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Application of E-Skin in Healthcare: An Overview

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Abstract

Electronics play an important role in developing devices that can be used for a wide range of purposes. Electronic skin (e-skin) is an incredibly thin electronic device that adheres to the skin and measures vital signs including heart rate, brain activity, and other bodily functions. Electronic skin is skin that has been created in a laboratory. E-skin can be used for replacing skin in persons with skin injuries such as burns, and skin illnesses, as well as in robotic appliances. Electronic skin (E-Skin) can be used to monitor health of a patient through the incorporation of sensors. This review discusses the construction of e-skin, its role in monitoring various biological parameters through non-invasive techniques and its applications. These sensors may pave the way for a slew of new applications remotely monitoring a patient's vital signs and body movements, providing data directly to computers that can better collect and store data for future decision-making. E-skin holds promise in detection as well as providing more advanced solutions than currently available commercial technologies.

Keywords: Electronic Skin, E-Skin, Nanomaterial, Tactile Sensor, Pressure Sensor, Nanowires, Artificial Skin

1. Introduction

Skin is the largest organ in the human body and has a wide variety of properties such as stretchability, self-healing ability, high mechanical toughness, and tactile sensing capability. Electronic skin, or e-skin, is the term used to describe devices that replicate certain characteristics of human skin and add new functions. E-skin has shown immense promise in the fields of robotics, prosthetics, and wearable or skin-attachable devices [1]. Before being affixed to human skin or being utilized as skin in robotics or prosthetics, e-skin must be firmly affixed to surfaces that move. Stretchability is essential if the e-skin is to stick to the body in these circumstances. The e-skin is prone to delaminating from the surface if it lacks elasticity. It is seen that the strength of the adhesive layers and the geometrical characteristics of the device both affect the conformal contact to a given surface. Furthermore, because flexible materials may stretch to match the skin's surface, users of skin-attachable applications will feel more at ease. Moreover, stretchability is necessary. In addition, stretchability is required to offer the mechanical degrees of freedom required to stop e-skin from breaking while using. When e-skin is attached to human skin or is replacing skin in prosthetics, the daily human motion will generate strain values up to 30%. Hence, without stretchability, the e-skin will likely undergo serious damage. In the case of robotics, the stretchability of the e-skin will enable the robot to take on a variety of shapes and enable high degrees of freedom in movement. Despite having the required mechanical qualities, e-skin will nevertheless be subjected to continuous and repetitive mechanical stressors. Because of this, e-skin is susceptible to wear and tear over time, which severely restricts its long-term endurance. Hence, the capacity of the e-skin for self-healing is the key to its successful application.

Tactile sensing is also necessary to enable skin-like functionality. Tactile sensing includes the ability to perceive temperature as well as physical stimuli including pressure, strain, shear, and slide. These sensors can be employed in skin-attachable devices to monitor health by detecting human mobility as well as vital indications including body temperature, breathing, and heart rate. Tactile sensors enable prostheses and robotics to perform essential tasks like manipulating objects. Other types of sensors such as chemical and electrophysiological sensors are particularly important for health monitoring in skin attachable devices. Large-area manufacturing and integration of sensors and devices must follow material development and individual device fabrication. It's crucial to first enable spatial tactile sense. Also, large-area e-skin 3D surface creation is essential, especially for robotics and prosthetics. Processing signals from numerous sensors is necessary to allow human-like tactile sense in robotics and prosthetics. As the number of sensors rises, this becomes a significant difficulty because of several problems, including complicated wiring, high power consumption, and time delays in the external read-out circuitry. Neuromorphic computing, which is built on artificial synaptic devices, presents a viable option as it allows for low-power parallel signal processing along with other features like classification and noise reduction based on learning [2].

2. Architecture of electronic skin

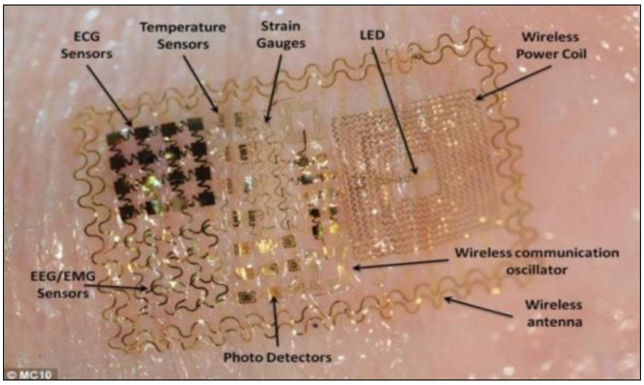

Fig 1: Architecture of electronic skin (M. Thakur, R. Dofe, S. Jadhav. Flexible electronic skin, Computer Science, 2014)

