Skin-Inspired Electronics and Its Applications in Advanced Intelligent Systems

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Recent interdisciplinary progress in flexible materials, devices, and system designs has brought about an emerging paradigm of skin-like multifunctional electronic platforms named skin-inspired electronics. Featured with excellent flexible mechanical properties, thin and conformal devices, and integrated sensing functions similar to those of human skin, skin-inspired electronics exhibit great potential in the application fields of wearable electronics and human–machine interfaces. Many real-world implementations of the intelligent system of skin-inspired electronics in healthcare monitoring, artificial prosthetics via the creation of sensitive skin, and robot tactile perception are demonstrated. Combined with the technologies of wireless data transmission, self-powered supply modules, and signal-processing circuits, skin-inspired electronics are expected to achieve improved portability, multifunctional integration, on-site analysis, and in-time feedback. Herein, recent advances in skin-inspired electronics, its promising solutions to engineering challenges, and opinions on future research directions are discussed.

1. Introduction

Electronic systems possessing skin-like flexibility and receptor capabilities have recently become the focus of a rapidly developing research field termed “skin-inspired electronics” or “electronic skin” (E-skin).[1,2] E-skin is an electric device or system that mimics the properties of natural skins, with excellent mechanical stretchability, conformability, self-healing, and biocompatibility, and is used to cover the entire surface of the human body or a machine, endowing its carrier with outstanding sensing capabilities to detect multiple stimuli (e.g., pressure, strain, temperature, humidity, ions, and molecules).[3–5] With the recent progress in flexible electronics and soft materials science, E-skin has quickly developed and exhibits great potential as a multifunctional flexible-electric platform in the application fields of wearable healthcare monitoring,[6–8] medical treatment and implants,[9] artificial prosthetic skin,[10] humanoid robots,[11] and human–machine interfaces.[10,11]

In the emerging era of the Internet of Things (IoTs), there is a new trend to incorporate E-skin with intelligent modules to achieve smart applications to meet the real-world needs of healthcare, industrial, and household applications (Figure 1). Much effort has been made in the following aspects:[12–14] 1) flexible, stretchable, self-healable electronic materials with stable performances were developed to realize conformal attachment to a body and multimodal measurement with high accuracy and resolution; 2) wireless modules were integrated onto E-skin for long-term, on-site, and in-time signal measurement and transmission for specific applications, for example, dynamic health monitoring during sports; and 3) data storage and processing units were combined on wearable circuits to allow instant signal-processing, transmission, and display in real time.[15,16] The integration and fabrication of E-skin systems with signal collecting, processing, and feedback modules will undoubtedly extend its practical applications in electronics relative to human lives.[17–19]

Starting with a short introduction to the efforts on material development and its applications in E-skins, we pay more attention to the combination of E-skin and intelligent technologies in this Review. We summarize several strategies to realize advanced functions (e.g., wireless communication, power supply optimization, and in-sensor signal processing) of an integrated E-skin system. Several engineering applications of E-skin are demonstrated, for example, robots/prostheses, human–machine interfaces, and health monitoring. Discussions about the challenges and future development of this field are provided in our conclusions.

2. Strategies Toward Advanced Functions

Recently, studies have focused on the accomplishment of such intelligent E-skin systems with relevant technologies. For
example, with the utilization of wireless communication functionality enabled by WiFi, ZigBee, or Bluetooth technology, a real-time display of information is realized using portable terminals (e.g., mobile phone, tablet, personal computer, and bracelet).\[29\] Optimization of the battery power and flexible signal-processing circuit elements helps to minimize the device volumes, improve the portability, and reduce the expenses.\[21,22\] Based on big data and machine learning, a closed-loop system with instant smart feedback can be achieved accordingly, removing the need for professional analysis or trained personnel and thus facilitating real-time, fast, and dynamic applications with high efficiency.\[23\]

2.1. Material Selection and Structure Optimization

Intelligent E-skin necessitates excellent stretchability, biocompatibility, a self-healing capability, and a multimodal sensory capability to fully mimic biological skin and acquire high-quality multiplex signals, calling for studies and innovations related to material selection and structural optimization.

2.1.1. Stretchability

E-skin is applied to human skin, which can stretch up to 100% during daily activities.\[24\] and complex surfaces of objects with bending curves and sharp edges. Traditional electronic devices composed of bulky hard silicon-based circuits and metals are consequently limited. Strategies are proposed for E-skin to possess skin-like stretchability while maintaining its functionality.

Materials, including poly(dimethylsiloxane) (PDMS),\[25,26\] polyurethane (PU),\[27\] Ecoflex,\[28\] and poly(styrene-block-(ethylene-co-butylene)-block-styrene),\[29\] have an intrinsically low elastic modulus and are suitable for utilization in substrate, encapsulation, and dielectric layers. To make materials more flexible or more electrically conductive, chemical and physical engineering strategies effectively tune their stretchability and conductivity via component additives and forming process control.\[29,30\] Nonionic plasticizer\[31\] and ionic additives\[32\] were reported to improve the stretchability of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS). Composites of elastomers and conductive fillers (e.g., metallic or carbon particles/flakes,\[33,34\] nanotubes,\[35\] and nanowires\[36\]) are synthesized as another type of promising stretchable electrode in E-skin (Figure 2a).

A structural design was proposed to introduce overall ductility to rigid materials. Serpentine mesh metal traces are inspired by biological structures, such as wrinkles, to interconnect between working electrodes.\[6\] The network of nanomesh metallic conductors forms a weaving reticulate structure with high mechanical compliance (Figure 2b).\[37\] Compared with the new nanomaterials mentioned earlier, metal nanostructures have superior electrical conductivity.\[108\]

2.1.2. Biocompatibility

E-skin is directly adhered to the skin surface during daily motions, implying the need to develop the biocompatibility of the device to minimize the induced negative effect.

