E-Skin: From Humanoids to Humans

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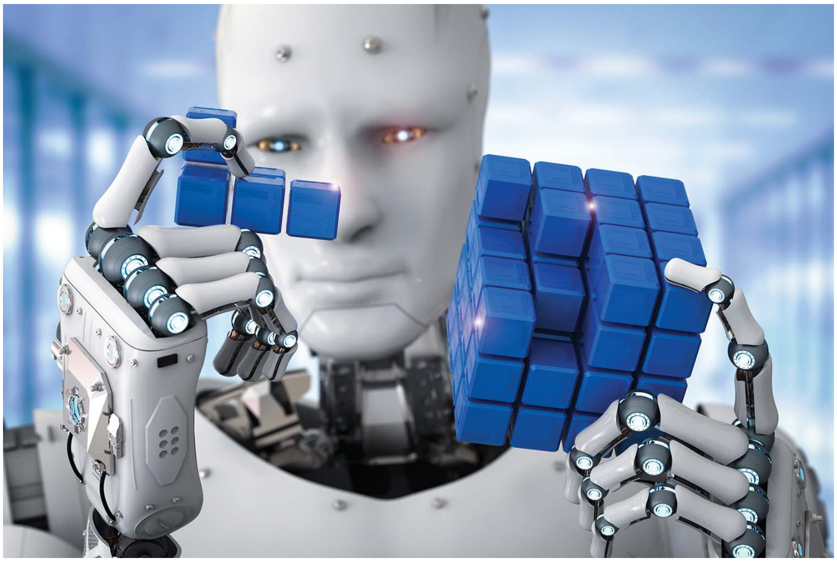

I. WHAT IS E-SKIN?

With robots starting to enter our lives in a number of ways (e.g., social, assistive, and surgery), the electronic skin (e-skin) is becoming increasingly important. The capability of detecting subtle pressure or temperature changes makes the e-skin an essential component of a robot's body or an artificial limb [1], [2]. This is because the tactile feedback enabled by e-skin plays a fundamental role in providing action-related information such as slip during manipulation/control tasks such as grasping, and estimation of contact parameters (e.g., force, soft contact, hardness, texture, and temperature during exploration [3]). It is critical for the safe robotic interaction—albeit as a coworker in the futuristic industry 4.0 setting or to assist the elderly at home.

In context with robotics and prosthetics, the e-skin is also referred to as tactile skin. To be an effective component of a robot's body, the e-skin should have a complex mix of functional and morphological features, such as: 1) multiple types of sensors distributed over large areas (entire body) to measure multiple touch sensing parameters (e.g., human skin has about 45k touch/pressure sensitive receptors in $\sim$1.5-m^2 area) [4], [5]; 2) appropriate placement of sensors to obtain varying degree of sensitivity over the entire body; 3) sensors (and associated electronics) integrated on or embedded into soft and stretchable *substrates* to allow conformability to 3-D surfaces (for superior object handing, improved user comfort, and reliable data acquisition); 4) capability to handle large data generated by the sensors through local processing or neural computing and extracting useful information (e.g., collecting the data for critical tactile feedback as well as decoding the user's intentions in real time); 5) high-performance (e.g., fast response) low-power electronics; and 6) sufficient energy for operation of touch sensors and associated electronics, particularly for autonomous robots. With these features, the e-skin seeks to resemble human skin.

