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Recent progress of skin-integrated electronics for intelligent sensing

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Abstract

Skin-integrated electronics are a novel type of wearable devices that are mounted on the skin for physiological signal sensing and healthcare monitoring. Their thin, soft, and excellent mechanical properties (stretching, bending, and twisting) allow non-irritating and conformal lamination on the human skin for multifunctional intelligent sensing in real time. In this review, we summarise the recent progress in the intelligent functions of skin-integrated electronics, including physiological sensing, sensory perception, as well as virtual and augmented reality (VR/AR). The detailed applications of these electronics include monitoring physical- and chemical-related health signals, detecting body motions, and serving as the artificial sensory components for visual-, auditory-, and tactile-based sensations. These skin-integrated systems contribute to the development of next-generation e-eyes, e-ears, and e-skin, with a particular focus on materials and structural designs. Research in multidisciplinary materials science, electrical engineering, mechanics, and biomedical engineering will lay a foundation for future improvement in this field of study.

Introduction

The human body is a remarkable biological system that operates complex and organised physiological processes. The detection of biophysical and biochemical signals deep in the body through the body surface is critical for health care. This also includes long-term, real-time monitoring of physiological signals in clinical applications. However, current clinically available monitoring systems typically rely on heavy equipment that are not suitable for long-term and real-time monitoring of patients. Electronic devices with lightweight, flexible, and portable features are suitable substitutes for multiple biomedical signal detection. In view of this, flexible electronics have attracted considerable attention and gradually played an irreplaceable role in healthcare monitoring[1,2]. Scientists from multiple disciplines, including physics, chemistry, materials science, electrical engineering, mechanical engineering, biology, and medicine, have made significant efforts in this field[3–7]. The superior flexibility and stretchability of flexible electronics are advantageous for portable and wearable technologies[8,9]. These advantages drive emerging applications in wearable and implantable flexible electronics[10,11], which involve neural interfaces[12–14], optogenetics[15–18], tumour targeting biopsies[19], and physiological signal monitoring[20], associated with developing bio-degradable/bio-compatible materials[21–23], deploying wireless communication/power stretagies[24] and exploring structural designs[25–34].

Integrating flexible electronics with various sensing functions on the skin gives rise to the development of skin-integrated electronics[35–39]. Physiological signals can be detected easily in real time for health monitoring, ranging from biophysical to biochemical signals using skin-integrated sensors[40]. From the standpoint of biophysical signals, biophysical sensors could be used for monitoring

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body temperature[41], pulse waves[42], electrocardiographs (ECG)[43,44], electroencephalograms (EEG)[45], blood pressure[46–49], blood flow[50] and other bio-related mechanical signals, based on the sensing technologies of temperature, strain, and biophysical electrical signals[51,52]. Biochemical sensors enable the detection of pH, glucose, and Na^+ ions from body fluids such as sweat and blood[53–57]. Skin-integrated sensors with stable and robust features can be comfortably worn on the body without interfering with daily life; this is closely associated with material, mechanical, and electrical designs. The stretchability of flexible devices can be significantly enhanced depending on the advanced mechanical design of the metallic electrodes[58]. Wireless power supply and communication are also realized by relying on thin and soft antennas[59–64].

Skin-integrated sensors that are sensitive to strain and temperature also act as electronic skin (e-skin), mimicking the real human skin[65]. Furthermore, the concept of "self-healing " that incorporates self-healable materials into electronics for self-healing with unchanged performance after damages such as scratching and cutting[66–70] has been proposed by scientists for application in soft electronic devices to better mimic real skin. Humans have a myriad of sensory receptors in different sense organs. With advanced intelligent sensing mechanisms, skin-integrated electronics could also perform a variety of sensory functions including visual, auditory, and tactile senses[71], which allow them to act as artificial eyes, ears, and skin. These could be used to rebuild corresponding sensations for patients who have lost their sense organs. Combining advanced micro-nanoscale manufacturing technologies with newly developed functional materials for mechanical and optically related sensing has proved to be a successful method for realising intelligent flexible electronics[72,73]. Moreover, the development of artificial nerve systems will also significantly expand the sensory functions of flexible electronics for practical and systematic application to the human body.

In this review, we summarise and illustrate the powerful capabilities of skin-integrated electronics from the perspective of intelligent sensing. Intelligent sensing is first reflected in the multi-functions of skin-integrated sensors for healthcare monitoring. The sensors are divided into two categories, biophysical and biochemical sensors, which detect all physiological signals from the body. Further, skin-integrated electronics demonstrate advanced intelligent sensing capabilities in artificial sensory perceptions, including visual, auditory, and tactile senses. We summarise the materials, structural designs, and operating principles of skin-integrated electronics corresponding to human sensory functions. Finally, we present the feedback interfaces of skin-integrated electronics to further demonstrate the potential of intelligent sensing functions. Skin-integrated electronics can not only passively detect external stimuli, but also initiatively endow feeling to the human body, which opens a new virtual reality (VR) and augmented reality (AR) modes. In recent studies, scientists have added tactile sense to VR. The sole reliance on visual and auditory senses will contribute to the advancement of the virtual world, gradually introducing new communication reforms, social media interactions, gaming, multimedia entertainment, and clinical medicine. In summary, skin-integrated electronics present various intelligent sensing functions in the form of skin-integrated sensors, artificial senses, and VR/AR interfaces.

Skin-Integrated Sensors for Healthcare Monitoring

Physiological signals are significant indicators of a person's health status. Thin, soft sensors attached to the skin can monitor the health of patients in real time. In this section, we present materials, devices, and integration strategies of skin-integrated electronics that have been reported and applied recently in physiological sensing. Biophysical and biochemical sensors in skin-integrated formats are discussed based on the nature of the signals. Biophysical sensors detect physical signals, including temperature, pressure, and strain, whereas biochemical sensors detect and analyse body fluids such as sweat and blood.

Biophysical sensors

With the rapid development of the human society, tracking infection and monitoring health conditions have attracted considerable attention worldwide. Skin-integrated electronics exhibit flexibility and stretchability that facilitate good contact with the skin and are therefore capable of accurately detecting and analysing various human physiological parameters including ECG, electronic acoustics, pulse rate, body temperature, and respiration rate[74–76]. Owing to their ultra-thin and lightweight features, skin-integrated sensors can be applied in diverse settings including hospitals, public places and homes, thus suitable for long-term and real-time health monitoring and disease tracking[77].

The use of portable electronics to track ECG for continuously monitoring cardiovascular diseases is a representation of the importance of real-time health monitoring because the signals detected in real-time directly reflect the activities of the heartbeat[44,78]. Clinically used ECG monitoring platforms adopt bulky boxes with

metal electrode buttons, wires, and rigid interfaces, which may cause skin irritation and limit daily activities. John A. Rogers group developed a number of skin-integrated devices with flexible and stretchable thin electrodes, wireless communication modules, and structurally designed interconnects for ECG monitoring, which present alternative strategies for current clinically available technologies[43,44,79–81]. In 2011, they first used the epidermal electronic system (EES) to measure ECG in conformal, skin-mounted modes without conductive gels or penetrating needles[43]. Subsequently, they reported an ultrathin, skin-integrated patch consisting of an interconnected collection of thin, filamentary serpentine conductive metal traces, and integrated electronic components for skin-attached ECG monitoring[79]. Owing to the extremely low elastic moduli and large deformability of the materials used, the flexible ECG electronics can be naturally mounted onto contoured surfaces. Recently, the group successfully applied skin-interfaced wireless electronic systems into neonatal and paediatric intensive care[44,80]. In traditional neonatal intensive care units (NICUs), ECG monitoring systems rely on hard-wired sensors adhered to the skin, which increase the risk of iatrogenic skin injuries in new born babies. Therefore, the development of soft and clinically relevant electronic systems is essential. Fig. 1a shows a wireless and battery-free epidermal electronic system for simultaneously recording ECG and photoplethysmogram[44]. Skin-like electronic devices can realise wireless, battery-free operation; real-time, in-sensor data analytics; and time-synchronized, continuous data streaming. Additionally, soft mechanics and gentle adhesive interfaces to the skin significantly increase the safety of neonatal skin. However, the operation distance of the reported electronics is only 30 cm, which may cause communication loss. To improve the operating distances of this system, they developed a new wireless skin-interfaced biosensor by introducing a coin cell and low-modulus silicone[80]. These skin-integrated devices substantially enhance the quality of neonatal and paediatric critical care based on ECG and other physiological monitoring with a working distance of 10 m.

In addition to ECG, flexible biophysical sensors also exhibit a remarkable ability for EEG detection. Conventional bulky EEG recording systems are not portable and often adopt rigid components to form physical interfaces to the head, which limit the widespread use of continuous real-time EEG measurements for medical diagnostics and sleep monitoring. Some researchers have focused their study on skin conformal polymer electrodes for clinical EEG recordings[82]. Flurin Stauffer et al. developed soft, self-adhesive, non-irritating, and skin-conformable biopotential electrodes that could be directly mounted on the skin without skin preparation or attachment pressure[83]. The polymer electrodes facilitated high-fidelity ECG recording of a professional swimmer during training in water. For conformal lamination on the complex surface topology of a curved body, Rogers' research group developed the EES for long-term, high-fidelity recording of EEG data[43]. Based on advanced mechanical designs, thin and foldable electrodes could mount directly and chronically on the auricle and mastoid[84]. They also explored skin-interfaced stretchable and wireless electronic measurement systems for continuous EEG monitoring by combining the system with a Bluetooth module[85]. They recently demonstrated a large-area epidermal electronic interface for ECG and EEG recordings that enable coverage of the entire scalp and circumference of the forearm (Fig. 1b)[45]. The signal distribution across the scalp is consistent with the expected distribution. High-quality EEG signals can be successfully acquired across the entire scalp using large-area epidermal sensors. Moreover, radio frequency-induced eddy currents can be minimised by designing filamentary conductive architectures in an open-network feature, making the skin-integrated interface compatible with magnetic resonance imaging (MRI).

Ubiquitous mechanical motion, ranging from subtle vibration to intense movement, can be used to characterise useful physiological health information. Recently, Lee et al. reported a soft wireless device for capturing mechano-acoustic signals by mounting the device onto the suprasternal notch (Fig. 1c)[86]. Unlike conventional stethoscopes that require manual manipulation during measurements, this small-scale, rechargeable battery-powered, flexible wireless system can obtain high-precision and high-bandwidth mechano-acoustic measurements. The optimised mechanical design ensures stretchability of up to 43% by incorporating considerable electronic components (microcontroller, peripheral passive components, etc.). It is worth mentioning that the small accelerometer functions as the core component in the entire system. The accelerometer can recognise different activities by measuring distinct features as functions of time and frequency during body motion. The maximum frequency measured by the device was as high as 800 Hz, which can fully cover normal daily human motion-related activities. Similarly, Zhao et al. developed a flexible electromagnetic vibration sensor based on a neodymium iron boron (NdFeB) membrane[51]. The device could offer various functions, including voice identification and motion detection with a sensitivity of 0.59 mV μm^{-1} at 1.7 kHz, owing to the electromagnetic induction between the copper coil and magnetic membrane.

