Electronic Skin

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Mimicking skin sensorial properties, the development of “electronic skin” (e-skin) holds the promise of developing medical monitoring and highly sensitive prosthetic devices, biocompatible compliant medical implants, enhanced robotics, and more. The e-skin-related research field is a robust interdisciplinary approach, which combines micro-/nanoelectronics, material science, biotechnology, data transmission, and data processing technologies. The potential of epidermal electronics as biomimetic sensors, soft neural probes, prosthetics, implantable biomedical electronics, robotics, and a whole range of other skin-inspired devices show great potential to change the world. Its feasibility, however, relies on the desired e-skin characteristics such as flexibility, stretchability, self-healing ability, self-powering, biocompatibility, biodegradability and last, but not least, the reliability of large-scale manufacturing processes.

Keywords: electronic skin (e-skin) ; flexible electronics ; wearable devices ; health monitoring sensors

1. Introduction

The skin, the largest human organ, weighs about 16% of the total body weight and completes numerous and various functions. First and foremost, it is a powerful physical and immunological barrier between the body and the external environment while providing efficient housing for the muscles, bones, internal organs and fluids. The skin also acts as a highly efficient temperature and, to some extent, humidity sensor and regulator. As the primary interface between the external environment and the central nervous system, skin provides tactile, thermal, humidity and pain-related information [1]. The remarkable multi-functional organ possesses excellent elasticity and healing abilities. Suppose we were to translate its biological functions into electronics terminology. In that case, the skin is a massive array of highly sensitive sensors with negative feedback control loops, able to process a considerable amount of data in real-time and further control the balance of the human functions (homeostasis).

Mimicking skin sensorial properties, the development of the “electronic skin” (e-Skin) holds the promise for medical monitoring applications, highly sensitive prosthetic devices, biocompatible compliant medical implants, enhanced robotics and even more. The e-Skin-related research field is a robust interdisciplinary approach, which combines micro-/nanoelectronics, material science, biotechnology, data transmission and data processing technologies. The potential of epidermal electronics as biomimetic sensors [2], soft neural probes [3], prosthetics [4], implantable biomedical electronics [5], robotics [6], and a whole range of other skin-inspired devices [7] show great potential to change the world [8]. The feasibility, however, relies on the desired e-skin characteristics such as flexibility, stretchability, self-healing ability, self-powering, biocompatibility, biodegradability and last, but not least, reliability of processes and large-scale manufacturability [9].

The present work revises e-skin development and provides a historical overview, describes the recent trends in material development and fabrication techniques, analyzes some of the most promising health-oriented e-skin sensors and finally addresses e-skin power-related management. Thoughts on future research trends and current limitations conclude the paper.

2. The concept of e-skin: A short history and schemata

2.1. e-skin: from fiction to science

In the early 1950s, researchers explored the possibility of human/machine interfaces for prosthetics control, with first attempts to exploit the phantom-limb pain of amputees for motion control of motorized prostheses [10]. The 1960s saw the advent of the “*artificial touch-sense*” when researchers used pressure transducers fitted on hand prostheses to generate stimuli. These developed sensors, applied to the skin with the help of electrodes [11], and implants provided direct neural stimulation [12]. The feedback-based sensory systems, demonstrated in the 1970s, allowed proportional nerve stimulation and prosthesis control [13][14]. Essentially, the research on artificial touch with the development of robotic skins and mainstreaming of the touchscreen flourished in the 1980s [15]. In the 1990s, the advances in flexible materials, particularly polymers, such as polyimide (PI) [16] and polydimethylsiloxane (PDMS) [17], allowed the design of large surface flexible circuits [18][19].