With this background, the e-skin can be defined as a multisensory patch or system (see Fig. 1), having a set of sensors (e.g., touch, temperature, gas, display, energy scavengers, and electrochemical sensors) and associated electronics either integrated on flexible/bendable/stretchable substrates or embedded into soft substrates [6]. The parameters to be measured, and hence the types of sensors, depend on the target application. For example, in the case of robots and prosthesis, humanlike tactile feelings can be attained by measuring sensing parameters such as contact force, temperature, pain, and

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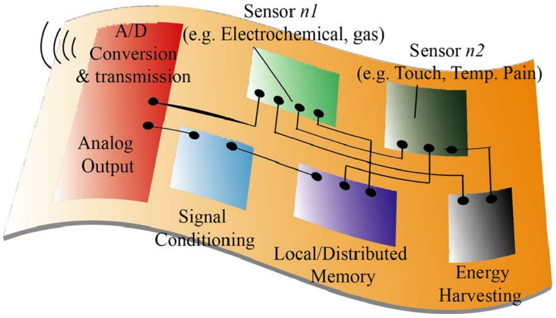

Fig. 1. ***E-skin concept with multiple functionalities integrated over ultrathin flexible substrates.***

slip. With these sensors, the e-skin can advance the capabilities of robots by allowing them to exploit area contacts and complement or replace internal sensors (e.g., simultaneous use of tactile and proprioceptive sensing). A rudimentary illustration of e-skin can be seen in touch screens in wide use today. Touch screens detect the contact location in the manner of a simple switch, i.e., "contact" or "no contact."

When applied to healthcare applications such as real-time monitoring of chronic diseases, the e-skin (also referred to as "second-skin") should have sensors to measure variations in the composition of analytes or biomarkers present in the bodily fluids (e.g., sweat or tears) or the physiological parameters (e.g., pulse rate and blood pressure) in real time [7], [8] For health and medical applications, there are additional requirements, such as substrates that should be disposable, dissolvable, bioresorbable, and biocompatible [9], [10]. Such e-skin patches could either be placed directly on the body surface or on daily wearables, such as clothes, a watch, or jewelry. In fact, in the latter case, a much wider variety of sensors can be integrated on an e-skin patch, e.g., the face masks with gas sensor.

Fig. 2 shows some of the scenarios and use cases for e-skin in robotics, prosthetics, wearables, and health monitoring [11]–[13]. The e-skin, as described earlier, could enable advances in areas, such as electronics manufacturing, mobile health, and robotics, and will open the interesting avenues for applications ranging from wearable systems for individual-centric health monitoring or self-health management to instrumented smart objects for the Internet of Things (IoT) and surgical tools. New applications could also emerge because of the new form of electronics needed for the development of e-skin.

II. TECHNOLOGICAL EVOLUTION

Technological advances have motivated numerous multidisciplinary investigations leading to the development of artificial organs, such as electronic nose, ear, and bionic eyes. Development of these artificial organs was challenging, but they also have the advantage in terms of their centralized locations (i.e., unlike skin, they are not distributed over the whole body). Furthermore, the number of sensory parameters that they are required to acquire is much lower than the skin. As a result, it was possible to use a single technological solution to develop these artificial organs, e.g., complementary metal–oxide–semiconductor imagers for high-performance cameras and bionic eye. To a greater extent, a better understanding of the centralized sensory modalities, such as vision in humans, has also contributed to the successful development of artificial organs, such as electronic nose, ear, and bionic eyes. On the contrary, the details about the working of human sense of touch are still emerging and being debated [5]. Nonetheless, the advances in electronics technology are helping to bridge the gap.

From a historical perspective, tactile sensing began to develop in the 1970s and early works focused on the developing sensors by exploring various transduction mechanisms (e.g., resistive, capacitive, optical, piezoelectric, and magnetic) [3], [5], [11]. A large number of experimental devices and prototypes reported in the literature show a good diversity among the types of sensors that were developed in the 1980s. Particular attention was given to the development of tactile sensing arrays for the object recognition. The creation of multifinger robotic hands in the late 1980s increased interest in tactile sensing for robotic manipulation, and the works utilizing tactile sensing in the real-time control of manipulation started to appear [14]. Likewise, in the 1990s, the multifinger prosthetics hands increased the interest in tactile feedback, although the major focus was on methods such as EMG-based control, and this continues till date. These early solutions for tactile sensing are nowhere close to the complexity of the e-skin system defined earlier. The anticipated use of robotics in tasks such as human–robot working side by side in the emerging Industry 4.0 setting, exploiting whole-body contacts for tasks in an unstructured environment, and assistive/rehabilitation tasks, has brought to the fore the importance of large-area tactile skin, i.e., over the whole body of robotic/prosthetic limbs [2]. Likewise, using e-skin as "second skin" in human health monitoring is opening new opportunities (see Fig. 2). These new scenarios demand e-skin to have several functional elements in addition to the challenging requirement of being conformable, stretchable, and lightweight. Accordingly, new designs, materials, and manufacturing methods are currently areas of intensive investigation. This is also evident from the recent surge in the number of publications (see Fig. 3) related to e-skin and flexible electronics. The major technological approaches that are being explored for the development of e-skin are briefly described in the following.

