Large-Area Soft e-Skin: The Challenges Beyond Sensor Designs

This article presents the state of the field of large-area tactile sensing in robotics and prosthetics, particularly focusing on neural-like tactile data handling, energy autonomy, and advanced manufacturing based on printed electronics.

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ABSTRACT | Sensory feedback from touch is critical for many tasks carried out by robots and humans, such as grasping objects or identifying materials. Electronic skin (e-skin) is a crucial technology for these purposes. Artificial tactile skin that can play the roles of human skin remains a distant possibility because of hard issues in resilience, manufacturing, mechanics, sensorics, electronics, energetics, information processing, and transport. Taken together, these issues make it difficult to bestow robots, or prosthetic devices, with effective tactile skins. Nonetheless, progress over the past few years in relation with the above issues has been encouraging, and we have achieved close to providing some of the abilities of biological skin with the advent of deformable sensors and flexible electronics. The naive imitation of skin morphology and sensing an impoverished set of mechanical and thermal quantities are not sufficient. There is a need to find more efficient ways to extract tactile information from mechanical contact than those previously available. Renewed interest in neuromorphic tactile skin is expected to bring some fresh ideas in this field. This article reviews these new developments, particularly related to the handling of tactile data, energy autonomy, and large-area manufacturing. The challenges in relation with these advances for tactile sensing and haptics in robotics and prosthetics are discussed along with potential solutions.

KEYWORDS | Energy autonomy; e-skin; flexible electronics; neuromorphic skin; printed electronics; tactile sensing.

I. INTRODUCTION

Rapid advances in the design, manufacturing, electronics, materials, computing, communication, and system integration have opened new areas for applications of robots and engineered systems [1]. As a result, we no longer speak of robots as only the industrial tools needed for repetitive tasks such as picking and placing, or robots kept away from people. Not that such tasks are unimportant, it is that significant progresses have been made in these application areas and now the focus is gradually shifting toward robots handling real-world objects under arbitrary circumstances, working safely alongside humans, and assisting them. This trend will continue as we enter the era of smart factories, industry 4.0, social robots, telesurgery, etc., where robots are intended to work closely with a human. We are looking at a profound evolution, where artificial intelligent (AI) systems will be extended into robots with new embodiments. In other words, as AI-like systems become pervasive in science and daily life, and their instantiations correspond to new embodiments (robotized home appliances, drones to deliver parcels, advanced social humanoids, and so on) and these systems will find new applications, such as brain-controlled robots and haptic avatars (Fig. 1). A rich sensorization will be critical to such advances endowed with large numbers of different sensors types

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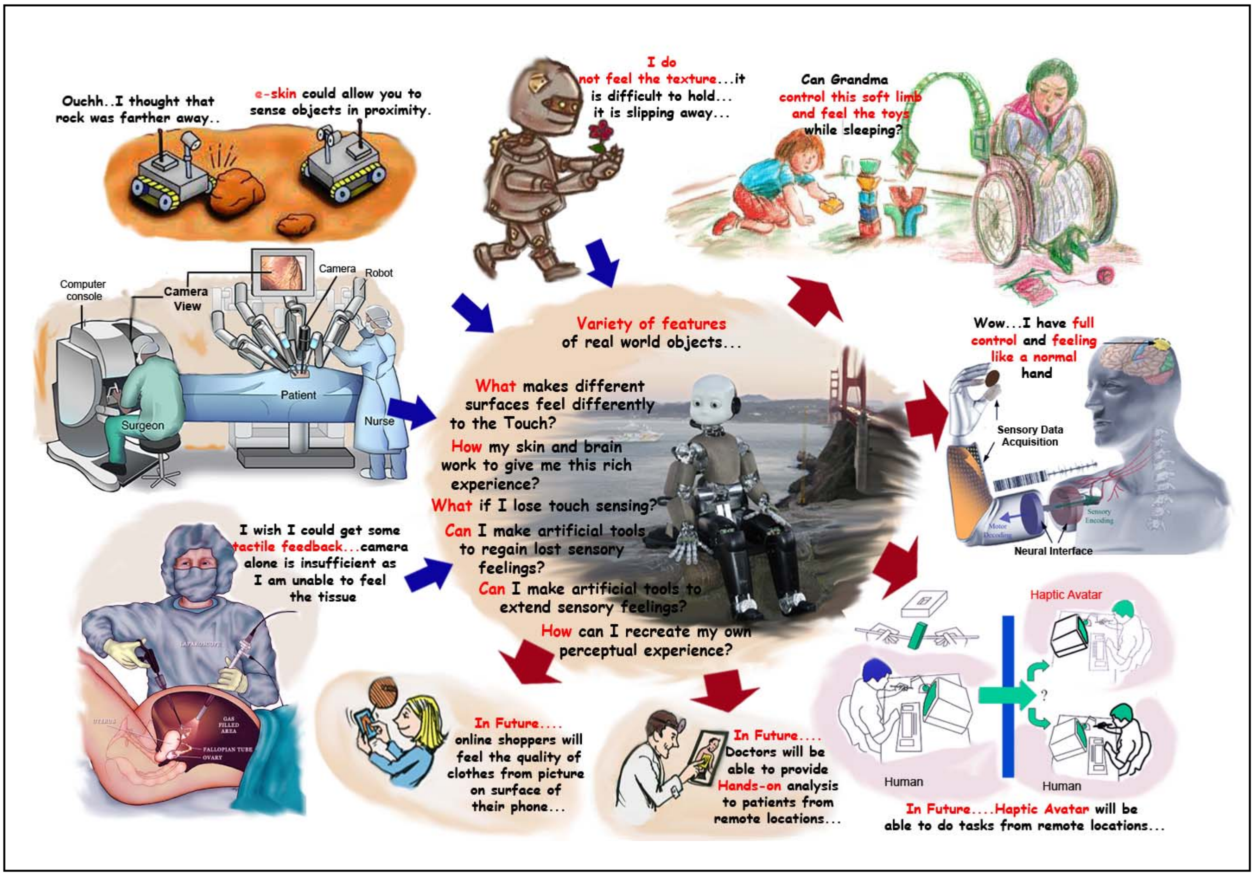

Fig. 1. ***Few example applications where e-skin is needed to enable immediate advances and are thus pushing the development of e-skin (left). Various scientific dimensions of physical interactions which will be unraveled by the e-skin (middle). Few example applications where e-skin will be needed to enable advances in the future and thus will be pulling further development of e-skin (right).***

(touch, temperature, pain, electrochemical, gas sensors, idiothetic sensing, etc.). Critical to these advances are the ways in which electronic skin (e-skin) can be employed to understand various dimensions of physical interaction needed to deal with unconstrained environments and also to achieve a safe human–robot interaction. Some of these are discussed in Fig. 1, where current push factors as well as future pull factors are presented in support of the development of e-skin along with the key scientific questions it will address.

Although vision and audition are widely studied, it is self-evident that touch—or somatosensation—is fundamental to any mechanical interaction. Yet, touch has begun to receive greater attention only recently, possibly due to the complexity and the technological bottlenecks associated with its development of large-area e-skin. Touch is utterly important for the development of many cognitive functions such as the acquisition of the sense of self. First, the sense of touch involves direct mechanical interaction with the environment, rather than the reception of propagating energy from sources and surfaces. Mechanical interaction greatly complicates the design of sensing techniques that are fundamentally robust to sensing conditions and resilient to wear and abrasion. For artificial tactile skin to function like human skin, it needs to: 1) be impervious to many types of mechanical loads (impacts, sharp objects, elastic objects, multiphase materials, etc.) and surfaces during contact (abrasive, wet, lubricated, fibrous, composite, etc.); 2) account for the distributed nature of tactile sensing; 3) account for multiple mechanical sensing parameters (e.g., tensorial quantities describing strain, permanent damage, etc.) as well as other forms of stimulation (thermal and chemical); 4) respond within time scales compatible with behavior; 5) cope with wiring complexity and limited information transmission capacity; 6) minimize energy requirements for the operation of sensors and associated electronics; 7) contend with geometrical nonconformability; and 8) handle large amounts of data and provide reliable ways to extracting information that is useful for behavior. Although these challenges have received some attention, a holistic approach, where they are simultaneously considered, is needed. For example, numerous tactile sensors using various transduction mechanisms have been reported [2]–[8]. Yet, the tactile skin is still, today, not an integral component of robotic technology —not as much as visual and auditory sensors are.

This article surveys the state of the field of large-area tactile sensing in robotics and prosthetics, particularly regarding the above issues. There have been other surveys that discussed various types of tactile sensors and some of the issues related to the effective utilization of tactile sensing [9]–[11]. The detailed discussion on already reported aspects related to e-skin is not included in this article. Instead, the focus of this article is to highlight the challenges laying beyond sensor designs. This article focuses on issues such as the hardware approaches for e-skin to continuously interact with the environment, the handling of large tactile data, including distributed local processing in neurallike fashion, energy requirements, and the manufacturing processes for large-area e-skin with high-performance devices. This article is organized as follows: historical research developments of human tactile sensing and how those key understandings are feeding into the research on artificial tactile sensing are presented in Section II. This section is followed by a discussion in Section III related to various strategies that have been adopted for to meet the energy requirement of e-skin or to develop energy-autonomous e-skin. Section IV presents advances toward tactile data encoding and the handling of large tactile data from distributed tactile sensors for large-area e-skin, including the initial advances toward neuromorphic tactile skin. This section is followed by Section V, where an overview of advanced manufacturing and nanostructure printing techniques for large-area electronics and e-skin is presented. Finally, a summary of the conclusions and future directions is presented in Section VI.