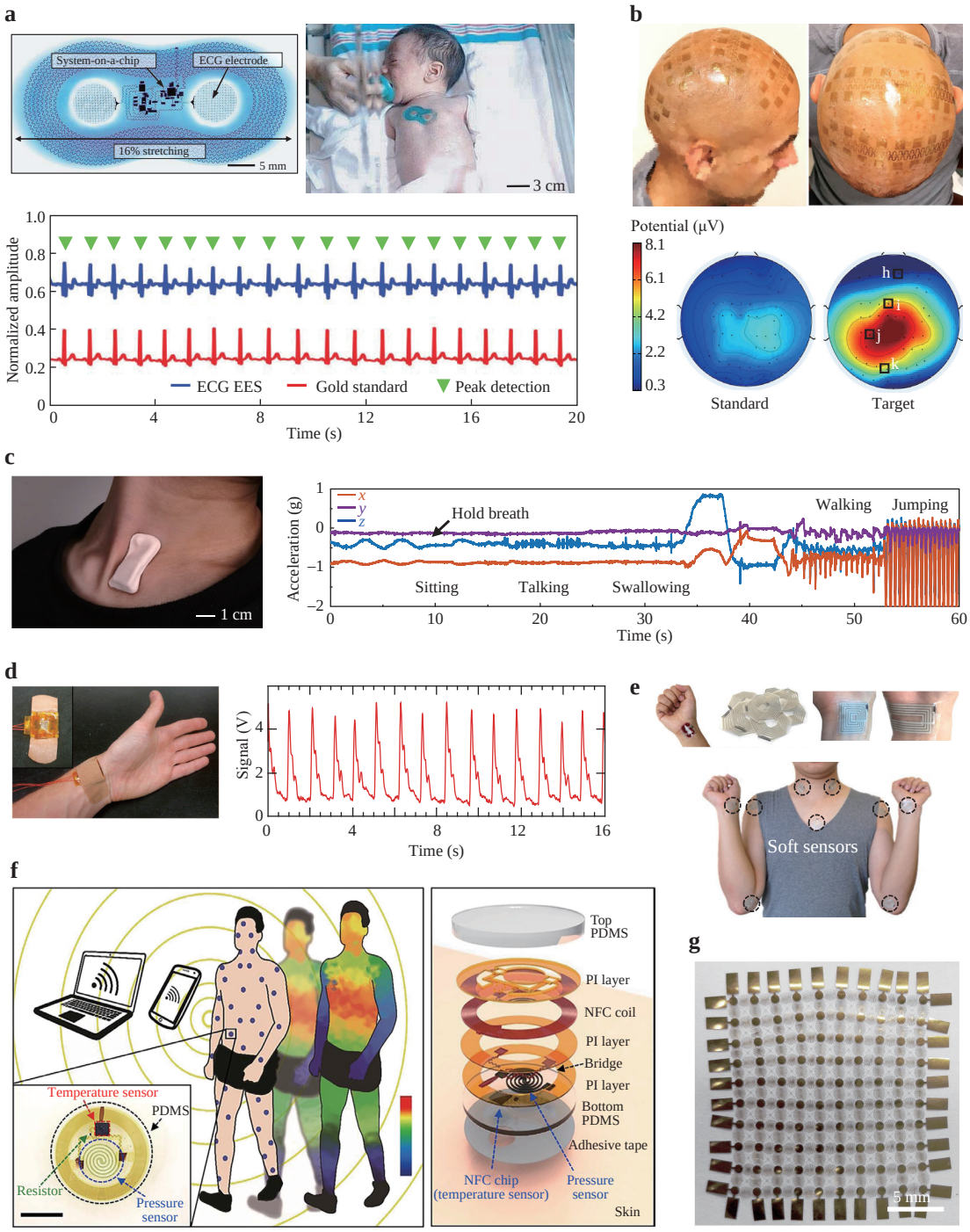

Fig. 1 Skin-integrated biophysical sensors. a Image of a wireless epidermal electronic system for neonatal intensive care. An ECG device with good stretchability is attached on the chest of a neonate to detect the ECG signals[44]. **b** Large-area epidermal electronic interface with 68 EEG electrodes covering the scalp of the subject is used for EEG detection[45]. **c** Soft wireless device is placed at the suprasternal notch for mechano-acoustic sensing of physiological processes and body motions. Results of recorded data during various activities including sitting at rest, talking, drinking water, changing body orientation, walking, and jumping[86]. **d** Pulse wave of the radial artery measured using flexible polymer transistors with high pressure sensitivity. Pressure sensor attached to the wrist[42]. **e** Photograph of a person wearing multiple skin sensors with different designs[93]. **f** Illustration of conformable skin-mounted wireless sensors for full-body pressure and temperature mapping. The sensor is composed of the NFC microchip, temperature sensor, pressure sensor, external resistor, NFC coil, and PDMS (polydimethylsiloxane) encapsulation[95]. **g** Optical image of highly stretchable and conformable matrix networks (10 × 10 array) for multifunctional sensing[105]. Images reprinted with the following permissions: **a** [44] from AAAS, **b** [45], **c**.[86], **d** [42], and **e** [93] from Nature Publishing Group, **f** [95] from AAAS, and **g** [105] from Nature Publishing Group.

Continuous pulse recording at home or hospital settings remains an urgent issue in biophysical signal monitoring for its valuable information in preventing cardiovascular disease attacks. The development of wearable electronics for long-term pulse monitoring has been a hot research topic for years[46,87–92]. Pressure or strain sensors are very common low-cost devices that do not require complicated fabrication processes. Developing new materials or novel device structures for pressure or strain sensors to realise flexible formats facilitates the detection of tiny forces induced by pulses on the skin surface and consequently facilitates pulse wave or blood pressure monitoring. Fig. 1d presents a flexible pressure-sensitive organic thin film transistor-based sensor developed by Gregor Schwartz et al.; the device exhibits a maximum sensitivity of 8.4 kPa^{-1}, a fast response time of < 10 ms, and remarkable stability verified by over 15000 cycles tests[42]. By attaching the device onto an adult wrist, the pressure sensor can accurately capture human pulses for over 16 periods with three clearly distinguishable peaks. To detect multiple signals from different body locations, Niu et al. reported an over-body area sensor network based on on-body sensors and an external circuit for wireless signal readout (Fig. 1e)[93]. The entire system exhibits excellent mechanical characteristics with stretchability of up to 50% owing to its intrinsically stretchable materials. Additionally, the device can simultaneously monitor human pulse, body movement, and respiration in real-time without an external hard wire, which shows its applicability in clinical systems for next-generation personal health monitoring systems.

Temperature is a vital signal in the human body that provides direct evidence for diagnosing fever in an individual. Measuring the skin temperature of specific areas of the body can provide more comprehensive human body information to predict diseases. Either commercially available or home developed small-scale temperature sensors can be directly integrated into flexible circuits for wearable body temperature monitoring[74,94,95]. For instance, Han et al. utilised near-field communication (NFC) chips with a temperature-resistance type embedded measurement system as a temperature sensor to develop epidermal electronic devices for continuously monitoring the temperature of the entire body (Fig. 1f)[95]. To evaluate sleep quality, the skin-integrated sensors can continuously monitor the full-body temperature for an entire night based on the wireless power delivery and data communication functions of NFC technology. Advanced mechanical designs of metallic or nanocomposite flexible thin films have also been adopted to improve the flexibility and stretchability of the flexible sensors[96–101]. Temperature sensing relies on the measurement of changes in the resistance, conductivity, or optical properties of a functional material. For example, tinny metal traces (gold) have good temperature sensing performance with good flexibility and stretchability under structural and mechanical designs[102–104]. Fig. 1g shows a multifunctional matrix network with a Pt thin film sensor array for temperature sensing[105]. The temperature coefficient of resistance could be up to 2410 ppm $°C^{-1}$. The mechanical design of the meandering interconnects causes ultrahigh flexibility and stretchability. The meandering wires do not show any obvious changes when stretched to 800%.

Generally, the skin-integrated biophysical sensors exhibit good applicability in health monitoring through physical and physiological signal detection.

Biochemical sensors

Sweat is a fluid excreted by the widely distributed glands under the skin[106]. Eccrine sweat contains a lot of chemical physiological information, including electrolytes, nitrogenous compounds, metabolites, hormones, and xenobiotics. The concentrations of these chemicals in sweat are closely related to health conditions such as diseases, metabolic disorders, and mental conditions. For example, ethanol concentration in sweat is closely related to blood ethanol levels[107,108]; glucose in sweat could also be a qualitative indicator of blood glucose levels[109–111]; lactate concentration can identify physical stress and the transition from aerobic to anaerobic states[112–114]. Abnormally high chloride concentration in sweat is the gold standard for diagnosing cystic fibrosis[115,116]; uric acid (renal disease[117], gout[118,119], etc.), urea (kidney failure[120]), and tyrosine (tyrosinemia[121], liver diseases, etc.) are also usually used for disease diagnosis. In addition, the average sweat loss rate[122] and pH[123] are related to electrolyte balance, hydration status, and overall body health. In recent decades, skin-integrated microfluidic/electronic systems have been developed to noninvasively monitor and analyse the chemical concentration of sweat. The universal method involves introducing microfluidic channels for on-body sweat collection and detection with high fidelity by minimising the evaporation and contamination of sweat samples, which was a tough nut to crack before the emergence of skin-integrated systems[124–126].

With the development of sweat sensors in recent years, detection systems have not only focused on electrolytes with high concentrations, but also realised breakthroughs in monitoring trace chemicals, such as hormones. Cortisol, which is a glucocorticoid-based hormone that mobilises energy in the body to cope with mental stress, is referred to as the “stress hormone”. The disturbances in circadian patterns of cortisol are highly relevant to post-traumatic

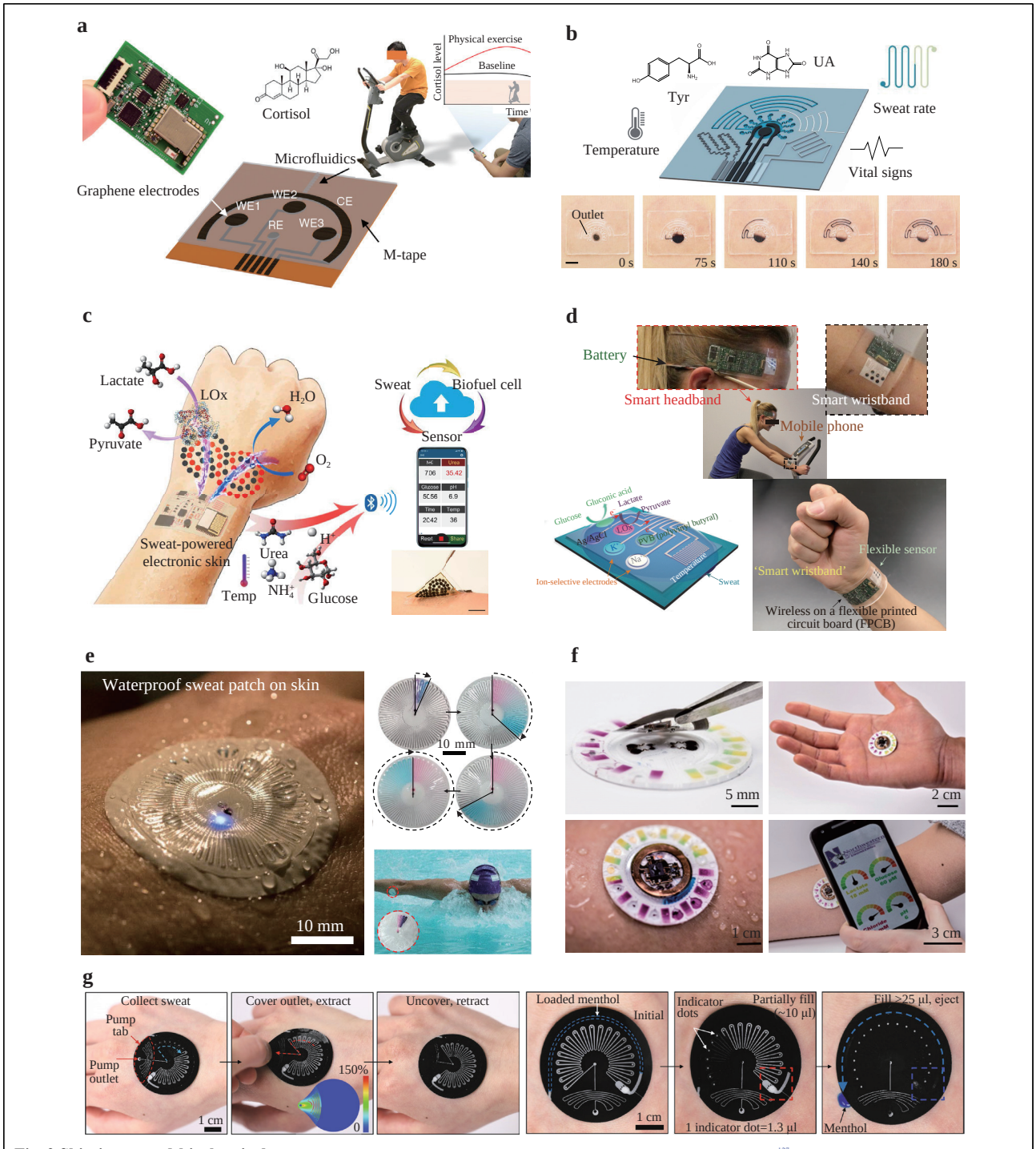

Fig. 2 Skin-integrated biochemical sensors. a Wireless sweat cortisol sensor for dynamic stress-response monitoring[127]. **b** Laser-engraved multimodal sensor for sensitive detection of uric acid and tyrosine in sweat, also capable of sensing temperature, strain and sweat loss/rate[128]. **c** Biofuel-powered soft electronic skin with multiplexed and wireless sweat sensing (urea, NH_4^+, glucose and pH) and strain sensing for human-machine interfaces[131]. **d** Fully integrated wearable sensor arrays on a flexible printed circuit board (FPCB) for multiplexed in situ perspiration sensing (glucose, lactate, Na^+ and K^+) and analysis, in form of smart headband/wristband[132]. **e** Waterproof epidermal microfluidic devices for sweat loss measuring, chloride sensing, and wireless thermography in aquatic environments[133]. **f** Multimodal microfluidic/electronic systems for simultaneous electrochemical (glucose & lactate), colorimetric (pH & chloride), and volumetric analysis of sweat[134]. **g** Skin-interfaced microfluidic sweat collection device, which is resettable by pumping out sweat (left) and giving chemesthetic hydration feedback when dehydration limit is crossed (right)[135]. Images reprinted with the following permissions: **a** [127] from Elsevier, **b** [128] from Nature Publishing Group, **c** [131] from AAAS, **d** [132] from Nature Publishing Group, **e** [133] from AAAS, **f** [134] from AAAS, and **g** [135] from Nature Publishing Group.