Skin has more sensors than other organs [5]. Many companies use this concept to create various circuits in-house. Cambridge based MC10 has created flexible electronic devices that adhere to the user's skin and remotely and cost-effectively monitor patients' health. In 2012, MC10 designed Biostamps containing large number of transistors, as well as resistors, LEDs, and a radio-frequency antenna. A Biostamp powers itself by harvesting energy from near-field communication (NFC) radio signals such as the wearer's cellphone. Several labs are in the process of designing similar e-skins that can perform complex functions in healthcare as well as cosmetic fields. Although the e-skin has many uses and can adapt to different energies, one of the problems that may occur is the slowdown of signal transmission and the reading of data from sensors. Juvey *et al* overcame this drawback by using nanowires with excellent electrical properties and found a way to create flexible, large-area electronic devices (Fig 1). Another team created electromagnetic coupling for the e-Skin, which allows for fasterwireless transmission response speed [5, 6].

3. Electronic skin design and fabrication

The skin is a flexible organ and changes slightly during the time the e-skin is attached to it. Therefore, the e-skin must be designed accordingly. A high-performance flexible thin sheet can be used to reduce its thickness. In addition, the sensors used in e-skin must have high sensitivity, high resolution and high performance. The field of stretchable and flexible electronics has grown rapidly in recent years. Although it is challenging and difficult to create an elastic and flexible e-Skin, various strategies can be used to achieve this goal, such as using thin materials with low Young's modulus, and bonding it to flexible rubber or elastic substrates. Tactile sensors are also used in the design of the e-skin [3]. Sensors measure information about the body's interaction with the environment and convert it into electrical signals. However, when more than one sensor is used, the problem of signal interference between sensors arises. This is a big challenge for the development of e-skin. However, crosstalk between different pressure sensors can be reduced to some extent by using transistors. Transistors consume less power due to their expansion and signal transmission properties and have quick decoding properties. So, not only the pressure sensor array but also a transistor array is used [4].

4. Mimicking the mechanical and chemical properties of human skin

Human skin has various distinct features that set it apart from traditional electronics. Skin, for example, may be stretched to tens of percent strain without permanent distortion, allowing the human body to move freely. Furthermore, skin has the potential to mend itself (autonomous self-healing), significantly enhancing its resilience and longevity. To correctly apply skin-attachable devices, prosthetics, and robots, the aforementioned features of human skin should be reproduced in e-skin devices. This section provides an overview of recent developments in stretchy and self-healing materials and devices [3].

4.1 Stretchable Materials and Devices

E-skin will be subjected to a range of mechanical loads, resulting in strains in multiple directions. It is therefore critical that the e-skin maintains its functioning under such conditions. In this regard, much research on stretchable electronic materials and devices has been conducted, and significant progress has been made in recent years. Several ways to achieve stretchability, materials with inherent stretchability, and stretchy e-skin devices are discussed in this section.

4.2 Self-Healing Materials

The long-term use of e-skin devices may result in unexpected mechanical damage over time. Self-healing ability endows e-skin with advantages such as long-term robustness and reliability. Ideally, for practical applications, self-healing should occur at room temperature without any external stimuli; such behaviour is called "autonomous self-healing." This section summarizes the design principles of self-healing materials and their applications [7, 8].

4.2.1 Self-Healable Insulators

The current research in self-healing materials is mainly centred on the development of stretchable and self-healing polymeric materials that can potentially be used as dielectrics in electronics. For self-healing materials, the recovery of mechanical properties is most commonly discussed in terms of "healing efficiency." Several property values such as fracture strain and fracture energy can be used to calculate healing efficiency. Self-healing polymers based on noncovalent dynamic bond formation may exhibit autonomous healing, high healing efficiency, and toughness. Several studies have tested several self-healing polymers as dielectrics. For example, PDMS-based polymers with metal–ligand coordination have been used in fully stretchable organic field-effect transistors that did not suffer from gate leakage current or large hysteresis [9]. Furthermore, high dielectric constants were achieved because of the high polarizability of metals and ligands.

4.2.2 Self-Healable Conductors

Self-healing conductors were prepared using N-heterocyclic carbenes and transition metals. These polymer networks were severed by razor blades, and mechanical damage was healed by heating at 150ºC in the presence of dimethyl sulfoxide (DMSO) vapor. Another (more common) approach relies on the use of composite systems. In this approach, conductive fillers are incorporated into a self-healing polymer matrix, which has advantages such as relatively high conductivity and ease of fabrication. Several organic and inorganic materials such as metal particles, CNTs, Ag NWs, and liquid metals have been used as conductive fillers. Interestingly, although the above conductive fillers are not self-healable, the mechanical and electrical properties of the corresponding composites were recovered after mechanical damage [10, 11].