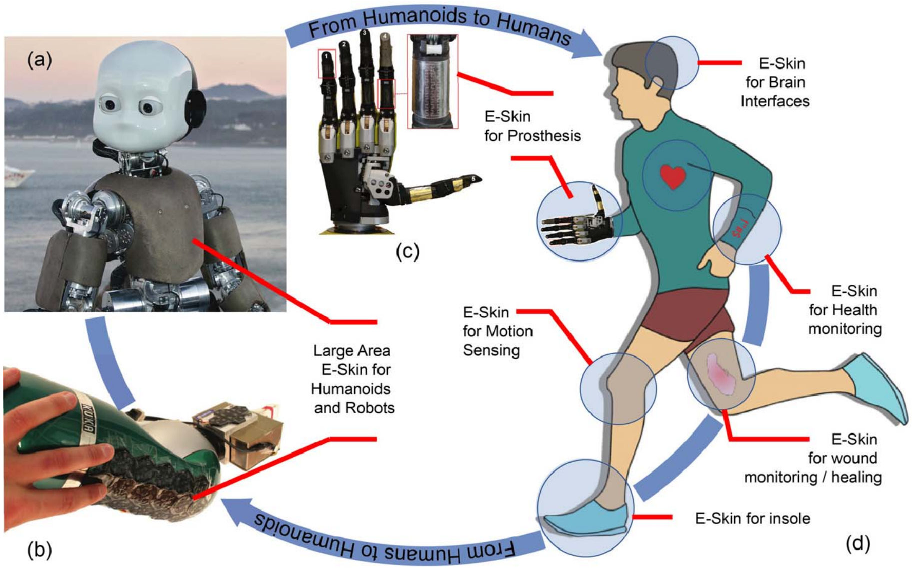

Fig. 2. *The need to cover 3-D surface of (a) and (b) robot's body and (c) prosthetic limbs with a large number of touch sensor has been a key driver application for flexible and conformable e-skin. (d) E-skin is now being used to develop wearable patches (or "second skin") with sensors for health monitoring.*

A. E-Skin With Off-the-Shelf Components

To meet the immediate need of tactile feedback in various robotic tasks, various e-skin alternatives have been explored, with off-the-shelf sensing/electronic components soldered on to flexible printed circuit boards (FPCBs) [11] or stitched to the flexible surfaces [14]. In these cases, the e-skin is made of mechanically integrated but otherwise distinct and stiff subcircuit islands of off-the-shelf components connected with wires or stretchable metal interconnects. This approach has been explored by various research groups. These semirigid FPCB-based skin patches conform to surfaces with large curvature, such as arms of humanoid robots (see Fig. 2), and have served some of the urgent needs, such as tactile feedback from whole body or large parts of the body. In fact, such large-area implementations of e-skin have changed the robotics research paradigm—from hand-based manipulation to exploiting multiple contact points or areas contact to plan and execute robotic tasks/movements. Further improvements in the FPCB- or stitching-based e-skin can be made by including more functional components, such as local memory. However, any new addition of nonbendable off-the-shelf components would severely constrain the e-skin in terms of bendability or conformability.

