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Electronic skin technologies: From hardware building blocks and tactile sensing to control algorithms and applications

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ABSTRACT

E-skin technologies are poised to reshape numerous sectors, offering new possibilities through their thin, flexible, and highly sensitive interfaces. By integrating advanced transducer mechanisms and edge artificial intelligence computing, these interfaces not only enhance the quality of services and products but also promote greater user interaction and real-time data processing. Prosthetic and rehabilitation devices equipped with human-machine interfaces can improve the lives of people with disabilities, enabling them to interact more naturally with their environment. Furthermore, recent studies and advanced sensors have achieved sensitivity and accuracy levels not only comparable to human tactile receptors but even superior, enabling unprecedented touch perception and interaction. In the field of robotics, e-skins provide robots with human-like tactile sensitivity, enhancing their efficiency and safety when interacting with humans, machines, and the environment. The integration of e-skins with soft robotics and edge AI technology opens new frontiers in device design, making them more adaptable and capable of dynamically responding to user needs. Recent advances in flexible interfaces have led to improved transducer sensitivity and energy-efficient processing, ensuring better integration with wearable devices and interactive systems. These developments highlight the growing emphasis on real-time data processing and adaptive learning algorithms, key to the future of human-machine interactions. This paper delves into the materials, structures, and mechanisms that constitute flexible electronic interfaces and their applications. Progress and challenges in implementing effective human-machine interfaces are examined. The paper concludes with a discussion on the prospects and current challenges in the field of human-machine interfaces, particularly in medical robotics.

1. Introduction

Electronic skins (e-skins) have emerged as transformative technologies designed to mimic the tactile, mechanical, and physiological properties of human skin [1]. This innovation is crucial for applications in various domains, including robotics, prosthetics, and wearable healthcare devices (Fig. 1). The primary objective of an e-skin is to provide advanced sensory feedback and interaction capabilities, facilitating more natural and effective interfaces between humans and machines [2]. In wearable devices, e-skin capability to monitor physiological parameters such as body temperature, pressure, and skin deformation offers significant advancements in personal healthcare management [3]. In robotics, the ability to replicate human skin tactile feedback enables robots to perform tasks with greater precision and safety, while in prosthetics, e-skins can restore a sense of touch for amputees, to enhance their quality of life [4,5]. The development of e-skin requires a multidisciplinary approach, combining materials science, microfabrication techniques, and advancements in artificial

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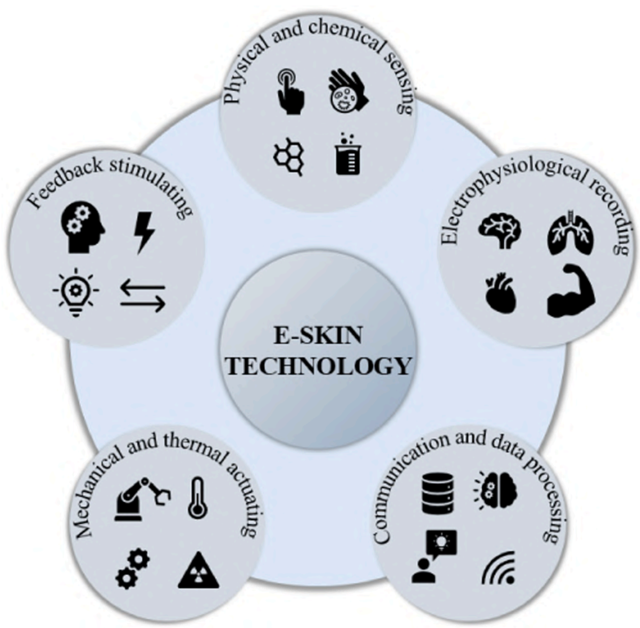

Fig. 1. Overview of e-skin technologies.

intelligence (AI) [6]. Recent progress in materials science has led to the development of highly sensitive and flexible systems. The tactile sensing capabilities of e-skin technologies are pivotal for their application in robotics and prosthetics. Tactile sensors embedded within e-skin can detect pressure, strain, and temperature variations, mimicking the ability of human skin to perceive touch and environmental changes [7]. In robotics, these sensors enable robots to interact with objects and humans more intuitively, improving their ability to handle delicate tasks and enhance user safety [8]. In prosthetics, tactile sensors provide feedback that allows users to feel and respond to their environment, improving their ability to perform daily activities. E-skin potential in healthcare extends beyond prosthetics to include various wearable health monitors. These devices can track vital signs, detect physiological changes, and provide continuous health monitoring, offering significant benefits for managing chronic conditions and improving overall health outcomes [9]. For instance, e-skin can be used to monitor heart rate, respiration, and body temperature, providing real-time data to healthcare providers and enabling more responsive and personalized medical care [10]. These systems utilize various types of sensors—pressure, temperature, and strain sensors—embedded within flexible substrates to detect and respond to environmental stimuli [11]. The integration of AI algorithms allows these sensors to process complex data in real-time, enhancing the functionality and responsiveness of e-skin [12]. E-skin technologies should exhibit at least a subset of features among certain critical requirements: flexibility, stretchability, self-healing, and high sensitivity. These attributes are essential for ensuring that e-skin can conform to complex surfaces and endure the mechanical stresses associated with human and robotic movements. E-skin must be designed to adhere to irregularly shaped surfaces [13] and withstand repeated mechanical stresses. Stretchable and self-healing materials are critical for maintaining functionality over time [14]. Stretchability ensures that e-skin can conform to dynamic surfaces, such as human joints, without delaminating. Self-healing properties enable the repair of minor damage, extending the lifespan of e-skin devices. These characteristics are achieved by means of advanced polymers and composites that can endure significant strain without losing their electromechanical properties [15]. The fabrication of e-skin involves complex processes to ensure the seamless integration of sensors and electronic components into flexible, stretchable substrates. Techniques such as microfabrication and nanotechnologies are employed to manufacture high-resolution sensor arrays that can be embedded within e-skin [16]. These processes must be scalable to facilitate the mass production of e-skin devices, making them accessible for widespread use [17]. In addition to mechanical resilience, biocompatibility is a crucial requirement for e-skin, especially for applications involving direct contact with human skin. Biocompatible materials prevent adverse reactions, ensuring that e-skin can be safely worn for extended periods [18]. Research into biodegradable materials is also advancing, aiming to create e-skin devices that can decompose naturally after their useful life, reducing their environmental impact [19]. Despite significant advancements, several challenges remain in the development of e-skin. These include improving the durability and longevity of e-skin devices, enhancing their sensitivity and accuracy, and reducing production costs [20]. Addressing these challenges requires ongoing research and innovation in materials science, electronics, and fabrication techniques [21].

Table 1 provides an overview of the most common device-level approaches employed in the fabrication of e-skins, highlighting key features, benefits, and drawbacks. This summary serves as a foundation for understanding how the hardware building blocks described in the following sections come together to form a functional artificial skin.

This review follows a logical progression to ensure a structured and focused discussion, transitioning from fundamental principles to advanced applications. The organization is designed to build a

Table 1
Overview of the main approaches for the creation of e-skins.

Approaches/ Devices	Characteristics	Advantages	Disadvantages
Polymeric film (e.g. PDMS, TPU)	Elastomer thin film structure, with built-in sensors and protective layer.	- High flexibility and transparency - Easy integration with piezo, triboelectric sensors, etc. - Good biocompatibility (PDMS)	- Sensitive to mechanical and thermal aging - In some cases, low thermal conductivity
Multi-layer "sandwich" structure (outer, middle, final)	Outer layer of protection, middle layer with active sensors/ devices, final layer for processing and communication interfaces.	- Allows modularity and layer replacement - Mechanical protection of the sensitive layer - Integration of CMOS or MCU circuits	- More complex manufacturing process (ply alignment) - Increased total thickness
Transistor-based e-skin	Integrated FET and touch transistors (short/ long-term memory, spike-rate plasticity) on a flexible substrate.	- Enables local processing (edge computing) - Can mimic biological neurons (spiking circuits) - Fewer external data transfer requests	- Requires lithography or specialized CMOS processes - Higher cost and complexity - Management of energy consumption
Magnetosensitive e-skin	Embedded magnetic sensors (m-MEMS) to detect magnetic fields, adding a "sixth sense" to artificial skin.	- Non-contact detection of magnetic objects - Possibility of fusion with other signals (triboelectric, optical, etc.)	- Shielding required if used in highly disturbed environments - Sensitive to temperature
Printed e-skin	Use of printing techniques (screen printing, inkjet) to deposit electrodes and sensitive layers on flexible substrates.	- Scalability and low cost - Quickly customizable layouts - Possible integration with disposable fabrics or patches	- Print resolution sometimes limited - Ink-substrate adhesion - Mechanical performance depends on the post-treatment process

comprehensive understanding of electronic skins by first introducing biological inspiration, then exploring enabling technologies, and finally discussing control strategies and real-world implementations. The paper critically reviews the field of e-skin with a specific focus on sensors, processing electronics hardware, control algorithms, and applications. The paper is organized as follows: i) an overview of the sense of touch and tactile perception in humans, ii) a discussion on the hardware building blocks of e-skins, detailing the materials and structures that enable its functionality, iii) a description of tactile sensors, exploring various types of sensors integrated within e-skin and focusing on their mechanisms and applications, iv) an overview of relevant healthcare applications, highlighting the role of e-skin in wearable health monitors, prosthetics, and other medical devices, v) a summary of the current state of e-skin technology and an outlook on future prospects and challenges in this rapidly evolving field.

Electronic skins (e-skins) represent a convergence of materials science, sensor technology, and artificial intelligence to create interactive, tactile interfaces for various applications. While e-skin research spans multiple domains, this review specifically focuses on the integration of flexible sensors, tactile sensing mechanisms, and intelligent control algorithms within electronic skin technologies. By structuring the discussion from fundamental principles to practical implementations, this work provides a comprehensive overview of recent advances and future directions in e-skin development. To fully understand the role of e-skin technologies, first it is essential to examine the fundamental mechanisms of human tactile sensation, which serve as a biological blueprint for artificial touch perception.