II. HISTORICAL DEVELOPMENTS RELATED TO HUMAN SENSE OF TOUCH AND ARTIFICIAL TOUCH SENSING TECHNOLOGIES

Skin yields the body interface with the environment and is the largest human organ, comprising about 15% of the body mass [12]. It is robust enough to be damaged by a continuous interaction with the environment and can repair itself when damaged. The skin houses various receptors that enable us to detect various stimuli such as skin temperature disturbance, pain (i.e., high threshold), skin strain and strain rate (i.e., low threshold), and rapid skin oscillations. These receptors allow us to be sensitive to surface asperities, texture, substance, object compliance, slip, the presence of lubricants, and many more properties of things we touch including noxious stimulation. Biology often provides models for technologies and the human skin too has also contributed to advancements in tactile skin or e-skin [11], [13]–[18]. The timeline of some of the key findings related to human touch sensing, which have enabled advances in artificial tactile skin, is given in Fig. 2. In recent years, emulating the sensory ability of human skin has become an area of growing interest due to its applications in the field of the prosthesis [19], robotics [20], [21], health monitoring [22], and human–machine interaction [22]. Although our present understanding of human tactile sensing is not as deep as that of vision or audition, it has come a long way since the naming of the five senses by Aristotle around 400 BC [23]. The many sensory capabilities of skin posed challenges at that time too. Aristotle wondered whether the touch was one sense or many.

Early studies of the sense of touch (Fig. 2) showed that a great many touch-sensitive receptors could be observed in the skin; in the glabrous skin inside the hands and on the soles of feet; in the hairy skin that covers most of the body; and in various types of mucosal skin. Deep mechanosensitive end-organs are found in most load-bearing soft tissues, especially tendons and muscles, which provide the brain with sensory information that also participates in tactile sensations owing to the propensity of transient and persisting mechanical stimuli to propagate over large distances. Conversely, proprioception, or awareness of one's position in space, is, in part, mediated by the deep end-organs and also by the receptors in the hairy skin that are stimulated when our joints move. Sensory inputs originating from receptors embedded in the skin typically provide information about direct mechanical contact, such as the traction exerted by the glabrous skin during manipulation or the sliding movement of an object on hairy skin.

In the initial years of robotics, there were very few developments of artificial skin. Perhaps the earliest example of e-skin realization is from the 1970s when an artificial hand covered with skin was explored to detect grip strength, slip, and certain properties of a held object such as texture and hardness [24]. In the late 1980s, the use of infrared sensors on large area of robotic arm was shown to evade obstruction or to avoid contact [25]. Nowadays, robots are expected to be involved in tasks requiring a physical interaction with the environment, objects, or humans. As a result, there is an increased focus on developing artificial skins with tactile capabilities [26], [27] and safe physical contact [14], [28]. Cutaneous skinlike devices have also found applications in wearable systems as the second skin or tattoolike skin to measure various physiological parameters to monitor health condition [1], [29]–[31]. In all these cases, it is important to consider the sensor distribution, the readout, and a suitable integration strategy [20].

The e-skin technology development, thus far, focused mainly on mimicking certain aspects of human skin and have accounted for parameters such as sensor types and density. Electrophysiology studies have identified several types of responses to mechanical stimuli. The light indentation of the glabrous skin with a pointed object elicits a response from the receptors near the contact. Interestingly, the response is most of the time transitory, that is, stronger during the ramping periods of the indentation at the beginning and the end of the stimulus, suggesting that the stimulated receptors respond to strain rate. Less often, the response is related to the intensity of the indentation although there is always a degree of temporal adaptation. These responses have been associated with different anatomically identified end-organs. The first, the most common, is called the Meissner corpuscles tucked in cavities observed in the internal face of the

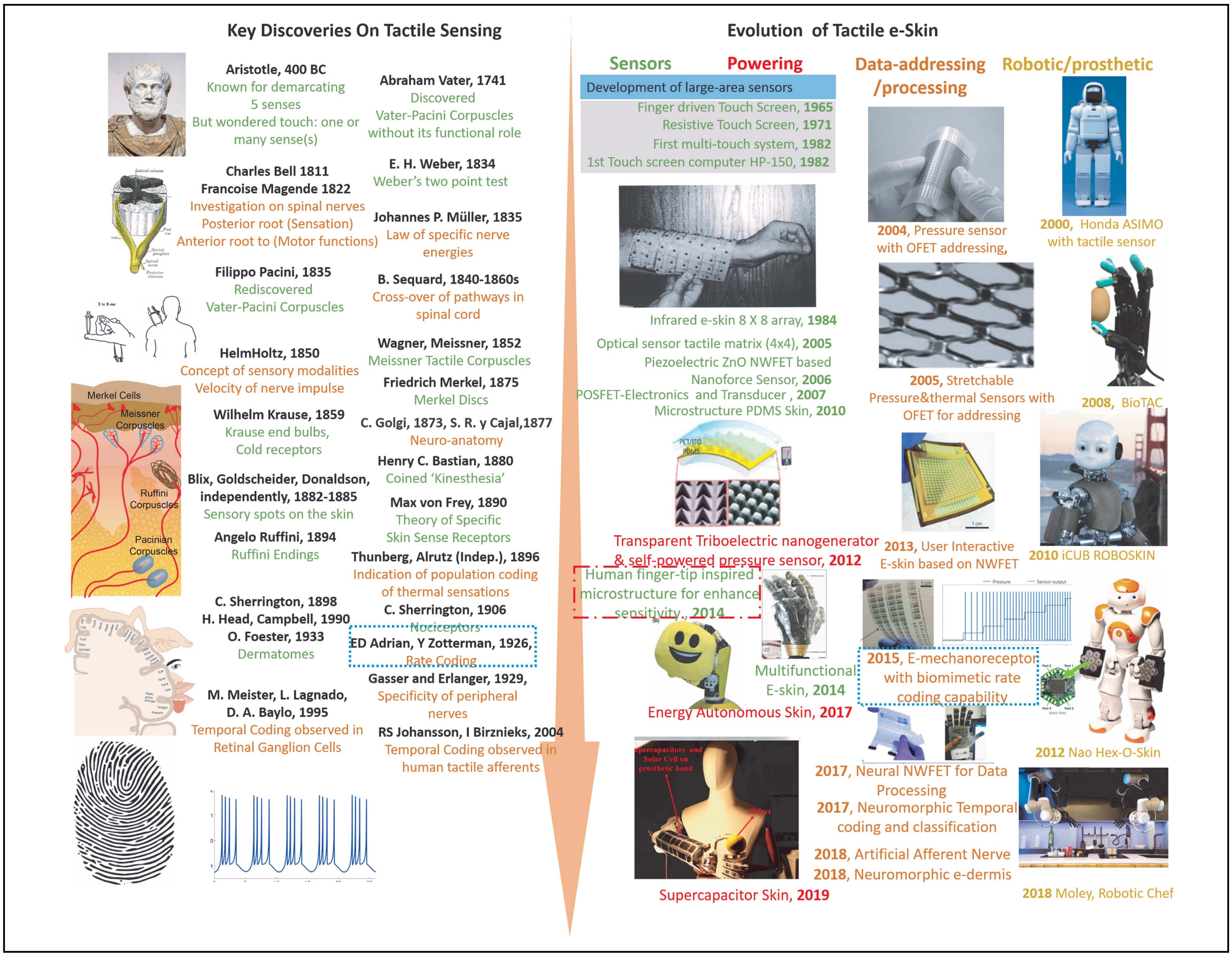

Fig. 2. *Timeline of key research developments in the field of human tactile sensing and the artificial tactile skin.*

epidermis [9]. There are about 30 such receptors (25 μm in diameter) per millimeter square in the healthy skin of fingertips. The other type of end-organ corresponds to what is identified as a "neurite complex." This term designates a structure where a nerve fiber terminates in numerous branches. This end-organ, found at the interface of the dermis and the epidermis (territory range of 20–2000 μm), is called Merkel cell–neurite complex. It corresponds to the slowly adapting response observed from electrophysiology studies. A comparatively large end-organ (200–1000 μm in diameter), called the Pacinian corpuscle, is also observed in many types of soft tissues throughout the body. In the hand, there is a couple of hundred of them that are opportunistically distributed. They show extreme sensitivity (in tens of nanometers of membrane displacement) and a particular phase-locking physiological response to oscillating stimuli. The fourth type of response observed from the human hand, when large regions of glabrous skin are pulled sideways elicit a steady response in a comparatively small number of nerve fibers, is thought to be due to a population of end-organs called Ruffini endings [34]. Astonishingly, there is no modern observation of these organs in the hand (yet, they are observed in other connective tissues, such as ligaments). The hairy skin, which is histologically distinct from glabrous skin, since it lacks the reticulated structure of glabrous skin, does not have Meissner corpuscles. Furthermore, it has Merkel cell complexes arranged in 1000-μm clusters called touch domes separated from each other by several millimeters [32], [33]. This brief picture would not be complete without mentioning the presence of the so-called C-fibers in all skin types. These nonmyelinated nerve fibers slowly conduct nerve impulses from the entire skin surface to the brain. They are associated with nociception (pain), but in recent years, these very numerous fibers have also been shown to participate in light touch, in addition to the fast system with the multiple receptor types just described.