4.2.3 Self-Healable Semiconductors

In self-healable semiconductors achieving both high performance and self-healability is challenging. Bao *et al*. reported self-healing semiconductors based on hydrogen bonds, showing that exposure to solvent vapor and heat allowed semiconductor mobilities to be recovered and caused the disappearance of nano cracks. Mei and co-workers investigated the self-healing of melt-processable semiconductors, [12] which contained flexible conjugation-break spacers to achieve low melting temperatures. Once these semiconductors were blended with their fully conjugated counterparts, the blend exhibited moderate mobility and melt processability. For example, mechanically damaged semiconducting blend films of this type could be healed upon heating at 160 °C.

4.3 Biocompatible Materials

Because e-skin devices will be in intimate contact with humans, they must be biocompatible. These materials should not have any harmful influence on the host body Natural or nature-inspired materials can be used to create biocompatible materials. Paper, for example, is a low-cost, lightweight seminatural material that has the potential to be employed as a biocompatible substrate. Paper transistor arrays have been proven to have a modest mobility of 0.2 cm^2/Vs and a high yield of 92%. In additional research, polypeptides, chicken albumen, nucleobases, and sugars were utilized as dielectrics of organic field-effect transistors, resulting in conventional transfer curves with no deleterious effects.

Synthetic insulating materials can also be biocompatible, as demonstrated by PDMS, which has been certified by the National Heart, Lung, and Blood Institute in the United States. Another advantage of using polypeptides as dielectrics is the ability to vary the pH, which affects the peptide dipole moment [13, 14]. PDMS is a preferred substrate and dielectric layer for electronic devices due to its great biocompatibility, robust dielectric behavior, and high degree of stretchability. Other synthetic polymers with biocompatibility include poly (ethylene glycol) (PEG) and poly (vinyl alcohol) (PVA) [15].

5. Role of tactile sensors in e-skin

To apply e-skin technology to skin-attachable devices, robotics, and prosthetics, tactile sensing is of critical importance. Tactile sensing includes the detection of various stimuli such as pressure, strain, temperature, shear, bending, vibration, and slip. The tactile sensors must be flexible and stretchable so that they can conformably cover irregularly shaped curvilinear surfaces and endure mechanical stress of various kinds. For skin-attachable devices, tactile sensors can be used to detect vital signs (blood pressure, respiratory rate, etc.) as well as monitor body activities and position (i.e., proprioception). Hence, skin-attachable devices can provide useful information such as fitness, posture, abnormal gait patterns, or sudden tremors in limbs [16]. In the case of robotics and prosthesis, tactile sensors must allow a robot or an amputee to probe its physical environment, which will allow tasks such as handling and manipulation of everyday objects, and interaction with other people. For robotics, proprioception (a perception or awareness of the position and movement of its body) is an important feature for it to operate properly. Particularly for soft robotics, since their shape is prone to alter into various conformations when external forces are applied, monitoring proprioception is especially challenging [17]. In addition, since soft robots generally use elastomers, they tend to have nonlinear, hysteretic, and viscoelastic properties, rendering monitoring of proprioception even more difficult.

5.1 Pressure and Strain Sensors

Pressure and strain sensors detect pressure and strain through several transduction principles (e.g., capacitance, piezo resistivity, piezoelectricity, and triboelectricity). Among these sensors, piezoresistive and capacitive sensors are most commonly employed, owing to their design simplicity and the capability to detect both static and dynamic signals [16]. A piezoresistive sensor detects pressure or strain in three different ways: 1) through the change in the percolation network of conductive materials in a polymer matrix, 2) change in contact resistance between a piezoresistive material and electrodes, and 3) change in the intrinsic resistance of the material itself (i.e., inducing a change in bandgap). Most capacitive sensors feature a dielectric layer sandwiched between two electrodes. As pressure or strain is applied, the capacitance between the electrodes changes due to geometrical deformation (i.e., change in the distance between electrodes and/or the device area), and/or the change in the effective dielectric constant of the dielectric layer. In this section, we will explain the strategies for enhancing the performance of pressure and strain sensors, focusing primarily on materials selection and architectural design.