2. Tactile sensation and perception in human skin

Human skin is a highly specialized organ capable of perceiving and processing tactile stimuli with remarkable precision. The ability to replicate this sophisticated sensing system in artificial electronic skin requires an understanding of the biological structures and mechanisms responsible for touch perception. The somatosensory system enables humans to perceive and interact with the environment, functioning as the bridge between the periphery and the brain. One particular aspect of the somatosensory system, in comparison to other senses, is its distributed transduction ability throughout the large area covered by the skin. Through this intricate network, humans can experience the world and translate external stimuli into sensations. The sense of touch arises from a complex integration of somatosensory inputs, coordinated by various neural systems responding preferentially to different stimuli. In essence, somato-sensation is based on the signaling of mechanical, thermal, and chemical signals onto or in the body, which can be encoded by three main classes of receptors: mechanoreceptors, thermoreceptors, and nociceptors (Fig. 2). Most afferents generally respond preferentially to one type of stimulation, although some can be multi-modal. Below, we cover the main classes of afferents found in humans:

Mechanoreceptors are specialized sensory receptors responsible for the perception of mechanical stimuli, i.e. deformation, including pressure, vibration, and torsion. These can occur in the skin (cutaneous mechanoreceptors) or in deeper tissue such as muscles and joints. Mechanoreceptors allow us to regulate the movement and position of our body during interactions with objects, according to the perceived sensation [22]. Low threshold cutaneous mechanoreceptors located in the skin are innervated by myelinated, fast-conducting Aβ-fibers, as well as low-threshold, unmyelinated, slowly conducting C-fibers, termed C-tactile afferents (CTs) or C-low threshold mechanoreceptors (CLTMRs). The specific type and density of mechanoreceptive afferent differs all over the skin, making it highly specialized, depending on several characteristics including the type of sensation elicited, rate of adaptation, morphology, and size of receptive field. In the glabrous, non-hairy skin, such as that of the hands, four main types of Aβ mechanoreceptive afferent are found, namely: (i) fast-adapting type I (FAI, Meissner's corpuscles) and type II (FAII, Pacinian corpuscles) mechanoreceptors, which rapidly cease firing to a sustained indentation, and (ii) slow-adapting type I (SAI, Merkel cells) and type (II, Ruffini endings) mechanoreceptors that take much longer to cease firing to indentation [23]. In the hairy skin that covers most of the body, FAI mechanoreceptors are not found, although there are additional hair follicle afferents and field afferents, both of which are highly sensitive to small skin deformation, being fast-adapting and connected to fast-conducting Aβ fibers [24]. The slowly conducting CT afferents are found more densely in the hairy skin of the upper body [25]. Conversely, deeper in the body, other afferents can encode mechanical stimuli, such as fast-conducting fibers coming from type Ia and type II muscle afferents that are activated by changes in the stretch of a muscle, Golgi tendon organs that sense muscle tension, as well as various afferents found in the joints [26]. Overall, mechanoreceptive afferents are primarily activated by deformation of the end receptor, but they can show some sensitivity to thermal and chemical stimuli.

Thermoreceptors are specialized sensory receptors that contribute to the perception of temperature, including static temperature and changes in temperature, and mainly cover the innocuous, non-painful range. Thermoreceptors can be generally divided into those detecting decreases in temperature (cooling) and increases (warming) [27]. Thermoreceptors tend to be thin-fiber afferents, with Aδ fibers for cool detection, and C-fibers covering both cool and warm detection [28]. Overall, thermoreceptors are highly sensitive to temperature, with very small responses to mechanical stimulation, yet they can be readily modulated by chemical stimulation, such as menthol-induced activation, giving a perception of cooling [29]. The capability of C-fibers to detect temperature enriches and colors our sense of touch, where combined mechanical and thermal stimuli are highly relevant, for example, for the detection of wetness [30].

Nociceptors generally signal well into the noxious, painful range and are specialized sensory receptors responsible for the perception of potential and actual tissue damage [31]. Nociceptors are widespread throughout the body and are highly sensitive to painful stimuli, such as cuts, burns, high forces, and irritating chemicals. This makes them complex, as depending on the type, they can have different sensitivities to mechanical, thermal, and chemical stimuli (Fig. 2). There exist at least two main types of cutaneous C-fiber nociceptors, namely mechanosensitive and mechanoinsensitive, but each sub-class can be further divided into different sub-populations [32]. There is sparse literature on

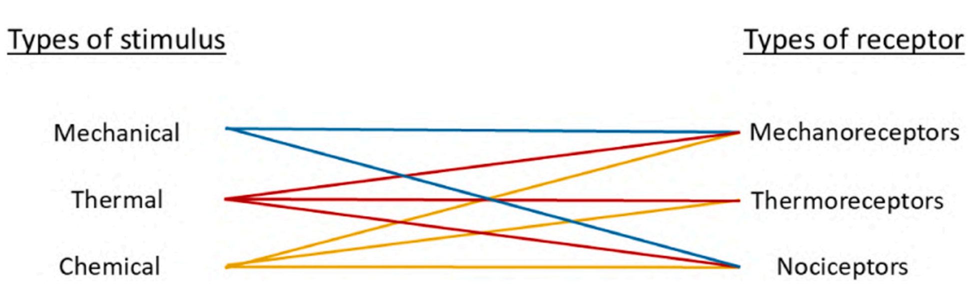

Fig. 2. Overview of somatosensory afferents. The main types of stimuli that can activate the primary classes of somatosensory afferent.

deeper nociceptors, but muscles are known to contain group III and IV afferents that generally have a nociceptive role in detecting increases in temperature and chemical release that are accompanied by extended muscle activity [33]. The primary function of nociceptors in general is to detect the risk of harmful stimuli, triggering protective responses that lead to defensive reactions or avoidance of further damage.

In summary, mechanoreceptors primarily act to signal tactile interactions mainly on the skin, such as pressure and vibration, but mechanoreceptors are involved in sensing muscle and joint movements. Thermoreceptors allow us to perceive innocuous temperature and nociceptors function to signal pain and tissue damage. All these receptors are fundamental to our ability to perceive and respond to stimuli from the surrounding environment and maintain the body's homeostasis. Although e-skins typically focus on mechanosensation, which is essential for touch perception, the input from other types of receptors is nevertheless important and should be considered for future e-skin development. In somatosensation, a chain of interconnected processes occurs, from external stimulation, encoding, processing, perception, and resulting cognitive and emotional implications. When the skin comes into contact with an object, it adapts to its shape and temperature, transmitting the information, encoding its characteristics preferentially, and sends action potential via the nerve fiber to the spinal cord and into the brain. Tactile information is processed in related areas, such as the secondary somatosensory cortex, as well as being integrated with other sensory inputs contributing to higher-order functions such as object recognition and social significance.

In this pathway, there is a progressive processing of tactile information at increasingly higher levels of the nervous system, contributing to complex tactile perception and the understanding of the characteristics, localization, and meaning of stimuli [34].

Drawing inspiration from these biological principles, researchers have developed advanced electronic skin architectures that integrate sensors and processing units to mimic the functionality of human touch. The next section explores the hardware components essential for constructing e-skins, highlighting how material choices and fabrication techniques influence tactile performance.

3. E-skin hardware building blocks

Developing e-skin that effectively replicates human touch perception requires an intricate balance between material properties and sensor integration. The fundamental hardware components, including flexible substrates, sensor arrays, and signal processing units, serve as the building blocks of artificial skin. We explore the key structural elements that enable e-skin to conform to complex surfaces while maintaining robust sensing capabilities. The sense of touch plays a critical role in collaborative robotics, where robots work alongside humans or other robots to perform common tasks. Tactile sensation is a crucial factor in collaborative robotics because it enables cobots (collaborative robots) to operate safely, precisely, and flexibly in environments shared with humans, allowing them to interact more naturally and effectively [35]. Tactile sensors endow robots with the ability to perform a wide range of complex tasks, particularly enabling them to detect the presence of humans or other objects, which is essential for ensuring safety during interactions between robots and people. They also allow robots to precisely regulate the force exerted on objects, a fundamental capability in scenarios where robots need to grasp and manipulate items without causing damage. Additionally, tactile sensors provide tactile feedback, serving as a means of communication between the robot and the human operator, allowing intuitive interaction. Furthermore, these sensors enhance precision in task execution, helping robots recognize tactile patterns and adapt to unexpected variations in the environment. These capabilities make tactile sensing indispensable for cobots to function effectively in dynamic and human-centric settings.

To endow electronic skin (e-skin) with all the capabilities of human skin, it is essential to ensure that it possesses various properties to enable the reception of information that humans acquire through sensory organs.

The ultimate goal in creating electronic skin is to mimic the full range of responses to stimuli of human skin, the response mechanism of which is built upon: information acquisition, which corresponds to the skin sensory function; information transmission, which is carried out by the nerves; and information processing, which is handled by the brain.

Therefore, it is crucial to equip e-skin with high-resolution sensors, algorithms to interpret sensor information, and reliable feedback control corresponding to the coupling functions of skin, nerves, and brain. The following summarizes the main characteristics artificial skin should present (Fig. 3):

- High sensitivity/resolution: the ability to detect minute changes in pressure, texture, temperature, and other physical parameters, like human skin.
- Flexibility and stretchability: the capability to conform to complex surfaces and undergo significant deformations without losing functionality.
- Durability and robustness: the resilience to withstand repeated mechanical stress, environmental factors, and potential damage.
- Self-healing: the ability to repair minor damage autonomously to maintain continuous functionality.
- Biocompatibility: the property to be safe for direct contact with human skin and not cause any adverse reactions.
- High spatial resolution: the capacity to detect fine spatial variations in stimuli, enabling detailed tactile perception.
- Low power consumption: efficiency in preserving the power supply of devices, a crucial requirement for wearables, and reducing energy requirements.
- Real-time data processing: the capability to perform fast and accurate processing of sensory data to provide immediate feedback and responses.

By integrating these properties, e-skin can effectively emulate the sensory and functional capabilities of human skin, making it suitable for a wide range of applications in healthcare, robotics, and beyond. The characteristics necessary to confer tactile sensation to e-skin are outlined in Fig. 4.

The e-skin's substrate, while integrating pressure/deformation sensors, temperature sensors, and inertial sensors must also be elastic, thin, flexible, electrically insulating, heat transparent, and possess consistent

Fig. 3. E-skin key features.