The use of FPCB-based approach can also be seen in the application, such as health monitoring and wearable systems, e.g., FPCB-based wearable e-skin-like patches to monitor chronic conditions such as diabetes [8], [15]. A wide variety of wearable gadgets for wellness applications are also available in market today, and the use of FPCB-based sensing patches can also be seen in fashion.

The additive manufacturing explored recently for 3-D PCBs could offer advances in the FPCB-based approach. For example, printed sensors embedded in 3-D printed artificial limbs will lead to robust and cost-effective robotic platforms with inherent tactile sensing (or structurally integrated sensing), which is also free from the traditional wear and tear issue associated with e-skin. However, for this, the 3-D printing techniques must evolve from current single material (either metal or polymers) printing to simultaneous multimaterial printing. Some recent works have already been hinting at these advances in 3-D printing [16]. When it comes to artificial limbs, new designs will also be needed to allow routing of wires within the 3-D printed structures. In fact, the approach can be extended to any 3-D structure where inherent sensing is desired and can open new avenues for electronics packaging and manufacturing.

B. E-Skin With Printed Electronic/Sensing Components

Another approach for obtaining e-skin components or patch involves printing of sensors on flexible substrates [17], [18]. In fact, printing has been widely explored for next-generation electronics. Several tactile skin patches with printed (e.g., screen printing and inkjet printing) sensors using composites, such as conductive fillers in the PDMS matrix, have been reported [17]. In these cases, the sensitive materials are directly printed on flexible and soft substrates.

The sensors readout on e-skin as well as some sensing devices (e.g., transistors or solid-state sensors) require high-performance electronics on flexible and conformable surfaces. The conventional materials for high-performance electronics, such as silicon (Si), are not

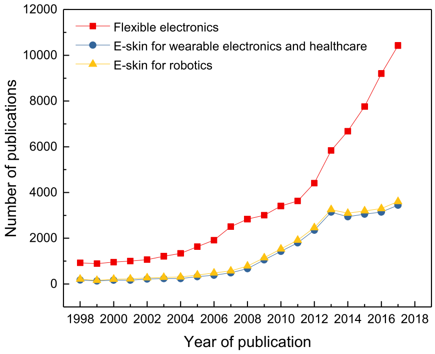

Fig. 3. ***These e-skin applications have also contributed significantly to the growth of the field of flexible electronics as evident from a rapidly increasing number of publications on e-skin in robotics and health monitoring. The trend matches with the growth in the field of flexible electronics. The data for these plots were taken from the Web of Science by using relevant keywords (e.g., tactile skin, e-skin, and flexible electronics).***

flexible, and often, devices from them require high-temperature processing steps. In this regard, the innovative methods, such as transfer printing and contact printing, are attractive as they help overcome such issues related to conventional electronics technologies.

Transfer printing involves picking a set of basic building blocks, such as nanowires and ribbons from Si and graphene, from a mother or growth substrate to the flexible receiver substrates using elastomeric stamp such as PDMS. Transfer printed microstructure/nanostructure form an electronic grade ultrathin layer on receiver substrates, which is ultimately used to develop the active/passive electronic components. With this approach, the high-temperature processing steps (e.g., high-quality oxide deposition) are carried out, while the microwire/nanowire are still on the wafer and the remaining low-temperature processing steps, such as metallization, are carried out after completion of transfer process [19], [20]. Among several e-skin patches that have been developed using this approach, a few notable ones are conformable tattoo, such as e-skin patches for health monitoring [13], thermoelectric energy harvesting [21], and graphene-based transparent energy-autonomous e-skin [12].

