Summary of results of triboelectric sensing for e-skin applications.

Reference	Materials	Sensitivity	Power Density	Open Circuit Voltage	Spatial Resolution	Stability
[34]	PDMS/VHB/ Hydrogel	0.013 kPa^{-1} @ > 70 kPa	35 mW m^{-2} @ 70 $\text{M}\Omega$, 328 mW m^{-2} @ 7 $\text{M}\Omega$	145 V, 182 V	$1 \text{ cm} \times 1 \text{ cm}$ sensible, 3×3 array	20 000 cycles
[35]	PDMS/P(VDF- TrFE) ^a /AgNWs	0.55 V kPa^{-1} @ 19.8 kPa	$46.7 \mu\text{W cm}^{-2}$	64 V	$1 \times 1.5 \text{ cm}^2$, $1.5 \times 1.5 \text{ cm}^2$ sensible	10 000 cycles
[36]	PDMS/Ionogel	1.76 V N^{-1} @ 0.1-1 N	n/a	1.38 V @ 8 Hz	$2 \times 1.5 \text{ cm}$	6000 cycles
[37]	PDMS/FKM ^b / LIG ^c /TiO ₂ ^d	n/a	715 mW m^{-2}	148 V	$10 \text{ mm} \times$ 10 mm	3000 cycles

a) Poly(vinylidene fluoride-trifluoroethylene); b) Fluoroelastomer; c) Laser-Induced Graphene; d) Titanium Dioxide.

3. Design and Material Composition of E-skin Sensors

E-skin sensors are primarily composed of flexible multilayer structures which are crucial for the sensor's overall performance. These structures include flexible substrates, sensing layers, as well as external or integrated circuitry. This basic composition aids in detecting and converting external stimuli into electrical signals. The structural design of e-skin sensors also involves other approaches to enhance their functional properties, including sensitivity, stretchability, and many more. These approaches range from integrating novel structures like wavy and helical designs to enhancing sensing properties through surface-structured architectures.

3.1. Flexible Structures

Human skin can withstand deformation of up to 30 %, hence stretchability becomes a crucial requirement for e-skin sensors [42]. E-skins

fundamentally achieve stretchability through two widely accepted approaches, thus designing flexible structures from conventional materials or using innately stretchable materials to achieve stretchability [1, 2, 42]. Flexible structures are designed based on the rule that the bending strain of materials decreases with material thickness. Hence, various material types in the formats of ribbons and wires can achieve stretchability [42].

Innately stretchable materials also provide an alternative route to stretchable electronics. These materials have the innate property of stretchability and can recover their original state after applied deformation. They comprise elastomers and liquid metals with stretchability based on long polymer chains or weak intermolecular forces [42]. The development of e-skin sensors heavily relies on carefully selecting materials that satisfy core requirements and can conform to curvilinear surfaces while retaining their functionality under deformation. The growing interest in the field of flexible electronic devices has led to the emergence of a diverse range of materials to meet these core requirements.

3.1.1. Stretchable Substrates

Stretchable substrates serve as the platform for which functional components of e-skin sensors are integrated. E-skin sensors satisfy the requirements of conforming to curvilinear surfaces largely based on the ability of substrates to bend, stretch, and adhere to such surfaces, for instance, human skin.

3.1.1.1. Polymers

Polymers such as Polyimide, Polyaniline, Polyurethane, Polyethylene Terephthalate (PET), Acrylic, Hydrogenated Nitrile Rubber (HNBR), and Parylene have all been widely used as e-skin substrates due to their flexibility and stretchability. Polymers could generally also be used as encapsulation for electronic components of e-skin sensors. Polyurethane offers a large tear strength and resistance to abrasion compared to silicon rubbers and is thus ideal for substrates which will be subject to impact and scratches [42].

Acrylics can be used as passive substrates, while acrylic elastomers are softer than PDMS and offer high stretchability [42]. As shown in [43], the authors demonstrate using an acrylic elastomer as the substrate for fabricating compliant and stretchable electrodes with stretchability reaching 300 %.