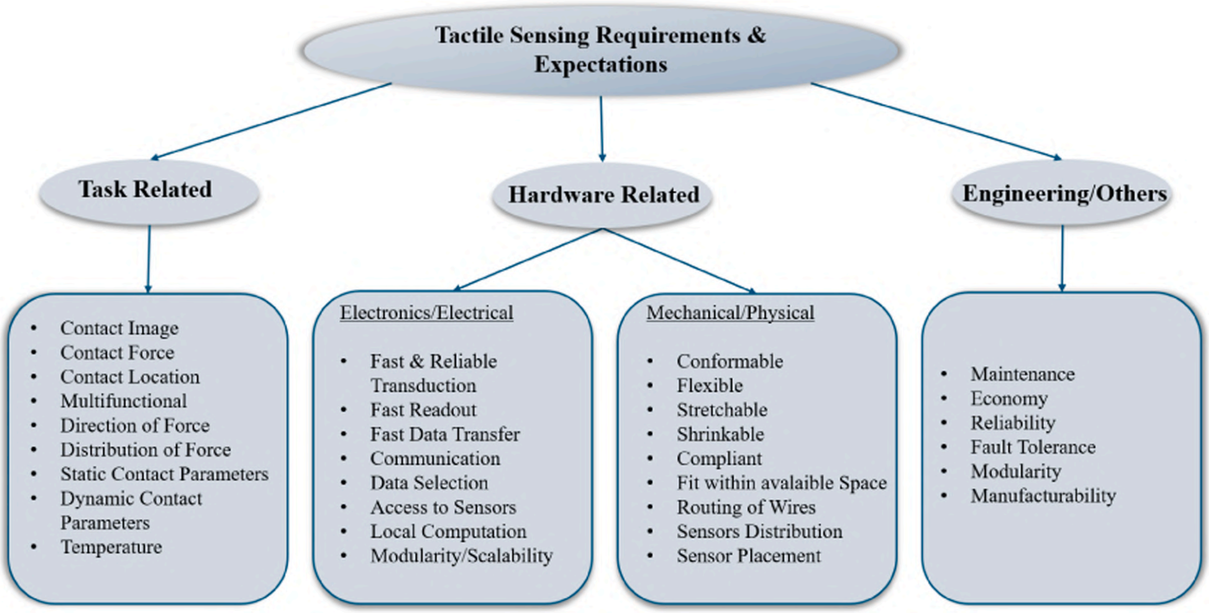

Fig. 4. Characteristics to confer tactile sensation to e-skin.

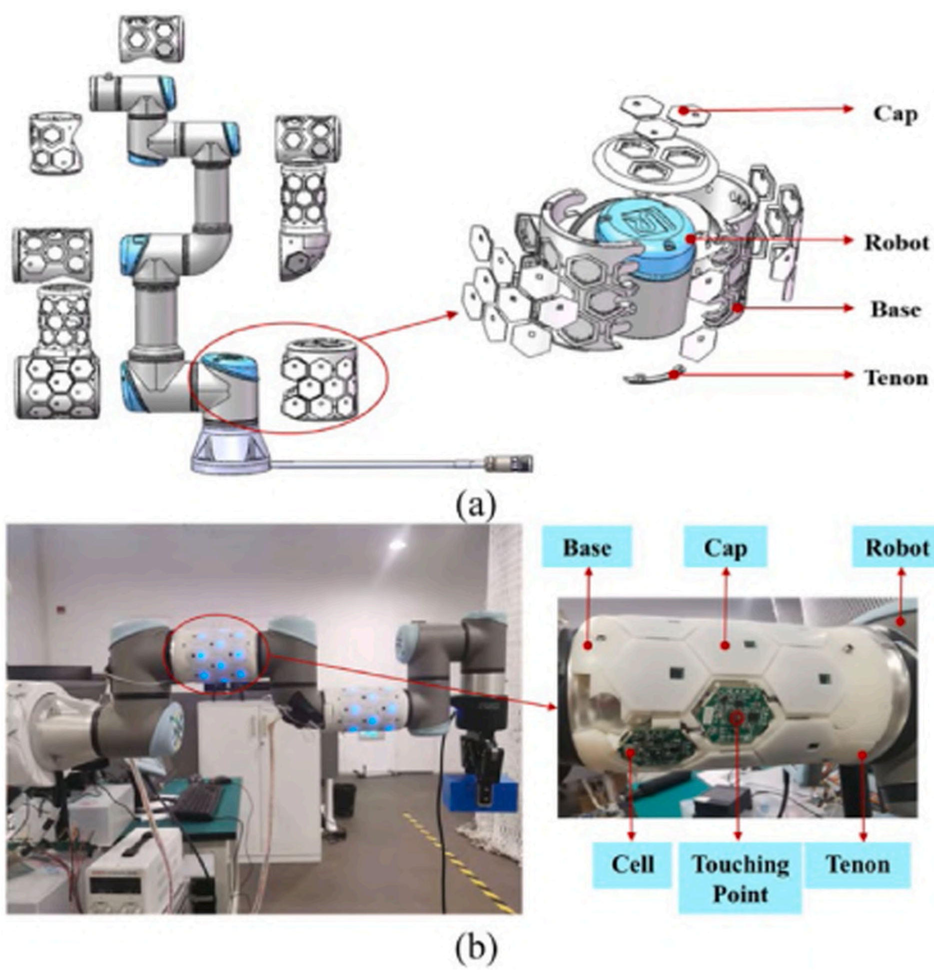

Fig. 5. TACSUIT Design: The tactile cell is constructed with multimodal tactile sensors, and a local computing MCU. (a) Suit design of the skin with 3-D printing. (b) Mounting of the skin on the robot surface. Reprinted under CC-BY policy from [41].

mechanical properties to ensure a uniform sensor response across its entire surface.

Electronic skins employ various sensing and processing technologies to emulate human tactile sensitivity. They mimic human mechanoreceptors using sensors capable of detecting dynamic and static forces, emulating the capabilities of rapidly and slowly adapting mechanoreceptors [36]. The design of electronic skin is inspired by the way human skin perceives the stress field, using a layered structure and distributed mechanoreceptors. Complex tactile signals can be transformed into field information through the concept of stress field sensing. By analyzing the stress field, it is possible to determine three-dimensional forces with high spatial resolution. The integration of sensor arrays on curved surfaces does not result in variations in stress field measurements, suggesting that sensory elements can be modularly constructed [37].

Typically, an e-skin is composed of three parts: an outer layer detecting stress field or deformation, a middle layer integrating sensory elements, and a final layer capable of processing signals detected by the sensor array. The outermost layer is often a polymer to increase the mechanical durability of the sensors underneath it and to isolate them from the surrounding environment, thereby improving precision and reproducibility [38].

The sensing elements of the middle layer can rely on different sensing principles, including triboelectric, piezoelectric, and piezoresistive transducers, which convert physical stimuli into electrical signals. For example, piezoelectric sensors detect pressure and vibration changes, while triboelectric sensors generate signals based on contact and friction. By using a triboelectric sensor, it is possible to simultaneously recognize material and texture [39]. The sensor generates signals upon contact with objects, which exhibit characteristics such as amplitude, frequency, and small vibrations. These signals are then processed by algorithms, such as convolutional neural networks, or by integrated circuits utilizing neural network technology to interpret and classify tactile data [40]. These integrated circuits are miniaturized and combine various electronic functions into a single chip, enabling rapid and precise analysis. It is possible to create a cell and block structure that integrates MEMS (micro electro-mechanical systems) sensors, an MCU (MicroController Unit) module, and a communication module to connect and transmit the information detected by the modules to the computer [41] (Fig. 5).

E-skins based on multichannel sensing systems integrate real-time data acquisition chips, a data processing system, and a closed-loop feedback control. The system includes a module that converts digital signals and transmits them to the MCU. It is responsible for recording data, processing and controlling tactile sensors, and transferring sensory information to the computer, which is useful for transmitting the corresponding feedback commands to the robot [42].

Transistor-based e-skins are designed to endow robots with sensory capabilities similar to human skin. These devices exhibit short- and long-term memory capabilities and spike-rate-dependent plasticity. A recently developed prototype e-skin integrates event-driven sensors capable of converting tactile signals into spikes. These sensors are connected to circuits made with standard CMOS components, thus imitating the behavior of biological neurons [43]. Spiking readout circuits mimic the functioning of biological neurons, transmitting signals only when they exceed a certain threshold, improving energy efficiency. Spike encoding is performed at the hardware level, making the system more energy-efficient compared to solutions that use software encoding. This approach allows for asynchronous spike generation, reducing the bandwidth required for transmitting sensory data [44].

New developments have introduced unconventional sensory capabilities, such as magnetic field detection, to provide an electronic sixth sense, an additional information channel that allows the use of surrounding magnetic fields as contactless stimuli [45]. Magnetosensitive electronic skins can be combined with other sensory functionalities, such as magnetic microelectromechanical systems (m-MEMS).

The structures of electronic skins allow them to adapt to curved surfaces and complex movements, extending a device's durability and reliability. The integration of these features makes electronic skins suitable for numerous applications, from humanoid robots to advanced prosthetics.

4. Tactile sensors

The ability to sense and respond to external stimuli is what truly defines the functionality of e-skins. While selecting appropriate materials and structural designs are crucial for the durability and flexibility of an e-skin, the true functionality of artificial skin arises from its ability to detect and respond to external stimuli. Tactile sensors are essential as they enable precise and safe perception and interaction with the environment. As an example, Meissner corpuscles, specialized in detecting light contact and vibration, inspire the development of advanced tactile sensors to replicate human touch sensitivity (Fig. 6), which is crucial in delicate applications such as robotic surgery [46].

Artificial skins can be categorized based on their fabrication and implemented technology. Tactile sensors should be able to detect stimuli such as pressure, shear force, and deformation, convert physical stimuli into analog electronic signals, and provide accurate and effective measurements as well as monitoring of external stimuli. Ideally, they should offer an accurate, repeatable, fast, and linear response without being affected by hysteresis [47]. Traditional detection mechanisms, including piezoresistive, capacitive, triboelectric, and piezoelectric detection, have been widely used in various types of force sensors. The main types are:

4.1. Capacitive sensors

A capacitive sensor exploits the charge storage capability of a capacitor. When an external object, such as a finger, approaches the sensor, it alters the sensor capacitance changing the distribution of electric charges (Fig. 11). This variation is converted into an interpretable output signal proportional to the distance or presence of the object. The capacitance is given by:

$$C = (A\varepsilon_r\varepsilon_0)/d \tag{1}$$

The dielectric constant of the capacitor material is represented by ε_r, while ε_0 is the permittivity in vacuum. A represents the area of the capacitor, and d is the distance between the capacitor plates.