Strong adhesion enhances robustness but brings potential irritation to the skin. The choice of adhesive materials, therefore, relies on the application scenario to make a trade-off between adhesion performance and safety. For example, Reeder et al. utilized Scapa Unifilm U884, a commercial, pressure-sensitive, strong adhesive film, in a sweat analysis patch that is capable of performing during intense swimming activities.\[39\] Yeo et al. proposed a glue-free epidermal device with a low elastic substrate that can be adhered to skin via van der Waals alone and eliminates irritation or discomfort during long-term monitoring.\[40\]

Breathability is another factor for E-skin that must be considered to ensure skin comfort. Porous-structured material is proved to be permeable and effective in reducing inflammation during prolonged implementation. Chen et al. developed a breathable E-skin temperature sensor with a porous PU semipermeable film as the encapsulation and substrate (Figure 2c).\[41\] The pore size enables skin breathability and sweat evaporation and prevents external interference. The nanomesh metallic network possesses excellent gas and water vapor permeability as well, without blocking sweat glands and avoiding inflammation.\[37\]

For implantable devices, more efforts are needed to develop environmentally friendly and biodegradable materials, which

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enable E-skin to degrade into nonharmful components over time to solve the difficulties in performing extraction surgery and disposing electronic waste.\(^\text{42}\) Degradable functional materials are mostly based on natural substances, such as silk and cellulose and synthetic polymers, including piezoelectric poly(t-lactic acid),\(^\text{43}\) dielectric poly(glycerol sebacate),\(^\text{44}\) conductive PU-based polymer linked with polycaprolactone diol, conductive aniline trimers, and dopant dimethylolpropionic acid.\(^\text{45}\)

2.1.3. Self-Healing

Inspired by the autonomous self-repair of biological skin after physical damage, intelligent E-skin is developed with a self-healing quality to enhance its adaptive capability and extend its service life. Materials generally acquire self-healing by dynamic interactions and reversible bonds between molecules. Through composite methods and cross-linking techniques, self-healing electronic functional elements are introduced. The current focus is mainly on realizing the recovery of damaged connections without applying external stimuli, such as heat. Recently, Markvicka et al. reported a material architecture for establishing a self-healing circuit (Figure 2d).\(^\text{46}\) The device is composed of EGaIn microdroplets, which can spontaneously re-establish new electrical pathways around the damaged region.

2.1.4. Multimodal Sensory Capability

In multimodal perception, resisting disturbance from different sensors is challenging because the sensory material usually reacts to several stimuli and consequently output coupled signals (e.g., the resistance of metal changes under both temperature and strain variation). On the one hand, E-skin may decrease the extent of coupling by careful material selection with selective stimuli sensitivities. Hua et al. adopted platinum (Pt) as a temperature-sensitive material and constantan alloy as a strain sensory element.\(^\text{47}\) Although both materials are resistively sensitive to temperature and strain, Pt possesses a higher temperature coefficient of resistance and a lower strain sensitivity than those of the constantan alloy, which enables output decoupling. On the other hand, structural designs, including setting up reference sensors and using diverse sensing principles, are also promising to eliminate interference effects and decouple the output. For example, Zhao et al. proposed a thermosensation-based E-skin pressure sensor via a thermal conductivity measurement. The adjacent reference sensor with negligible heat transfer provided selective temperature acquisition and helped to decouple the voltage output of the Pt ribbon, which was intrinsically sensitive to both temperature and thermal conductivity.\(^\text{48}\) Measuring multiplex signals based on distinct sensing principles, sensors prevent signal coupling at the first step of perception. Zhang et al. reported a temperature-pressure sensor relying on thermoelectric and piezoresistive effects that enables...
simultaneous monitoring of the dual parameters by analyzing naturally decoupled outputs.

2.2. Signal Processing

Natural skins exhibit a strong capability of signal encoding and transmission to convey sensing information into the nervous system. These capabilities indicate that signal processing and analysis play equally important roles in encoding the electrical output of E-skin. For example, salient data may be hidden in the noise caused by the environment, and human motion and decoupling analysis are important challenges in wearable multiplex sensors. In addition, the digitalization of collected analog information is favorable for achieving reduced interference during transmission. Therefore, in-sensor signal-processing modules (e.g., amplifier, filter, and converter) are expected to be incorporated to improve the quality of the collected signals and satisfy the subsequent need for data transmission.

In signal processing, challenges lie in establishing soft electronic elements that replace hard, planar, and brittle circuits and constructing wearable signal-processing modules matching the mechanical properties of human skin. For example, a flexible printed conductive board is considered a “hard-soft” integration, having combined silicon chip technologies with flexible thin plastic foils. However, the large size of the device is another problem to be solved. The key electronic components have been dependent on the utilization of metal membranes, silicon electronics, carbon materials, and organic semiconductors. For example, Tee et al. reported a printed organic ring oscillator circuit that can output a digital signal for converting pressure stimuli into voltage pulses (Figure 3a).

The ring oscillator consisted of three repeating inverters with inkjet-printed organic semiconductors and electrodes of silver (Ag) nanoparticles. The oscillator had a pressure-dependent frequency output with low power consumption and stable oscillations.

Integration is another important aspect. Highly integrated electronics are desirable in multifunctional E-skin devices. Organic transistors have been an excellent candidate due to their multiplexing ability, ease of integration, mechanical flexibility, and large-area manufacturing. Viventi et al. designed an implantable sensor system with 2016 transistors within an area measuring 14.4 mm × 12.8 mm (Figure 3b). The device was based on silicon nanomembranes (260 nm) and was specifically
located at a neutral mechanical plane to enable reliable, bending-insensitive operation. The device was composed of an 18/16 array of amplifiers at each electrode enabling measurement of a 1 mV signal, and a switching speed of nearly 1 MHz ensured fast multiplexed sampling of biological signals. This design has demonstrated the potential of fabricating flexible functional circuit units with high temporal and spatial resolution.

2.3. Power Supply

E-skin circuits integrating a high density of sensing electronic components\textsuperscript{[49, 60, 61]} lead to higher demands on the power supply strategies in terms of the wiring of the circuit,\textsuperscript{[62]} power consumption,\textsuperscript{[63]} battery life,\textsuperscript{[64]} and portability.\textsuperscript{[65]} Traditional battery power sources are bulky and rigid, making it difficult for sensors to fit perfectly within skin or biological tissues and offering continuous power.\textsuperscript{[66]} The fundamental way to solve these problems is to build self-powered wearable devices or transmit the power wirelessly.

Solar energy, as a universal, renewable, and clean energy, has shown the potential for the wireless power supply of E-skin.\textsuperscript{[67]} Solar energy harvesting by solar cells can be further improved to ensure the high transparency of E-skin.\textsuperscript{[68]} However, solar cells cannot provide continuous energy to E-skin due to the periodic absence of sunlight;\textsuperscript{[69]} a hybrid of flexible power devices and energy storage devices can address this problem.