stress disorder (PTSD) and major depressive disorder. Therefore, it is important to study the dynamic stress-response profile of cortisol secretion for quantitatively understanding the neural circuits of some subjective emotions and sensations, such as pain and fear. A graphene-based wireless mHealth system for dynamic cortisol sensing in human sweat was recently reported (Fig. 2a)[127]. Cortisol was detected by electrochemical sensing electrodes made of carboxylate-rich pyrrole derivative grafted and subsequently, modified graphene. Using this skin-integrated electronic/microfluidic device, the authors systematically studied the relationship between the concentration of cortisol in sweat and serum and continuously monitored the dynamic stress-response profile of cortisol levels. The collected signals were processed on the device and then transmitted wirelessly by a Bluetooth low energy (BLE) module. Therefore, the compact device was composed of a rigid but mini printed circuit board (PCB) and a flexible sensor. Based on the same Sensor-BLE dual module structure, Y. Yang et al. presented a laser-engraved wearable sensor for the sensitive detection of uric acid (UA) and tyrosine (Tyr) in sweat[128]. Unlike the sweat cortisol sensor, this device is a multimodal sensing system with two physical sensors for temperature and strain sensing, a three-electrode chemical sensor for UA & Tyr sensing, and a microfluidic channel for sweat loss visualizing (Fig. 2b). All sensors are graphene-based and fabricated by CO_2 laser engraving, that is, the laser-induced graphene (LIG) technique[129,130]. This technology is capable of rapid pattern engraving and graphene deposition, making the scalable manufacturing of wearable sensors feasible. Batteries in these two systems make the device thick and bulky. Therefore, a multiplexed and wireless sensing soft, electronic skin that harvests energy from perspiration through a lactate biofuel cell was proposed (Fig. 2c)[131]. This is not only a sweat sensing system that detects several key metabolic analytes (urea, NH_4^+, glucose, and pH), but also a wireless self-powered electronic skin that monitors muscle contractions and acts as a human–machine interface. Most importantly, the power used for data processing and wireless communication is purely harvested from human sweat. The biofuel cell has a power density of 3.5 mW cm^{-2} and offers a stable 60-hour continuous operation. These types of multimodal electrochemical sensing, signal processing, and transmitting systems integrated on a single wearable device could be traced back to 2016. Gao et al. first presented a fully integrated wearable sensor array that realised in situ signal conditioning (amplifying, filtering, analog-digital converting) and processing (calibration, temperature compensation) by utilising a wireless flexible PCB (Fig. 2d)[132]. The sensor array simultaneously measures sweat metabolites (glucose and lactate) and electrolytes (sodium and potassium ions), using a resistance-based temperature sensor for precise compensation. It provides an on-body real-time perspiration analysis during exercises such as cycling or jogging without any external computing.

In addition to the above-mentioned sweat sensors with microcontroller units and related integrated circuits for signal processing and transmission, sweat sensors can be developed by relying less on complicated electronics and focusing more on microfluidic designs. A waterproof epidermal microfluidic system for sweat collection and analysis, even in aquatic environments, is demonstrated in Fig. 2e[133]. The flexible microfluidic device is based on the elastomer poly(styrene-isoprene-styrene), which exhibits excellent hydrophobicity, resistance to water transport, optical transparency, low elastic modulus, and high elasticity. These properties make the sweat sensor suitable for the underwater monitoring of key hydration metrics of swimmers. This device utilises colorimetric reagents for sweat detection, food dye for sweat loss visualisation in microchannels (1.5 μL for one turn), and silver chloranilate suspension for chloride concentration. An NFC module with a light-emitting diode was used for skin temperature sensing and reading. Combining integrated electronics with microfluidic colorimetric sensing could also realise both the volumetric and electrochemical analysis of sweat[134]. Fig. 2f shows a device designed in a detachable style with a disposable soft microfluidic network and a reusable thin NFC electronic module. Information on the pH, chloride, sweat rate/loss, lactate, and glucose concentration can be acquired wirelessly. This sweat sensor also inspired an advanced microfluidic design concept. The ratcheted channel, capillary bursting valves, and isolated chambers are beneficial for the precise quantification of the sweat rate, efficient sweat routing, and zero cross-talk between sensors. Devices based on digital reading may not be effective for warning athletes of dehydration during intense sports. To address this, Reeder et al. proposed a resettable skin interfaced microfluidic sweat collection device that could provide chemesthetic hydration feedback to the skin as a sensory warning of excessive sweat loss[135]. The corresponding device was a microfluidic-only wearable patch without any electronic components that could only measure sweat loss and give feedback when the loss exceeded a pre-set limit. When the sweat loss approached the pre-set limit (25 μL), the athletes could rehydrate their body and then pull the pump tab of the device to extract the sweat from the microchannel and reset the measurement (Fig. 2g left). If this “safe sweat loss” limit was crossed, a foaming agent would be activated by the sweat and the

chemesthetic agent would be (e.g. menthol or capsaicin) ejected onto the skin surface (Fig. 2g right), thus giving a sensory warning feedback. Efficient and subjective interaction between sensing systems and users is a critical direction for next-generation smart sweat sensors.

Other than sweat, tears and saliva are also typical easy-collectable body fluids with abundant chemical physiological information. The health conditions of the eyes and oral cavity can also be monitored by developing wearable microfluidic/electronic sensors in the form of contact lens[136] and mouthguards[137]. Skin-integrated chemical sensors are exhibiting high potential for biomedical applications; we believe that a full-featured, universal body fluid sensing system may soon be realised.

To facilitate the application of skin-integrated biophysical and biochemical sensors in on-patient healthcare monitoring, specific requirements are still necessary. For instance, novel functional soft materials are needed to achieve interfaces that are more comfortable and conformal with the skin to prevent delamination or irritation during daily use. Furthermore, skin-integrated sensors are still limited by the accuracy and durability of traditional rigid biomedical instruments. Therefore, more effort should be directed towards the development of new materials and novel device designs and exploring unique sensing mechanisms in skin-integrated sensors. The application of optics in wearable sensing technologies is also important. For instance, the use of reflection or refraction methods in wearable electronics has been successfully developed for the detection of blood flow, blood oxygen levels, body fluids, etc[7,12,47,59,138]. The advantages of non-invasive and high sensitivity optical sensing techniques make them irreplaceable in skin-integrated sensors. Therefore, research on optics-based multidiscipline areas in the field of skin-integrated electronics requires continuous efforts.

Skin-integrated electronics for sensory perception

The remarkable functions of flexible sensors enable skin-integrated electronics to detect physiological signals from the body surface. Skin-integrated electronics can also respond to various kinds of external stimuli such as human eyes, ears, and skin, which correspond to external sight, sound, and touch. Therefore, skin-integrated electronics have the corresponding sensory perceptions of visual, auditory, and tactile senses.

Visual sense

As our dominant sense, visual sense plays a prime role in acquiring information from the external world. Human eyes are an extremely intricate visual system, consisting of a concavely hemispherical retina and light-management photoreceptor. As the incoming light beams are focused on the retina, the visual cell perceives the light and generates optic nerve signals to the brain. An artificial vision system with a wide field of view and high resolution are required to mimic biological eyes[139]. However, the configuration of the hemispherical detector geometry poses a great challenge in the design and fabrication of biomimetic devices. Many novel methods based on flexible materials and systems have been reported in recent years to overcome this challenge[140–144]. Song et al. for the first time reported novel digital cameras that mimicked the compound eyes of insects by combining elastomeric compound optical elements with high-performance silicon photo detectors (Fig. 3a)[72]. Dictated by the parameters of the lens and viewing angle, every lens creates an image of the project. Individual photodiodes could be triggered only if a portion of the image formed by the associated micro-lens overlaps the active area. Thus, the stimulated detectors produce a sampled image of the object that can then be reconstructed using the optics models. Consequently, these digital cameras are in nearly full hemispherical shape and flexible, offer nearly infinite depth of field, and an outstanding wide-angle field of view, with zero image aberration. Similarly, the entire array of thin-film single-crystalline Si-based photo detectors was transferred onto deformable elastomeric material to form a hemispherical electronic eye camera that mimics human eyes[145]. This approach inspired the integration of traditional planar electronic devices onto the curved surfaces of more complex objects. Furthermore, the adjustable zoom capability of the electronic eye was realized using a dynamically tuneable plano-convex lens and substrates[146]. More recently, the resolution optimisation of such artificial visual systems has been demonstrated by origami methods. Fig. 3b shows a hemispherical electronic eye system with dense and scalable photodetector arrays with more than 250 photodetectors[147]. A soccer-like geometric shape was remapped onto a flexible single-crystalline Si-based nanomembrane. Some pixels at a specific designed location were then cut by a laser so that the remaining pixels could form a hemispherical shape with a gapless conjunction. This origami approach can be used for both concave and convex curvilinear photodetector arrays. However, low-cost and facile methods to demonstrate a hemispherical artificial visual sense system are still urgently needed, leading to practical application in further camera and automatic technologies.

The utilisation of novel materials, such as ultrathin two-dimensional (2D) nanomaterials and perovskite[148,149], can

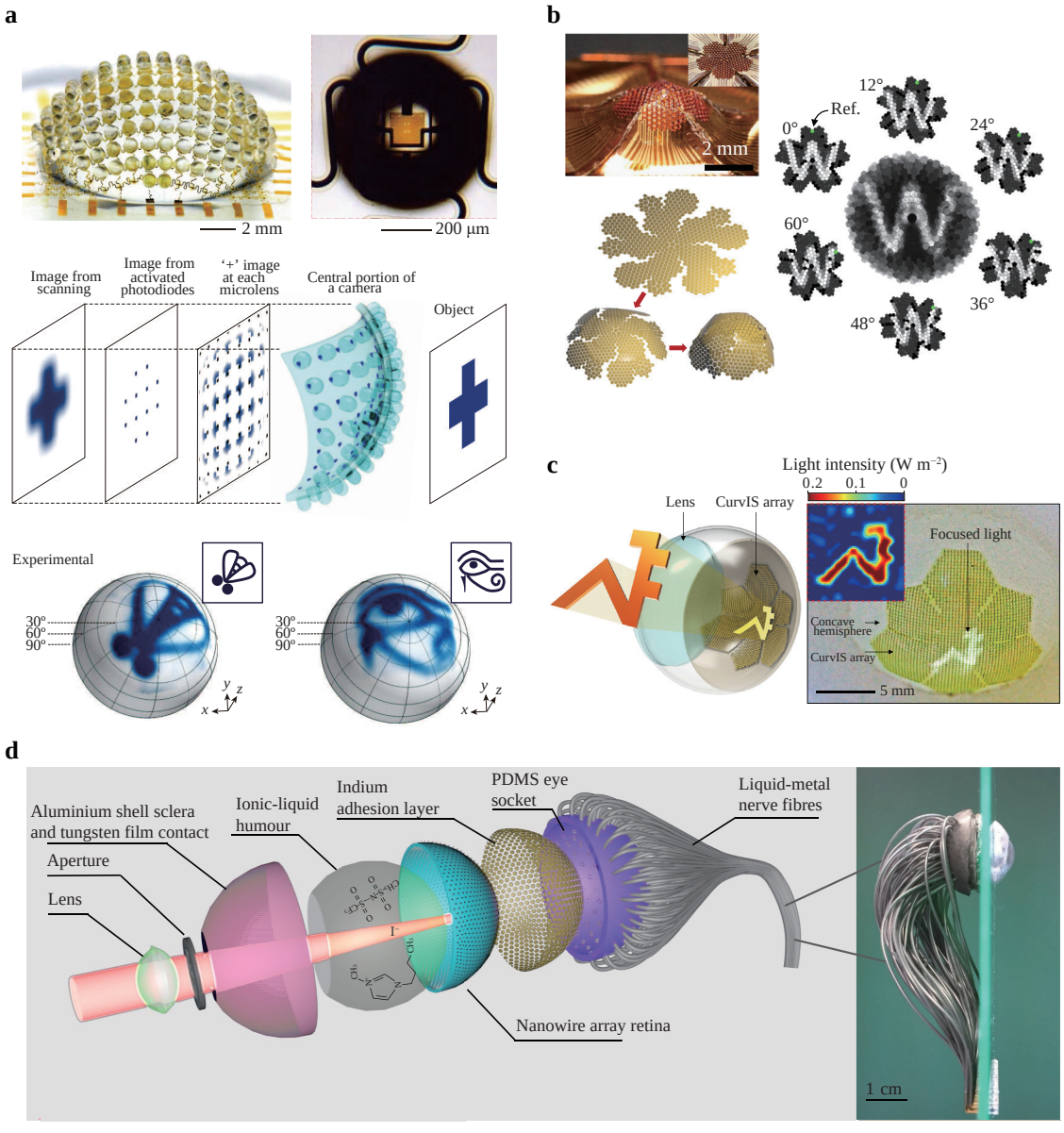

Fig. 3 Skin-integrated electronics for visual sense. a Artificial eye mimicking insect compound eyes and acquired view of image formation, reconstructed using optic models[72]. **b** Origami method for high-density curved photodetector arrays.[147] **c** Human eye-inspired soft electronic visual system based on MoS_2-graphene heterostructure[150]. **d** Exploded view of spherical biomimetic electrochemical eye (EC-EYE) with a hemispherical retina made of a high-density perovskite nanowire array[73]. Images reprinted with the following permissions: **a** [72], **b** [147], **c** [150], and **d** [73] from Nature Publishing Group.

further improve the performance of artificial visual systems. Fig. 3c presents a human eye-inspired soft electronic visual system using a high-density MoS_2-graphene-based image sensor array[150]. Owing to the inherent softness and ultrathinness of MoS_2, the curved sensor array exhibits much lower induced strain than the fracture strain of the composing materials. Moreover, the hemispherical image sensor array exhibits infra-red blindness and thus optimises the device with noise elimination and thickness reduction compared to silicon-based devices. Gu et al. proposed an electronic eye with a hemispherical retina based on a high-density array of perovskite nanowires (Fig. 3d)[73]. The single-crystalline perovskite nanowires have a pitch of 500 nm, reaching a density of up to 4.6×10^8 cm^{-2}, which is much higher than that of the photoreceptors in the human retina, indicating the potential to capture high-resolution images. This biomimetic design lays the foundation for the development of the electronic eye. In addition to the design of the receptors, high sensor design and high-density pixels, the

design of nerve systems present an additional challenge. Neuromorphic visual systems have considerable potential to emulate the basic functions of the human visual system. In 2019, Yang Chai's group reported a two-terminal optoelectronic resistive random access memory synaptic device for an efficient neuromorphic visual system, which enabled image sensing and memory functions as well as neuromorphic visual pre-processing[151].To classify images like the human brain, Lukas Mennel et al. proposed ultrafast machine vision using 2D material neural network image sensors[152]. The image-sensor array could simultaneously capture and identify optical images and rapidly process the information[153].