Capacitive sensors are widely used for pressure detection. The advantages of these sensors are their high sensitivity, flexibility, fast response time, high resolution, and low hysteresis. A capacitive sensor typically consists of a dielectric layer enclosed between two electrodes. A conventional strategy to enhance the sensitivity of capacitive sensors is to construct microstructures within the dielectric layer. For example, Wang et al. designed a microarray electrode enclosing a thin dielectric layer, which made it possible to achieve high sensitivity (Fig. 7) [48]. Additionally, besides the aforementioned microstructures, Sencadas et al. introduced air chambers into the elastomeric polydimethylsiloxane (PDMS) dielectric layer, resulting in significantly higher sensitivity than solid PDMS [49]. Another common strategy to increase the sensitivity of capacitive sensors is to improve the relative dielectric constant of dielectric layers by adding active charges.

In practice, the microstructures and air chambers both act to increase the compressibility of the dielectric layer, so that even slight deformations cause measurable changes in capacitance. Likewise, doping the polymer matrix with charges can amplify the permittivity contrast under stress, enhancing the output signal. By carefully tuning the shape, density, and distribution of these features, it is possible to significantly boost sensitivity without overly complicating the sensor's fabrication process.

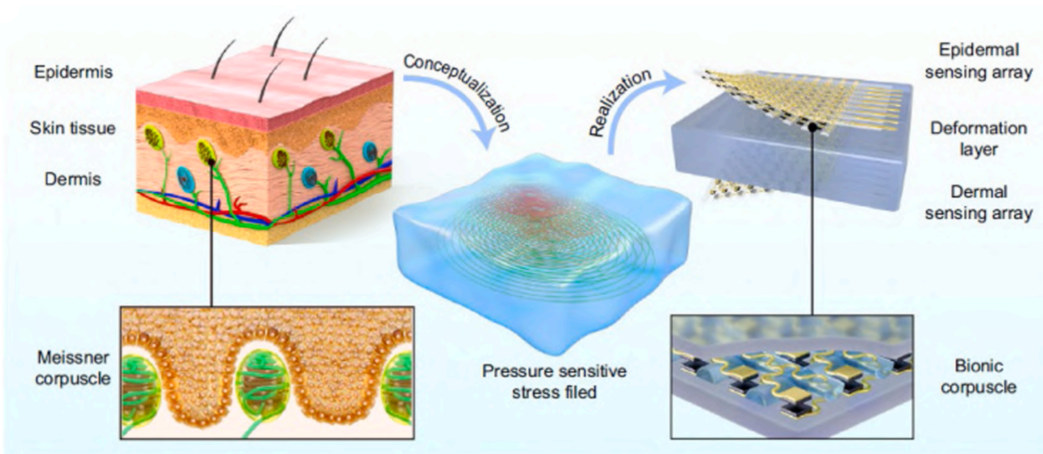

Fig. 6. Concept of stress field sensing and Meissner corpuscle structures. Reprinted under CC-BY policy from [37].

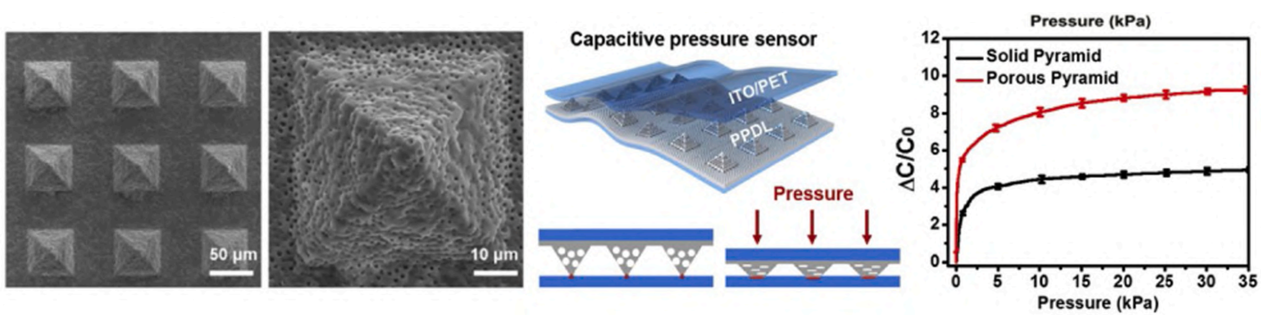

Fig. 7. Images of a dielectric layer featuring porous pyramid arrays, a schematic representation of a capacitive pressure sensor utilizing this structured dielectric, and a graph illustrating the relative capacitance change as a function of applied pressure for sensors with solid and porous pyramid structures. Reprinted under CC-BY policy from [48].

4.2. Piezoresistive sensors

Piezoresistive sensors utilize the change in electrical resistance of a piezoresistive material in response to mechanical deformation, such as pressure or contact from an external object (Fig. 11). The semiconductor material which these sensors are composed of has its crystalline structure deformed when subjected to mechanical stress, affecting the mobility of electrons and charge carriers. This variation in the material's structure leads to a change in its electrical resistance, proportional to the applied force or pressure on the sensor's surface. The variation in resistance can be represented as a function of axial deformation and the intrinsic piezoresistivity of the material can be quantified as follows:

$$PZR = (\Delta\rho / \rho)/\varepsilon_a \quad (2)$$

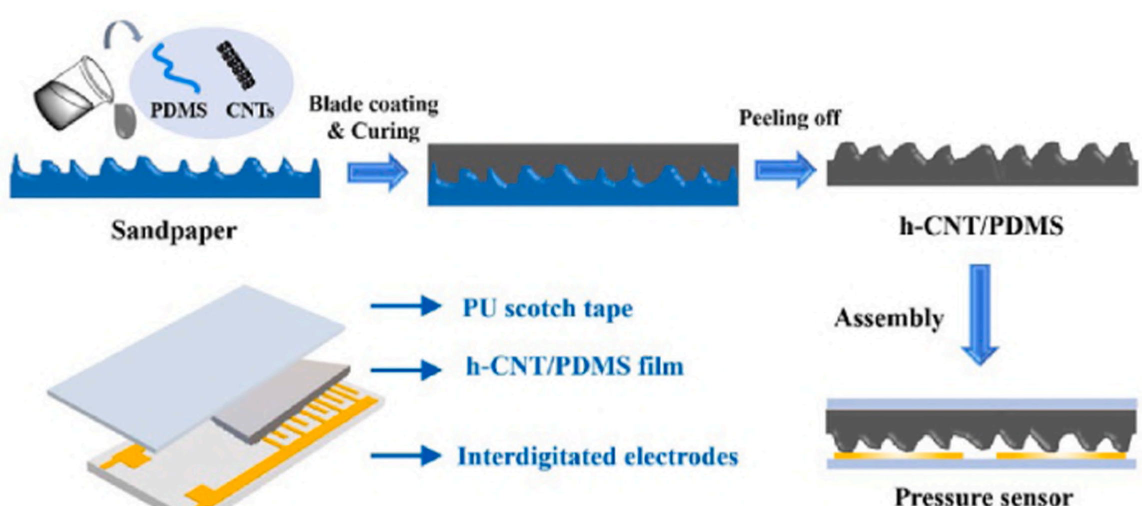

Fig. 8. Schematic diagram of the fabrication process of the h-CNT (hierarchical Carbon Nanotubes)/PDMS-based flexible pressure sensor. Reprinted under CC-BY policy from [51].

where ρ is the electrical resistivity of the material and ε_a is the axial strain, which is a function of the length of the conductor. The choice of appropriate sensing material is crucial to enhance the sensitivity of a piezoresistive sensor. The conductivity of the sensing materials will determine the sensor detection performance. Integrating flexible matrices, such as rubber, PDMS, Ecoflex gel, and others, can significantly increase the conductivity of the sensing materials, thereby improving sensor sensitivity. Constructing microstructures could also be a strategy to increase the sensitivity of these sensors, such as creating cracks [50] or hierarchical structures (Fig. 8) [51].

The advantages of these sensors are their high sensitivity, short response times, wide material selection possibilities, as well as their miniaturization and integration capabilities. The disadvantages primarily lie in poor linearity, stability, and susceptibility to interference.

In essence, micro structuring the sensing layer concentrates strain in specific regions, yielding larger resistive changes under the same applied force. For example, engineered cracks can open and close during deformation, causing abrupt modifications in conductive pathways. This design allows piezoresistive sensors to detect minute pressure differences, though it may require careful sealing or encapsulation to maintain robustness.

4.3. Piezoelectric sensors

Piezoelectric materials can generate an electrical potential when stimulated by external pressure, a phenomenon known as the "piezoelectric effect." Specifically, external stimulation, such as deformation due to bending or stretching, exceeding a certain threshold value, alters the length and spacing of the electric dipole in the material (Fig. 11). Consequently, voltage will be generated between two electrodes due to an accumulation of compensating charges on the material surface [52] (Fig. 9). The piezoelectric sensor is a type of sensor that does not require input power, thus achieving self-powered functionality. However, since the polarization of internal charges is an instantaneous dynamic process, such sensors may not efficiently respond to static stress.

The relationship between mechanical stress, deformation, and electric charge generated by a piezoelectric sensor can be expressed through the piezoelectric constant as follows:

$$Q = d \cdot P \tag{3}$$

where Q is the generated electrical charge, d is the piezoelectric constant, and P is the pressure or force applied to the material. This formula represents a simplification, as the actual operation of the sensor may involve other factors such as the area of the piezoelectric surface involved, the sensor geometry, and the frequency of force application [53].

Although piezoelectric sensors excel at capturing dynamic events like vibrations or impacts, they can struggle with slowly varying or static loads. To mitigate this limitation, some designs incorporate a coupling layer that partially redistributes stress over time, enabling brief bursts of measurable charge even under quasi-static conditions. This approach maintains the advantage of self-powered sensing while extending the sensor's range of detectable phenomena.