3.1.1.2. Silicon-based Elastomers

These materials exhibit good mechanical adaptability and can withstand continuous deformation while recovering their elastic properties, making them great choices for e-skin applications [44]. They tend to possess high electrical conductivity, low glass transition temperature, large thermal coefficient of expansion, and high flexibility [42]. Polydimethylsiloxane (PDMS), Fluorosilicone, Ecoflex, and Dragon skin are among the commonly used elastomers for e-skins. PDMS is readily accessible and can be made using available laboratory techniques; hence, it tends to be a widely used elastomer for e-skin sensors [42]. Jiang et al. demonstrated using a PDMS substrate with a thin gold layer, achieving a stretchability of up to 300 % while remaining highly conductive [45]. Chen et al. also developed a strain sensor that comprised a PDMS film, graphene/silver nanoparticle network, and thermoplastic polyurethane. It achieved a high stretchability of up to 1000 % [46]. Ecoflex is also commonly used as a substrate material for e-skins. Based on its Young's modulus exceeding 125 kPa, it exhibits mechanical compliance like that of the human skin [47]. It is also biocompatible, highly stretchable, and easily adheres to the skin [48].

3.1.2. Sensing Layers

These are crucial components in designing e-skin sensors as they are the primary functional components

that interact with external stimuli and enable their conversion into electrical signals. They form the active materials of the e-skin sensor. They depend on the sensing mechanism for transducing stimuli into electrical signals that can be measured and processed. Sensing layers for e-skins generally comprise conductive materials such as conductive polymers in an elastomer matrix (for instance, CNTs in PDMS), piezoelectric materials, dielectric materials, triboelectric materials, and ionic conductors. Each of these materials plays a significant role in the sensing capabilities of e-skin sensors. Some sensing layers, like conductive polymers and ionic conductors, serve the dual purpose of also being used as electrodes to ensure reliable signal transmission while under deformation.

3.1.2.1. Conductive Polymers

These are kinds of polymers that possess a unique property of exhibiting metallic conductivity. They are usually elastic and can recover their original state after applied deformation [49]. This, coupled with their conductive properties, makes them suitable for various applications. In the case of e-skins, these polymers are usually made by combining stretchable polymers with conductive fillers like nanoparticles, nanotubes, or nanowires [50]. Nanoparticles tend to ensure greater mobility when used in a polymer matrix compared to nanotubes and nanowires [51]. Conductive polymers can generally be categorized into 1-dimensional (1D), 2-dimensional (2D), and 3-dimensional (3D) conductive polymers based on their composition. Examples of 1D, 2D, and 3D conductive polymers are polyacetylene, polythiophene, and polypyrrole, respectively [52].

Dinh et al. reported on an electrically conductive multiwalled carbon nanotube and polymer nanocomposite using various polymerization techniques. They achieved conductive films with stretchability ranging from 400 % to 1600 % depending on the fabrication process used [53]. Wang et al. reported an elastic conductor made of polyurethane and silver nanowires which had a high conductivity of 9190 S cm⁻¹ and stretchability reaching 310 % [54]. Kim et al. also demonstrated a stretchable conductor made of polyurethane containing spherical nanoparticles. The authors utilized two methods of fabrication, thus a Layer by Layer (LBL) deposition and Vapor-Assisted Flocculation. The LBL method yielded a polyurethane nanoparticle composite reaching a conductivity of 11000 S cm⁻¹ and a maximum strain of up to 115 % after lamination. In comparison, the VAP method yielded a conductivity of 1800 S cm⁻¹ and a maximum strain reaching 486 % after lamination [51].