Furthermore, the early 2000s introduced the concept of electronic skin referred to as "*sensitive skin*" and defined as "*a large-area, flexible array of sensors with data processing capabilities, which can be used to cover the entire surface of a machine or even a part of a human body*" [20]. Lumelsky *et al* [21]presented an extensive overview of the first workshop dedicated to the electronic skin and organized in 2000 by the NSA and DARPA. Consequently, the world of the e-skin expanded rapidly with some of the first stretchable metal electrodes presented in [22]. One step further, taken in 2014, demonstrated how the graphene-based transparent neural microelectrode arrays allowed simultaneous imaging and optogenetic neural stimulation [23]. A few years later, in 2018, Tybrandt *et al* [3] used a composite material of gold-coated titanium dioxide nanowires in a silicone matrix to develop stretchable electrode grids for chronic neural recording. A recent paper described a silk-based transparent e-skin for thermoregulation with potential application in arthritis treatment [24]. Moreover, Gao *et al* proposed a bifunctional temperature and pressure imaging e-skin with self-healing capabilities [25]. The device integrated polyurethane and multi-walled carbon nanotubes on the same flexible cellulose nanocrystals carboxylated nitrile rubber polyethyleneimine (CNC XNBR) substrate.

2.2 The concept of e-skin systems

The currently accepted concept of e-skin implemented into research can be described in Fig. 1 (which provides the overview of the main building blocks of an e-skin system). First, there is the sensing block, which picks up the relevant biological stimuli, such as blood glucose levels, pulse rate (PR), peripheral capillary oxygen saturation (SpO_2), temperature, etc. and translates their magnitude in a measurable electrical signal. Next, a data processing and transmission unit, which can include filters, amplifiers, and a radiofrequency (RF) front end can be included directly into e-skin. This unit collects the analog signals from the sensor block and performs initial processing of the signal. The RF front end generates and modulates an RF signal, with the output usually connected to an antenna for wireless data transmission. The data is then relayed to an external unit (dedicated receiver, mobile phone, cloud or other means) using WiFi, Bluetooth, or near field communication (NFC). All blocks are supplied with energy by the power supply and management block, which can use an exchangeable/rechargeable battery, wireless power transfer (WPT) or perform energy harvesting in a self-powered scenario.

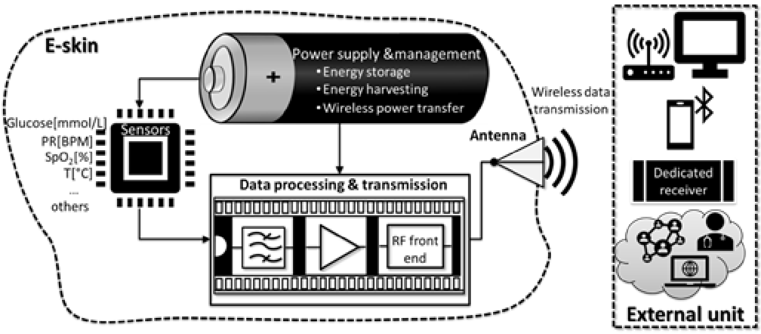

Figure 1. Working principle of an e-skin system.

3. MATERIALS & FABRICATION METHODS

3.1 General considerations

Developing *mechanically flexible* and *stretchable* materials similar to the human epidermis is challenging when the fabrication of high-performance e-skin sensors is attempted. These materials must allow and *maintain intimate contact* between devices and dynamically structured human skin or complex machine surfaces (for robotics applications)[26]. Moreover, developing *patterning and assembling technologies* of these materials to fabricate of classical electronic components is a crucial element for building stretchable electronic systems. In this direction, the microfabrication technologies developed for rigid materials need to be modified to obtain electronic devices capable of withstanding torsions, elongations, compressions with preserved electrical functions. If the monitoring of biological parameters is the targeted application of the designed e-skin sensors, the *wearability and biocompatibility* will be other elements to be considered. Therefore, the sensors must not cause discomfort, irritation, or local sweating over that targeted attachment period to the skin. Wang *et al* reported that thinner and softer sensors with smaller contact pressure between substrate and epidermis are more comfortable to wear[26].

Meanwhile, studies explore the potential use of *biodegradable* advanced 2D materials for health monitoring devices. Recently, ultra-thin, soft elastomeric materials have demonstrated conformal contact with the skin surface. The performance of this class of integrated electronic e-skin sensors, mounted onto epidermis based only on van der Waals interactions, is improved through increased contact area and fewer motion artefacts[27][28]. It also has been observed that the materials used for the fabrication of the e-skin sensors must present elastic moduli between 0.5 and 1.95 MPa and stretchability of more than 140%[29].