In humans, the tactile sensation has been investigated using a unique technique called microneurography, where a small-diameter needle electrode is inserted in a peripheral nerve and the activity from single nerve fibers can be recorded [35]. This technique, not available in humans for other sensory modalities, made it possible to correlate peripheral nerve activity ("spiking activity") and sensations. Yet, a fair understanding of the sense of touch is

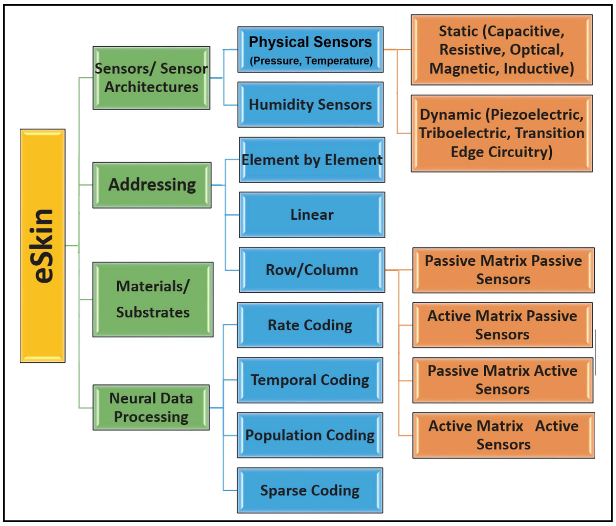

Fig. 3. ***Various components of e-skin including sensors and the interfacing methods to read the sensory data.***

still elusive because what is currently known about single receptors is not sufficient to develop reliable integrative models able to predict the behavioral aspects of the tactile function.

The discovery and understanding of the properties of various mechanoreceptors in human skin have contributed to the development tactile sensors for e-skin. One of the key messages from these studies has been that the e-skin should have tactile sensors to detect both static and dynamic contact events such as those that take place during slip or contact with objects (Fig. 3) [36]. Complex contact states involve traction distributions at the surface of the skin that have more dramatic effects when the skin is compliant. The mechanical state of the skin, which is a deformable solid, requires an infinite number of coordinates to be described since, macroscopically, it appears as a 3-D continuous medium. Yet, touch sensors generate scalar outputs, suggesting a tremendous dimensionality reduction and providing the beginning of an explanation as to why touch requires the availability of sensors with different properties. In this regard, embedding sensors in elastic material at different depths can provide a basis for the sought-after variability. However, sensors arrangements so far have rarely considered this possibility [20].

As far as the sensing mechanisms are concerned, capacitive transduction has been extensively explored for static or quasi-static events and the piezoelectric and triboelectric transduction for dynamic events. Capacitive sensors are a popular choice due to their high sensitivity, low power consumption, simple device architecture, and simple readout electronics. The piezoelectric and triboelectric transduction mechanisms are attractive as they could lead to self-powered sensors [4], [6], [37]. For example, triboelectric nanogenerators (TENGs) and planar electrostatic induction coils are utilized as a self-powered analog smart skin [Fig. 4(k)] to detect location and contact velocity [38]. To imitate the elasticity of human skin, touch sensors are sometime developed together with elastomers having microstructures [36], [39], [40]. Several review articles have compared the touch sensors based on various transduction mechanisms (e.g., optical, magnetic, and ultrasonic) and recent advances related to materials and fabrication technologies, including conformable electronics [41]–[44].

Factors such as density and the number of receptors are also important when body-wide sensitive skin is considered. There are about 45 000 mechanoreceptors distributed in human skin [35], [45]–[48] along with a large number of thermoreceptors, and C-fiber system [45]. The resolution, density, and response time of human skin have been emulated with different sensor architectures and readout interfaces (Fig. 3). For example, the high-spatial resolution active matrix of field-effect transistor (FET)-based sensors arrays on planar or flexible substrates. To this end, both organic and inorganic semiconductor materials-based sensors have been explored [49], [49]–[52].

Although the distributed nature of skin poses challenges for technology development, it also offers interesting opportunities that are not possible with other sensory modalities. Specifically, the skin partially wrapped around the objects to be interacted with could make a whole range of sensory dimensions possible [53] (Fig. 1). Recent advances in neuroscience indeed suggest that the brain does make use of this possibility [54]. The high dimensionality inherent to touch paves the ground for rich representations of such skin–object interactions. The sense of touch allows access to properties of the physical world that other senses do not allow. In robotics, utilizing this potential would also translate to a system with a higher capability than presently available. As discussed in the next section, there has been the new interest in exploiting the area of body surface to generate energy [55]–[57].

With the large number of sensors, the e-skin must also handle a large amount of tactile data within limited available communication bandwidth. In this regard, the insights into the ways of tactile information flow in the skin show us some direction. The empirical correlations established between impoverished stimuli supposed to reflect the coding properties of the individual tactile sensors are clearly insufficient. The most interesting and useful effects of touch arise from the integrated information from large populations of touch sensors that are activated during the simplest interaction with actual objects. Therefore, the structure of skin, its morphology, micromechanical, and tribology properties modulate the collective response of many receptors when it comes into contact with objects. This observation has profound implications for the development of future large-area tactile skin. Clearly, there is a need to delve deeply into the working of skin and the touch sensory system to develop an effective bioinspired artificial tactile skin. The field would benefit from the contributions by computational neuroscientists who will help to understand how neural codes related to stimulus properties, or haptic dimension, and which processing architecture or hardware arrangements could support the encoding and decoding of tactile information.

The science of touch has long neglected how the mechanical skin properties intrinsically tune the skin sensors signals to instead focus on the properties of individual tactile sensors in the skin. However, this approach to study the tactile sensing will find itself limited in explaining how the brain is able to develop stable perception of the environment, e.g., experience the heaviness of a cup, despite the large variations in sensing conditions, e.g., whether the cup is held by the handle between two fingers or rests on the palm. For the brain to interact in a meaningful way with the environment, it is required to learn the sensor dependencies that depend on the skin and the structures that support it [53]. Similarly, e-skin sensors and supporting structures should be embedded in a deformable substrate and their mechanical properties carefully considered.

III. ENERGY AUTONOMY OF e-SKIN

The true replication of the functionalities of human skin requires e-skin to have a network of distributed network of large number of sensors, actuators, and electronics over large area, i.e., whole body of robot or prosthetic limb. This significantly raises the energy requirements and makes e-skin a power-hungry system. For example, about 8 W is needed to power about 1000 capacitive touch sensors on humanoid robot “iCub” [55], [58]. The power consumption would be much higher if human skin, having about 45-K mechanoreceptors in 1.5-m^2 body area [48], is mimicked and if all these sensors are to remain active all the time. The high energy requirement poses a new challenge to the application of e-skin in robotics, particularly an unstructured environment. For example, the frequent charging of the batteries or other energy storage devices discourages amputees and reduces the chances of acceptance of the prosthetics limbs. The energy requirement also poses a hurdle to the widespread use of e-skin in applications such as wearable health monitoring systems.

Despite the critical need to power the large number sensing/actuating/electronic components, the issue has not received much attention for e-skin. A few solutions reported in recent years are mainly related to wearable health monitoring patches. These include wireless powered or solar-powered sensor patches with low-power electronics [14], [57]. The low-power sensors based on materials such as indium tin oxide ($\sim$100 μW/cm^2) [48] and graphene ($\sim$20 nW/cm^2) [14] have alleviated the issue to some extent. For example, with just 20 nW needed per centimeter square, the graphene-based sensors require 3.9 μW over an area of 1.5 m^2 [14], [55]. Although such calculations do not include the power needed for readout electronics, it is clear that the energy autonomy of e-skin has deservedly started to receive the attention. This is also evident from recent review articles on energy-autonomous e-skin [55] and works focusing on sensors with energy generators [Fig. 4(a)–(d)], storage devices [Fig. 4(e)–(g)], self-powered systems [Fig. 4(h) and (i)], and their applications [Fig. 4(j)–(l)].