Although the existing electronic eyes are not fully skin-integrated, their flexibility still allows the integration or wearing of the corresponding devices on the human body. In the future, these e-eyes may not only act as the visual sense for automation systems but may also be implanted into the human body as artificial eyes. In addition to system-level integration, optical sensing is another important research area because the artificial eyes need to enhance their resolutions to mimic the functionality of a real eye for imaging. The development of nanomaterials in optical sensing has facilitated new advancements[73]. Independently transmitting the sensed signal by an individual nanoscale sensing unit is a step closer to the ultimate goal.

Auditory sense

Similar to visual sense, auditory sense is another very important perceptual system through which the human body can remotely receive external information. The vibrations of human vocal cords produce voices. The vibrations of the sound waves in the air are then transmitted to our ears so that we can hear them. The skin-integrated electronics can not only detect the vibrations of human vocal cords, but also those of sound waves in the air. Therefore, we can conclude that skin-integrated electronics can remarkably realise the hearing functions of human ears. In the future, combining 3D-bioprinting,

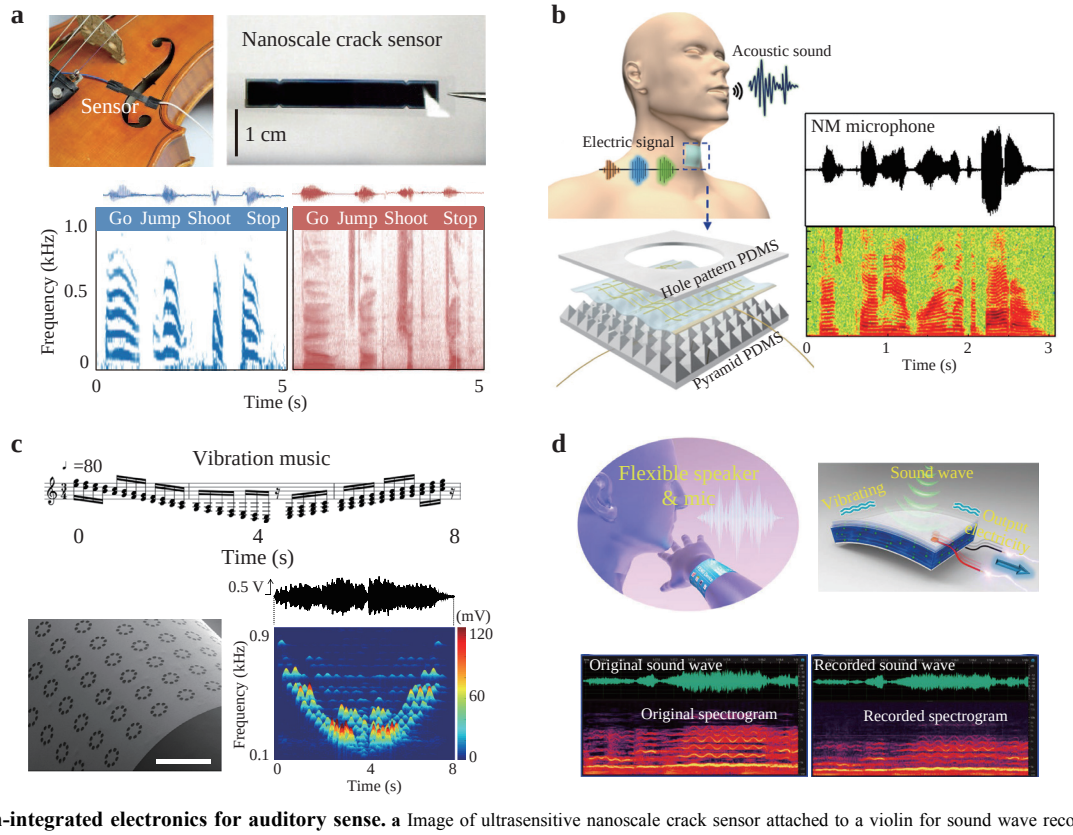

Fig. 4 Skin-integrated electronics for auditory sense. a Image of ultrasensitive nanoscale crack sensor attached to a violin for sound wave recognition[156]. **b** Schematic of skin-attachable microphone based on transparent and conductive nanomembranes with orthogonal silver nanowire arrays[157]. **c** Ultrathin vibration-responsive electronic skin used for vocal recognition. The waveform and frequency spectrum are acquired based on the detected vibrational output while a sheet music is played by a vibration speaker[158]. **d**. Nanogenerator-based self-powered thin patch loudspeaker or microphone. Mechanism of various applications of FENG-based acoustic device[159]. Images reprinted with the following permissions: **a** [156] from Nature Publishing Group, **b** [157] from AAAS, **c** [158] from Nature Publishing Group, and **d** [159] from Nature Publishing Group.

biological neuroscience, and flexible electronics sensing will create artificial ears[154,155].

An intuitive way of detecting sound involves directly connecting the flexible devices with the vibration source[155]. To achieve highly sensitive detection, D. Kang et al. developed an ultrasensitive mechanical crack-based sensor inspired by the spider sensory system[156]. Fig. 4a shows a nanoscale crack sensor connected to a violin to detect sound based on the resistance changes of the sensor. Therefore, the electrical signal of sound is recorded. Simultaneously, the researchers also attached sensors on the skin surface of a person's vocal cords to acquire sound information by detectable vibrations when the person speaks. In auditory-related sensors, nanomaterials are mostly used as sensing media. For instance, a silver nanowire-based nanomembrane was used for sound sensing (Fig. 4b)[157]. The wearable device functioned as a loudspeaker based on the thermoacoustic effect and as a microphone through a triboelectric voltage signal. In addition, the nanomembranes can react to the sound waves in the air and accurately recognise a user's voice, creating real auditory sensing.

Air is the most important non-contact medium for the transmission of sound. An artificial ear must detect sounds in the air. Specifically, when music or a person's voice reaches the artificial ear through the air, the sound waves should be converted into an electrical signal by the sensor in real time. As shown in Fig. 4c, the vibration-responsive electronic skin can clearly record music emitted from a loudspeaker[158]. Remarkably, voice authentication and control can be easily realised in a noisy environment when integrating the device on the skin. In addition to acoustic sensing based on resistance changes and vibration responses, Wei Li et al. reported a nanogenerator-based self-powered thin loudspeaker and microphone (Fig. 4d)[159]. The mechanical waves of sound facilitate the production of electrical outputs by the nanogenerator, which could be used for sound detection, voice recognition as well as identity recognition. The sound sensing of skin-integrated electronics is potentially applicable as flexible speakers, self-read e-newspapers, active noise cancellation systems, and project screens with speakers.

The auditory sense demonstrated by skin-integrated electronics can be widely used in the future. Playing the role of an ear, it can be attached to deaf and dumb people to improve their hearing and speaking skills, respectively. For the deaf, the device can detect other people's voices, which can then be translated into words. Consequently, the deaf are able to understand what others are saying. Skin-integrated electronics can also help the dumb communicate with others. Although their vocal cords are still working, most dumb people cannot speak because they cannot hear their own voice. Integrating these devices on the skin surface of their vocal cords can convert the detected vibration into words or voices. Thus, the deaf and dumb can lead a normal life relying on the flexible e-ears. Moreover, these flexible devices act as e-ears for voice reception and intelligent control.

Tactile sense

The skin is the largest organ of the body for the sensory system. The tactile nerves transmit physical stimuli from the external environment to the brain; thus, we can react accordingly. In recent years, the e-skin has been widely studied owing to its good stretchability and skin compatibility[160–163]. The e-skin with various sensing functions is the most suitable device for mimicking the real skin. Similar to human skin, the ability to experience pressure, strain, and temperature gives the e-skin the sense of touch[164,138]. As an intuitive application, Fig. 5a shows a prosthetic system and tactile process[165]. When the prosthesis grasps an object, the tactile information is transformed into a neuromorphic signal through the prosthesis controller. The prosthesis can perceive touch and pain through transcutaneous nerve stimulation. Therefore, it is possible to create prosthetic hands with a natural tactile sense, which allows people without limbs to experience the world through the sensory perceptions of the prosthetic hands. However, the real tactile sense is based on the system engineering, whose first task is to obtain accurate sensing.

Skin-integrated electronics that receive tactile signals (e.g., temperature, strain, and pressure) are often based on different functional components, such as piezoelectric films[166], thin-film transistors[167,168], triboelectric nanogenerators (TENG)[169–172], silicon sensors[173], and metal oxide semiconductor nanomembranes[174]. J. Park et al. demonstrated a piezoelectric multifunctional e-skin inspired by human fingertips to simultaneously detect static pressure and temperature and monitor the pulse pressure and temperature of arteries (Fig. 5b)[175]. This piezoelectric e-skin could also detect dynamic touch and acoustic waves. The introduction of graphene oxide sheets into PVDF made this piezoresistive e-skin sensitive to both pressure and temperature. PVDF, a flexible organic piezoelectric film, is a very common functional film for the piezoelectric-effect-based e-skin[176]. Compared to the normal hard PZT material, the organic piezoelectric material significantly enhances the comfort of the e-skin; organic field-effect transistors (OFETs) play the same role. OFETs, serving as sensors, are flexible, lightweight, biocompatible, and enable multianalyte sensing and subsequent decision-making in