In conclusion, the main “building blocks” of the e-skin electronic components such as substrate, conductors, semiconductors, and dielectrics must meet specific requirements: they should bend, twist or being stretch without modification of functional properties and electronic performance during operation.

3.2 Trends in e-skin’s materials

The use of *self-healing* materials could increase the lifetime of electronic devices that come into intimate contact with the skin surface and move in tandem with the skin[30]. During long-term wearing, due to fatigue or accidental damage, the composite surfaces may develop micro-cracks that can spread throughout the substrate, conductors, or dielectric. In extrinsic self-healing composites, these microcracks cand be healed, their propagation can be prevented, thus the major structural damage is avoided. To date, different methods of obtaining self-healing electronic materials have been tested. One of them is to use microcapsules, which release the healing agent in the form of liquid monomer. This monomer polymerizes in the presence of a catalyst, a process initiated by the contact between the microcracks and the microcapsules[31]. A fundamental condition for an efficient self-healing is the homogeneous distribution of these microcapsules within the entire mass of the composite. Another method is the incorporation of conductive fillers into a self-healing network, a common approach to obtain self-healable electronic conductors. In intrinsic self-healing materials, the repair of the cracks in composites occurs through reversible covalent, non-covalent, and hydrogen bonds. For example, Song *et al* reported a dynamic Ag–S bonds (between Ag from an AgNW aerogel and S from sulfur-containing molecule in a ternary network hydrogel to obtain 93% healing under near-infrared (NIR) laser irradiation[32]. Markvicka *et al* used liquid metal droplets (GaIn eutectic) evenly distributed in a soft, silicone elastomer[33]. By controlled pressure, the microcapsules break and gather to form pathways with high electrical conductivity. In general, some progress has been made in the recent years towards the solutions to increase the potential of self-healing materials, despite the decrease in material’s stretchability[34].

Since these sensors are in close contact with the skin and could be worn for a long time, they should be *biocompatible and comfortable*. To comply with these requirements, air permeability was considered as an essential property for wearable skin-like electronics, materials with interconnected pores have been proposed as substrates. For example, Yang *et al* [35] developed a poly(vinylidene fluoride) nanofiber membrane with hydrophobicity and breathability. These nanofiber membranes (NM) obtained by electrospinning have high porosity, flexibility, and smoothness and could be incorporated in light, breathable, and printable electronic.

3.3 Deposition methods

In almost all e-skin applications, the substrate must comply with two main requirements: flexibility and stretchability. Usually, the selected substrate for the application is the one that defines the right technology to be used for sensors, transistors, resistors, or any other necessary types of electronic components. E-skin devices fabrication techniques can be grouped into two major groups: (1) classical techniques based on conventional microfabrication processes such as photolithography, vacuum based-deposition technology, etching, and (2) printing techniques.

Conventional *vacuum deposition (sputtering and e-beam)* could be mentioned as the most used technological process in the fabrication of thin-films (TF) for e-skin applications such as sensors, thin film transistors (TFT) and flexible printed circuit boards (PCB). Nevertheless, the fabrication cost is relatively high (considering the required area of the e-skin device). However, this issue is compensated by significant advantages such as low temperature, which controls material growth and the possibility of reactive deposition for unique materials such as AlN or PZT ($Pb(Zr, Ti)O_3$) for piezoelectric sensors on flexible materials[36]. *Metal-organic chemical vapour deposition (MOCVD)* and *Metal-organic molecular beam deposition (MOMBD)* have great technological importance in the fabrication of an extensive range of electronic devices; however, the temperatures used in both cases are pretty high [37] once the substrates are considered for e-skin devices. Still, this process is used to fabricate sensors or rigid substrates for e-skin devices. An alternative to the method mentioned above is the *low-temperature pulsed laser deposition (LT PLD).* It is a physical vapour deposition (PVD) technique, which comprises a high-power ultrashort pulsed laser beam focused inside a vacuum chamber and used to strike a target of the material to be deposited. The material is heated, vaporized from the target and then deposited as a thin film on a substrate facing the target. Some recent developments in this area [38] demonstrated that this method could succeed in PZT thin-film pressure sensors fabrication. *Spray pyrolysis* is often used for the deposition of doped ZnO thin film layers for TFT on flexible substrates[39][40]. *Ultrasonic spray* was used to deposit graphene materials on textile [41] and *air spray* to deposit conductive films (Ag NWs)[42].