As discussed in Section II, the presence of skin over a large area also offers new opportunity to harvest ambient energy to develop energy-autonomous e-skin. For example, with conformable solar cells (with reported power density in 1–35-mW/cm^2 range and power conversion efficiency up to 46% for rigid semiconductor solid-state device [Fig. 4(a)] [55]) present over the whole body of a robot or prosthetic limb, it may be possible to generate sufficient power to operate the e-skin as well as other devices. However, the economic feasibility of such solutions is currently a challenge, which possibly will be addressed by large scale use of photovoltaic (PV) cells. In a previous work, we demonstrated this approach for self-powered tactile skin by integrating graphene-based transparent coplanar capacitive touch sensor (sensitivity 4.3 kPa^{-1} over 0.11–80-kPa range) on a PV cells [Fig. 4(h)]. The excellent transparency ($\sim$98%) of touch-sensitive layer allowed most of the light to reach the PV cell underneath to harvest the energy. The ultralow power ($\sim$20 nW/cm^2) needed by the touch-sensitive layer in this work is much lower than the power generated by commercial flexible a:Si PV cells (power density $\sim$19 mW/cm^2). The energy generated will be significant if the presence of touch-sensitive layer over an area equivalent of an adult human skin (i.e.,$\sim$2 m^2) is considered. This surplus energy could be stored for later use (e.g., when there is no sunlight) by integrating an energy storage device with this e-skin and could also be utilized to operate the actuators in robots or prosthesis hand. The first demonstration of flexible supercapacitors (SCs) integrated underneath the solar cells [Fig. 4(j)] to operate the actuators on robotic hand was reported recently [56]. The output voltage of these SCs ($\sim$2.25 V) is compatible with the requirements of most of the electronics in use today. The wireless power transfer technology will add significant value to these new approaches, particularly in terms power management [59]. Similar opportunities are difficult with other sensory modalities such as vision and audition, which, unlike skin, are centralized and present in small areas. The demonstrations such as the one described above are good examples of turning challenges into opportunities. With current advances in the field of PVs, such as the development of ultraflexible PV cells [60]), favoring the development of self-powered or energy-generating e-skin, it will be possible to extend the benefits to other areas such as wearable systems for health monitoring. In this regard, recent works such as fully flexible self-powered health monitoring patch, with chemiresistive pH sensor powered by flexible SCs and PV cell, are worth noting [57].

The nonconventional approaches such as textile-based battery (capacity of 13 mAh) with solar cell (at a voltage of 0.4 V, and under simulated AM 1.5G illumination at 100 mW/cm^2) and stretchable battery with wireless

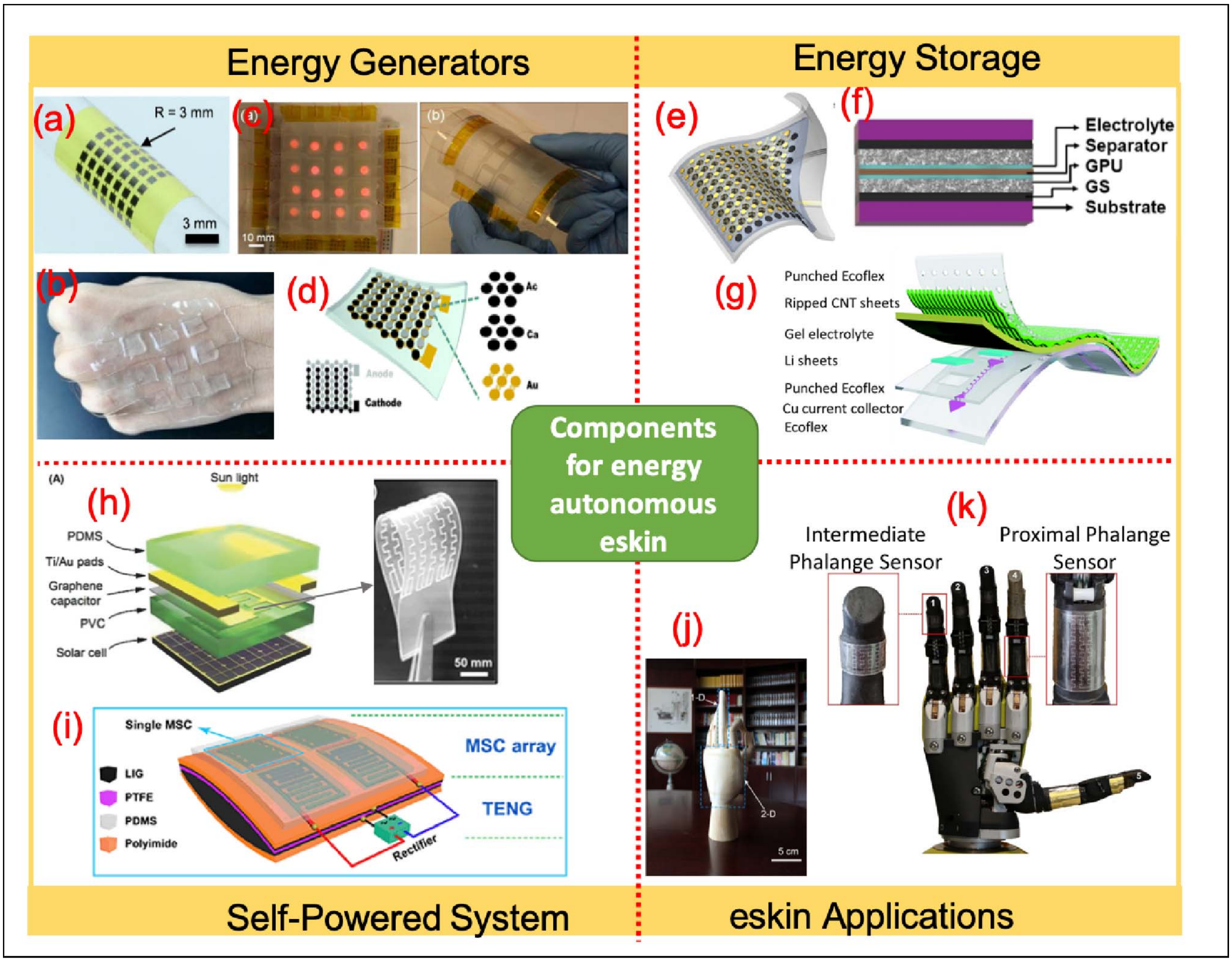

Fig. 4. ***Various energy generation/storage systems and their use for e-skin. (a) Ultrathin vertical GaAs-based solar microcell array. Reprinted from [60], with the permission of AIP Publishing. (b) Soft-skin with 3 × 3 triboelectric energy (TENG)-based tactile sensor. Adapted from [65]. (c) Transparent, bendable TENGs on the LED array. Reprinted with permission from [66]. Copyright 2013 American Chemical Society. (d) Exploded view of biofuel cells-based e-skin. Reproduced with permission from Royal Society of Chemistry [67]. (e) Stretchable batteries with serpentine interconnects. Reprinted by permission from Springer Nature [61]. Copyright 2013. (f) Flexible SC (GS-graphene sheet; GPU-graphite polyurethane). Adapted from [56]. (g) Stretchable Li-air battery (CNT-carbon nanotube). Reproduced with permission from Royal Society of Chemistry [63]. (h) Graphene-based transparent touch sensors on top of PV cell (PDMS-polydimethylsiloxane; PVC-polyvinyl chloride). Adapted from [14]. (i) Schema of flexible self-charging micro-SC (MSC) power unit (PTFE-polytetrafluoroethylene; LIG-laser-induced graphene) [64]. (j) Artificial hand with analog skin. Adapted from [38]. (k) Graphene capacitive sensor on a robotic hand. Adapted from [14].***

charging [Fig. 4(e)] [61] are other interesting alternatives, currently being explored for wearable applications [62], for prosthesis and robotics. The conventional Li-ion batteries are not suitable for e-skin as they are not flexible or stretchable and are not lightweight. In this regard, recent advances in the area of flexible/stretchable batteries and flexible SCs [57], [63] [Fig. 4(e)–(g)] are promising.

Energy harvesting using mechanisms such as piezoelectric, thermoelectric, triboelectric, and electromagnetic could also be applied to e-skin [37], [55]. For example, thermoelectric energy harvesters could tap the heat generated by the actuators on robots. Similarly, the piezoelectric harvesters can tap the ambient mechanical vibrations to power microdevice/nanodevice distributed in the e-skin. A detailed description and comparison of many of these energy harvesting mechanisms are given in [55]. Among these, the triboelectric energy generators (TENGs), which generate energy by touching, pressing, twisting, stretching, etc., are particularly interesting for e-skin. An example of TENG integration with microswitched capacitor (SC) for self-powered sensor applications is shown in Fig. 4(i) [64]. Another example considers a soft skin, which can sense low pressures ($\sim$1.3 kPa) [Fig. 4(b)], with TENGs providing the open-circuit voltage up to 145 V and an instantaneous areal power density 350 W/cm^2 [65]. The single electrode-based TENGs (power density $\sim$5 kW/cm^2 on a load of 100 MΩ), explored for touchpads [Fig. 3(c)], are also suitable for robotics and human–machine interface applications [66]. The pressure sensors requiring $<$1 mW could be powered by TENGs [56]. Biofuel cells offer another interesting direction for energy autonomy, particularly for wearable systems. Such approaches are extremely

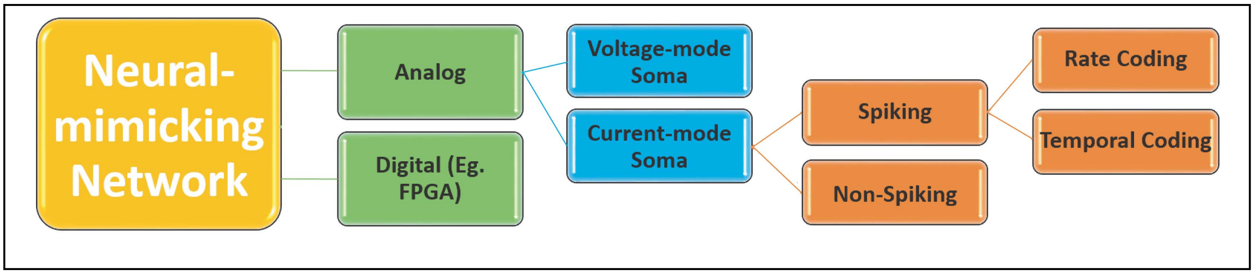

Fig. 5. ***Various neuromimicking data processes.***

attractive when extended to using body fluids such as saliva, urine, sweat, etc. for the generation of energy through electrochemical reactions. An example includes soft, stretchable biofuel cells using sweat as electrolyte [Fig. 4(d)] to generate 1 mW/cm^2 power [67].