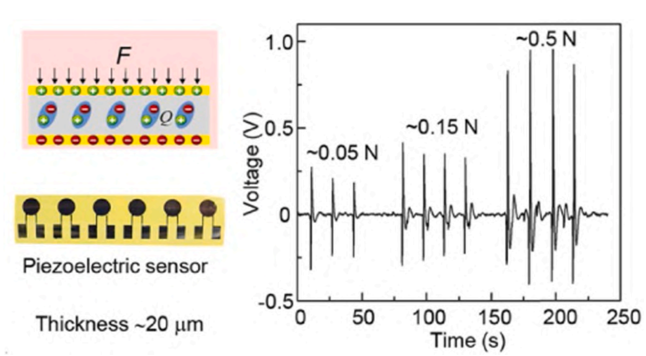

Fig. 9. Flutter and impact detection: The operating principle of a piezoelectric sensor under dynamic stimuli, illustrating the output voltage variations as pressure is repeatedly applied to the sensor. Reprinted under CC-BY policy from [52].

4.4. Triboelectric sensors

The triboelectric nanogenerator is one of the most studied triboelectric mechanical sensors, first reported in 2012 by Wang et al. [54, 55], based on the electrification by friction and electrostatic induction effects. When two different materials come into contact and separate, mechanical energy is converted into electrical energy; specifically, positive and negative electrostatic charges are generated when different materials come into contact and separate when the two materials move apart (Fig. 11). Four operating modes of triboelectric sensors can be distinguished: a single-electrode triboelectric layer, a lateral sliding triboelectric layer, a vertical contact-separation triboelectric layer, and an independent triboelectric layer. The four modes operate similarly; however, the single-electrode mode is the most studied due to its simplicity, flexibility, and low cost (Fig. 10) [56].

Zhang et al. designed an electronic skin inspired by fingerprints using single-electrode triboelectric sensors, achieving 93.33 % accuracy in collecting electrical signals through artificial neural networks [57]. The basic theory of a triboelectric sensor can be expressed as:

$$Q = f(F, A, \mu) \tag{4}$$

where Q is the generated charge, and it is a function of the contact force (F), the contact surface area (A), and the material's friction coefficient (μ). The relationship can vary depending on various factors, such as the specific sensor design, the materials used, the type of friction, and the rate of charge separation [58].

In practice, triboelectric sensors are particularly useful for detecting dynamic interactions, such as tapping, sliding, or vibration, since repeated contact-separation cycles continuously regenerate charges. Designing the surfaces with microgrooves or patterned structures can increase the effective contact area, improving charge density and overall sensitivity. However, material wear may become an issue if contact is too frequent or forceful.

4.5. Optical sensors

Unlike traditional tactile sensors, which rely on electrical or mechanical transduction, optical sensors provide a complementary mode of detection, expanding the capabilities of e-skin by leveraging light-based signal processing. These sensors detect contact or the presence of an object by measuring the light reflected from the object's surface and using this information to generate an interpretable signal. A basic formula to describe the operation of a proximity optical sensor is as follows:

$$I_r = I_0 \cdot f(d) \tag{5}$$

where I_r is the intensity of the reflected light, I_0 is the intensity of the incident light, and f(d) is a function dependent on the distance between the sensor and the object. Generally, as the distance between the sensor and the object increases, the intensity of the reflected light decreases. The function f(d) may vary depending on the type of sensor and the technology used. Fiber optic-based sensors can be realized using different principles, including light intensity modulation and Fiber Bragg Grating (FBG) fibers [59]. Recently, a system based on light intensity modulation has been developed by employing two optical fibers: one for the transmitted light and one for the light reflected by mirrors (Fig. 12).

The force-sensitive area comprises a cylinder of deformable material with two mirrors inclined at 45° inside. This configuration allows

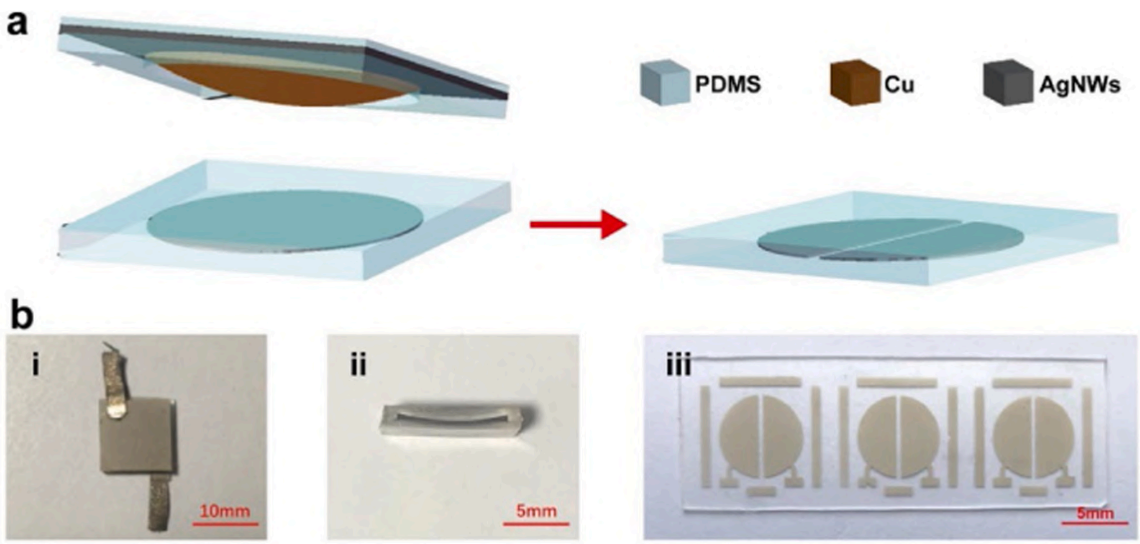

Fig. 10. TENG-based E-skin sensor: (a) Structural schematic of the TENG-based E-skin sensor. (b) Photographic images showcasing the TENG-based E-skin sensor. Reprinted under CC-BY policy from [56].

modulation of the output light intensity in response to the application of force; the modulated light signal is captured by a camera and analyzed by software capable of translating variations in light intensity into information regarding the applied force. Another approach is based on Fiber Bragg Grating (FBG) fibers [13], where a light source illuminates the FBG. Part of the light spectrum is transmitted, while the remaining portion, centered on the Bragg wavelength, is reflected backward (Fig. 13). The Bragg wavelength is influenced by both the effective refractive index of the light beam propagating in the fiber and the grating period or pitch, both of which are sensitive to deformation. Consequently, any variation in deformation is reflected in a variation of the reflected light signal.

Fiber-based solutions can be integrated into flexible substrates, allowing the sensor to conform to curved surfaces while maintaining high accuracy. Additionally, by selecting materials with minimal thermal expansion, optical sensors can reduce temperature-induced drift, further improving measurement reliability in applications that demand stable, interference-free data.

In control applications, optical sensors can enhance data fusion strategies by complementing electrical signals from capacitive or piezoresistive sensors. This integration improves overall sensing accuracy, reduces false positives, and enables more precise environmental perception in robotic and prosthetic applications. For instance, combining optical readouts with electrical signals from other sensors can improve the detection of object surfaces, leading to better grip control in prosthetic hands and robotic manipulators. This synergy makes optical sensors particularly useful in tasks requiring high precision, such as surgical robotics, where minimizing misinterpretation of contact information is critical.

Among the sensors listed in this paragraph, capacitive sensors stand out for their high spatial resolution and sensitivity, but they have disadvantages such as hysteresis and crosstalk. Piezoresistive sensors offer good spatial resolution at a low cost, but they are subject to hysteresis and temperature sensitivity. Piezoelectric sensors feature high sensitivity and accuracy; however, their low spatial resolution and high cost limit their usage. Triboelectric sensors have the advantage of low cost and efficiency, but they have limited precision, making them more suitable for dynamic measurements. Finally, optical sensors provide rapid response speed, high spatial resolution, and immunity to electromagnetic interferences, but like piezoresistive sensors, they are also sensitive to temperature which might affect the relevant information. Table 2 outlines the advantages and disadvantages of each type of sensor discussed herein.

In conclusion, the choice of sensing technology for the development of an e-skin strongly depends on the specific requirements of the intended application and should consider a trade-off between the advantages of each sensor type and the corresponding disadvantages to ensure optimal performance in the desired context of use. Although individual sensors offer unique capabilities, the integration of multiple sensing mechanisms, combined with real-time processing, is necessary for e-skin to function effectively in dynamic environments.

5. Control algorithms

Tactile sensors alone are insufficient for real-world applications; they must be integrated with intelligent control mechanisms that process sensory inputs and translate them into meaningful responses. The functionality of electronic skin extends beyond sensory detection; it must also process and respond to tactile data in real time. This is achieved through advanced control algorithms that analyze sensor inputs, optimize responses, and adapt to changing conditions.

In the previous sections, we explored various tactile sensing approaches, ranging from capacitive and piezoresistive sensors to optical methods, highlighting how each technology offers distinct advantages for e-skin applications. When these heterogeneous signals (e.g., light-based measurements from optical fibers, voltage shifts from triboelectric layers, or resistive changes from piezoresistive films) are combined, machine learning (ML) techniques become essential to fuse (data fusion) and interpret (pattern recognition) different information in real time. Recent advances in multi-modal sensor fusion have shown that integrating diverse data streams significantly improves the robustness of tactile sensing and perception, enabling real-time interactions in robotics and biomedical applications [60].

Adopting sensor fusion algorithms allows, for example, electrical and optical signals to be managed simultaneously, combining them into a single representation of the state of the environment or of the robotic limb. At the control level, this may involve a hierarchical architecture in which low-level control modules (e.g. a PID or impedance controller) regulate basic movements, while more advanced machine learning algorithms (CNN, RNN or reinforcement learning methods) analyze complex tactile patterns, formulating high-level decisions (e.g. when to release an object, how to vary the grip, etc.).