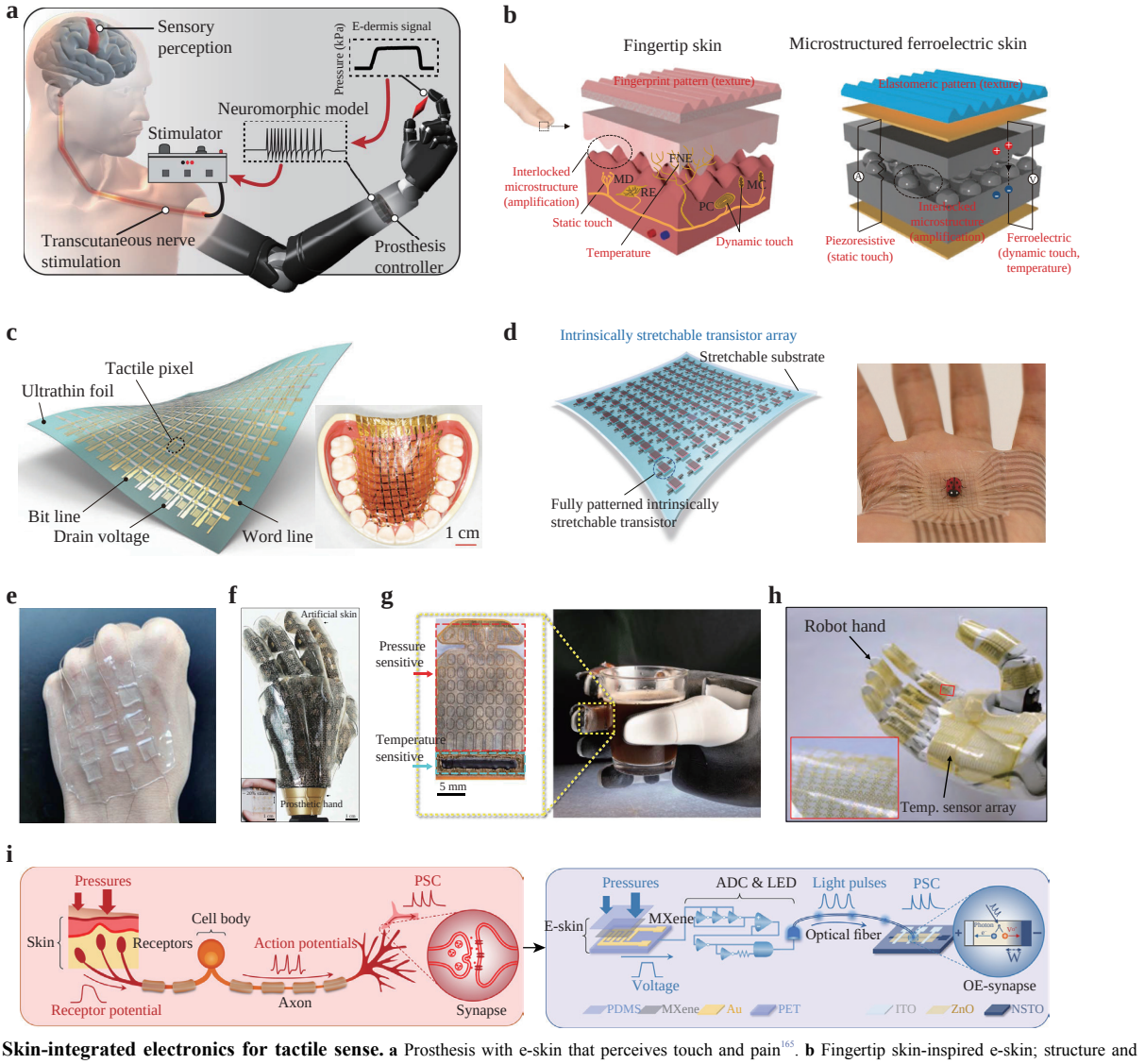

Fig. 5 Skin-integrated electronics for tactile sense. a Prosthesis with e-skin that perceives touch and pain[165]. **b** Fingertip skin-inspired e-skin; structure and functions of human fingertips (left); artificial multimodal e-skin (right)[175]. **c** Illustration of ultra-lightweight large-area tactile flexible electronics[178]. **d** Intrinsically stretchable transistor array for e-skin. The array enables accurate sensing of the position of a synthetic ladybug with six conductive legs[179]. **e** Image of a triboelectric nanogenerator-based e-skin attached on a curvy hand[180]. **f** Photograph of an artificial skin with stretchable silicon nanoribbon electronics covering the entire surface area of a prosthetic hand[173]. **g** Photograph of a prosthetic hand with a multi-modal sensor on the finger grasping a cup of hot coffee[181]. **h** Prosthetic hand wearing a temperature sensor array[174]. **i** Schematic diagram of the biological and bio-inspired optoelectronic spiking afferent nerve systems[191]. Images reprinted with the following permissions: **a** [165], and **b**[175] from AAAS, **c** [178], and **d** [179] from Nature Publishing Group, **e** [180] from AAAS, **f**.[173] from Nature Publishing Group, **g** [181], **h** [174] from AAAS, and **i** [191] from Nature Publishing Group.

logic circuits[177]. A very thin and lightweight design is essential for making the e-skin imperceptible after sticking onto the skin. Fig. 5c presents an ultra-lightweight design for imperceptible plastic electronics[178]. It is composed of thin large-area active-matrix sensors with 12 × 12 tactile pixels. The ultrathin electronic film is extremely lightweight (3 gm^{-2}, 60-fold lighter than conventional polyimide substrate). Moreover, it can accommodate stretching of up to 230% and can be operated at high temperatures and in aqueous environments. As an example, the tactile sensor sheet is tightly connected to a model of the human upper jaw (Fig. 5c right). This type of imperceptible e-skin can be integrated on the skin and work with tactile sense by temperature or infra-red sensing. In addition to creating light-weight e-skins, integrating more sensors per unit area is also extremely important, because tactile nerves in real skin are very rich. Bao et al. advanced the e-skin by fabricating an intrinsically stretchable transistor array with an unprecedented device density of 347 transistors per square cm (Fig. 5d)[179].

Specifically, they fabricated a large-scale array with 6,300 transistors in an area of approximately 4.4 cm × 4.4 cm. Such high-density sensor arrays enable the e-skin to perform high-resolution tactile responses. The photograph on the right in Fig. 5d shows that the e-skin on a human palm enables accurate position sensing of a synthetic ladybug with six conductive legs. In this e-skin, the transistors serve as sensor elements. To realise skin-like stretchability, they incorporated stretchable materials, such as cross-linked polystyrene-block-poly (ethylene-ran-butylene)-block-polystyrene (SEBS) as the stretchable dielectric, conjugated polymers as the stretchable semiconductors, and carbon nanotubes as the stretchable electrodes. Consequently, this transistor array successfully combined advanced electronic functionality with high skin-like stretchability. In addition to the functional units, organic stretchable materials are also the most used substrate materials. In this case, triboelectricity is generated by external touch on the e-skin. Some researchers have designed new e-skins using the principle of triboelectricity. A soft skin-like device was developed by X. Pu et al based on TENGs. The resulting e-skin was characterized by both biomechanical energy harvesting and touch sensing using an elastomer and ionic hydrogel as the electrification layer and electrode, respectively[180]. Fig. 5e shows the TENG-based e-skin with 3 pixel × 3 pixel tactile sensors attached to a curvy hand. The unique energy harvesting and tactile perception capabilities of the TENG-based e-skin may be used for the fabrication of a self-powered electronic skin in the future.

Inorganic materials are also widely used in the field of skin electronics. They are easier to fabricate in high resolution and are more stable and durable. Silicon and metal are often used as functional elements and conductive electrodes. Kim et al. developed a smart artificial skin with integrated stretchable sensors and actuators covering the entire surface area of a prosthetic hand, based on ultrathin, stretchable single crystalline silicon nanoribbons, as shown in Fig. 5f[173]. The e-skin integrated prosthetic hand has many sensory functions by detecting strain, pressure, temperature, and humidity. Experiencing various types of external stimuli is the ultimate goal for amputees, and converting external stimuli only to electrical signals is not enough. The output signals must be processed and transmitted to stimulate the corresponding peripheral nervous system. The aforementioned smart artificial skin took a step forward to demonstrate the interconnections between the prosthesis and peripheral nervous fibres. By stimulating the sciatic nerve, the corresponding electrophysiological signal can be detected from the thalamus in the right hemisphere of the brain. Therefore, the development of an e-skin with an intelligent artificial nerve system will be the next breakthrough. However, for the future e-skin system, readout latency bottlenecks and complex wiring still exist as the number of sensors increases. To solve this problem, W. Lee et al. introduced the asynchronous coded electronic skin (ACES) that enabled the simultaneous transmission of thermotactile information, maintaining exceptionally low readout latencies, even with more than 10,000 sensors[181]. Based on this ACES platform, it is possible to integrate skin-like sensors for artificial intelligence, including autonomous prosthesis, dextrous object manipulation, and somatosensory perception. As an application, a prosthetic hand with flexible multimodal sensors grasps a cup of hot coffee, as shown in Fig. 5g. Fig. 5h shows a similar example in which a prosthetic hand wears a skin-like temperature sensor array[174]. Therefore, applying the e-skin to prostheses enables them to sense external tactile stimuli. This suggests that a prosthesis with a tactile system similar to that of a human body can sense the external world. Enabling prostheses to communicate or collaborate with humans is another goal. Based on this idea, many researchers have conducted studies on wearable human-machine interfaces (HMIs)[182–187]. HMIs primarily sense physical signals from humans and then enable the prostheses to perform specific corresponding functions.

Integrating tactile sensing and neural network processing into one system will be a future strategy towards realising intelligent e-skins[188–190]. Inspired by biological nerve systems, Hongwei Tan et al. demonstrated an artificial afferent nerve with neural coding, perceptual learning, and memorising capabilities (Fig. 5i)[191]. The system could recognise, learn, and memorise based on neural coding and perceptual learning. In summary, the above series of research has built the foundation of the e-skin for tactile sensing, smart prostheses, and human-machine interactions.

However, initial attempts of implanting skin-integrated electronics on artificial sensations are still in their infancy. Based on the platforms established by the current technologies, future research may consider developing high channel counts sensing pixels in soft electronics to significantly improve the sensory resolution or integrate various functional sensing systems. Moreover, it is extremely important and difficult to build neural networks that deliver external stimuli to the brain to obtain corresponding responses from the body.

Skin-integrated electronics for haptic interfaces

Skin-integrated electronics are worn on the human body for healthcare and enhancing the human sensory

experience. They can achieve various health monitoring goals, including signal detection, transmission, and storage, as well as perform visual, auditory, and tactile sensory functions. To enhance the human experience, they could create a scenario in which humans feel perceptual information from other dimensions of time and space via skin-integrated electronics, referred to as VR. VR is an emerging area of technology but is not unknown to us. Usually, we use visual and auditory senses to experience the virtual world, just like we can see and hear things on a television. However, in addition to visual and auditory senses, our tactile sense provides the most profound, deepest, and emotional connection between people. It is an undisputed fact that developing tactile senses and haptic interfaces would significantly enhance the VR experience[192]. Consequently, we can achieve remote contactless "touch".

Based on vibration-like sensations via mechanical stimulation, we can feel the tactile sense of our surroundings using spatio-temporal patterns of force on the

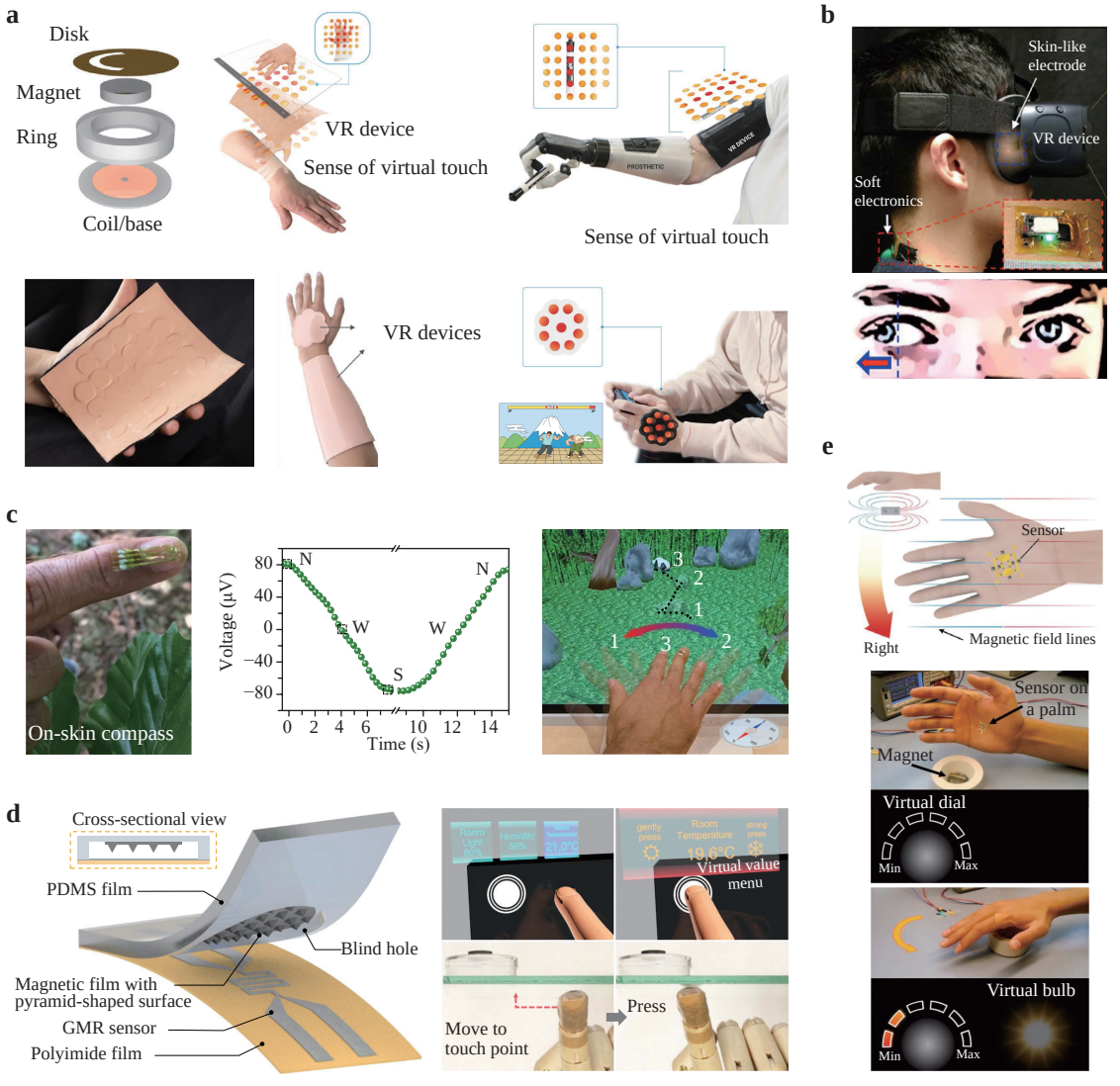

Fig. 6 Skin-integrated electronics for feedback interfaces in virtual and augmented reality. a Skin-integrated wireless haptic interfaces for virtual and augmented reality. Epidermal VR device with a haptic actuator array that can sense virtual touch. Amputees can distinguish the shape characteristics of objects with the aid of a prosthetic hand and this VR device. Players can experience real tactile senses in the game[194]. **b** Wearable electronics for real-time detection of eye vergence in virtual reality[195]. **c** E-skin compass and geomagnetic interaction with virtual reality environment[196]. **d** Soft e-skin for touchless tactile interaction and 3D touch in augmented reality[197]. **e** Magnetosensitive e-skins with directional perception for augmented reality. A sensor is applied to the palm of the hand for light dimming via a virtual bulb[198]. Images reprinted with the following permissions: **a** [194] from Nature Publishing Group, **b** [195] from AAAS, **c** [196], and **d** [197] from Nature Publishing Group, and **e** [198] from AAAS.

skin. Several years ago, Novich et al. designed a wearable vibrotactile vest and proposed an effective method of encoding vibrotactile data in both space and time to the skin to yield information transfer beyond visualization[193]. However, such wearable vibrotactile vests are bulky with wire connections, motors, and batteries. Recently, our laboratory demonstrated the skin-integrated wireless haptic interfaces for the first time. A skin-integrated wireless haptic interface was developed for VR/AR, as shown in Fig. 6a[194]. Using the wirelessly controlled and powered skin-integrated VR/AR system, the user can experience touch easily by wearing a bandage-like thin, soft, and adhesive device. The development of a complex system involves multiple disciplines of materials science, electrical, mechanical, and biomedical engineering. The sense of touch, which is felt by the body, is derived from the simulation of millimetre-scale vibrations by haptic actuators. Based on advanced mechanical designs, haptic actuators require less than 2 milliwatts to induce a notable sensory vibration. Chip-scale integrated circuits and antennae enable wireless powering and control in the actuators. Skin-integrated wireless haptic interfaces with thicknesses of only 3 mm were acquired by integrating the actuators and hundreds of functional components into a thin soft cloth substrate. They are breathable, reusable, and functional within a full range of bending and twisting motions. Moreover, the haptic actuators are driven by energy wirelessly harvested by radio frequency through a flexible antenna, which allows users to move freely. The explored skin-integrated sensory interface significantly enhances our life experiences. In the clinical field, the interface can be used for surgical training, virtual scene development, prosthetic control, and rehabilitation. Amputees could sense touch at the fingertips of their prosthetics through sensory inputs on the upper arm. Their brains can then receive the sensation on the upper arm to sense touch. For our daily lives, the innovation has considerable potential in communication, social media interaction, gaming, and multimedia entertainment. For example, it could be possible to sense a hug from friends and family members through a video call. Virtual touch can be achieved using pressures and patterns through a touchscreen interface. In summary, skin-integrated haptic interfaces could be a significant component of VR for social interactions, clinical medicine, and other applications.