The management and efficient utilization of available energy is another challenge that requires attention for effective use of e-skin. For example, while lifting a heavy sandbag, a humanoid robot will require sensory feedback from sensors on hands and front part of the body. In such case, there is no need for the sensors from body areas not in contact with bag to be energized. There are several such robotic tasks where feedback from all touch sensors is not needed and, therefore, it is sensible to plan dynamically the sensory area to be energized [20], [28]. Various energy management strategies and AI techniques that are being explored in areas such as zero power Internet of Things (IoT) could also be adopted for energy-efficient e-skin. AI techniques are already being explored for effective power distribution and operation [68], [69]. Similarly, energy management can be achieved with power-optimized system implementations, supported by advanced technologies such as wireless power transfer and batteryless operations. The attractive designs used for system-on-chip, with peak active power consumption of ~3 mW [70]—an order of magnitude lower than compared with Bluetooth- or Zigbee-enabled sensor nodes, could also be useful for e-skin. With recent advances in flexible electronics, a few wireless powering solutions based on flexible printed circuit boards (FPCBs) have been reported [71]. Although these approaches are in early stage and seamless integration is far from the sight, they could offer promising solutions for energy or power management.

IV. SKIN WITH NEURONAL LIKE COMPUTING

The efficient ways of transferring a large amount of tactile data and deriving inferences have been another major challenge for effective use of e-skin in robotics. Similar issues faced in vision and auditory sensing led to emulating the spiking neural and neuromorphic mechanisms [72] to bridge the efficiency gap between artificial systems and their biological counterparts [73]. Similar approaches for tactile perception have started to receive attention only recently. Various algorithms explored for processing of tactile information include support vector machine (SVM), linear discriminant analysis (LDA), *k*-nearest neighbors (*k*NNs), spiking neural network (SNN), extreme learning machine (ELM), and Bayesian analysis [74]. A classification of various neuromimicking data processes is given in Fig. 5. These efforts have led to the development of sensory systems that have been used in a variety of software-based NNs for tactile recognition tasks, including texture, shape, and object recognition [75]–[79]. Due to the lack of large-scale parallel processing, the software-programmed NNs are slower and less energy-efficient [75], [80], thereby making it necessary to have hardware-implemented neuromorphic tactile data processing along with NNs like algorithms. Furthermore, touch is fundamentally different from vision, and therefore, the commonly used techniques, which were developed for vision sensing, are not always suitable for handling of the tactile data [1]. For example, the neuronal network-derived preprocessing can also be obtained without spiking, and in this regard, the neuroscience knowledge is important to know how to design the interface in terms of network structure and learning rules, and how to design the subsequent decoding in an intelligent robotic system “attached” to the e-skin. As far as the hardware implementations of neurallike tactile sensing are concerned, these are mainly limited to the development of sensors. For example, flexible organic semiconductor-based devices have been developed to mimic the slow adapting mechanoreceptors [81]. The intensity of mechanical stimuli in these devices is reflected through the frequency of digital signals.

The signal transfer in the nervous system is essentially aiming to maximize the fidelity with the time-continuous voltage signal of the sensor (or the neuron inside the brain), but the spike generation mechanism takes that signal as a probability density function and converts it into spikes (and “discretizes” or “binarizes” the signal). Hence, in the spike generation step, we inevitably lose fidelity [82]. However, in biology, it is not possible to transmit time-continuous signals because the biological cabling system (axons) cannot support the long-distance transfer of information due to electrical constraints. Hence, biology made the tradeoff of losing signal quality while solving the critical signal transfer issue. In engineered systems, one could probably get around this problem of signal transfer and instead transmit the time-continuous voltage signal

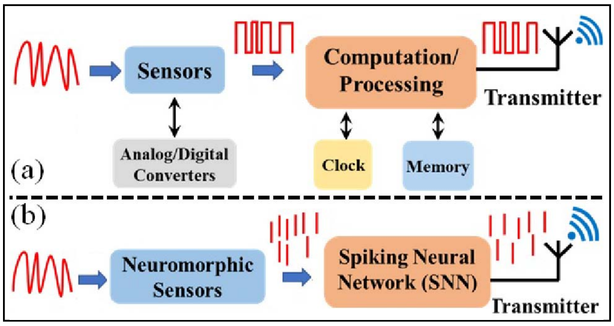

Fig. 6. *(a) Conventional sensor readout and transmission. (b) Spike-domain sensing-processing learning-communication based on neuromorphic sensors and artificial intelligence.*

(e.g., using a single cable for each sensor). This saves a lot of computational power and processing effort compared to spike-based solutions, which require an additional module to generate spikes. However, in practice, such schemes are impractical as the large number of cables will add to the weight and complexity of e-skin. For this reason, the tactile information, in the tactile-sensitive systems reported thus far, is largely transmitted serially (Fig. 3), even if this comes at the expense of readout latency and high energy requirements. For example, "always-on" device-type approach [Fig. 6(a)] can be extremely inefficient, as standard digital architectures over large area e-skin will consume power—in order to run clocks, mixers, and analog/digital (A/D) converters—irrespective of the relevance of the information being recorded and processed. Above issues with current engineered systems could possibly be resolved, just like in biology, by converting the signal into spikes, before it is transferred [Fig. 6(b)]. These spikes could be event-driven, e.g., occurring only when a change is detected at the output of a neuromorphic touch sensor. This means that energy is consumed only in the presence of relevant information. The neuromimetic architectures such as asynchronous output representation systems, which carry the timing information similar to spikes in the nervous systems, could possibly enable the simultaneous transmission of tactile information while maintaining low readout latencies [83]. This was demonstrated recently with an array of 240 sensors, by transmitting events at a constant latency of 1 ms while maintaining an ultra-high temporal precision of $<$60 ns, thus resolving fine spatiotemporal features necessary for rapid tactile perception [84].

In the brain, tactile information is extensively preprocessed before it reaches the neocortex [54], [85], which could also be implemented in e-skin in order to reduce the amount of data that need to be transmitted. The biological solution: a distributed local processing of tactile data with partial processing close to the sensing elements and sending of smaller amounts of processed data to higher perceptual levels, could be advantageous as an engineered solution as well. Although biomimetic solutions often focus on generating spiking signals (which is, in fact, a limitation of the biological system), engineered solutions to transfer of sensor information from an e-skin may be that each individual sensor generates a scalar value depending on the load experienced locally, an early processing system could then collect information from the population of sensors and achieve a reduction of the bandwidth needed to transmit a compressed information.

Devices such as neural nanowire FET (υ-NWFET) (Fig. 7), which imitate the working of the biological neuron [Fig. 7(a)] in a simplified manner, can be an excellent building block for such hardware NNs (HNNs) [48]. The structure of υ-NWFET is a variant of a neuron MOSFET with NWs providing the functional channel region [86]–[88]. The floating gate of υ-NWFET, which modulates the channel current, is capacitively coupled to several gates. The overlap width of the individual gates over the floating gate determines the initial synaptic weight of the neural input on which further schemes of plasticity operate. This imitates the synaptic summation of weighted inputs in the cell body (soma) of the biological neuron or the artificial neuron [Fig. 7(a)–(c)]. The activation function is performed at the circuit level [48]. It may be noted that the biological neural systems also have plasticity, i.e., the ability to strengthen or weaken the synaptic weights over time. In fact, this plasticity is central to the dimensionality reduction performed by the early processing stages in the brain, i.e., before the information reaches the neocortex [89]. The υ-NWFETs-based circuits could also exhibit similar plastic behavior, as discussed in [48]. Other hardware neuromorphic architecture implementations reported in the literature are based on devices such as memristor [90], spin logic [91], [92], memristor [93], neuron MOSFET [88], [94], analog circuit-based neurons [95], field-programmable gate array (FPGA) [75], and software-programmed NNs [96]. Although none of these have been used for tactile skin, they could possibly offer solutions. These technologies have advantages and challenges in terms of complexity, scalability, speed, reliability, repeatability, cost, nonbendability, power consumption, etc., which limit their use in the emulation of biological systems. For example, the memistor, a three-terminal electrochemical cell element, achieved limited success because of scalability issues [90]. Similarly, the spintronic neurons are energy efficient [91] but realizing a practical large-scale neuromorphic architectures and readout is challenging. Recently, two-terminal memristive devices have gained attention as the state of their internal resistance could indicate the history of the voltage across and/or current through them [97]–[99]. The memristive approach is promising in terms of low-energy, high-density memories and neuromorphic computing [100], but as memristors are two-terminal devices, it may not be possible to simultaneously execute the signal transmission (computation or reading phase) and learning functions (writing phase). A potential solution is to use memristors with υ-NWFET-based circuits as basic building block in one transistor—one memristor