3.1.2.2. Ionic Conductors

Ionic conductors are useful in electronic skin sensors as they facilitate sensing by converting stimuli

to electrical signals through ionic conduction. They offer important properties of biocompatibility and flexibility, making them suitable for e-skin sensor applications to detect various stimuli, including temperature and pressure. High ion conductivity and mechanical flexibility are highly sought-after properties of e-skins, thus elevating the significance of ionic conductors for e-skins. Ionic conductors serve the dual purpose of being used as stretchable electrodes, sensing layers, or performing a hybrid role of being both a sensing layer and an electrode in more advanced e-skin sensor designs. Stretchable ionic conductors, including hydrogels, ionogels, and liquid-free ion-conductive elastomers, have been utilized for e-skin applications [55].

Hydrogels, a type of ionic conductor used in developing electronic skin sensors capable of detecting various stimulus, have shown significant promise. Hao et al. demonstrated a conductive hydrogel sensor with conductivity reaching 5.6 mS cm^{-1} and remarkable stretchability of up to 4000 % [56]. Guo et al. developed an electronic sensor using a photocurable ionic hydrogel with high sensitivity reaching 171 kPa^{-1} for pressures from 0 to 60 kPa [5]. Ionic gels have also recently yielded high conductivity when used for e-skins. Niu et al. developed a micropyramid electronic skin array utilizing polyimide, copper, and gold electrode arrays with an ionic gel yielding sensitivities reaching 655.3 kPa^{-1} at pressure ranges below 0.5 kPa [57]. The authors further developed a full-skin bionic electronic skin by combining PDMS with an ionic gel resulting in a sensor with a high sensitivity reaching 8053.1 kPa^{-1} for pressure ranges below 1 kPa [58].

3.1.3. Stretchable Electrodes

Electrodes are a crucial component of e-skin sensors as they facilitate the detection of physical signals. They are used for detecting and transmitting a variety of inputs, including pressure, temperature, and strain, mainly by detecting changes in electrical properties. In the case of electronic skins, electrodes used in these sensors tend to have properties of flexibility and stretchability, thus enabling them to maintain electrical conductivity while being subject to mechanical deformation [59]. They achieve these features based on their structural design using stretchable conductive materials. Various materials have been explored for developing e-skin electrodes.

3.1.3.1. Metallic Electrodes

Metallic electrodes are usually made from conductive metals such as gold, copper, aluminum, chromium, platinum, and many others. For electronic skin sensors, electrical conductivity, biocompatibility, and cost are essential considerations for the choice of material for developing electrodes. Biocompatibility is

especially important with regard to healthcare-related applications. Metals usually offer excellent electrical conductivity; hence metallic electrodes can be used to detect and measure electrical signals due to some form of applied stimuli. Thin films from metallic materials can be designed into special formats such as fractal, helical, and pre-strained bulking to achieve stretchability beyond 100 % [42]. Jiang et al. reported a thin, stretchable conducting electrode made of a 50 nm thin gold layer and a $1.2 \text{ }\mu\text{m}$ PDMS film, which achieved stretchability reaching 300 % [60].

3.1.3.2. Liquid Metal-based Electrodes

Liquid Metals, based on their unique fluid-like properties and electrical conductivity, have also been explored for applications in e-skin sensors. These materials are innately deformable and can be integrated into stretchable materials such as elastomers to create conductive pathways that maintain electrical conductivity under deformation. Liquid-metal-based devices can withstand large amounts of strain up to 800 % and offer significant potential in e-skin sensors as they can sense pressure linearly over a broader range [42].

3.1.3.3. Carbon-based Electrodes

Carbon-based electrodes present unique properties of high electrical conductivity making them attractive materials in developing electrodes for e-skin sensors. They offer high conformability and enhance the functionality and performance of e-skin sensors. Examples of these include carbon particles, carbon nanotubes, carbon fibers, and graphene. Carbon nanotube fibres tend to offer significant advantages over carbon nanotube composites, especially by avoiding aggregation problems, which are typically common in randomly dispersed carbon nanotubes. They also provide high mechanical strength and low voltage operation and are cost-effective [61].

Graphene has also been explored in developing piezoresistive sensors. It is a lightweight material with excellent mechanical properties, simple fabrication methods, and electrical properties with electrical conductivity reaching $200000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ [13]. Its versatility allows it to be used alongside elastomers such as PDMS to exhibit reversible deformation.