Fig 6b shows soft, wireless periocular wearable electronics for real-time detection of eye vergence in VR[195]. Combining fully wearable skin-conformal sensors and the VR system, eye movements can be tracked with high sensitivity. This VR case combines skin-integrated electronics and vision. Similar to light, magnetic fields do not need a medium to travel. The geomagnetic field is ubiquitous in air. An e-skin compass was developed based on this concept, as shown in Fig. 6c [196]. The e-skin compass system facilitates orientation with respect to the Earth's magnetic field. The compass was fabricated on a 6-μm-thick polymeric film and easily integrated on the skin. When a person rotates from the magnetic north (N) to the magnetic south (S) via the west, the output voltage of the e-skin compass changes correspondingly. Therefore, the e-skin compass can be used to fabricate interactive devices for virtual and augmented reality. For example, it is possible to use the e-skin compass for the touchless control of virtual units in a game engine. Denys Makarov's group conducted a study on touchless tactile sense and control using this touchless property of magnetic fields. Fig. 6d shows a bimodal soft e-skin for tactile and touchless interaction in real time[197]. The combination of a giant magneto resistance sensor on a thin film, a round silicon-based polymer cavity, and a flexible permanent magnet with pyramid-like tips formed a touchless tactile interaction system, where the sensor was placed on the fingertip. On a glass plate with a permanent magnet, a finger with this e-skin device could select the desired virtual buttons by interacting with the permanent magnet. Subsequently, they also realised the touchless manipulation of objects based on interaction with magnetic fields (Fig. 6e)[198]. Using magnetosensitive e-skins with directional perception on the hand, the light intensity of a virtual bulb could be controlled by turning the hand with respect to the direction of the magnetic field lines of a permanent magnet. In VR, these technologies enable navigation, motion tracking, sports, and gaming interaction.

Compared with visual and auditory senses, tactile sense in VR should be subject to further development in the future. In addition to the stimulation from electromagnetism-induced mechanical vibration, thermal stimulus is a potentially suitable substitute, owing to the skin's sensitivity to temperature. The interconversion of different perceptions is another idea worth considering. For instance, a sound sensor and haptic interface can be integrated on the body of a deaf person. The haptic interface and auditory sense system can then convert auditory signals into tactile signals during conversations. Furthermore, the auditory sense system could translate the detected sound into visual texts to enable understanding for the deaf person, enhancing effective communication with others. Developing a novel integrated system that can intelligently select the use of different senses in specific situations would be challenging but also promising, because such a system considerably promotes the

development of skin-integrated electronics in AR/VR.

Conclusions

In this review, we summarised the intelligent sensing of skin-integrated electronics, sensors, and sensory perception to VR/AR. Skin-integrated electronics used as flexible sensors can detect physiological signals of the body to obtain health status information in real time. Scientists spend considerable energy studying the effectiveness of these sensors in a variety of body parts for different purposes, which significantly enhances the function of skin-integrated sensors. Improving the detection accuracy of such sensors is necessary to widely expand their applications. This is because the detection capability of the current flexible devices is still not as effective as that of corresponding rigid devices or analytical equipment in the laboratory. Exploring novel functional materials, better understanding the sensing mechanisms, and developing highly advanced structural designs in electronics are the foundations for improving the accuracy of detection in skin-integrated electronics. Meanwhile, combining light power supplies, data collection and storage components, as well as wireless transmission modules is key in system-level skin-integrated sensors. In addition to traditional functions such as sensors, skin-integration electronics are also useful as sensory perception systems owing to their special visual, auditory, and tactile sensory functions. In the current stage, the remarkable function of the electronics as sensory systems is still in the machine stage, displayed with the aid of prostheses. Replacing the real eyes, ears, and skin, which has a long way to go, requires the efforts of researchers from all disciplines, especially neuroscience. Optical sensing technology is also a possible breakthrough for sensory perception systems. Recent studies also have potential in the development of skin-integrated electronics for AR/VR. The introduction of touch in the virtual world considerably elevates the human experience. Not only can we have remote tactile communication, but amputees can also experience the joy of touch again. In the future, new opportunities for AR/VR technology may come from the development of new stimulus types or interconversion between different sensory perceptions.

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Author contributions

X. Y and D. L proposed the framework of this review. All authors contributed to the writing of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

1. Xu, S., Jayaraman, A. & Rogers, J. A. Skin sensors are the future of health care. *Nature* **571**, 319-321 (2019).
2. Ray, T. R. et al. Bio-integrated wearable systems: a comprehensive review. *Chemical Reviews* **119**, 5461-5533 (2019).
3. Chen, X. D. et al. Materials chemistry in flexible electronics. *Chemical Society Reviews* **48**, 1431-1433 (2019).
4. Rogers, J., Bao, Z. N. & Lee, T. W. Wearable bioelectronics: opportunities for chemistry. *Accounts of Chemical Research* **52**, 521-522 (2019).
5. Rogers, J. A., Chen, X. D. & Feng, X. Flexible hybrid electronics. *Advanced Materials* **32**, 1905590 (2020).
6. Li, J. H., Zhao, J. & Rogers, J. A. Materials and designs for power supply systems in skin-interfaced electronics. *Accounts of Chemical Research* **52**, 53-62 (2019).
7. Lee, G. H. et al. Multifunctional materials for implantable and wearable photonic healthcare devices. *Nature Reviews Materials* **5**, 149-165 (2020).
8. Rogers, J. A., Someya, T. & Huang, Y. G. Materials and mechanics for stretchable electronics. *Science* **327**, 1603-1607 (2010).
9. Hong, Y. J. et al. Wearable and implantable devices for cardiovascular healthcare: from monitoring to therapy based on flexible and stretchable electronics. *Advanced Functional Materials* **29**, 1808247 (2019).
10. Won, S. M. et al. Emerging modalities and implantable technologies for neuromodulation. *Cell* **181**, 115-135 (2020).
11. Song, E. M. et al. Materials for flexible bioelectronic systems as chronic neural interfaces. *Nature Materials* **19**, 590-603 (2020).
12. Shin, J. et al. Bioresorbable optical sensor systems for monitoring of intracranial pressure and temperature. *Science Advances* **5**, eaaw1899 (2019).
13. Na, K. et al. Novel diamond shuttle to deliver flexible neural probe with reduced tissue compression. *Microsystems & Nanoengineering* **6**, 37 (2020).
14. Shen, W. et al. Microfabricated intracortical extracellular matrix-microelectrodes for improving neural interfaces. *Microsystems & Nanoengineering* **4**, 30 (2018).
15. Samineni, V. K. et al. Fully implantable, battery-free wireless optoelectronic devices for spinal optogenetics. *Pain* **158**, 2108-2116 (2017).
16. Shin, G. et al. Flexible near-field wireless optoelectronics as subdermal implants for broad applications in optogenetics. Neuron **93**, 509-521.e3 (2017).
17. Zhang, Y. et al. Battery-free, lightweight, injectable microsystem for in vivo wireless pharmacology and optogenetics. *Proceedings of the National Academy of Sciences of the United States of America* **116**, 21427-21437 (2019).
18. Gutruf, P. et al. Fully implantable optoelectronic systems for battery-free, multimodal operation in neuroscience research. *Nature Electronics* **1**, 652-660 (2018).
19. Yu, X. G. et al. Needle-shaped ultrathin piezoelectric microsystem for guided tissue targeting via mechanical sensing. *Nature Biomedical Engineering* **2**, 165-172 (2018).
20. Won, S. M. et al. Recent advances in materials, devices, and systems for neural interfaces. *Advanced Materials* **30**, 1800534 (2018).

21. Koo, J. et al. Wireless bioresorbable electronic system enables sustained nonpharmacological neuroregenerative therapy. *Nature Medicine* **24**, 1830-1836 (2018).
22. Guo, Q. L. et al. A bioresorbable magnetically coupled system for low-frequency wireless power transfer. *Advanced Functional Materials* **29**, 1905451 (2019).
23. Yu, X. W. et al. Materials, processes, and facile manufacturing for bioresorbable electronics: a review. *Advanced Materials* **30**, 1707624 (2018).
24. Gutruf, P. et al. Wireless, battery-free, fully implantable multimodal and multisite pacemakers for applications in small animal models. *Nature Communications* **10**, 5742 (2019).
25. Yan, Z. et al. Mechanical assembly of complex, 3D mesostructures from releasable multilayers of advanced materials. *Science Advances* **2**, e1601014 (2016).
26. Nan, K. W. et al. Compliant and stretchable thermoelectric coils for energy harvesting in miniature flexible devices. *Science Advances* **4**, eaau5849 (2018).
27. Liu, Y. M. et al. 3D printed microstructures for flexible electronic devices. *Nanotechnology* **30**, 414001 (2019).
28. Bai, W. J. et al. Freestanding 3D mesostructures, functional devices, and shape-programmable systems based on mechanically induced assembly with shape memory polymers. *Advanced Materials* **31**, 1805615 (2019).
29. Kim, B. H. et al. Three-dimensional silicon electronic systems fabricated by compressive buckling process. *ACS Nano* **12**, 4164-4171 (2018).
30. Ning, X. et al. Mechanically active materials in three-dimensional mesostructures. *Science Advances* **4**, eaat8313 (2018).
31. Wang, H. L. et al. Vibration of mechanically-assembled 3D microstructures formed by compressive buckling. *Journal of the Mechanics and Physics of Solids* **112**, 187-208 (2018).
32. Ning, X. et al. Assembly of advanced materials into 3D functional structures by methods inspired by origami and kirigami: a review. *Advanced Materials Interfaces* **5**, 1800284 (2018).
33. Ning, X. et al. 3D tunable, multiscale, and multistable vibrational micro-platforms assembled by compressive buckling. *Advanced Functional Materials* **27**, 1605914 (2017).
34. Didier, C., Kundu, A. & Rajaraman, S. Capabilities and limitations of 3D printed microserpentines and integrated 3D electrodes for stretchable and conformable biosensor applications. *Microsystems & Nanoengineering* **6**, 15 (2020).
35. Jeong, H. et al. Modular and reconfigurable wireless E-tattoos for personalized sensing. *Advanced Materials Technologies* **4**, 1900117 (2019).
36. Wang, Y. et al. Epidermal electrodes with enhanced breathability and high sensing performance. *Materials Today Physics* **12**, 100191 (2020).
37. Huang, Z. L. et al. Three-dimensional integrated stretchable electronics. *Nature Electronics* **1**, 473-480 (2018).
38. Wang, C. F. et al. Materials and structures toward soft electronics. *Advanced Materials* **30**, 1801368 (2018).
39. Lin, M. Y., Gutierrez, N. G. & Xu, S. Soft sensors form a network. *Nature Electronics* **2**, 327-328 (2019).
40. Wang, B. H. et al. Flexible and stretchable metal oxide nanofiber networks for multimodal and monolithically integrated wearable electronics. *Nature Communications* **11**, 2405 (2020).
41. Crawford, K. E. et al. Advanced approaches for quantitative characterization of thermal transport properties in soft materials using thin, conformable resistive sensors. *Extreme Mechanics Letters* **22**, 27-35 (2018).
42. Schwartz, G. et al. Flexible polymer transistors with high pressure sensitivity for application in electronic skin and health monitoring. *Nature Communications* **4**, 1859 (2013).
43. Kim, D. H. et al. Epidermal electronics. *Science* **333**, 838-843 (2011).
44. Chung, H. U. et al. Binodal, wireless epidermal electronic systems with in-sensor analytics for neonatal intensive care. *Science* **363**, eaau0780 (2019).
45. Tian, L. M. et al. Large-area MRI-compatible epidermal electronic interfaces for prosthetic control and cognitive monitoring. *Nature Biomedical Engineering* **3**, 194-205 (2019).
46. Dagdeviren, C. et al. Conformable amplified lead zirconate titanate sensors with enhanced piezoelectric response for cutaneous pressure monitoring. *Nature Communications* **5**, 4496 (2014).
47. Kim, J. et al. Miniaturized battery-free wireless systems for wearable pulse oximetry. *Advanced Functional Materials* **27**, 1604373 (2017).
48. Ma, Y. J. et al. Relation between blood pressure and pulse wave velocity for human arteries. *Proceedings of the National Academy of Sciences of the United States of America* **115**, 11144-11149 (2018).
49. Wang, C. H. et al. Monitoring of the central blood pressure waveform via a conformal ultrasonic device. *Nature Biomedical Engineering* **2**, 687-695 (2018).
50. Boutry, C. M. et al. Biodegradable and flexible arterial-pulse sensor for the wireless monitoring of blood flow. *Nature Biomedical Engineering* **3**, 47-57 (2019).
51. Zhao, Y. C. et al. Fully flexible electromagnetic vibration sensors with annular field confinement origami magnetic membranes. *Advanced Functional Materials* **30**, 2001553 (2020).
52. Jang, K. I. et al. Self-assembled three dimensional network designs for soft electronics. *Nature Communications* **8**, 15894 (2017).
53. Zhang, Y. et al. Passive sweat collection and colorimetric analysis of biomarkers relevant to kidney disorders using a soft microfluidic system. *Lab on A Chip* **19**, 1545-1555 (2019).
54. Kim, S. B. et al. Soft, skin-interfaced microfluidic systems with wireless, battery-free electronics for digital, real-time tracking of sweat loss and electrolyte composition. *Small* **14**, 1802876 (2018).
55. Choi, J. et al. Soft, skin-integrated multifunctional microfluidic systems for accurate colorimetric analysis of sweat biomarkers and temperature. *ACS Sensors* **4**, 379-388 (2019).
56. Zhao, Y. C. et al. A wearable freestanding electrochemical sensing system. *Science Advances* **6**, eaaz0007 (2020).
57. Ortega, L. et al. Self-powered smart patch for sweat conductivity monitoring. *Microsystems & Nanoengineering* **5**, 3 (2019).
58. Li, K. et al. A generic soft encapsulation strategy for stretchable electronics. *Advanced Functional Materials* **29**, 1806630 (2019).
59. Xie, Z. Q. et al. Flexible and stretchable antennas for biointegrated electronics. *Advanced Materials* **32**, 1902767 (2020).
60. Xie, Z. Q., Ji, B. W. & Huo, Q. Z. Mechanics design of stretchable near field communication antenna with serpentine wires. *Journal of Applied Mechanics* **85**, 045001 (2018).
61. Kim, J. et al. Battery-free, stretchable optoelectronic systems for wireless optical characterization of the skin. *Science Advances* **2**, e1600418 (2016).
62. Jeong, Y. R. et al. A skin-attachable, stretchable integrated system based on liquid GaInSn for wireless human motion monitoring with multi-site sensing capabilities. *NPG Asia Materials* **9**, e443 (2017).
63. Kim, J. et al. Miniaturized flexible electronic systems with wireless power and near-field communication capabilities. *Advanced Functional Materials* **25**, 4761-4767 (2015).
64. Kim, J. et al. Epidermal electronics with advanced capabilities in near-field communication. *Small* **11**, 906-912 (2015).
65. Oh, J. Y. & Bao, Z. N. Second skin enabled by advanced electronics. *Advanced Science* **6**, 1900186 (2019).
66. Son, D. & Bao, Z. A. Nanomaterials in skin-inspired electronics: toward