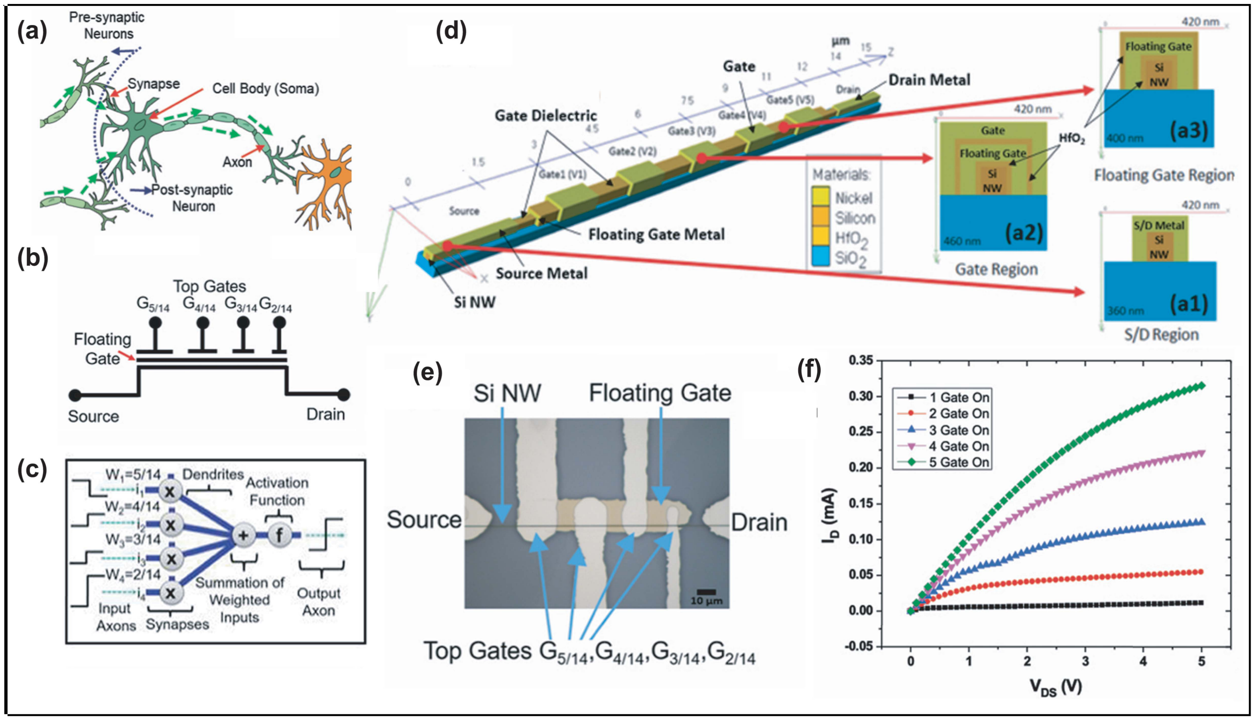

Fig. 7. ***(a) Illustration of biological neuron. (b) Symbol of υ-NWFET. (c) Block diagram of an artificial neuron with specific weights. (d) Scheme of υ-NWFET. (e) Fabricated υ-NWFET. (f) Output characteristics of υ-NWFET. Adapted with permission from [48].***

(1T-1M)-type structure (discussed in the following section). The biological neural system is highly computationally efficient (eight to nine order more efficient than current digital circuits) [101]. Possibly, they could be emulated with 1T-1M-type devices and neuromorphic circuits to develop an efficient, compact, and fault-tolerant e-skin system, which can reliably interpret the noisy sensory signals to provide feedback to robots.

On the information processing level, e-skin could also use biological principle to efficiently use information from various embedded sensors. Any haptic interaction involves a very large number of widespread skin sensors whose signals have a relationship that is intrinsically modulated by the contact with the environment and the skin mechanics. Combined with predictive actions and proprioceptive signals, the brain is able to generate highly enriched percepts of the interactions that we make, which yields an essential part of the brain's development of the concept of contingencies and a rich and stimulating understanding of the physical world. Developing such a predictive coding approach for robotic systems equipped with haptic sensing may provide them stable representations of their environment, as humans have.

V. ADVANCES IN MANUFACTURING TECHNIQUES FOR e-SKIN

The CMOS has been the workhorse technology for advances in several areas, including bioinspired artificial organs such as hearing aids and high-resolution vision imagers [102], [103]. The e-skin is not untouched by CMOS technology as several touch sensors such as piezoelectric oxide semiconductor FETs (POSFET) have been developed using this technology [104]–[107]. Largely implemented using single-crystal silicon (Si) wafers, the CMOS technology is continuing to serve the electronic industry through reliable manufacturing processes and stable devices, circuits, and systems. However, when it comes to large area soft e-skin, the brittle and nonflexible nature of Si, the cost-prohibitive fabrication (particularly for large area coverage), and the high-temperature fabrication steps (incompatibility with plastic substrates) pose hurdles. Some of these issues have been managed through interesting preprocessing/postprocessing methods. For example, various methods for obtaining flexible ultrathin chips (UTCs) (with tens of micrometer or even lower thickness) have been reported [108], [109]. Although issues such as handling of UTCs and heat dissipation remain to be resolved [110], the possibility of having chips bending to a radius of curvature down to 1.4 mm is encouraging as they could be integrated into flexible electronic system [108], fulfilling various challenging requirements related to sensor interface, data processing, and efficient driving. Alternative methods to overcome the issue of nonbendability, such as integrating the planar off-the-shelf electronics on FPCBs. The FPCB-based approach is akin to having mechanically integrated but otherwise distinct and stiff subcircuit islands of off-the-shelf electronic devices, connected to one another by metal interconnects. Although these alternative solutions offer limited flexibility or conformability, they have been successfully used to

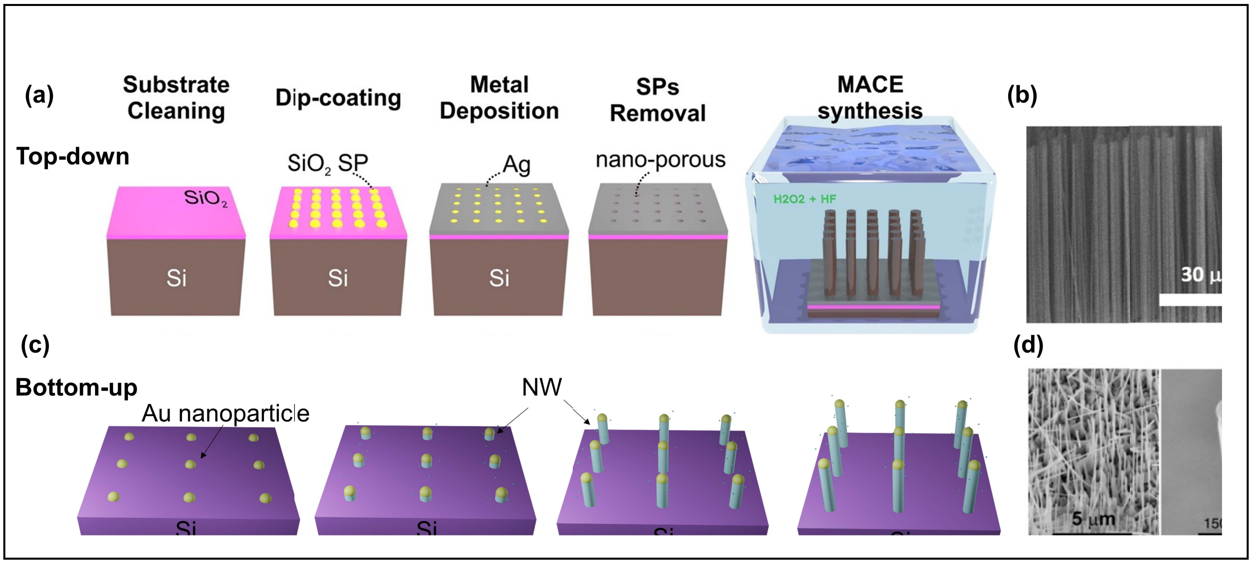

Fig. 8. *Top-down and bottom-up synthesis of NWs. (a) 3-D illustration of top-down process. Adapted with permission from [133]. Copyright 2018 American Chemical Society. (b) SEM images of NWs obtained using this approach. Adapted with permission from [133]. Copyright 2018 American Chemical Society. (c) Bottom-up synthesis of NWs. (d) SEM images of NWs obtained using this approach. Adapted with permission from [162].*

develop large-area robotic skin [1], [111]. Researchers are also exploring innovative strategies (some are compatible with standard CMOS processes) to realize the high-performance flexible electronic systems, which can be used in soft e-skin. These include large-area uniform nanomaterial synthesis, their transferring or printing onto a flexible substrate, and further realization of electronic devices, circuits, and system. To this end, a wide range of materials has been explored including quasi-1-D NWs and nanotubes, quasi-2-D materials, and organic semiconductors [112]–[119]. Here, inorganic Si NW is taken as an example to generally explain the progress and challenges. The choice of Si NWs is motivated by the promise they hold for the development of high-performance flexible electronics. The progress related to other materials can be found in several reviews on flexible electronics [11], [41], [43], [120], [121].