The contact printing involves the directional sliding of a donor substrate, consisting of free-standing nanowires, on top of a receiver substrate. During the sliding step, the nanowires tend to be aligned and combed due to the sliding shear force. Then, nanostructures are detached from the donor substrate due to the accumulation of structural strain and, finally, are anchored to the receiver substrate by the Van der Waals interactions. Unlike transfer printing, contact printing does not require the elastomeric transfer substrate. The method has been used to develop flexible e-skin patches using nanowires made from both the bottom–up [22] and top–down approaches [23]. Owing to miniaturized dimensions, the microwire/nanowire is highly flexible and the e-skin with this approach is highly flexible. Extending this approach with multiple gate Si nanowire, demonstrated for neuronlike processing [4], it will be possible to obtain next-generation neuromorphic e-skin or tactile skin.

The e-skin with printed high-mobility semiconductor nanowires is likely to lead us to the high-performance flexible electronics at low-fabrication cost. With this unique combination of high-performance and the low-cost fabrication, this transfer printing and contact printing approach offers an attractive alternative to organic semiconductor-based approach [24], [25].

C. Ultrathin Flexible Chips

The relevance of ultrathin chips (UTCs) to e-skin is in context with the bridging technology needed to realize a fully flexible high-performance system. For example, with compact electronics on flexible chips, the UTCs (thickness $<50\ \mu$m) offer solution for efficient driving or output unit, sensor readout, and signal conditioning and on-site processing of the raw tactile data gathered from e-skin. The UTC-based approach can also be followed to develop the skin patches for body parts requiring high density of touch sensors, e.g., piezoelectric oxide–semiconductor field-effect transistor device-based touch sensors and flexible chip [26], [27] for body parts such as fingertips. Furthermore, owing to the bendability and excellent form factor, it is easy to integrate the UTCs on flexible substrates in comparison with the conventional thick chips, and hence, they could be used to advance the FPCB-based large-area tactile skin discussed earlier. Furthermore, due to reduced package volume and lower parasitic capacitance, they have better high-frequency performances, lower power consumption, and stable electronic response for a particular bending state [28]. They hold the potential to open up new avenues for heterogeneous integration of various semiconductor materials (e.g., organic- and inorganic-based electronics, which is the characteristic of an e-skin system). With these features, UTCs can underpin advances in several emerging applications, such as robotics, wearable systems, mHealth, smart cities, IoT, body area network, body dust, and neural interfaces.

D. Energy-Autonomous E-Skin

Energy autonomy is a key to the next-generation portable and wearable systems for several applications. The high density of multiple types of electronic components (e.g., sensors, actuators, and electronics) required in e-skin, and the need to power them without adding heavy batteries, has fuelled the development of compact flexible energy systems to realize self-powered or energy-autonomous e-skin. The compact and wearable energy systems consisting of energy harvesters, energy storage devices, low-power electronics, and efficient/wireless power transfer-based technologies, are expected to revolutionize the market for wearable systems and, in particular, for e-skin. In a recent review article [29], we have discussed a wide range of solutions such as lightweight e-skin with wearable energy harvesters (e.g., photovoltaics, thermoelectric, piezoelectric, and triboelectric) and energy storage devices (e.g., flexible batteries and supercapacitors). Among various energy harvesters, the photovoltaics generate the most and have good potential for energy-autonomous e-skin—as demonstrated recently through graphene-based transparent e-skin integrated on photovoltaic cells [12]. Wireless powering is another attractive alternative, which is possibly more suitable for e-skin application in health monitoring as user comfort is important.

E. Neural E-Skin

Efficient ways are needed to process the sensory data, especially in the case of large-area e-skin where a large number of touch sensors are needed. As an example, a human-inspired e-skin will require about 45k mechanoreceptors in $\sim$1.5-m^2 area [4], [5]. With whole-body tactile sensing, the tactile data will increase rapidly and, therefore, will be the challenges related to compilation and processing. Currently, limited solutions are available to deal with large data generated in the tactile skin, let alone for the resulting perception.