soft and robust skin-like electronic nanosystems. *ACS Nano* **12**, 11731-11739 (2018).
67. Kim, S. H. et al. An ultrastretchable and self-healable nanocomposite conductor enabled by autonomously percolative electrical pathways. *ACS Nano* **13**, 6531-6539 (2019).
68. Kang, J. et al. Tough and water-insensitive self-healing elastomer for robust electronic skin. *Advanced Materials* **30**, 1706846 (2018).
69. Oh, J. Y. et al. Stretchable self-healable semiconducting polymer film for active-matrix strain-sensing array. *Science Advances* **5**, eaav3097 (2019).
70. Son, D. et al. An integrated self-healable electronic skin system fabricated via dynamic reconstruction of a nanostructured conducting network. *Nature Nanotechnology* **13**, 1057-1065 (2018).
71. Jung, Y. H. et al. Bioinspired electronics for artificial sensory systems. *Advanced Materials* **31**, 1803637 (2019).
72. Song, Y. M. et al. Digital cameras with designs inspired by the arthropod eye. *Nature* **497**, 95-99 (2013).
73. Gu, L. L. et al. A biomimetic eye with a hemispherical perovskite nanowire array retina. *Nature* **581**, 278-282 (2020).
74. Liu, Y. et al. Epidermal electronics for respiration monitoring via thermo-sensitive measuring. *Materials Today Physics* **13**, 100199 (2020).
75. Hong, S. et al. Wearable thermoelectrics for personalized thermoregulation. *Science Advances* **5**, eaaw0536 (2019).
76. Lou, Z. et al. An ultra-sensitive and rapid response speed graphene pressure sensors for electronic skin and health monitoring. *Nano Energy* **23**, 7-14 (2016).
77. Krishnan, S. R. et al. Epidermal electronics for noninvasive, wireless, quantitative assessment of ventricular shunt function in patients with hydrocephalus. *Science Translational Medicine* **10**, eaat8437 (2018).
78. Ha, T. et al. A chest-laminated ultrathin and stretchable E-tattoo for the measurement of electrocardiogram, seismocardiogram, and cardiac time intervals. *Advanced Science* **6**, 1900290 (2019).
79. Yeo, W. H. et al. Multifunctional epidermal electronics printed directly onto the skin. *Advanced Materials* **25**, 2773-2778 (2013).
80. Chung, H. U. et al. Skin-interfaced biosensors for advanced wireless physiological monitoring in neonatal and pediatric intensive-care units. *Nature Medicine* **26**, 418-429 (2020).
81. Jeong, J. W. et al. Capacitive epidermal electronics for electrically safe, long-term electrophysiological measurements. *Advanced Healthcare Materials* **3**, 642-648 (2014).
82. Leleux, P. et al. Conducting polymer electrodes for electroencephalography. *Advanced Healthcare Materials* **3**, 490-493 (2014).
83. Stauffer, F. et al. Skin conformal polymer electrodes for clinical ECG and EEG recordings. *Advanced Healthcare Materials* **7**, 1700994 (2018).
84. Norton, J. J. S. et al. Soft, curved electrode systems capable of integration on the auricle as a persistent brain-computer interface. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 3920-3925 (2015).
85. Jang, K. I. et al. Ferromagnetic, folded electrode composite as a soft interface to the skin for long-term electrophysiological recording. *Advanced Functional Materials* **26**, 7281-7290 (2016).
86. Lee, K. H. et al. Mechano-acoustic sensing of physiological processes and body motions via a soft wireless device placed at the suprasternal notch. *Nature Biomedical Engineering* **4**, 148-158 (2020).
87. Pang, C. et al. A flexible and highly sensitive strain-gauge sensor using reversible interlocking of nanofibres. *Nature Materials* **11**, 795-801 (2012).
88. Wang, X. W. et al. Silk-molded flexible, ultrasensitive, and highly stable electronic skin for monitoring human physiological signals. *Advanced Materials* **26**, 1336-1342 (2014).
89. Pang, C. et al. Highly skin-conformal microhairy sensor for pulse signal amplification. *Advanced Materials* **27**, 634-640 (2015).
90. Park, D. Y. et al. Self-powered real-time arterial pulse monitoring using ultrathin epidermal piezoelectric sensors. *Advanced Materials* **29**, 1702308 (2017).
91. Sekine, T. et al. Fully printed wearable vital sensor for human pulse rate monitoring using ferroelectric polymer. *Scientific Reports* **8**, 4442 (2018).
92. Pang, Y. et al. Epidermis microstructure inspired graphene pressure sensor with random distributed spinosum for high sensitivity and large linearity. *ACS Nano* **12**, 2346-2354 (2018).
93. Niu, S. M. et al. A wireless body area sensor network based on stretchable passive tags. *Nature Electronics* **2**, 361-368 (2019).
94. Li, D. F. et al. Aging improvement in Cu-containing NTC ceramics prepared by co-precipitation method. *Journal of Alloys and Compounds* **582**, 283-288 (2014).
95. Han, S. et al. Battery-free, wireless sensors for full-body pressure and temperature mapping. *Science Translational Medicine* **10**, eaan4950 (2018).
96. Zhang, Y. H. et al. Theoretical and experimental studies of epidermal heat flux sensors for measurements of core body temperature. *Advanced Healthcare Materials* **5**, 119-127 (2016).
97. Gao, Z. Y. et al. A self-healable bifunctional electronic skin. *ACS Applied Materials & Interfaces* **12**, 24339-24347 (2020).
98. Zhu, C. X. et al. Stretchable temperature-sensing circuits with strain suppression based on carbon nanotube transistors. *Nature Electronics* **1**, 183-190 (2018).
99. Dagdeviren, C. et al. Conformal piezoelectric systems for clinical and experimental characterization of soft tissue biomechanics. *Nature Materials* **14**, 728-736 (2015).
100. Yamamoto, Y. et al. Efficient skin temperature sensor and stable gel-less sticky ECG sensor for a wearable flexible healthcare patch. *Advanced Healthcare Materials* **6**, 1700495 (2017).
101. Hong, S. Y. et al. Stretchable active matrix temperature sensor array of polyaniline nanofibers for electronic skin. *Advanced Materials* **28**, 930-935 (2016).
102. Webb, R. C. et al. Ultrathin conformal devices for precise and continuous thermal characterization of human skin. *Nature Materials* **12**, 938-944 (2013).
103. Tian, L. M. et al. Flexible and stretchable 3ω sensors for thermal characterization of human skin. *Advanced Functional Materials* **27**, 1701282 (2017).
104. Krishnan, S. R. et al. Wireless, battery-free epidermal electronics for continuous, quantitative, multimodal thermal characterization of skin. *Small* **14**, 1803192 (2018).
105. Hua, Q. L. et al. Skin-inspired highly stretchable and conformable matrix networks for multifunctional sensing. *Nature Communications* **9**, 244 (2018).
106. Sonner, Z. et al. The microfluidics of the eccrine sweat gland, including biomarker partitioning, transport, and biosensing implications. *Biomicrofluidics* **9**, 031301 (2015).
107. Buono, M. J. Sweat ethanol concentrations are highly correlated with co-existing blood values in humans. *Experimental Physiology* **84**, 401-404 (1999).
108. Kamei, T. et al. Novel instrumentation for determination of ethanol concentrations in human perspiration by gas chromatography and a good interrelationship between ethanol concentrations in sweat and blood. *Analytica Chimica Acta* **365**, 259-266 (1998).
109. Oh, S. Y. et al. Skin-attachable, stretchable electrochemical sweat sensor for glucose and ph detection. *ACS Applied Materials & Interfaces* **10**, 13729-13740 (2018).