5.2 Temperature Sensors

Skin is not only able to detect mechanical stimuli such as pressure and strain but also temperature through the use of thermoreceptors. Hence, temperature sensing is an essential aspect of tactile sensing that can be used in robotics or prosthetics. Temperature sensors can also be utilized to detect illnesses such as fever, heat stroke, and infection when used as skin-attachable devices [18]. Commercial temperature sensors employ thermoresistive effect of pure metal or ceramic-based semiconductors; however, owing to their intrinsic rigidity, they are not compatible with e-skin devices. Therefore, structurally engineered metal and Si nanoribbons with enhanced stretchability (i.e., serpentine, buckling, net-shaped), CNT, graphene, nanoparticles (NPs), and nanocrystals (NCs) are considered to be promising materials for the fabrication of e-skin compatible thermoresistive sensors. The resistivity of thermoresistive materials changes with temperature due to the change in mobility and/or the charge carrier density. Metal-based thermoresistive sensors such as serpentine-shaped metal, Cu NW mesh, and graphene Nano walls/PDMS have been demonstrated to exhibit an increase in resistivity (attributed to a decrease in mobility) with increasing temperature [19].

5.3 Slip and Force Vector Sensors

To grasp and manipulate objects, pressure, strain, and temperature sensing per se is insufficient; rather, detecting the slippage and direction of applied pressure (i.e., differentiation of normal and tangential forces) is critical. Since slippage requires dynamic input detection, piezoelectric and triboelectric devices are often used. Fabricated parallel ridges on the surface of a PVDF-based piezoelectric pressure sensor to detect texture-induced vibrations, showing that the surface roughness of various materials can be detected, i.e., exhibits texture perception capability [20].

5.4 Multifunctional Sensors and Decoupling Technology

The ability of the human skin to simultaneously detect and distinguish various external stimuli (e.g., pressure, strain, vibration, and temperature) can be attributed to the presence of various sensory receptors. These receptors include mechano-, thermo-, and nociceptors, and each receptor is specialized in detecting a specific stimulus and transmitting corresponding nerve impulses to the brain. For e-skin to fully mimic the sensing properties of human skin, it should have the ability to detect and distinguish multiple stimuli.

6. Embedded sensors for health monitoring

In addition to tactile sensing capabilities, the detection of other physical and chemical information from the body will enable precise monitoring of basic health and early diagnosis of a variety of diseases. This section summarizes the recent advances in skin-attachable chemical and electrophysiological sensors.

6.1 Chemical Sensors

Biofluids typically contain electrolytes, metabolites, and hormones. Consequently, chemical sensors that detect and analyze such biomarkers will provide important physiological information at the molecular level, which will in turn enable early diagnosis and prevention of diseases, e.g., both the shortage and excess of heavy metals have detrimental effects on the human body. Therefore, constant monitoring of heavy metal concentration allows for appropriate actions to be taken. In this regard, skin-attachable chemical sensors for medical purposes are highly sought after [21].

6.1.1 Working principle of chemical sensors

Chemical sensors are primarily composed of electrochemical devices, chemiresistors, and transistors [1]. Once exposed to target chemicals, these devices typically show changes in potential, current, or resistance. Exposure of electrochemical sensors (which contain reference, working, and auxiliary electrodes) to target analytes leads to a change of potential (for charged analytes) or current (for redox-active analytes). For instance, potentiometric sensors generally use ion-selective electrodes to selectively respond to target analytes, whereas in amperometry sensors, electrode-immobilized enzymes catalyze the redox reactions of target materials. Chemiresistors are composed of a sensing element in between two electrodes; the resistance of the sensing element changes upon exposure to target analytes. Finally, transistor-based chemical sensors feature a semiconducting layer, a dielectric layer, and three (source, drain, and gate) electrodes. In other words, transistors can be viewed as chemiresistors modified with an added dielectric layer and a gate electrode to allow for signal amplification and high sensitivity. The use of chemical sensors in practical applications requires many factors to be taken into account. For example, biofluids in human bodies contain chemicals at low concentrations; therefore, practically applicable chemical sensors should exhibit high selectivity, low limit of detection, high sensitivity (to precisely determine analyte concentrations), and a high level of repeatability [22, 23].

6.1.2 Selection of Biofluids

Blood is the most widely used biofluid in medical clinics; however, invasive finger-pricking to extract blood limits their real-time and long-term usage. Thus, minimally invasive or non-invasive acquisition of biofluids is required for skin-attachable chemical sensors. Examples include tears, saliva, urine, sweat, and interstitial fluid (ISF). Among these biofluids, the analysis of tears, saliva, and urine samples is of inconvenience to the user. Thus, sweat and ISF sensors are preferable for long-term usage and comfort [24].