Thermoelectric generators (TEGs) primarily convert thermal energy into electrical energy based on the thermoelectric effect. A renewable thermoelectric flexible energy collector based on glass fiber was reported; it has a self-supporting collector structure to avoid the heat loss caused using Si and Al\textsubscript{2}O\textsubscript{3} as substrates.\textsuperscript{[70]} Zheng et al. developed an energy autonomous sensing element with integrated organic-transistor-based chemical sensors and a flexible organic thermoelectric generator (OTEG).\textsuperscript{[71]} The OTEG, consisting of 162 legs of PEDOT:PSS on a flexible paper, has a maximum output voltage of 0.52 V and an output power of 0.32 $\mu$W (Figure 4a). Moreover, the OTEG can provide an ultralow working voltage for the gas sensors, which respond to 1 ppm of ammonia.

Piezoelectric materials are widely used in self-powered sensors, which generate electrical energy upon deformation. Flexible self-powered devices based on piezoelectric materials have been demonstrated.\textsuperscript{[72, 73]} Chen et al. reported a flexible piezoelectric nanogenerator based on P(VDF-TrFE)/BaTiO\textsubscript{3} nano-composite micropillar arrays fabricated by nanoimprinting, which realized an output voltage of 13.2 V and a current density up to 0.33 $\mu$A cm\textsuperscript{-2}.\textsuperscript{[74]}

In addition, TENGs have attracted extensive attention due to their ability to be easily manufactured, their strong power supply capacity, and their low cost. Fan et al. reported nanofriction generators converting mechanical energy into electrical signals.\textsuperscript{[75]} Yi et al. constructed a sensor with an aluminum electrode array and a polytetrafluoroethylene (PTFE) film. Based on friction-based electric generation, the sensor provided information, such as the speed and acceleration of movement (Figure 4b).\textsuperscript{[76]} The schematic illustration shows the structure of a self-powered bionic membrane sensor.\textsuperscript{[77]} When the external pressure brings the PTFE in contact with nylon, the PTFE is negatively charged. When the pressure is released, the two materials are separated and create a potential difference for the energy supply. The sensor was used in wearable medical detection to monitor the pulse.
waves of human low-frequency arteries and acquired high-frequency laryngeal sounds through a single device.

In addition to a single energy source, researchers are looking into hybrid flexible self-powered energy sensors that can generate electricity freely by collecting multiple energy sources. Wen et al. reported a prototype of a fabric-hybridized self-charging power system that harvests solar energy from ambient light and gathers mechanical energy from human motion. The hybrid sensor is composed of three kinds of function devices, including fiber-shaped dye-sensitized solar cells (F-DSSCs), fiber-shaped supercapacitors (F-SCs), and fiber-shaped triboelectric nanogenerators (F-TENGs). F-DSSCs, F-TENGs, and F-SCs are used to convert solar energy, mechanical energy, and chemical energy into electricity, respectively. The hybrid sensor achieved a power conversion efficiency of 5.64%. Yang et al. reported a flexible hybrid energy cell integrating the nanogenerator based on polarized polyvinylidene fluoride (PVDF) with a ZnO-poly(3-hexylthiophene) heterojunction solar cell. Among them, the nanogenerator collects mechanical and thermal energy, and the solar cells on the top surface harvest solar energy.

Due to the problem of potential differences between self-powered devices and functional devices, the power transformation device is important for intelligent wearable systems. A flexible, convenient wireless power supply can be achieved by electromagnetic induction transformation. Huang et al. presented a device that can be laminated onto the surface of the skin and can measure dielectric and surface strain properties wirelessly. The device consists of an inductor–capacitor (LC) resonator with...
capacitive electrodes and a coil connected to an impedance measurement device (Figure 4c). The radio frequency characteristics of the capacitive electrode vary with the skin characteristics, corresponding to the resonant frequency of the LC resonator changes, which can be measured wirelessly by the absorption of electromagnetic energy by the coil. Based on this measurement mechanism, the wireless sensor can be applied to dermatology and cosmetology.

Capacitive coupling has the advantages of a simple structure, fewer side elements, and a good electromagnetic interference performance. Jegadeesan et al. presented a near-field capacitive coupling (NCC)-based wireless powering scheme to transfer power to implants efficiently.[84] The NCC links were built using flexible conductor patches, which can be attached to the skin well and transmit energy wirelessly. Near-field inductive coupling based on electromagnetic induction is also a key approach for achieving a wireless power supply.[85] Samineni and co-workers reported fully implantable, battery-free wireless optoelectronic devices for spinal optogenetics.[86] Inductively coupled wireless power transmission can be realized when the device is placed within the boundary of the external double-loop antenna located around the cage.

Although several kinds of wearable self-powered devices have been demonstrated, such as photoelectric, thermoelectric, and piezoelectric devices, and those coupling multiple energy sources, challenges remain in some aspects, e.g., how to improve the conversion efficiency in various transmission modes and how to integrate more energy conversion blocks together.

### 2.4. Wireless Data Transmission

For conveniently portable applications, wireless data transmission will simplify the complicated electrical connection structures.[52,87,88] Wired connections limit daily activities and are not suitable for implanted applications. Wireless functions in E-skin can communicate with the embedded modules of smart terminals, such as smart phones and bracelets, to realize data transmission and display.[89–92]

A near-field communication (NFC) technology, based on inductive coupling, is an important tool for battery-free, passive wireless communication in wearable electronics, enabling non-contact data transmission at 13.56 MHz short range (less than 10 cm), and has been widely applied in many fields, such as health monitoring, gas sensing, and food status monitoring. [93,94] For example, Jeong et al. used an NFC layer in a modular and reconfigurable e-tattoo through a “cut-solder-paste” process (Figure 5a).[95] The reader coil can record the electrocardiography (ECG) signal, store it in the integrated circuit, and transmit it to a laptop. Araki et al. combined the NFC technology with colorimetric epidermal UV sensors through a screen printing and lamination process.[96] Xu et al. designed an electrochemical system for sweat analysis with an integrated-sensitive electrode, stretchable circuit, and NFC module (Figure 5b).[97] The system realized the dynamic detection of on-body sweat for glucose, Na⁺, K⁺, and pH, with assistance from a mobile phone.