Most of the e-skin sensors do not require the resolution and performances of conventional microsensors. Once disposable e-skin sensors become the fabrication target, *printing* can be a solution for low-cost and mass production of such devices. The printing techniques are also suitable for exploring new avenues for materials processing and for developing sensors and systems on even non-planar surfaces. It is acknowledged that such outcomes are reached with difficulty via the conventional wafer-based fabrication techniques[43].The most frequently used methods for printing on flexible substrates are screen printing [44], inkjet printing [45], gravure printing[46] ,and air-jet printing[47] .Certain applications use e-skin with a specific appropriate curvature to be further attached to the corresponding 3D structure, or e-skin fabricated onto a 3D surface. 3D printing of sensors, antennas and conductive traces are promising. For instance, Huang *et al* [48] mentioned a 3D printed tactile sensor of an elastomer made of graphene and PDMS, Adams *et al* [49] presented a 3D printed antenna made of silver nanoparticle, and Valentine *et al* [50] presented PCB conductive flexible traces made of highly-stretchable thermoplastic polyurethane (TPU) and silver flakes.

A recent trend in e-skin fabrication is based on *mask-free and chemical-free methods, which* employ a laser to prepare graphene and fabricate graphene-based electronic skins. Furthermore, Xiong *et al* [51] presented the technique of chemically derived graphene oxide (GO) preparation using laser, while Ye *et al* [52] reported further significant advances in mask-free created micro-patterns.

4. APPLICATIONS

The e-skin sensors designed and developed nowadays measure variables like heart rate, blood oxygen saturation, glucose, or moisture and display them, sense capabilities of transparent [53] or semitransparent [54] layer-based devices extended for most of the sensing organs of the human body[55], to detect colorless and odorless gasses[56], vibration-, respiration-, sound- and pulse-changes[57] .The analysis of biomarkers and stimuli signals occurs in a network of e-skin sensors. For instance, flexible sensor tag kits can monitor the surface temperature long-term and non-invasively for a precise diagnostics and feedback treatment[58]. Various requirements in terms of performance and multiple functions for dedicated sensing features are met by the array structures of biomaterials systems and conventional or hybrid polymers grown on top of flexible and stretchable substrates[59]. Active matrix temperature sensor arrays [60], or passive sensors for temporary implants [61], are characterized by excellent sensitivity and stretchable reversibility. Thin-film materials deposition [62], and additive material deposition [63], can be done onto different substrates to enable sensing functions for precise physical quantities measurements as skin surface temperature changes. For such e-skin-mimic sensors alike, it is necessary to increase the sensitivity and the resolution, reduce the detection limit, and expand the monitoring range, (i.e. to recognize temperature changes as small as 0.02° C [64]).

5 POWER MANAGEMENT APPROACHES

In order for e-skin technology to be practically implemented the whole system needs to be considered. This includes the means to power the e-skin, including the various types of sensors and/or actuators, and the means of signal extraction and processing.

Wearable devices need to have enhanced portability and should not rely on interchangeable batteries. The main approaches considered for e-skin devices are based either on self-powering schemes for long term continuous use sensors or wireless power transfer (WPT) systems for on-demand data acquisition. A good example are electronic tattoos such as the one presented in [65] where a flexible Ag-In-Ga coil is used receive up to 300 mW when placed directly on the skin and up to 100 mW if implanted.

Self-powering or autonomous e-skin devices need to employ energy harvesting schemes. They take advantage of naturally available energy sources such as light, heat, movement or bio-chemical elements which are harvested using dedicated transducers[66]. By storing the excess energy in a battery or supercapacitor, continuous operation can be achieved. Out of these, *flexible photovoltaic cells* have the highest reported power conversion efficiency (PCE) with a maximum of 30.8% for a InGaP-GaAs tandem solar cell reported in [67].

As far as *flexible batteries* are concerned the main research directions have focused on lithium (Li) based batteries with flexible electrodes [68], supercapacitors [69][70] and combinations of traditional and carbon-based materials.