6.1.3 Sweat Sensors

The past few years have witnessed significant advances in the field of wearable sweat sensors, as exemplified by the development of a wide range of sweat sensors for analyzing glucose, lactate, ethanol, pH, and electrolytes [25]. These wearable sweat sensors are mostly composed of electrochemical electrodes. Specifically, amperometry is often used for the enzymatic detection of ethanol and metabolites, while charged species are mostly detected by potentiometry. As mentioned above, amperometric sensors usually utilize redox reactions of biomolecules. In such devices, enzymes such as lactate oxidase, glucose oxidase, and alcohol oxidase are immobilized on the electrodes to allow for selective oxidation/ reduction of target analytes. Since the measured current increases with analyte concentration, the latter parameter can be deduced from the former. For example, Mercier and co-workers developed a skin-worn wearable sensory system that detects both lactate and ECG signals [26]. Specifically, the lactate sensor utilized a working electrode functionalized with lactate oxidase, where the increase in current was correlated to lactate concentration in sweat.

Ion-selective electrodes are often used for potentiometric sensors, such as those previously developed for the detection of charged species (e.g., ammonium, potassium, and sodium ions as well as protons) in sweat.

6.1.4 ISF Sensors

In 2001, the FDA approved the very first commercial non-invasive glucose sensors, namely GlucoWatch biographers. These wristband-type sensors used reverse iontophoresis to extract ISF and analyze its glucose levels, which could be correlated to blood glucose levels. Importantly, GlucoWatch performed periodic glucose concentration measurements, which is desirable for patients with diabetes. However, many users of GlucoWatch reported discomfort and skin irritation, and the production of these sensors was subsequently decommissioned [27].

7. Applications

To understand the depth and usage of e-skin, below are some applications:

1. When the skin is severely injured due to disease or burns, human skin is replaced by artificial skin.
2. It can detect heart electrical activity, brain functions, muscular activity, and other critical signs.
3. This is a smart bandage with localized electrical stimulation.
4. It can recognize normal stress and shear stress using an interfacial stress sensor.
5. It is also employed by robots. Pressure, touch, moisture, temperature, and closeness to an object are all sensed by the robot [1, 13].

8. Challenges

Despite advances in the fabrication of highly stretchable and tough self-healing rubbery polymers, their applications in e-skin are still in their early stages. Most self-healing materials have thus far been conductive composites; self-healing semiconductors are currently limited in their development. When embedded in a self-healing polymer matrix, semiconductors may also exhibit autonomous self-healing capabilities, but at the expense of decreased mobility. More crucially, self-healing materials must be capable of self-repairing to be useful in actual applications. As a result, processes of quick, reproducible, and autonomous self-healing should be studied further. As a first step toward the commercialization of self-healing electronics, self-healing devices such as transistors, displays, and logic circuits, and their integration must be shown. Tactile sensing applications must have high sensitivity, fast response time, minimal hysteresis, and a wide dynamic range. Due to the viscous nature of self-healing materials, achieving such qualities with self-healing potential is currently a difficult challenge. To tackle this problem, novel engineering concepts are required.

Finally, self-healing materials may be incompatible with the fabrication process established in the silicon industry. Therefore, scalable and reliable fabrication processes such as patterning or printing should be developed for the mass production of self-healing devices and electronics.

9. Conclusion

Due to the availability of novel materials and techniques, the research on e-skin has accelerated substantially during the last decade. As a result of this advancement, the possibilities of e-skin are fast converging. E-skin has the potential to;

1. Promote the development of highly interactive and adaptable robots capable of executing complicated tasks in less regimented contexts.
2. Make conformable screens and optics possible.
3. Provide biometric prostheses, continuous health monitoring technology, and extraordinary diagnostic and treatment proficiency to revolutionize healthcare.

In many ways, sensors and circuitry have already surpassed the qualities of biological skin. Flexible tactile sensors with vastly superior spatial resolution to human skin have been demonstrated, and tactile and temperature sensors with enhanced sensitivity over their natural counterparts are available. Despite significant advancements, there is still much more work to be done before the objective of combining various functionalities into vast areas, and low-cost sensor arrays is fulfilled. E-skin requires active circuitry to address a large number of devices with little wire complexity and quick scan rates. Furthermore, the ability to emulate the mechanical qualities of human skin (e.g., elasticity and stretchability) is crucial to adapt. The user's movements are varied. This can be achieved by using inherently flexible components or solid device islets connected by flexible interconnects.

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