110. Lee, H. et al. A graphene-based electrochemical device with thermoresponsive microneedles for diabetes monitoring and therapy. *Nature Nanotechnology* **11**, 566-572 (2016).
111. Abellán-Llobregat, A. et al. A stretchable and screen-printed electrochemical sensor for glucose determination in human perspiration. *Biosensors and Bioelectronics* **91**, 885-891 (2017).
112. Martín, A. et al. Epidermal microfluidic electrochemical detection system: enhanced sweat sampling and metabolite detection. *ACS Sensors* **2**, 1860-1868 (2017).
113. Jia, W. Z. et al. Electrochemical tattoo biosensors for real-time noninvasive lactate monitoring in human perspiration. *Analytical Chemistry* **85**, 6553-6560 (2013).
114. Biagi, S. et al. Simultaneous determination of lactate and pyruvate in human sweat using reversed-phase high-performance liquid chromatography: a noninvasive approach. *Biomedical Chromatography* **26**, 1408-1415 (2012).
115. Sato, K. et al. Biology of sweat glands and their disorders. I. Normal sweat gland function. *Journal of the American Academy of Dermatology* **20**, 537-563 (1989).
116. Emaminejad, S. et al. Autonomous sweat extraction and analysis applied to cystic fibrosis and glucose monitoring using a fully integrated wearable platform. *Proceedings of the National Academy of Sciences of the United States of America* **114**, 4625-4630 (2017).
117. Kohagura, K. et al. An association between uric acid levels and renal arteriolopathy in chronic kidney disease: a biopsy-based study. *Hypertension Research* **36**, 43-49 (2013).
118. Major, T. J. et al. An update on the genetics of hyperuricaemia and gout. *Nature Reviews Rheumatology* **14**, 341-353 (2018).
119. Terkeltaub, R. Update on gout: new therapeutic strategies and options. *Nature Reviews Rheumatology* **6**, 30-38 (2010).
120. Al-Tamer, Y. Y., Hadi, E. A. & Al-Badrani, I. E. I. Sweat urea, uric acid and creatinine concentrations in uraemic patients. *Urological Research* **25**, 337-340 (1997).
121. Russo, P. A., Mitchell, G. A. & Tanguay, R. M. Tyrosinemia: a review. *Pediatric and Developmental Pathology* **4**, 212-221 (2001).
122. Godek, S. F., Bartolozzi, A. R. & Godek, J. J. Sweat rate and fluid turnover in American football players compared with runners in a hot and humid environment. *British Journal of Sports Medicine* **39**, 205-211 (2005).
123. Wang, S. Y. et al. Effect of Exercise-induced sweating on facial sebum, stratum corneum hydration, and skin surface pH in normal population. *Skin Research and Technology* **19**, e312-e317 (2013).
124. Ghaffari, R. et al. Soft wearable systems for colorimetric and electrochemical analysis of biofluids. *Advanced Functional Materials* **30**, 1907269 (2020).
125. Yang, Y. R. & Gao, W. Wearable and flexible electronics for continuous molecular monitoring. *Chemical Society Review* **48**, 1465-1491 (2019).
126. Choi, J. et al. Skin-interfaced systems for sweat collection and analytics. *Science Advances* **4**, eaar3921 (2018).
127. Torrente-Rodríguez, R. M. et al. Investigation of cortisol dynamics in human sweat using a graphene-based wireless mHealth system. *Matter* **2**, 921-937 (2020).
128. Yang, Y. R. et al. A laser-engraved wearable sensor for sensitive detection of uric acid and tyrosine in sweat. *Nature Biotechnology* **38**, 217-224 (2020).
129. Ye, R. Q., James, D. K. & Tour, J. M. Laser-induced graphene: from discovery to translation. *Advanced Materials* **31**, 1803621 (2019).
130. Lin, J. et al. Laser-induced porous graphene films from commercial polymers. *Nature Communications* **5**, 5714 (2014).
131. Yu, Y. et al. Biofuel-powered soft electronic skin with multiplexed and wireless sensing for human-machine interfaces. *Science Robotics* **5**, eaaz7946 (2020).
132. Gao, W. et al. Fully integrated wearable sensor arrays for multiplexed *in situ* perspiration analysis. *Nature* **529**, 509-514 (2016).
133. Reeder, J. T. et al. Waterproof, electronics-enabled, epidermal microfluidic devices for sweat collection, biomarker analysis, and thermography in aquatic settings. *Science Advances* **5**, eaau6356 (2019).
134. Bandodkar, A. J. et al. Battery-free, skin-interfaced microfluidic/electronic systems for simultaneous electrochemical, colorimetric, and volumetric analysis of sweat. *Science Advances* **5**, eaav3294 (2019).
135. Reeder, J. T. et al. Resettable skin interfaced microfluidic sweat collection devices with chemesthetic hydration feedback. *Nature Communications* **10**, 5513 (2019).
136. Kim, J. et al. Wearable smart sensor systems integrated on soft contact lenses for wireless ocular diagnostics. *Nature Communications* **8**, 14997 (2017).
137. Arakawa, T. et al. Mouthguard biosensor with telemetry system for monitoring of saliva glucose: a novel *cavitas* sensor. *Biosensors and Bioelectronics* **84**, 106-111 (2016).
138. Lou, Z., Wang, L. L. & Shen, G. Z. Recent advances in smart wearable sensing systems. *Advanced Materials Technologies* **3**, 1800444 (2018).
139. Huang, C. C. et al. Large-field-of-view wide-spectrum artificial reflecting superposition compound eyes. *Small* **10**, 3050-3057 (2014).
140. Liu, H. W., Huang, Y. G. & Jiang, H. R. Artificial eye for scotopic vision with bioinspired all-optical photosensitivity enhancer. *Proceedings of the National Academy of Sciences of the United States of America* **113**, 3982-3985 (2016).
141. Floreano, D. et al. Miniature curved artificial compound eyes. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 9267-9272 (2013).
142. Tang, X. et al. Towards infrared electronic eyes: flexible colloidal quantum dot photovoltaic detectors enhanced by resonant cavity. *Small* **15**, 1804920 (2019).
143. Liu, X. Q. et al. Rapid engraving of artificial compound eyes from curved sapphire substrate. *Advanced Functional Materials* **29**, 1900037 (2019).
144. Wang, W. J. et al. Fabrication of hierarchical Micro/Nano compound eyes. *ACS Applied Materials & Interfaces* **11**, 34507-34516 (2019).
145. Ko, H. C. et al. A hemispherical electronic eye camera based on compressible silicon optoelectronics. *Nature* **454**, 748-753 (2008).
146. Jung, I. et al. Dynamically tunable hemispherical electronic eye camera system with adjustable zoom capability. *Proceedings of the National Academy of Sciences of the United States of America* **108**, 1788-1793 (2011).
147. Zhang, K. et al. Origami silicon optoelectronics for hemispherical electronic eye systems. *Nature Communications* **8**, 1782 (2017).
148. Xue, J. et al. Narrowband perovskite photodetector-based image array for potential application in artificial vision. *Nano Letters* **18**, 7628-7634 (2018).
149. Tsai, W. L. et al. Band tunable microcavity perovskite artificial human photoreceptors. *Advanced Materials* **31**, 1900231 (2019).
150. Choi, C. et al. Human eye-inspired soft optoelectronic device using high-density MoS_2-graphene curved image sensor array. *Nature Communications* **8**, 1664 (2017).
151. Zhou, F. C. et al. Optoelectronic resistive random access memory for neuromorphic vision sensors. *Nature Nanotechnology* **14**, 776-782 (2019).
152. Mennel, L. et al. Ultrafast machine vision with 2D material neural network image sensors. *Nature* **579**, 62-66 (2020).
153. Chai, Y. In-sensor computing for machine vision. *Nature* **579**, 32-33

(2020).
154. Mannoor, M. S. et al. 3D printed bionic ears. *Nano Letters* **13**, 2634-2639 (2013).
155. Yang, J. et al. Eardrum-inspired active sensors for self-powered cardiovascular system characterization and throat-attached anti-interference voice recognition. *Advanced Materials* **27**, 1316-1326 (2015).
156. Kang, D. et al. Ultrasensitive mechanical crack-based sensor inspired by the spider sensory system. *Nature* **516**, 222-226 (2014).
157. Kang, S. et al. Transparent and conductive nanomembranes with orthogonal silver nanowire arrays for skin-attachable loudspeakers and microphones. *Science Advances* **4**, eaas8772 (2018).
158. Lee, S. et al. An ultrathin conformable vibration-responsive electronic skin for quantitative vocal recognition. *Nature Communications* **10**, 2468 (2019).
159. Li, W. et al. Nanogenerator-based dual-functional and self-powered thin patch loudspeaker or microphone for flexible electronics. *Nature Communications* **8**, 15310 (2017).
160. Wang, S. H. et al. Skin-inspired electronics: an emerging paradigm. *Accounts of Chemical Research* **51**, 1033-1045 (2018).
161. Yang, J. C. et al. Electronic skin: recent progress and future prospects for skin-attachable devices for health monitoring, robotics, and prosthetics. *Advanced Materials* **31**, 1904765 (2019).
162. Sim, K. et al. Fully rubbery integrated electronics from high effective mobility intrinsically stretchable semiconductors. *Science Advances* **5**, eaav5749 (2019).
163. Chen, S. et al. Recent developments in graphene-based tactile sensors and E-skins. *Advanced Materials Technologies* **3**, 1700248 (2018).
164. Boutry, C. M. et al. A hierarchically patterned, bioinspired e-skin able to detect the direction of applied pressure for robotics. *Science Robotics* **3**, eaau6914 (2018).
165. Osborn, L. E. et al. Prosthesis with neuromorphic multilayered e-dermis perceives touch and pain. *Science Robotics* **3**, eaat3818 (2018).
166. Liu, Y. M. et al. Skin-integrated graphene-embedded lead zirconate titanate rubber for energy harvesting and mechanical sensing. *Advanced Materials Technologies* **4**, 1900744 (2019).
167. Yu, X. G., Marks, T. J. & Facchetti, A. Metal oxides for optoelectronic applications. *Nature Materials* **15**, 383-396 (2016).
168. Lee, S. et al. A transparent bending-insensitive pressure sensor. *Nature Nanotechnology* **11**, 472-478 (2016).
169. Liu, Y. M. et al. Recent progress on flexible nanogenerators toward self-powered systems. *InfoMat* **2**, 318-340 (2020).
170. Liu, Y. M. et al. Thin, skin-integrated, stretchable triboelectric nanogenerators for tactile sensing. *Advanced Electronic Materials* **6**, 1901174 (2020).
171. Gao, Z. et al. Stretchable transparent conductive elastomers for skin-integrated electronics. *Journal of Materials Chemistry C* **8**, 15105 (2020).
172. Yao, K. M. et al. Mechanics designs-performance relationships in epidermal triboelectric nanogenerators. *Nano Energy* **76**, 105017 (2020).
173. Kim, J. et al. Stretchable silicon nanoribbon electronics for skin prosthesis. *Nature Communications* **5**, 5747 (2014).
174. Sim, K. et al. Metal oxide semiconductor nanomembrane-based soft unnoticeable multifunctional electronics for wearable human-machine interfaces. *Science Advances* **5**, eaav9653 (2019).
175. Park, J. et al. Fingertip skin-inspired microstructured ferroelectric skins discriminate static/dynamic pressure and temperature stimuli. *Science Advances* **1**, e1500661 (2015).
176. Liu, Q. X. et al. Highly transparent and flexible iontronic pressure sensors based on an opaque to transparent transition. *Advanced Science* **7**, 2000348 (2020).
177. Shi, W., Guo, Y. L. & Liu, Y. Q. When flexible organic field-effect transistors meet biomimetics: a prospective view of the internet of things. *Advanced Materials* **32**, 1901493 (2020).
178. Kaltenbrunner, M. et al. An ultra-lightweight design for imperceptible plastic electronics. *Nature* **499**, 458-463 (2013).
179. Wang, S. H. et al. Skin electronics from scalable fabrication of an intrinsically stretchable transistor array. *Nature* **555**, 83-88 (2018).
180. Pu, X. et al. Ultrastretchable, transparent triboelectric nanogenerator as electronic skin for biomechanical energy harvesting and tactile sensing. *Science Advances* **3**, e1700015 (2017).
181. Lee, W. W. et al. A neuro-inspired artificial peripheral nervous system for scalable electronic skins. *Science Robotics* **4**, eaax2198 (2019).
182. Kim, M. K. et al. Soft-packaged sensory glove system for human-like natural interaction and control of prosthetic hands. *NPG Asia Materials* **11**, 43 (2019).
183. Shih, B. et al. Electronic skins and machine learning for intelligent soft robots. *Science Robotics* **5**, eaaz9239 (2020).
184. Charalambides, A. & Bergbreiter, S. Rapid manufacturing of mechanoreceptive skins for slip detection in robotic grasping. *Advanced Materials Technologies* **2**, 1600188 (2017).
185. Sundaram, S. et al. Learning the signatures of the human grasp using a scalable tactile glove. *Nature* **569**, 698-702 (2019).
186. Jeong, J. W. et al. Materials and optimized designs for human-machine interfaces via epidermal electronics. *Advanced Materials* **25**, 6839-6846 (2013).
187. Yiu, C. et al. Skin-like strain sensors enabled by elastomer composites for human–machine interfaces. *Coatings* **10**, 711 (2020).
188. Shim, H. et al. Stretchable elastic synaptic transistors for neurologically integrated soft engineering systems. *Science Advances* **5**, eaax4961 (2019).
189. Someya, T. & Amagai, M. Toward a new generation of smart skins. *Nature Biotechnology* **37**, 382-388 (2019).
190. Tee, B. C. K. et al. A skin-inspired organic digital mechanoreceptor. *Sicence* **350**, 313-316 (2015).
191. Tan, H. W. et al. Tactile sensory coding and learning with bio-inspired optoelectronic spiking afferent nerves. *Nature Communications* **11**, 1369 (2020).
192. Zhu, M. L. et al. Haptic-feedback smart glove as a creative human-machine interface (HMI) for virtual/augmented reality applications. *Science Advances* **6**, eaaz8693 (2020).
193. Novich, S. D. & Eagleman, D. M. Using space and time to encode vibrotactile information: toward an estimate of the skin' s achievable throughput. *Experimental Brain Research* **233**, 2777-2788 (2015).
194. Yu, X. G. et al. Skin-integrated wireless haptic interfaces for virtual and augmented reality. *Nature* **575**, 473-479 (2019).
195. Mishra, S. et al. Soft, wireless periocular wearable electronics for real-time detection of eye vergence in a virtual reality toward mobile eye therapies. *Science Advances* **6**, eaay1729 (2020).
196. Cañón Bermúdez, G. S. et al. Electronic-skin compasses for geomagnetic field-driven artificial magnetoreception and interactive electronics. *Nature Electronics* **1**, 589-595 (2018).
197. Ge, J. et al. A bimodal soft electronic skin for tactile and touchless interaction in real time. *Nature Communications* **10**, 4405 (2019).
198. Cañón Bermúdez, G. S. et al. Magnetosensitive e-skins with directional perception for augmented reality. *Science Advances* **4**, eaao2623 (2018).