Bluetooth is another wireless transmission technology that can transmit a signal over hundreds of meters and greatly facilitate the intelligent system in terms of the connection speed and transmission rate.[98,99] Zhong et al. converted the physiological pressure signal obtained by E-skin into an audio signal through a Bluetooth processing module and transmitted it to a mobile phone over a distance of ≈ 1 m (Figure 5c).[100] The transmitter module then transmitted the amplified signal to the mobile phone without distortion and displayed it through an audio recording software. In addition, with current Bluetooth low

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**Figure 5.** Demonstration of wireless data transmission module applied in an intelligent E-skin system. a) Schematic illustration of the e-tattoo, including the NFC module, ECG circuit module, electrode module (left), and wirelessly recorded ECG signals. Reproduced with permission.[95] Copyright 2019, Wiley-VCH. b) Schematic illustration of the epidermal electrochemical system (left) and a demonstration of the data transmission and display on an NFC-enabled mobile phone (right). Reproduced with permission.[97] Copyright 2019, Wiley-VCH. c) Illustration of the wireless sensor based on a Bluetooth module, which is used to record weak pulse signals simultaneously by a mobile phone. Reproduced with permission.[100] Copyright 2016, The Royal Society of Chemistry. d) Schematic illustration of the wearable real-time UV monitor based on WiFi. Reproduced with permission.[100] Copyright 2018, Wiley-VCH.
energy (BLE) technology, the energy consumption of Bluetooth-based wireless data transmission in intelligent systems can be greatly reduced without sacrificing efficiency and speed.\[101\]

WiFi has always maintained a leading position among all kinds of wireless data transmission methods due to its “always on” feature and its ability to simultaneously transmit multiple terminals with a high rate instead of carrying out point-to-point transmission.\[102\] For example, Xu et al. proposed a system that receives a signal from a wearable device capable of sensing UV intensity through a data collector and then sends it to the smartphone terminal via WiFi (Figure 5d).\[103\] The wearable UV intensity sensor has a high sensitivity and photoresponse and can, therefore, be well integrated with existing commercial data collectors. Acquiring the UV intensity information, the data collector transmits it to the smartphone via WiFi and displays a real-time message through a certain App on the mobile phone. In addition, the possibility of sharing information through multiple connected terminals makes WiFi technology feasible in extensive applications in the field of IoTs.\[104\]

### 3. Potential Real-World Applications of E-Skin

With advances in technologies related to the process of data acquisition, processing, and transmission, intelligent E-skin possesses adaptive measurement, in-sensor analysis, a stable power supply, and the ability to carry out wireless data transmission. On the basis of these improvements and innovations, efforts have been made to apply intelligent E-skin in measurement of the external environment, human instructions, and the physiological status of individuals, bringing about a progressive revolution of the future real world in robotic tactile perception, the human–machine interaction, and health monitoring devices.

#### 3.1. Artificial Tactile Sensation of Robot Hands and Prosthesis

Constructing artificial E-skin to confer tactile sensation to humanoid robots and prostheses is one of the most important engineering application fields. Smart humanoid robots and prostheses are designed to assist humans in various manipulations accurately and rapidly. However, robots and prostheses are not currently able to fully mimic humans in terms of performing certain complicated operations, which, more specifically, include interacting with uncertain objects and in-hand manipulations with multiple fingers.\[9\] These obstacles indicate the need for such systems to measure and distinguish the contact position, direction, and magnitude of various mechanical stimuli, including the normal force, shear force, and bending strain, to better interact with the environment.\[105\] For example, contact pressure and shear force feedback are crucial in situations where robotic hands need to pick grapes without crushing them. The sensors currently integrated in robots and prostheses are simple and lack the capability to measure the mentioned parameters concurrently during sophisticated manipulation. Therefore, there is growing interest in designing multifunctional flexible E-skin to realize its advantages in robotic systems toward the ultimate goal of an integrated sensing function in the following aspects: 1) the measurement of multiple mechanical stimuli in real-time operation to provide essential tactile feedback when interacting with an unexpected environment, especially one involving fragile objects; 2) integration with multifunctional sensors that can detect the temperature, humidity, hardness, stickiness, texture, etc.; and 3) wireless signal transfer and control of the robot and human–machine interface of the prosthesis.

Several groups have reported E-skin designs for the end effector of robots and prostheses to provide tactile feedback. Based on the resistive,\[106\] piezoelectric,\[107\] capacitive,\[108\] and triboelectric transduction methods,\[109\] researchers have developed unique structures that can measure both normal pressure and lateral shear forces. For example, the biomimetic structure of spinosum was used in a tactile sensing device, which has a hierarchical structure consisting of interlocked micropyramids,\[110\] hemispheres,\[112–114\] and nanoneedles.\[115\] The device was capable of sensing various mechanical stimuli at the same time. The interlocked geometry enabled stress concentrated at the contact points to enhance its sensitivity, with exclusive deformation of the spinosum-like structures.\[112\] Choi et al. developed a pyramid-structured tactile sensor composed of an ionic gel and an engraved iron electrode with improved sensitivities, which could work in both the piezoelectric and capacitive sensing modes (Figure 6a).\[116\] The ionic gel is an ionic thermoplastic polyurethane (i-TPU) composed of a polymer matrix (TPU) and ionic liquids. The device can be applied to the interface area of a robot or prosthesis and distinguish between different types of mechanical forces by the specific response pattern in the output. The method has feasibility in advanced tactile sensing and simple fabrication processes, but it also has limitations at the signal-processing level. To evaluate the applied force by comparing with the known stimuli output patterns, processors need to buffer a sequence of output signals, which slows down the feedback rate and indicates a smaller certainty when confronting a short-time input. A promising solution to this inherent drawback of this type of device is to increase the amounts of sensory elements and separate them to solely detect stimuli influences. Boutry et al. reported their novel design involving the modification of the spinosum structure.\[117\] They integrated an array of 25 capacitors, with carbon nanotubes (CNTs) as top and down electrodes, around a single PU elastomer hemisphere for tactile signal amplification (Figure 6b). Different stimuli correspond to different spatial distributions on the 25 capacitors. The task of discrimination is switched to spatial signal processing, which can be performed at every single time step. Spiral grid organization of the pyramids at the top, similar to sunflower florets, further optimized the detection performance by combining higher sensitivity in the outer ring of the hill and a faster response time in the inner ring. Challenges to this approach are noise suppression and reduction of the parasitic coupling influences because these small elements are susceptible to slight changes in the environment.\[118\] A design of triboelectric flexible E-skin was demonstrated by Lai et al.; it was able to sense the pressure on the robotic actuator while it held up a doll’s hand.\[119\] The device comprised a silver-flake matrix sandwiched between silicone rubber without a power source input and achieved great deformability. Figure 6c shows the structure of the triboelectric-effect-based sensor and the output during the test, indicating the ability to conformably attach to nonregular objects and monitor the operation status in real time.
In addition, multifunctional sensing also aims at enriching the perception ability of robotic systems in different dimensions. Multifunction integration is not simply stacking up different sensors but minimizing the interference between different elements and retaining the flexibility of E-skin. Hua et al. presented a sensor with a conformable matrix network capable of obtaining various physical quantities from the environment simultaneously, which utilizes Pt as a resistor to sense the temperature, constantan alloy as a resistor to sense the in-plane strain, polyimide as the capacitive dielectric layer to sense the humidity, ZnO to sense the UV illumination, Co/Cu composite multilayers to sense the magnetic field based on the giant magnetoresistive effect, and an Ecoflex dielectric layer sandwiched between Ag electrodes as a capacitor to sense the pressure. The integrated multilayer sensor showed excellent orthogonality when various stimuli were applied at the same time. A prosthesis hand with pressure and temperature sensing abilities was constructed (Figure 6d). During the movements involved in grasping and releasing a cup of water, the pressure sensor showed the contact pressure on the five fingers of the prosthesis, whereas the temperature sensor on the thumb accurately measured the temperature of the water. The triboelectric skin was also able to perceive other physical quantities. Due to the triboelectric charge reduction caused by water molecules on the surface, the device could measure the humidity of the contact object. Figure 6e demonstrates the robotic gripper judgment regarding whether the baby doll’s pants were wet or dry and showed great differentiated output during the touch procedure.