Machine learning has become a crucial factor in enhancing the functionality of artificial and biomedical electronic skins by improving

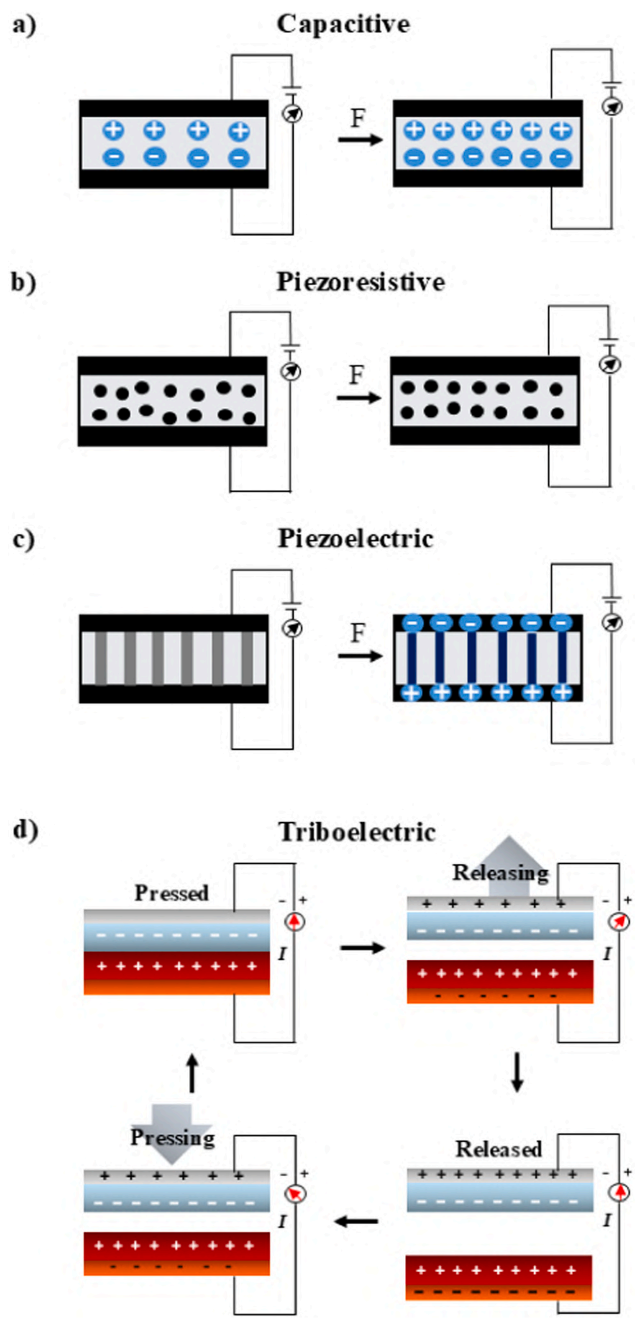

Fig. 11. a) capacitive tactile sensors; b) piezoresistive tactile sensors; c) piezoelectric tactile sensors; and d) triboelectric nanogenerator sensors.

data processing, control optimization, and pattern recognition (Fig. 14). These advanced algorithms help in interpreting complex datasets collected from the various sensors embedded within skin-like materials, making e-skins more efficient and effective in applications spanning robotics, prosthetics, and healthcare [61].

In the context of artificial e-skins used in robotics, prosthetics, and human-machine interfaces (HMIs), ML facilitates the development of closed-loop control systems that rely on real-time sensory feedback. These e-skins integrate tactile, temperature, vibration, and pressure sensors, allowing robots and prosthetics to interact more naturally with their environment. Supervised learning algorithms, such as support vector machines (SVM), k-nearest neighbors (kNN), and convolutional neural networks (CNN), are commonly used to analyze and classify tactile data from 2D arrays of sensors. This enables robots equipped with artificial e-skins to perform tasks such as object recognition, gesture classification, and determining tactile signatures, mimicking the somatosensory perception of human skin. In addition to supervised learning, unsupervised learning methods like k-means clustering and dimensionality reduction techniques are utilized to reveal hidden patterns in unlabeled data, enabling adaptation to new tactile inputs or environmental conditions without explicit programming. Reinforcement learning, which focuses on optimizing cumulative rewards through iterative actions and feedback, is employed to refine the decision-making processes of robots interacting with unpredictable environments. Recent developments in reinforcement learning (RL) frameworks have shown substantial improvements in robotic adaptation and human activity recognition, as these models dynamically adjust control policies based on continuous feedback, enhancing the responsiveness of e-skin systems to complex environments [62]. This is particularly beneficial for tasks such as robotic grasping, manipulation, and adaptive tactile-based policy optimization.

Specifically, control algorithms based on reinforcement learning can exploit tactile data collected in real time to constantly update the robot's action policy, improving its ability to adapt to unknown surfaces or irregularly shaped objects. In complex environments, the fusion layer integrates signals from multiple sensors (including optical ones) to reduce uncertainty and enable more robust decisions. This multi-layered approach ensures that fine control (e.g. grip strength) and pattern recognition (e.g. texture or presence of imperfections) are consistently coordinated.

For instance, innovative applications have seen the use of optoelectronic and biomimetic robotic skins, where different ML algorithms process tactile and visual inputs to create highly responsive robotic systems with fine manipulation and adaptive control [63]. Biomedical e-skins, designed for continuous health monitoring and therapeutic applications, also benefit significantly from the integration of ML. These e-skins collect real-time physiological data, such as electroencephalogram (EEG), electrocardiogram (ECG), and electromyogram (EMG) signals, which are then processed by ML models to provide actionable insights for medical diagnosis and therapy [64]. In this domain, supervised learning is the most widely used ML approach due to its need for well-defined training data and clear outcome objectives, making it particularly suitable for medical applications where accuracy is critical. CNN, for example, are employed in skin-interfaced devices for analyzing cardiac images and sweat biomarker patterns. These models can predict vital health metrics like stroke volume and cardiac output, essential for managing cardiovascular health and guiding clinical decisions [65]. A skin-interfaced microfluidic system, coupled with image processing algorithms, can detect sweat biomarkers and provide real-time hydration feedback, demonstrating the practical utility of ML in biomedical e-skin devices [66]. While supervised learning is predominant in biomedical applications, unsupervised and reinforcement learning are gradually being explored to address the complex, nonlinear nature of physiological data and to improve patient-specific feedback and therapeutic outcomes. These approaches have the potential to enhance the adaptability and effectiveness of biomedical e-skins by tailoring responses to individual physiological conditions and variability.

In addition to machine learning methodologies, it is possible to integrate predictive control techniques (Model Predictive Control, MPC) which, through dynamic models of the artificial skin, anticipate and compensate for delays or disturbances. This is crucial in cases where tactile sensors provide data from numerous channels (as is the case with taxel-dense e-skins) and feedback loops need to be performed in real time. To this end, the use of edge computing architectures or distributed algorithms can reduce latency, making the system scalable in industrial or clinical contexts. To address power constraints in e-skin applications, neuromorphic computing and AI-driven edge processing have emerged as promising solutions, significantly reducing energy consumption while ensuring high-speed sensory data interpretation. These advancements are particularly relevant for real-time wearable e-skin and prosthetic applications [67].

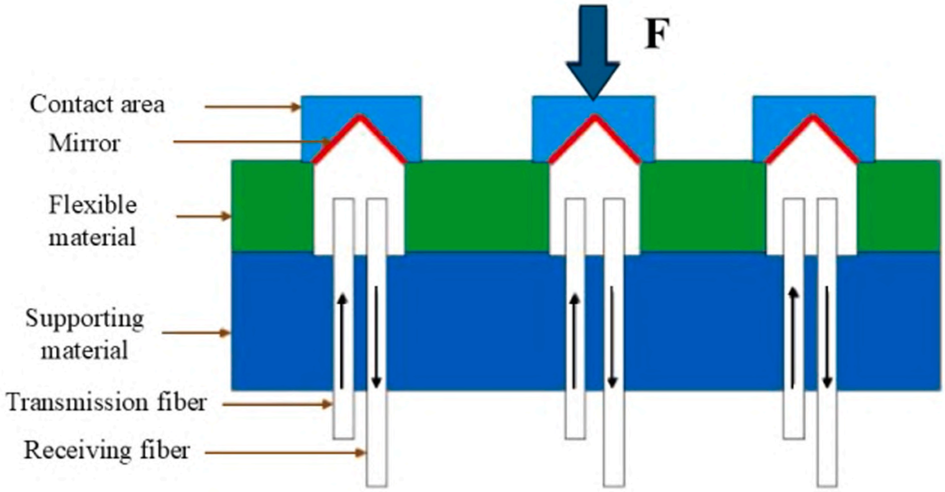

Fig. 12. Design of optical fiber-based tactile sensor with mirror displacement. Reprinted under CC-BY policy from [59].

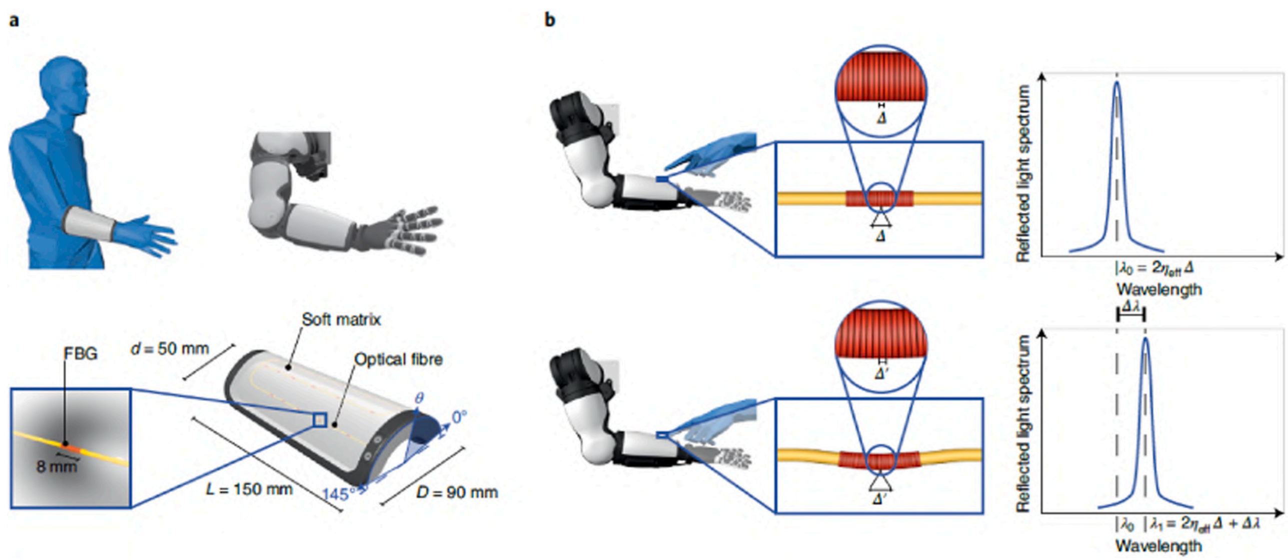

Fig. 13. Electronic skin integrating FBG transducers. a) Sensitive skin patch. b) FBG working principle. Reprinted under CC-BY policy from [13].