3.2. Surface Architectures for E-skins

E-skins were previously designed to be planar [62], thus in a flat, two-dimensional form, making them suitable for various applications. However, the introduction of surface-structured architectures, which include intricate designs such as micro-structured and nano-structured surfaces, enables e-skins to further mimic human skin functionalities and achieve unique performances. Examples of surface-structured architectures are illustrated in Fig. 5. Research has indicated that different microstructured geometries

respond uniquely to multidirectional mechanical forces [63]. Various microstructures have been investigated, including microdomes [64], micropyramids [57], micropillars [65], microcracks [45], and microchannels [66]. These structural shapes heighten the sensitivity of e-skin sensors by increasing the mode of contact under mechanical deformation.

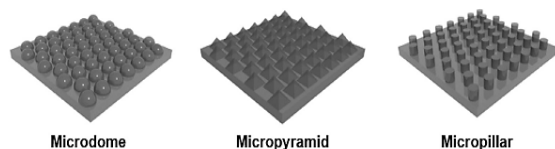


Fig. 5. Examples of surface-structured architecture for e-skins: Reproduced under the terms of the CC BY license. [63] Copyright 2018, The Authors, published by Nature.

Micropillar-shaped e-skins have been found to exhibit high sensitivity to shear stresses, while microdomes are optimal for normal, bending, and tensile stresses [63]. Microstructuring of dielectrics for capacitive e-skins has also been found to be a common strategy to significantly improve the sensor's performance, with micropyramids tending to exhibit the best sensitivity and performance for this use case [67]. Lee et al. highlights that the sensitivity of flexible pressure sensors improved by incorporating elastic pyramid-shaped microstructures [68]. Park et al. developed an ultrasensitive e-skin with an interlocked microdome structure, yielding a low detection limit of about 0.2 Pa and a rapid response and relaxation times of approximately 0.04 s [17].

To further understand the effect of the different microstructures on e-skin sensitivity, Park et al. analyzed the effect of pressure on single-sided and interlocked microstructured e-skins in comparison to planar shape [63]. For single-sided microdome, micropyramid, and micropillar structures, microdome shape yielded the highest linear sensitivity while all the other microstructured geometries had comparatively higher sensitivity than the planar-structured e-skin, confirming that different microstructured geometries influenced e-skin sensitivity [63]. These results are shown in Fig. 6.

Like microstructuring, nanostructures can also be integrated into e-skin architecture to improve overall performance. Nanostructures such as nanowires, nanoparticles, nanotubes, and nanofibers have been found to improve the functional properties of e-skins, and several studies have highlighted their significance. For instance, incorporating silicon dioxide nanoparticles in PVDF membranes has been found to achieve excellent pressure and temperature detection in e-skins, thus allowing multimodal sensing capabilities [32]. Ha et al. also demonstrated a bioinspired e-skin design of hierarchical micro and nano-structured Zinc Oxide (ZnO) nanowire arrays for sensitive detection of static and dynamic stimuli [9].

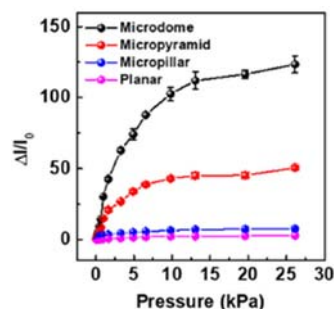


Fig. 6. Effect of single-sided geometry on e-skin pressure sensitivity: Reproduced under the terms of the CC BY license. [63] Copyright 2018, The Authors, published by Nature.

4. Applications for E-skin Sensors

By combining properties of the human skin, including flexibility, stretchability, and sensitivity, e-skin sensors have seen applications in healthcare monitoring, artificial intelligence devices, robotics, prosthetics, textiles, wearable devices, and human-machine interfaces. In the field of healthcare, the early detection of medical conditions is key to facilitating treatment. E-skin sensors have supported these efforts by monitoring vital life signals such as heart rate and body temperature, thus aiding in remote healthcare. Sun et al. explored the various efforts employed using polymer composites with functional properties to develop e-skins for health monitoring and artificial intelligence applications [69].