### 3.2. Human–Machine Interface

Contraposing the interpretation of human instructions to machine understandable signals and vice versa, the human–machine
interface is important for enabling machines to better assist people with efficiency and accuracy, especially in unseen processes. The human–machine interface is the Gordian technique for achieving rehabilitation therapy of the disabled and better control of equipment in robotics, prosthetic control, surgical instruments, virtual reality, etc. Vision-based recognition is currently the general approach for human–machine interfaces. However, people find it difficult to handle operations involving close contact and certain expressed information, such as voices, solely relying on visual perception. E-skin, which is capable of intimate attachment and results in accurate, long-term, multipositional sensing and actuation, provides a highly wearable and reliable solution to the demand. Although the interaction is bidirectional, the following notes focus more on the approaches and processes when picking up information regarding human instructions.

Recording electrical activity reflecting human movement provides a method for the accurate analysis of intention. Electromyography (EMG) is the technique for obtaining muscle motion. In recent years, wearable EMG technology has enabled applications in the remote control of drones and robot hands. Tian et al. reported large-area epidermal electronic interfaces for prosthetics control via EMG and cognitive monitoring via electroencephalography (EEG) (Figure 7a). Polymide layers encapsulate contact-mode photolithographic processed filamental serpentine gold interconnections between 17 fractal mesh chromium/gold (Cr/Au) electrodes that directly contact the skin to record EMG signals using electrochemical impedance spectroscopy. Microporous cross-linked silicone adhesive bonds to skin with moderate, nonirritating, and breathable adhesion. The ultrathin Ecoflex layer protects the inner device from external stimuli. The most outermost polyethylene terephthalate (PET) layer, which will be peeled off when the device is adhered, is coated for easy release manipulation. The device, with a total area exceeding 200 cm², ensured its biocompatibility with the unique microperforated structure in silicone adhesive. By dissolution of the transfer printed monolayer assembly of poly(methyl methacrylate) microspheres on the surface of the adhesive silicone, the micropores enabled tunable permeability of the device. With optimized density and pore size, the device can be adjusted to avoid sweat accumulation while being restorative. The robustness of the systems is validated by prolonged acquisition under various circumstances, a reduction in electrode shift and the countering of artificial interference, which are all unrealizable in traditional EMG sensors. The proposed interface was realized to control a transhumeral prosthesis with epidermal EMG around the residual limb. Through pattern recognition algorithms conducted by a trained classifier, successful performances of different motions with 89% average classification accuracy showed the potential for operating prostheses by limb-amputated patients who have undergone targeted muscle-reinnervation surgery. In addition, the system is compatible with magnetic resonance imaging (MRI) and can be mounted on the full scalp of an individual as an EEG sensor. Further development orientation should involve realizing neuromuscular electrostimulation to provide sensory feedback, combining what was discussed in the previous section.

Voice signals are another route for transmitting intention that can be utilized for the human–machine interface. Although microphones and speakers today are well miniaturized to be embedded in electronic products, most sound detectors and sound sources are not flexibly wearable due to their rigid configurations. Most importantly, the E-skin-type voice detector can be directly attached to the throat, nearest to the vocal cords, where the voice is originally generated, providing clear acquisition of the sound made by the user, including deaf-mute people with complete voice cords. Tao et al. developed an artificial throat combining sound detection and generation functions based on laser-induced graphene (LIG) (Figure 7b). The proposed one-step fabrication converts polyimide into porous graphene films capable of thermoacoustically producing periodic expansion of air and exerting current variation when external vibrations alter its impedance. In other words, the device can perform as a sound speaker and sound detector simultaneously. Many mute people still possess the ability to produce simple sounds, such as a cough, hum, and scream. Depending on the voice, trained mute people can be “heard” by the device, which further recognizes the vibration of the vocal cords by pattern recognition and converts them into a designed language and then sends it out. Notably, unlike most subsistent transducers, the device can be used both as a detector and an actuator owing to the low thermal conductivity, low heat capacity, and high sensitivity of LIG. With the thickness of the LIG and laser power in the fabricating process optimized, the artificial throat showed not only its hum recognition capability but also the potential to distinguish between different sound sources and pronounced words by the recording of characteristic peaks with high fidelity. Through further experiments, researchers found that the LIG film is much more sensitive to vibration of the vocal cords compared with external sound in the environment when adhered to the throat, exhibiting strong reliability and interference immunity for voice-based human–machine interfaces.