Data transfer from e-skin systems mainly relies on standard communication protocols such as RFID and near field communications (NFC)[71][72], Bluetooth Low Energy (BLE) [65][73], and Wi-Fi [74], for short range, medium range and long range transmission, respectively.

The choice of using an on-demand wireless power transfer and data acquisition configuration, energy harvesting for continuous sensing and data transmission configuration, battery powered configuration or an energy harvesting/battery storage/on demand data transfer combination is highly application and technology dependent.

6. Conclusions and Perspectives

Since active monitoring of health conditions is a pressing and continuous priority, efforts focused on developing methods and devices to support the diagnostic, therapeutic and preventive approaches. Recent development of technology opened new avenues for effective and patient friendly measurement of physical and biochemical physiological parameters and even for ongoing analysis for rapid and personalized interventions. Either minute collection of biofluids for biomarkers detection or collecting large data on physical and chemical homeostatic parameters could capture meaningful and timely health status variations to enable prompt interventions and allow appropriate prevention. Therefore, the past few years efforts consolidated the progress in designing and manufacturing of flexible electronic skin systems known as e-skin to contribute with cost-efficient products. Few aspects consolidated the profile of e-skin: the quality materials used with adequate flexibility[75][76], stretchability [77], transparency[78],), light weightiness[28][79], high precision sensorial functions [4] as well as the sensitive techniques for complex molecules detection.

Originally, organic transistors have been used for the active-matrix backplane of e-skin, and established the feasibility of the concept However, their low carrier mobility imposed the inorganic crystalline semiconductors, with miniaturized dimensions and superior mechanical flexibility [75][80] .The newly employed materials contributed to various kinds of flexible and stretchable devices based on an ultrathin [81] and stretchable design [28][82] have been developed for monitoring individual health status and delivering the corresponding feedback therapy [83][84]. However, the new designs require improved scalability, and multifunctionality to comply with the desired forms of the physical and chemical sensing e-skin and for future medical applications. One more aspect to be considered when developing e-skin is the previous biosensors' limitations, as they can only monitor a single analyte and do not have on-site signal processing circuitry and sensor calibration mechanisms)[85]. Therefore, further development of flexible platforms that can house several sensors simultaneously is a priority. The fully integrated platforms for continuous and simultaneous detection of several physiological parameters build inside passively activated microfluidic systems and from biocompatible protective compartment-sealing membranes may also be coupled with capabilities for wireless data collection. Such extended capability will contribute to the e-skin potential as real-time, multi-parameter concurrent analysis with little or no discomfort to the subjects being tested. This type of solution overcomes the problems associated with blood sample collection, and provide higher compliance among various users (e.g., athletes, patients).

The improved features will further develop the diagnostic application of e-skin based on the recent increase in collection of body biomarkers to detect presence of different biomarkers in the body and to include their measurement for physiological parameters, biomolecules, and bodily fluids monitoring. Furthermore, the progress of personalized medicine- and IoT-related fields is the motor for improved and consistent manufacturing of reliable and stable systems that integrate more sensing modalities[86]. Therefore, the next steps taken will employ artificial intelligence to address the motion artifacts, the interaction of e-skin with the human skin for higher level of comfort and accurate feedback. Moreover, expanding the wearable platform towards new more complex analytes such as sweat hormones and proteins requires more work to develop sensitive and selective techniques for measuring them. To date, developing such sensors have been difficult due to the intrinsic complexities of using antibodies or aptamers as biorecognition elements. However, achieving technological standards for these sensors could contribute tremendously towards a better molecular diagnostic and personalised therapy. The complexity of the multidisciplinary work involved in perfecting the e-skin will also strengthen the collaboration between the academia and industry to achieve long-term stability of the integrated e-skin platforms capable to facilitate ongoing monitoring, timely diagnostic for efficient therapy and prevention. The evolving technology will not only consolidate the transition from conventional electronics but will open new avenues for multifunctional, smart, user-friendly, and cost-efficient products. The variety of considerations presented established not only challenges but opportunities for new era of sensor technology to enable non-invasive investigation at molecular levels for personalized and predictive healthcare. The crucial goal of flexible and wearable health-monitoring devices for periodic health monitoring is to allow data to be collected and integrated for medical purposes and even to predict illness prior to the onset of symptoms.

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