A. Material Synthesis

To realize an electronic system interfacing large numbers of sensors, the controlled material synthesis over a large area is the first and most fundamental challenge to overcome. With regard to Si NWs synthesis, the two distinct approaches are top-down [Fig. 8(a)] and bottom-up [Fig. 8(b)] [122]. Various methods using bottom-up approach include vapor–liquid–solid growth, oxide-assisted growth, and solution-based growth [122]–[126]. The bottom-up methods have the potential to go beyond the limits and functionality of today's top-down technology. For example, there is the possibility of developing heterostructures such as Ge/Si core/shell NWs, which have high mobility and result in transparent contacts [127]. However, despite sustained efforts during the past 2 decades, the synthesis of NWs with controllable and uniform diameter, doping concentration, and good alignment is not easy with bottom-up approach [128]–[131].

In the top-down or subtractive approach, NWs (with mean diameter down to 4 nm), with good control over geometry, crystallinity, and doping levels are obtained by dimensional reduction of bulk materials (e.g., Si wafer) by a combination of lithographic and etching steps [132]. Within the top-down route, the two approaches are: 1) realizing "horizontal" Si-NWs (i.e., parallel to the wafer surface) and then following the transfer or stamp printing [Fig. 9(a)] and 2) top-down method to realize "vertical" Si-NWs (i.e., perpendicular to the wafer surface) and then directional printing onto flexible substrates [Fig. 9(d)]. Metal-assisted chemical etching (MACE) is generally used for obtaining vertical Si-NWs with a controlled diameter [Fig. 8(a)] [133]. The controlled doping is essential for obtaining ohmic junction in electronic devices and innovative devices such as junctionless FETs (JLFETs) [134], [135]. This can be attained by ion implantation or other methods.

B. Materials Printing and Device Fabrications

1) Transfer Printing: The transfer printing or stamp printing [Fig. 9(a)] was primarily explored to overcome the manufacturing problems in traditional microfabrication process such as material and solvent incompatibility and the thermal budget limitations in flexible and organic electronics. In this technique, the processing steps that require high temperatures are first carried out on Si wafer, which can withstand these temperatures and then the nanostructures such as NWs are picked and transferred to soft substrates, where further low-temperature fabrication steps are carried out [136]–[140]. Thin films, devices, and

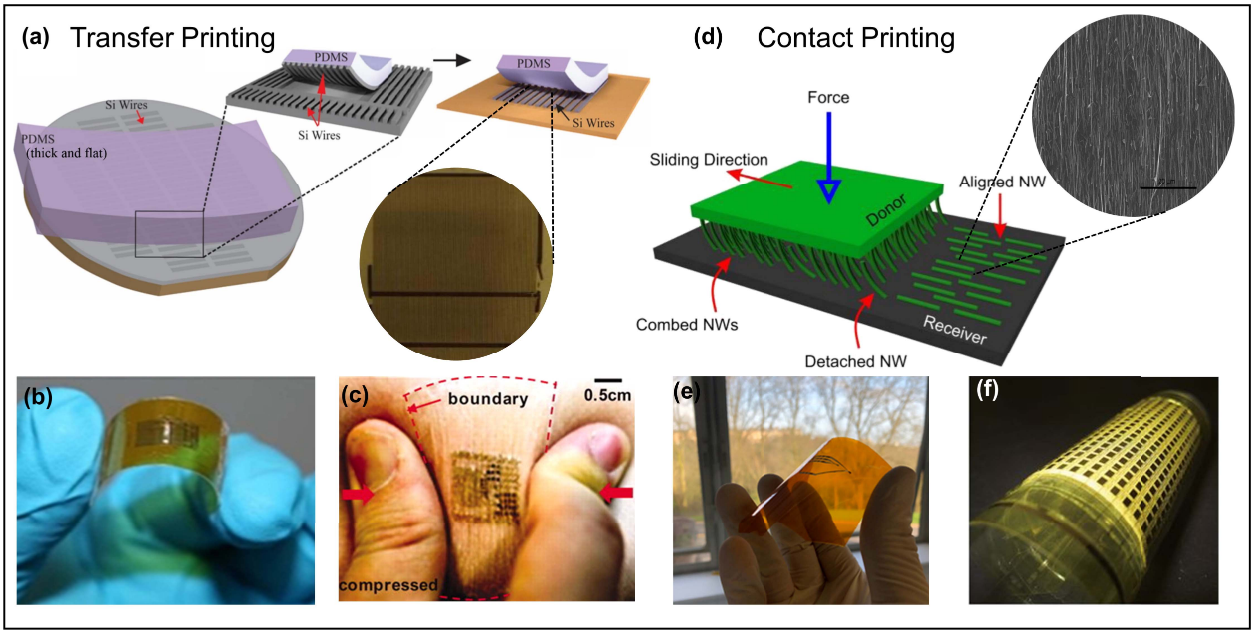

Fig. 9. ***Concept and examples for transfer printing and contact printing. (a) Schema of the transfer printing. Adapted with permission from [142]. (b) Si wires on flexible polyimide using transfer printing. Adapted with permission from [142]. (c) Photograph of "tattoo skin." Adapted with permission from [30]. Copyright 2011, The American Association for the Advancement of Science. (d) Schema illustrating the contact printing process. Adapted with permission from [122]. Copyright 2018, Cambridge University Press. (e) Ultraviolet photodetector fabricated by contact printing. Adapted with permission from [162]. (f) Flexible, NW-based active-matrix circuitry as artificial skin. Adapted with permission from [166]. Copyright 2010, Springer Nature.***

even UTCs [Fig. 9(b) and (c)] have been transferred on flexible substrates using this approach [108], [141]–[146]. For e-skin, the controllable and reproducible transfer of nanostructures, from the donor to the receiver substrate, is needed over large area, and hence, the precise control of the interface property is necessary. To this end, techniques such as surface functionalization, surface morphology modification, and peeling velocity control are helpful [141], [147]. Using this approach, the multistep stamp printing has been successfully demonstrated with feature resolution down to nanoscale [148].

The transferred Si NWs that are then used to develop the devices by carrying our further fabrication steps such as metallization. The approach has been used to develop Si-NW-based FETs, with planar [149] or gate-all-around architectures [150]. By adapting some of the steps used for mature Si-based electronics, the transfer printing approach makes it easier to achieve uniform and high-performance devices over large areas. Furthermore, with innovative device architectures, it is possible to develop novel NW-based sensors [151], [152] and neuromorphic devices [48]. The transfer printing approach has also been used for nonsilicon material such as carbon-based low-dimensional material [graphene and carbon nanotube (CNT)] [153]–[155], transition metal dichalcogenide monolayer (MoS_2, WS_2, etc.) [156]–[158], and organics [159]. The transfer printing of multiple types of materials opens interesting avenues for hybrid integrated systems, which is an ideal testbed for e-skin [30], [148], [160]. The details related to these advances can be found elsewhere in focused reviews and books [11], [41], [43], [120]–[122]. However, it should be noted that the transfer printing method is essentially a batch-to-batch process, which is less attractive for the large-area manufacturing as the time needed to transfer the nanostructures is relatively large in comparison with roll-to-roll (R2R)-type printing. For this reason, alternative methods such as contact printing have also been explored.

2) Contact Printing and Roll-to-Roll Printing: Contact printing refers to a process where donor substrate, with vertically grown 1-D nanostructures, is pressed against the receiver, whose sliding along a direction leads to transfer of nanostructures [Fig. 9(d)]. Unlike, transfer or stamp printing this method does not involve any transfer/carrier substrates such as an elastomeric stamp. The advantage of contact printing is that the as-printed NWs are allocated onto the receiver substrate in an aligned manner both for the transfer on the rigid and flexible substrates. Such alignment is enabled by the shearing force generated during sliding [161] and is favorable for the fabrication of large-area device array with uniform performance. Further study indicates that with controlled surface functionalization (e.g., with $-NH_2$-terminated monolayers) and optimum pressure between donor and receiver substrates, the NW printed with this method has shown excellent density and alignment [162], [163], demonstrating the great potential of contact printing approach for large-area manufacturing [Fig. 9(e) and (f)].