High-resolution perception is one of the most important features of E-skin with arrayed sensors to analyze precise operations in space. With the improvement of electronic element flexibly scalable integration and data handling capacity, a much larger volume of information is accessible for studying interaction processes at a deeper level. The unique qualification of E-skin defines its potential in contact-involved recognition, involving interpreting gestures and distinguishing objects, and acts as an impetus for developing the science of understanding the mechanism behind human manipulation. Recently, a scalable tactile glove with a uniformly distributed piezoresistive sensor array was demonstrated by Sundaram et al. (Figure 7c). The glove stood out for its complete coverage of the hand with high-resolution sensors, its low cost (~10 USD), and its application of deep neural networks to extract useful information from the dataset recorded during the hand manipulation process. The sensory element on the force-sensitive film (FSF) of the glove was addressed by the orthogonal conductive thread network, with a low-density polyethylene layer at the outermost insulation layer. By measuring the electrical resistance variation of the FSF, the system recorded and analyzed the normal pressure (ranging from 30 mN to 0.5 N) distribution in the time sequence with a frame rate of ~7.3 Hz. Demonstrations revealed its ability to proprioceptively recognize gestures, estimate categories, and weigh the grasped objects using a convolutional neural network. The conventional neural network exhibits improved accuracy compared with a naïve linear model and clustered input frames.
Figure 7. E-skin application on human–machine interface. a) A large-area epidermal electronic interface for monitoring both EMG and EEG signals. Demonstrations showed that when applied to the reinnervated amputated upper limb of a patient, eight channels of bipolar EMG signals were classified in different motion classes to control a transhumeral prosthesis. Reproduced with permission.[122] Copyright 2019, Nature Publishing Group. b) An LIG-based artificial throat capable of detecting and producing sound implemented near the vocal cords. The relative resistance changes of the proposed thin-film device are synchronous to the original sound profiles of audio played by a loudspeaker (orange insets). The artificial throat can be utilized by mute people to express their intentions by different humming types, which are then interpreted and voiced according to predesigned patterns. Reproduced with permission.[123] Copyright 2017, Nature Publishing Group. c) A scalable tactile glove integrated with 548 piezoresistive sensor elements covering the full hand. The glove showed its capabilities in recognizing gesture and weighing and distinguishing held objects by applying machine learning methods. Reproduced with permission.[124] Copyright 2019, Nature Publishing Group.
providing distinctive information and further improving the performance even with a smaller set of inputs than the number of frames imported to the model randomly. In addition, acquired data are informative for studies on the relationship between the pressure distribution and the mechanism behind grasping operation. Three experiments focusing on extracting hand pose signals and object-related pressure maps during the full grasping process were conducted, revealing that all fingertips highly correlated with the thumb base as the signature of human precision grip by an analysis of the Pearson correlation efficiency and the collaborative role between distal phalanges of the large fingers using canonical correlation analysis.

3.3. Health Monitoring Devices

Healthcare has received increasing pressure in modern society to meet the need for improved quality of life. The developing trends of health monitoring systems are the drive to make them portable and intellectualizing them for domestic diagnoses and therapies. Traditional health monitoring systems include bulky instruments and complex wiring connections. These limitations hinder protracted real-time monitoring, which is essential for the prevention and treatment of certain diseases. To address this issue, wearable and highly integrated health care devices have been developed. Conformally attached E-skins or skin devices are capable of addressing applications in monitoring vital signals, detecting chemical biomarkers, and delivering drugs equivalent to benchtop instruments. Due to the recent advances in flexible electronics, powering strategies, and safe adhesive interfaces, miniaturized medical patches are capable of intimate coupling with human skin, in-sensor analysis, feedback, and the wireless transmission of gathered data to terminals, such as cellphones or personal computers.

Aimed at attaching to human skin without hindering daily activities, epidermal electronic systems (EESs) need to satisfy strong and bioadhesive adhesion. The condition of the skin surface is unstable during daily routines due to not only mechanical stretching and compression but also unexpected skin-generated byproduct emergence. An EES has to overcome the aforementioned challenges to the robustness requirements while eliminating chemical and mechanical irritation to human skin when applied for protracted monitoring, which is a common issue for traditional adhesive patches. Principles for adhesion commonly used in EESs include chemical adhesion, self-adhesion enabled by the van der Waals force, and microneedle interlocking. Chemical adhesion is mainly based on acrylic or silicone formulations as a pressure-sensitive adhesive (PSA). PSAs can achieve sufficient adhesivity under small initially applied pressure regardless of various environmental stimuli. However, PSAs usually lead to iatrogenic injuries on the skin, especially for neonatal and elderly people. A gentler approach to skin adhesion is to utilize the van der Waals force on the intimate contact interface. The elastic modulus of the sensor material needs to be small enough to realize conformal and glue-free adhesion. Although adhesive-induced irritation to skin is greatly reduced, the adhesion strength of glue-free adhesive is lower than that of PSAs and can only be applied to thin-film sensors and under relatively moderate situations. To narrow the gaps between PSAs in terms of adhesivity, researchers have found ways to enhance the self-adhesive force via bioinspired structures. The microstructured contacting interface is inspired by geckos, grasshoppers, and cephalopods with micropillar geometries. This self-adhesion method has the potential to be reusable, unlike chemical adhesion with its inherent adhesion degradation after peeling off or contamination. In addition, microneedle-structured EESs used in transdermal drug delivery are also self-adhesive via an interlocking attachment enabling continuous and effective drug administration through the stratum corneum.