The potential to expand these technologies is vast, but challenges remain, particularly in integrating ML models with e-skins for real-time processing, maintaining data quality, and ensuring the biocompatibility and mechanical durability of devices [68]. Furthermore, developing efficient data acquisition, preprocessing methods, and energy-efficient data transmission remains critical to advancing these technologies. The convergence of ML and e-skin technology is expected to revolutionize both artificial and biomedical fields by creating more intelligent, adaptive, and versatile devices. However, the field faces significant hurdles, including the need for high-resolution data acquisition, seamless integration of diverse sensing modalities, and overcoming material and fabrication constraints. Moreover, the implementation of these devices in real-world clinical and industrial settings requires addressing issues related to data privacy, security, and regulatory compliance. Continuous interdisciplinary research is essential to fully realize the potential of ML-enhanced e-skins, making them an integral part of future soft robotics and personalized healthcare applications [69].

The integration of control algorithms significantly enhances the practical utility of e-skin, allowing it to function seamlessly in real-world applications, across diverse fields, from biomedical monitoring to advanced robotics.

6. Applications

The advancements in e-skin hardware and control algorithms have paved the way for a diverse range of applications. From health monitoring and prosthetic enhancement to intelligent robotic systems, e-skin is redefining how artificial systems interact with their surroundings. In the current landscape, we are witnessing a growing variety of developments in the field of electronic skins, characterized by a diverse range of functionalities tailored to specific applications (Fig. 15). These innovative artificial skins are designed to meet various needs, ranging from monitoring vital signs in neonatal intensive care [70] to the ability to discriminate between hot and cold temperatures [71], from measuring electrocardiograms [72] to advanced functionalities such as sweat testing for cystic fibrosis diagnosis [73]. This section reports the application prospects of electronic skins, considering three main categories: health monitoring, surgical and prosthetic tools, and brain-computer interfaces.

6.1. Health monitoring

Health monitoring plays a crucial role in the prevention and healing

Table 2
Comparison between tactile sensors.

Sensor's type	Advantages	Disadvantages
Capacitive Sensors	-High spatial resolution -High sensitivity -Wide dynamic range -Temperature independent	-Hysteresis -Crosstalk -Sensitivity to noise -Parasitic effects
Piezoresistive Sensors	-High spatial resolution -High robustness -Low cost -Simple design	-Hysteresis -Energy consumption -Temperature sensitivity -Low sensitivity
Piezoelectric Sensors	-High sensitivity -High accuracy -Wide range of frequencies -Wide dynamic range	-Low spatial resolution -High cost -Circuit complexity -Not suitable for static measurements
Triboelectric Sensors	-Low cost -High-performance capabilities -Simple design -Self-sufficient	-Sensitivity to wear -Limited precision - Only detect dynamic forces
Optical Sensors	-High spatial resolutions -Fast response speed -Wide detection range -Good reliability	-Dimensions -Temperature sensitivity -High cost

of various medical conditions, such as managing diseases like diabetes [74] or COVID-19 [75]. Indeed, as demonstrated by the COVID-19 pandemic, daily health monitoring was essential for preventing the spread of the virus. Wearable sensors, as in [76], represent an important resource for monitoring and managing diseases, enabling prompt and personalized action. Several research efforts have contributed to revolutionizing diagnostic perspectives and individual well-being, through the use of electronic skins in the context of daily health monitoring [77,78]. One approach is based on wearable and flexible strain sensors based on conductive hydrogels, as discussed in [79]. These sensors find practical applications in monitoring blood pressure, body temperature, respiration, and muscle movements. Screen-printing technology has also been utilized to produce low-cost electrodes, promoting non-invasive real-time chemical monitoring of sweat and interstitial fluid [80]. Recent developments in implantable and cutaneous electronics leverage the principles of piezoresistivity, capacitance, triboelectricity, and piezoelectricity [81]. An innovative example is the development of self-powered tactile sensors based on the triboelectric effect, inspired by trampoline mechanics [82]. These sensors are thin, soft, and stretchable, demonstrating excellent detection stability even under high deformation conditions, offering promising prospects for self-powered electronic skin for daily use. For real-time monitoring of human body physiological signals, such as temperature and other bioelectrical signals, numerous studies have demonstrated how wearable electronic skins can be used as on-site diagnostic tools for clinical practice [83,84]. Electronic skins represent an advanced frontier in wearable technology and health

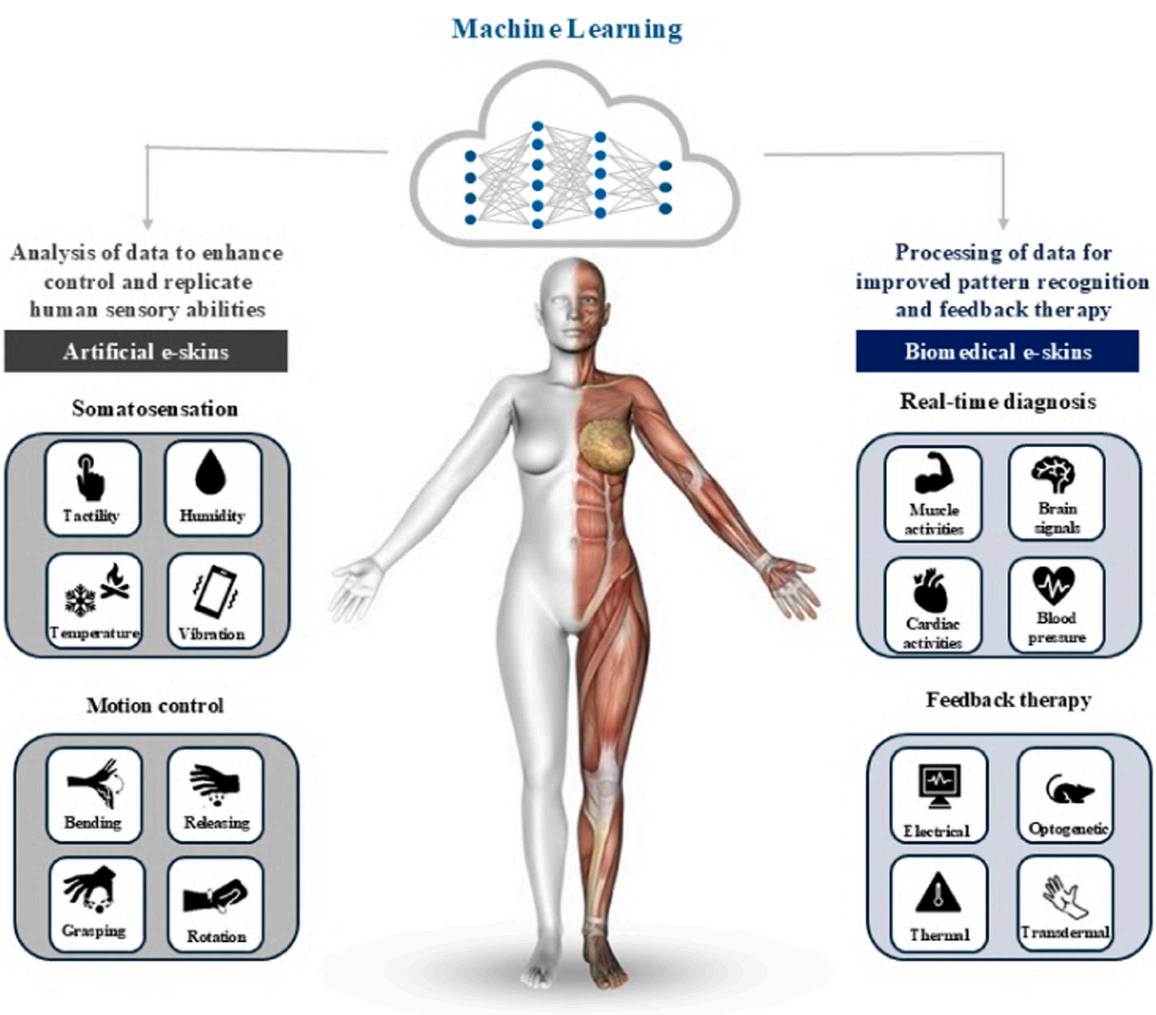

Fig. 14. Integration of Machine Learning with artificial electronic skin.

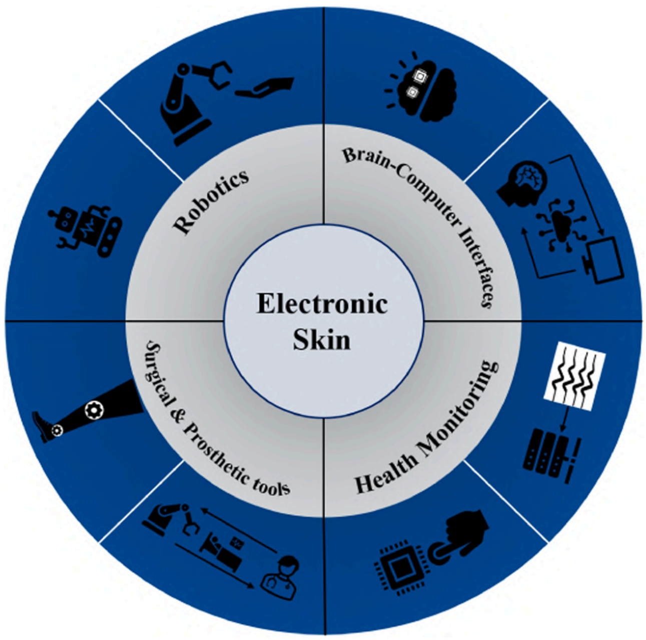

Fig. 15. Overview of electronic skin applications.

monitoring. These innovations are revolutionizing the concept of daily health monitoring, offering non-invasive solutions for collecting physiological data. One of the most innovative approaches is the development of closed-loop wearable systems [85], enabling glucose control. Other contributions, such as wireless hydrogel sensors with MXene nanosheets [86] or epidermal nanogenerators (ENG) [87], highlight the flexibility and skin affinity of such devices. Multiparametric monitoring devices, such as the epidermal patch for monitoring hemodynamic and metabolic biomarkers detailed in [88], integrate sensors for measuring blood pressure, heart rate, and other parameters, providing a detailed understanding of physiological responses to various activities. The adoption of advanced technologies, such as electronic skins, significantly contributes to the effectiveness of monitoring, as well as improving the accuracy, convenience, and continuity of measurements. In this way, monitoring becomes fundamental for preventing complications, enhancing treatment, and promoting a rapid and effective response to global health emergencies.