With the integration of machine learning, e-skin devices have advanced the field of robotics by enabling sense of touch, material perception, pressure, and temperature detection, thus improving the robot's interactions with objects, as shown in Fig. 7.



Fig. 7. Sample application of e-skin in Robotics for intelligent material cognition: Reproduced with permission. [58] Copyright 2022 John Wiley & Sons Inc.

Niu et al. developed an Artificial Intelligence (AI)-based e-skin with an advanced intelligent material recognition system to enable real-time cognition of materials through contact [58]. Dahiya [70] also emphasized the role e-skins play in manipulation or control-based tasks such as grasping objects and

estimating relevant contact parameters, including force and temperature. The breadth of applications of e-skins is continuously growing as more significant advancements are made.

5. Challenges

Despite the vast potential e-skins have in various fields, they are still plagued with several challenges, which researchers are actively working on mitigating. A key challenge affecting flexible electronic devices is the ability to remain highly sensitive while subjected to various modes of mechanical deformation, including bending and stretching [71]. The functional requirements of e-skins demand that they can conform to curvilinear surfaces while achieving high-performance sensing. E-skin sensors tend to lose sensitivity with increasing mechanical deformation, such as strain. One of the ways this could be addressed would be to develop e-skins that are highly conductive or capable of maintaining sensitivity while subjected to mechanical deformation. Following this, Lee et al. developed a bending-insensitive pressure sensor capable of detecting only normal pressure independent of mechanical stress to evaluate external stimuli on curvilinear surfaces. The authors achieved a sensor with a fast response while under complex bending conditions [68].

Additionally, e-skin sensors face the difficulty of reliable and long-lasting power sources, especially when used for continuous signal monitoring. This has necessitated the development of sensitive self-powered electronic skins to replicate high-performance sensing and continuous monitoring without external power supply [72]. Due to the complexities involved in the design and manufacturing processes of e-skins, the design of e-skin sensor arrays also requires addressing issues with flexibility and crosstalk, thus interference between adjacent sensor elements within the array. Overcoming the challenges associated with the development of e-skin sensors will help advance various fields of healthcare, robotics, wearable technology, and human-machine interface.

4. Conclusion

In this paper, we discuss e-skin sensor technology and the various efforts toward achieving unique flexible structures that can mimic the functionalities of human skin. We discuss the various sensing technologies employed in their development, their advantages, working principles, and research contributions utilizing sensing technologies to yield high-performance e-skins that mimic human skin functionalities. Carbon, Metal, and Conductive-polymer piezoresistive e-skin sensors have been found to realize excellent mechanical and electrical properties, while the use of capacitive e-skin sensors makes them suitable for proximity sensing

applications. The self-powered nature of piezoelectric and triboelectric e-skins also solves a relevant challenge facing e-skin sensor advancement.

We further discuss sensor structure design and various stretchable materials used in developing e-skin sensor technologies. We emphasize the relevance of structure design in improving contact area for flexible pressure sensors, thus elevating the sensing capabilities. Research advancements have also realized e-skin sensors which show good sensitivity while being subjected to large amounts of strain of more than 300 %, highlighting their capability of conforming to curvilinear surfaces. We further discuss the potential application of e-skin sensors in healthcare, robotics, prosthetics, and human-machine interfaces. The breadth of application of e-skin sensors is continuously growing as technologies keep advancing and new materials and manufacturing methods are being developed. We finally address some significant challenges hindering e-skin sensor development. However, the limitations these sensors face are being addressed as the technology grows further. Electronic skin sensors, as discussed in this paper, hold significant promises for the future. With continued research efforts to mitigate their key challenges, they will usher in innovations in the fields of healthcare, robotics, and wearable technology.

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