With carefully chosen adhesion configurations, epidermal health monitoring devices can perform accurate diagnosis tasks by continuous real-time sensing. Researchers have focused on monitoring physical vital information involving cardiovascular signals, respiration signals, blood pressure, the elastic modulus, hydration, and the body temperature or thermal conductivity. The mentioned parameters are important to reflect the physical status of individuals. For example, cardiovascular signals recorded by ECGs have superior value in terms of diagnosing arrhythmia, myocardial infarction, and several cardiovascular diseases; body temperature, generally monitored via a thermal resistive sensor, is related to diseases, such as fever, heatstroke, or inflammation after injuries or surgeries. Taking advantage of the accurate, multifunctional measuring ability and the negligible load interference of E-skin, a few novel and integral wearable health monitoring systems have been proposed. Chung et al. reported a binodal EES monitoring various vital signals during the real-time care of neonates (Figure 8a). In neonatal intensive care units (NICUs), existing monitoring systems with rigid hardware and complicated wired connections impede infants from bedside activities and contact with their parents. The proposed system consists of two wireless EESs mounted on the chest and sole of the foot. ECGs are recorded through two electrodes with filamentary metal mesh microstructures on the chest-mounted device, whereas the other electrode on the sole acquires photoplethysmograms (PPGs) by reflection-mode measurements. They used a collection of serpentine copper traces as an MRI-compatible electronic layer and PDMS for encapsulation, with Silbione covering the bottom side. The device is attached to the fragile skin of neonates via the van der Waals force alone, consequently avoiding possible skin irritation. The microfluidic chamber, filled with nontoxic ions and an optimized perforation pattern, further decreased the peel force by reducing the effective modulus of the system. With the in-sensor analysis of ECGs, PPGs, and thermal resistive sensor data, the system wirelessly transmits various physiological parameters, including the heart rate, respiratory rate (RR), body temperature, blood oxygenation (SpO2), and blood pressure, through NFC modules to the host system, which then decodes and transfers the data to a personal computer via the BLE system. NFC also plays the part of transferring radio frequency power to the EES from the primary antenna, which is connected to the host system under the mattress. Although the system is proposed for taking measurements during neonatal care, it can also be applied to ordinary conditions due to the good agreement in the monitored information, its simple setup, and its high mechanical compliance. To eliminate the traditional cuff-based devices used to gauge blood pressure and other physical
cardiovascular signals, a self-powered wearable system utilizing a triboelectric effect was reported by Meng et al. (Figure 8b). The two electrification layers are PET and PTFE, respectively. PTFE in strips is structured in an interlaced weaving pattern arranged above the PET layer, beneath which is the indium–tin oxide acting as the back electrode. Aligned surface polymer
nanowires with the weaving structure produced by plasma etching enlarged the effective contact area between the triboelectric layers and consequently boosted the electric output and sensitivity of the sensor. Owing to its efficient sensitivity, fast response time, low hysteresis, and flexible characteristics, the device is capable of recording pulse waves on various parts of an individual, extracting the cardiovascular information, heart rate, $K$ value, and artery compliance. The total peripheral resistance (TPR) can be directly calculated from the pulse waveform. To infer the blood pressure, two identical sensors on the fingertip and ear simultaneously record the signal and derive the pulse transmit time (PTT). The PTT is used in a linearized model to compute the blood pressure, in which the genetic algorithm is applied to estimate the coefficient. The processed signals are then transmitted to terminals with a user-friendly interface by Bluetooth. The testing results showed consistency with the commercial blood pressure measuring devices.

Chemical biomarkers are critical factors in determining human physiological status in addition to physical signals. Wearable epidermal devices can noninvasively obtain information from metabolites, electrolytes, and molecules in sweat and skin interstitial fluid (ISF). The concentrations of the biomarkers in biofluids have close correlation with their levels in blood and the state of health. Chloride, pH, and sweat rate indicate the electrolyte balance, hydration state, and overall physiological status. The continuous monitoring of sweat glucose levels is of great significance to diseases, such as diabetes; lactate is usually treated as the reflection of pressure ischemia and physical stress. Without traditionally collecting biofluid into laboratorial analytical instruments, E-skin devices can provide on-site and continuous detection results of the aforementioned information in two ways: electrochemically and colorimetrically. Electrochemical sensors measure the electron flow during the redox reaction on the anode and cathode by amperometric techniques. In contrast, the colorimetric approach is based on assays to give intuitive and semiquantitative detection of the biomarkers and sweat rate, which can be later read out by acquisition of the images via a smartphone. However, both of these methods have pros and cons. More complicated electronic components, including potentiostats, data transmission units, and the power supply, need to be configured in the electrochemical device, whereas the detection capability range of colorimetric sensors is limited to a smaller set of biomarkers. Combining electrochemical and colorimetric means, Bandodkar et al. introduced a microfluidic/electronic system capable of monitoring a wider scope of sweat information by taking advantage of the merits of both means. Their battery-free electrochemical platform is inspired by biofuel cells and the NFC interface for the power supply and data transmission to simplify the electronic module, making it lighter and smaller than the Bluetooth mounted device. Lactate and glucose in sweat are measured by the enzyme-functionalized pads above circularly cut CNT electrodes. The generated currents in the lactate oxidase enzyme sensor and glucose oxidase enzyme sensor are proportional to the concentration of the corresponding biomarker in sweat. Chitosan and polyvinyl chloride are coated membranes as encapsulations and mediators at the anode. At the cathode, the platinum back is the catalyst for oxygen reduction, with a Nafion polymer membrane for protection and enhanced oxygen adsorption. PDMS microfluid channels enable sweat rate counting by a water-soluble dye and deliver samples to colorimetric reagents. Collections of designed capillary bursting values enable routing sweat through ratcheted channels to visualize the sweat rate and filling a series of isolated chambers for sequential colorimetric sampling and electrochemical sensing. The results of chloride detection, by silver chloranilate, and pH measurement, via pH-sensitive dye and a phase-transfer catalyst, are shown in six chambers filled over time. The single-use microfluidic system, together with the colorimetric reagents, is connected to a reusable electrochemical platform by releasable magnetic coupling. Analyzed data of blood glucose and lactate levels from the proposed device show a similar trend to that of commercial devices, revealing the feasibility of such a dual modal system. Similar devices are constructed for diverse application situations in sportive sweat analysis and other wearable multifunctional detection. In addition, the available biofluid source for chemical detection is not limited to sweat, the production of which is not always stable and controllable. ISF, the biofluid filling up the space between cells, is another reliable source for analyzing biomarkers because the molecules or ions of interest are diffused directly from the nearby vessels. The common method for noninvasively extracting biomarkers from ISF inhabiting the skin surface is called iontophoresis, which involves direct migration of the molecules and ions by a mild electric current. The process can also be used for sweat stimulation by delivering a sweat-inducing drug. A recent study by Kim et al. coupled the sweat analysis and noninvasive ISF detection for simultaneous independent measurement of sweat alcohol and ISF glucose in a tattoo-like flexible iontophoretic system. At the anode side, iontophoresis is used to deliver pilocarpine, which is positively charged, into the skin for localized sweat generation. Next, the generated sweat is loaded onto the alcohol oxidase enzyme bioreceptor, which works similar to the research discussed earlier in this section. At the cathode side, positively charged cations (e.g., Na$^+$) are attracted to the surface of the skin. The cationic electro-osmotic flow with a defined major convective flux brought neutral molecules, including glucose, toward the cathode. The process is terminologically called reverse iontophoresis. The glucose level in ISF was then monitored by a glucose oxidase biosensor loaded on the cathode. Both electrodes consist of a layer of screen-printed Prussian blue as the transducer, an enzyme biosensor with chitosan for immobilization, and phosphate buffer saline (PBS)-loaded agarose gel to resist pH variation. Cryogel, as a porous hydrogel, is chosen as a sorbent for pilocarpine release, whereas agarose gel exhibits a less porous structure; hence, it is loaded with PBS to store the extracted ISF. The system achieved continuous monitoring that agreed with theory and avoided the mixing of two biofluids by controlled, on-demand localized sampling. By monitoring levels of alcohol and glucose, individuals can take precautions against diabetes when consuming alcohol, distinguish between different types of diabetes, and monitor glucose levels during treatment.