From the fabrication standpoint, a notable feature of both transfer and contact printing methodologies is that they dissociate semiconductor growth process from device

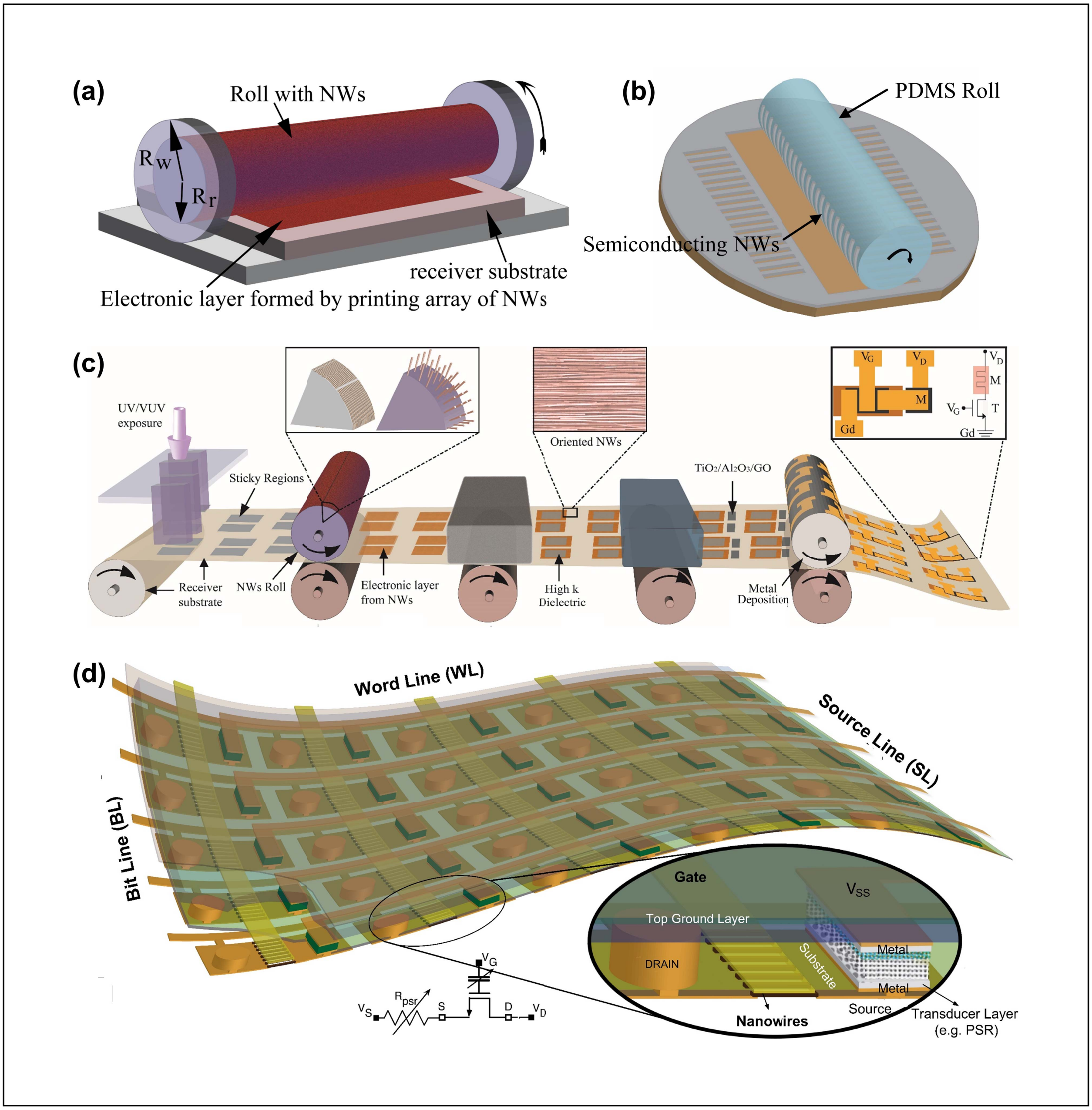

Fig. 10. *Various types of roll printing methods. (a) Differential roll printing to transfer the aligned NWs. (b) Concept of roll transfer printing technology. (c) Vision of an R2R production for NW-based functional circuits on large-area flexible electronics, including e-skin. (d) Scheme for printed e-skin using this method, showing printed NWs transistors-based sensors and circuits in the backplane.*

substrate. The advantage of doing so is the independence of these methods from traditional requirements for epitaxy and thermal budget, which allows the development of thin-film transistors (TFTs) at temperatures compatible with plastic substrates and that too without sacrificing the ability to incorporate high-quality single-crystal semiconductor building blocks. This opens avenues for advanced approaches such as NW synthesis on rolls to develop R2R manufacturing process. The synthesis of NW forests on tubes of glass, quartz, and stainless steel using bottom-up has been demonstrated in the past [164]. One could see new commercial opportunities in doing so, for example, commercializing NW rolls just as the Si wafers today. By using such rolls in differential roll-printing [164] and roll transfer-printing [165] settings, the contact printing approach can be extended to an R2R-type printing, as shown in Fig 10(a). In fact, with cylindrical stamps [Fig. 10(b)], it may also be possible to have R2R transfer or stamp printing, although this has not been attempted so far. The vision for a full R2R process for IT-1M structures shown in Fig. 10(c) could be the building block for neuromorphic architectures, including neuromorphic e-skin discussed in the previous section. These methodologies take advantage of various tools in use for standard Si-based electronics, which is attractive for large-scale manufacturing of high-performance flexible electronics. This also aligns with the electronic industry roadmap toward merged conventional microfabrication/nanofabrication and printing technologies. Overall, the above techniques show a great potential for cost-effective manufacturing of nanomaterials-based electronic systems, which can be further used to develop the high-performance large-area e-skin [166]. These could offer an alternative to the flexible backplane electronics, which has been explored in the past with materials such as organic TFTs active-matrix [49]. The organic semiconductors have favorable features such as low-temperature solution processing and inherent bendability, but their carrier mobility is much lower than Si-based device [167].

The advances in multimaterial additive manufacturing such as the development of 3-D PCBs could also offer new avenues for introducing e-skin like features in prosthesis and robotics [168]. For instance, such manufacturing processes could be employed to develop prosthesis with directly integrated or embedded touch sensors, thereby enabling robust limbs that are also free from wear and tear issues. The ability to simultaneously print multiple materials in 3-D (e.g., plastic and metal) will also address the traditional robotic e-skin issue of routing of wiring. Furthermore, this approach offers an interesting solution for the packaging of soft devices. Another important development for the soft e-skin is the use of intrinsically flexible/stretchable sensors or sensors connected with stretchable interconnects with different geometries [169]–[171] or intrinsically stretchable materials [172]–[177]. The higher flexibility or stretchability enabled by these approaches could lead to improved conformability of e-skin. Such techniques are generally relevant to other flexible electronic applications too.

VI. DISCUSSION AND CONCLUSION

Electronic skin is important for tactile feedback, needed for the safe interaction with the environment and the execution of complex manipulation tasks by robots for social interaction, assistance, and to facilitate surgery. In spite of rapid progress in terms of sensors, significant hurdles lie for the realization of large-area e-skin. Some of the challenges related to hardware development and potential solutions are discussed in this article. These include energy autonomy, transmission and processing of large data, including neuronallike approaches, and the manufacturing processes for obtaining high-performance soft e-skin, including recent advances in the field of flexible and printed electronics. This article also introduced recent neuroscientific advances that indicate that the sense of touch also relies on highly dynamic interactions between the partially wrappable skin and the objects it interacts with. This enables the generation of much higher dimensional information than available through any of the other human senses like vision and audition and is a main reason why the sense of touch is distinct. High dimensionality also implies a substantially richer information, which enables much richer representations of the objects we interact with and thereby a higher versatility of interaction, but also higher demands on engineered solutions that strive to copy the properties of the biological sense of touch. This demands the design of large-area compliant e-skin that can endure continuous contact with the environment and local shear forces while being able to reliably encode these forces at a high resolution through a distributed set of sensors. The solution would pave the ground for the next-generation hyperintelligent engineered systems and robots.

The e-skin development currently focusses on the application in rigid body robotics. However, robotics is evolving fast, and new generations of robots are expected to softer and compliant. The soft robots currently do not have much of sensory feedback, which is inevitably needed for precise control during manipulative movements and interactions. The challenges will lie in realizing the soft e-skin system with transduction sites of different bandwidths, dynamic range, resolution, sensitivity, and mechanical characteristics, using materials, and neural models that can take into account different adaptation characteristics of skin receptors. Possibly, the circuits interfacing the huge amounts of distributed sensors will also need to be looked into as the constraints on power consumption, spatial and time resolution, and compatibility with flexible and soft materials make the circuit design no less challenging. The solutions discussed in this article are expected to help tackle some of these challenges, and more effort may be needed as the new design and fabrication-related issues will possibly emerge. Although the discussion in this article is in context with large area e-skin, many of the presented challenges and solutions are also relevant to other applications such as health monitoring, flexible haptic displays, and wearable systems. Infact, e-skin (or second skin) is already being explored in health monitoring. The discussion about neuronal spiking like transmission of signal in e-skin is expected to stimulate new thoughts in the above application areas as they will face similar challenges when a number of sensors are significantly high. ■

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