New techniques for the management of the tactile data will add a significant value to the e-skin research. One option is to develop e-skin with local processing of sensory data, i.e., instead of sensing all raw data to central unit for processing and decision-making, sending only the partially processed data and allowing central unit to take higher level decisions. The neuroscience studies on human touch sensing suggest that such on-site distributed computing may be occurring in humans. For example, the ensemble of tactile data from peripheral neurons is considered to indicate both the contact force and its direction. Therefore, a neuronlike inference to handle the tactile data early on can be helpful. A few works have recently focused on such a processing at sensor level to detect force and pain [30]–[32]. Such approaches must be scaled up for large-area e-skin, even if this is not an easy task.

The software-based neural network (NN) approaches have also been explored for tasks, such as object recognition via texture or materials [33]. However, the software-based approach still requires all the data to be transferred to the central processing unit. The NN for inference from data gathered by e-skin could work for health monitoring of population in a region. The application of software-based approach for e-skin in robotics requires attention as the time between data gathering and reflex action could be very short. The software-based NN approaches are slower and less energy-efficient due to the lack of large-scale parallel processing. Instead, the hardware-implemented neuromorphic tactile data processing along with NNs like algorithms could be better alternative. A few hardware neuromorphic implementations reported in the literature, although not in context with e-skin, use spin logic [34], memristor, neuron MOSFET, analog circuit-based neurons, and field-programmable gate array. Although none of these have made major impact on robotic e-skin, they could be potential alternative despite challenges in terms of complexity, scalability, speed, reliability, nonbendability, and power consumption. The neural nanowire field-effect transistor-based approach is another option for hardware NN [4].

III. CHALLENGES AND OPPORTUNITIES

With technological advances over the past few years, particularly in the field of flexible and soft electronics, we have gotten closer to mimicking some of the abilities and morphology of real skin with sensors and electronics embedded in soft substrates. However, just copying skin morphology or capturing few parameters that we experience as touch is not enough. The challenge lies in reproducing the functions rather than the shape while accepting the fact that the shape (morphology), at the micro and macro levels, affects the functions. Therefore, we must focus on the functionalities as well, and in this regard, there is also a need to find the ways to extract the information from sensor data.

A meaningful e-skin, for a broad range of applications discussed here, requires a holistic approach starting from the way the data are acquired, encoded, and eventually acted upon. The way ahead lies in multidisciplinary teamwork: on the one side, neuroscientists and clinicians analyzing the multitechnological bases tactile encoding or clinical validity of sensors on e-skin, and on the other side, engineers and technologists synthesizing the artificial systems, not only as “living” proof-of-concept but also scaling up for real use. Of course, there are several challenges in the way. Major challenges related to comfortability, signal acquisition and transmission, and energy autonomy have been discussed in the previous sections along with the way technology is being developed to overcome some of them. Since various technologies that are being used to develop e-skin are themselves at various stages of development, it may take couple more years for widespread use of e-skin.

Challenges often come with opportunities. The opportunity for e-skin in various application areas has been already discussed. In addition, the development of e-skin is also acting as a catalyst for advances in other areas and is opening up new opportunities in those areas. For example, with requirement of bendability in e-skin, the conformable electronics has also advanced and has opened opportunities for developing predictive and accurate models for flexible devices, which could be exploited to predict the bending state or stress patterns. This is because device response changes constructively or destructively as a result of bending-induced stresses [35]–[37].

The e-skin or tactile skin in robotics and "second skin" in wearable applications are closely linked through flexible electronics technology. Altogether, these areas offer unprecedented opportunities for tackling several pressing societal challenges. For example, when wrapped around surgical tools (e.g., tool used in the pin-hole surgery), the flexible sensory patches could allow surgeons the feel tissues or palpate internal body parts. The disposable and wearable solutions enabled by advances in e-skin are aiding positive changes in health monitoring practices at the global scale. E-skin-type patches are also being explored as smart tags for real-time monitoring of food and drugs. Coupled with advances in the IoT, e-textiles, virtual reality, augmented reality, Industry 4.0, organ on chips, and artificial intelligence/deep learning, the e-skin technologies hold the promise of achieving a new level of human connectedness. ■

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