Controllable transdermal drug delivery is another research field for E-skin in health monitoring and therapy and is one step toward making use of the diagnostic feedback in the therapeutic process. As the third approach for drug administration after oral delivery and hypodermic injection, transdermal drug delivery is superior in its sustainability, controllability, and reduction of side
Bypassing drug absorption in the gastrointestinal system in oral delivery, this method avoids side effects such as irritation to the stomach. In addition, the first-pass effect through the liver hampers the effectiveness of the drug, resulting in a higher dosage. With painless and continuous drug administration, transdermal drug delivery offers a more convenient approach than injection and is capable of both topical and systemic treatment. In spite of its superiorities, current epidermal transdermal drug delivery systems have some few limitations. Only micromolecular, lipophilic, low-dose medicines are deemed applicable, as the others often fail to diffuse through the stratum corneum, the outermost layer of the epidermis. To remedy this situation, a microneedle array is demonstrated as an alternative to ordinary planar patches. The drug-loaded microneedles are able to effectively deliver medicinal substances by physically establishing microchannels through the stratum corneum. Owing to the microscale of the needles, being within hundreds of microns in height, microneedle drug delivery is considered a painless, minimally invasive approach to treatment. By controlling the release rate of drugs, including microfluidics and electrothermal, and photothermal heating, researchers have introduced smart epidermal systems with microneedles combining diagnostic and therapeutic functions. Lee et al. demonstrated a graphene-based EES with thermoresponsive microneedles for drug administration according to sensor feedback (Figure 8e). The diagnostic segment of the device is composed of a humidity sensor based on the impedance of interdigitated electrodes and electrochemical sensors monitoring both pH and glucose. Relative humidity is measured to ensure the presence of sufficient sweat, whereas the value of the pH is used to correct enzyme-based glucose sensor deviation. Once hyperglycemia is observed, defined as the period when the blood glucose level exceeds a certain threshold, the therapeutic segment with metformin-loaded microneedles begins to apply thermal actuation to release the pharmacological agent for diabetes treatment. The therapeutic and diagnostic segments can be wirelessly connected and transfer real-time data to remote mobile devices via an additional portable analyzer with a Bluetooth module.

4. Conclusions and Outlook

E-skin utilizes flexible electronics to integrate multifunctional devices on soft substrates. The whole device features low elastic stiffness and a lightweight, enabling wearable applications with conformal attachment to human skin. In recent studies, E-skin became more intelligent during the whole process of measurement, information transfer, analysis, data transmission, and feedback. However, engineering limitations exist in constructing advanced E-skin. Toward the ultimate implementation of E-skin, high-performance flexible configurations in terms of the device structure, analysis circuit, powering strategies, and wireless communication are usually discussed individually; nevertheless, they contribute equally to the overall system, and their integration is very important. Considering specific applications in robotic sensory, human–machine interfaces, and health monitoring, researchers have shown significant engineering examples of integrated intelligent systems.

In the future, the broader application of E-skin relies on technical breakthroughs including but not limited to the following topics: 1) Simplification of the manufacturing process. Most of the circuit structure of E-skin adopts a serpentine geometry to meet the need for bendability and stretchability. These conductive traces are assembled onto elastomeric substrates using transfer-printing techniques. Although it is practical, this approach normally requires cleanroom lithography and specialized process steps with much effort in their design and high expenses. More high yield, scalable, cost-efficient manufacturing techniques are required due to increasing future integration challenges in large-area thin-film configuration and multicomponent assembly. A promising method to simplify the manufacturing process is to take advantage of recent progress in printed electronics, including 3D printing and inkjet printing exhibiting advantages in terms of low-cost and scalable production. However, several challenges still exist in printing on flexible substrates, which have the potential for further optimization. 2) Enhancing multifunctional measurement of E-skin. Only a small number of multifunctional E-skin devices are applied at the present stage, especially for the integration of sensors measuring physical and chemical signals. On the one hand, to fully mimic and surpass biological skin, the acquisition of various forms of data within a single device is valued in advanced E-skin applications. On the other hand, more accurate results can be derived based on different forms of information (e.g., the pH value can be utilized to correct the result from enzyme-based glucose biosensors). 3) Integration of more intelligent modules for the analysis and control of E-skin. Current smart E-skin devices possess only primary signal-processing abilities and require external equipment during complex analytical processes involving large datasets and sophisticated algorithms. Miniaturized intelligent modules with stronger in-sensor computing power will undoubtedly broaden the scope of wearable applications by eliminating the use of rigid external devices and maximizing the utilization of data. In addition, precise means for feedback control implementation are important but are seldom proposed in practical applications. For example, quantitative drug release control in therapeutic epidermal devices has yet to be developed, other than the thermal-conducting approach initially applied for its simplicity.

In general, E-skin provides an innovative platform to integrate existing technologies of flexible electronics, biomedical engineering, wireless communication, energy, sensors, and information storage and processing to address the engineering challenges of next-generation personal healthcare devices, human–machine interfaces, robots, and medical and personal electronics. Playing an important role in the technical revolution, E-skin trends toward merging with intelligent systems provide improved service in daily life and industry.

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Conflict of Interest

The authors declare no conflict of interest.

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