6.2. Surgical and prosthetic tools

In the realm of surgery and prosthetics, there is significant progress being made thanks to innovations in electronic skin and advanced sensors. The integration of new classes of multifunctional robotic structures [89] is reshaping the approach to soft robot design, allowing them to change shape and vary their stiffness. Robot-assisted surgery represents a crucial step forward in clinical medicine, offering precision and speed in performing complex procedures [90]. The advancement of intelligent robots and prosthetics has greatly facilitated humans in their daily activities, enabling them to perform various operations with ease. The COVID-19 pandemic has underscored the importance of diagnostic testing and surveillance [91]; however, efficiency in collecting saliva samples has been a critical issue. Integrating artificial skins into robots would have allowed for greater protection of hospital staff [92]. In the context of surgery, the implementation of virtual reality (VR) in robots not only provides support during operations but also offers crucial feedback to doctors, helping to improve memory and practice [93]. While significantly improving the quality of life for amputees, prosthetics still have limitations in hazard and injury perception [94,95]. Currently, flexible electronic skin seeks to simulate tactile perception, through the use of high-sensitivity pressure sensors and feedback control [42,96]. The introduction of intelligent robots and non-invasive alternatives to skin grafts [97] is a significant step forward. An intriguing example is real-time interaction via VR devices, where a user can virtually touch a body part in a video; this touch is detected by artificial somatosensors embedded in pressure-sensitive e-skins, designed to mimic human skin receptors. The sensation is then replicated on the recipient's skin using wireless haptic interfaces that deliver spatio-temporally programmed vibrations [98], enabling physical touch perception through advanced sensors and feedback technology. These promising innovations outline a future where technology, such as robot-assisted surgery, advanced prosthetics, and electronic skin, come together to significantly enhance the quality of life and human experience.

6.3. Brain-computer interfaces

The interconnection between electronic skins (e-skins) and brain-computer interfaces (BCIs) is emerging as a promising research field. Currently, we use voice interpretation and recognition functions for many daily devices [99]; however, one can imagine that in the future, mind control could evolve through the transduction of brainwaves into electrical signals, transmitting instructions to devices. This perspective is realized in brain-computer interface (BCI) technology, where EEG signals become the means of communication and control between the human brain and computers or other devices [100]. In this context, e-skins serve as the tactile interface for BCI systems, translating brainwave commands into physical stimuli or enabling sensory feedback to the user through advanced haptic responses. Cutting-edge projects, such as those by Neuralink, are taking innovative paths using brain chips to address complex diseases and to create connections between humans and artificial intelligence [101]. These chips, equipped with 1024 electrode threads thinner than a human hair, are inserted into the brain using surgical robots and perform neuronal stimulation [102,103]. Another revolution in the field of BCIs is represented by soft BCIs, which replaces metallic needles with flexible electronic devices to interact with nerves [104]. This innovation not only avoids nerve damage but also improves accuracy in acquiring brain signals, opening new possibilities in the medical sector. The combination of BCI and e-skin offers promising prospects for significantly improving the quality of life of amputees and paraplegics, allowing them to experience greater freedom of movement, as well as healthy individuals [105,106].

7. Conclusions

As discussed in the previous sections, the development of e-skins involves hardware building blocks such as flexible, stretchable substrates and integrated sensor arrays, diverse tactile sensing modalities, and an ever-expanding range of applications spanning healthcare, robotics, and human-machine interfaces. These pillars form the foundation for next-generation electronic skins that emulate or surpass human tactile perception. However, several challenges remain, and ongoing research continues to push the boundaries of what e-skin can achieve.

Recent innovations in flexible and stretchable electronics are paving the way for the development of artificial skin perception systems, capable of processing sensory data directly at the point of detection. This approach promises rapid and energy-efficient system responses. The computational capabilities of artificial skins meet the requirements of relatively simple tasks such as threshold evaluation and spike detection. Currently, even more complex needs have been achieved, such as material recognition and shape perception. With emerging tactile sensors, it is possible to achieve an accuracy of 5 μm and a response frequency of 485 Hz, as demonstrated by the robotic skin that with its design can mimic the sensing mechanism of human tactile sensory cells [107]. Recent studies emphasize the ability to recognize ultrafine textures with a detection limit of 0.7 N, showcasing the effectiveness of using robotic skin for highly sensitive tactile perception [108], as well as material recognition capability with an accuracy of 94 % [109]. The integration of edge AI chips offers a promising solution to enhance artificial skin perception [110]. These chips can perform advanced AI processing directly within the device, reducing the need to transfer large volumes of data to external systems [111]. This would not only improve processing speed but also reduce overall energy consumption, making artificial skin systems more practical for everyday use, while also guaranteeing privacy by design to meet regulatory constraints. Despite these advancements, system-level integration remains a significant challenge. The combination of different materials and technologies, necessary to create a soft-hard interface, requires further developments in manufacturing processes and structural designs to improve system elasticity and reliability [112]. Reducing the form factor is another critical aspect, as many functional components, such as computing units, memory, and peripheral circuits, need to be integrated into the artificial skin perception system without compromising miniaturization and user comfort. Emerging computing devices show great potential for performing parallel and rapid processing. Finally, efficient energy management becomes essential, shifting the focus from energy consumption for data transmission to energy consumption for data processing. Artificial skin perception must overcome these challenges to realize practical applications in advanced wearable devices, adaptive prosthetics, and interactive robotics. With the development of increasingly sophisticated AI algorithms, integrated on the edge directly into flexible and stretchable structures, new opportunities are emerging to create intelligent systems that can dynamically adapt to the surrounding environment, significantly enhancing the capabilities and future applications of these innovative systems. Today's research trends include the integration of self-powered modules, high-density sensor arrays, and biocompatible substrates, aiming to extend e-skin usage into diverse application areas such as healthcare monitoring, surgical robotics, and brain-computer interfaces. Emerging studies also highlight the potential for fully autonomous e-skin systems with on-board computation, reducing both power demands and communication overheads.

Recent studies have also highlighted the potential of memristor-based tactile sensors as a future development in artificial skins. Unlike traditional capacitive, piezoresistive, or piezoelectric sensors, which primarily transduce external stimuli into electrical signals, memristors exhibit history-dependent electrical behavior. This unique characteristic enables them to store and process sensory data simultaneously, allowing e-skins to perform adaptive learning and dynamic response adjustments, similar to biological synapses in neuromorphic tactile sensing applications [113]. Memristor-based sensors provide several advantages over conventional tactile sensing technologies. They require lower power consumption due to their non-volatile memory properties, reducing energy demands for continuous operation. Additionally, their inherent signal-processing capabilities enable real-time learning and response optimization, making them particularly suitable for AI-driven robotic systems and prosthetics [114]. In contrast, traditional e-skin technologies rely on external processing units to interpret tactile signals, often resulting in increased power consumption and computational complexity.

Despite these advantages, memristor-based sensors face key challenges, including material stability, large-scale fabrication feasibility, and response consistency. Unlike well-established capacitive and piezoresistive sensors, whose manufacturing techniques are mature and scalable, memristor integration into flexible substrates remains an ongoing area of research. Nevertheless, a hybrid approach that integrates memristors with conventional tactile sensors could enable the development of next-generation e-skin systems, combining the robustness of existing sensing modalities with the intelligent, self-adaptive capabilities of memristor-based technology. These advances could push the boundaries of human-machine interfaces, enabling artificial skins that not only detect but also learn and adapt to environmental interactions over time.

Realizing the full promise of electronic skin requires continued innovation and interdisciplinary collaboration. Major challenges remain in mechanical robustness and manufacturing scalability, where flexible e-skins must maintain high resolution and functionality under repetitive mechanical stress. Another critical hurdle concerns standardization and interoperability, given the need to establish common protocols and benchmarks for sensor calibration, data exchange, and system integration. In biomedical applications, where continuous physiological monitoring is common, security and privacy issues become paramount, raising ethical and data-protection concerns. Finally, material sustainability and end-of-life management stand out as wearable technology proliferates, prompting a shift toward biodegradable or recyclable e-skins to mitigate environmental impact.

By addressing these fronts, future e-skins could seamlessly merge tactile sensing, environmental awareness, and user interaction into a single, adaptive platform. This convergence has the potential to transform not only into prosthetics and robotics but also everyday consumer devices, paving the way for wearable electronics that respond intelligently to user needs. In doing so, electronic skins stand poised to bridge the gap between biology and technology, opening up new avenues in personalized medicine, rehabilitation, and immersive human-machine interfaces.

CRediT authorship contribution statement

Elisabetta Leogrande: Writing – original draft, Validation, Investigation, Conceptualization. **Mariangela Filosa:** Writing – review & editing, Validation, Formal analysis. **Sara Ballanti:** Writing – review & editing, Validation, Formal analysis. **Luca De Cicco:** Writing – review & editing, Supervision, Conceptualization. **Stefano Mazzoleni:** Investigation, Conceptualization. **Rochelle Ackerley:** Writing – review & editing, Validation, Conceptualization. **Calogero Maria Oddo:** Writing – review & editing, Validation, Supervision, Conceptualization. **Francesco Dell'Olio:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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