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Wearable Sensors-Enabled Human–Machine Interaction Systems: From Design to Application

Ruiyang Yin, Depeng Wang, Shufang Zhao, Zheng Lou, and Guozhen Shen**

In comparison to traditional bulky and rigid electronic devices, the human–machine interaction (HMI) system with flexible and wearable components is an inevitable future trend. To achieve effective, intuitive, and seamless manipulation of high-performance wearable HMI systems, it is important to develop effective strategies for designing material microstructures on flexible sensors and electric devices with excellent mechanical flexibility and stretchability. The real-time acquisition of human physiology and surrounding signals through accurate and flexible sensors is the basis of wearable HMIs. Herein, the construction of a wearable HMI system that utilizes sensors, communication modes, and actuators is reviewed. The mechanisms and strategies for designing various flexible sensors based on different mechanisms are analyzed and discussed. The functional mechanism, material selection, and novel design strategies of each part are summarized in detail. The different communication modes in interactive systems and the manufacturing technology of soft machines are also introduced. Additionally, the most advanced applications of wearable HMI systems in intelligent identification and security, interactive controls for robots, augmented reality, and virtual reality have been highlighted. The review concludes with an overview of the remaining key challenges and several ideas regarding the further improvement of wearable HMI systems.

1. Introduction

The rise of flexible wearable devices in recent years heralds a new revolution in human–machine interaction (HMI), which can satisfy the growing pursuit of a more convenient and colorful life.[1–9] Humans are the most important part of HMI systems. Meeting the application requirements for customer services and improving user experiences are the core concepts of the HMI technology.[10,11] However, traditional bulky and rigid electronic devices obstruct the compliant interfacing with human skin. Therefore, conventional devices affect the comfort level of users to a large extent, and almost obliterate the possibility of various novel interactive methods in the future.[9,12] To overcome these drawbacks, it is essential to develop flexible sensors and electric devices with excellent mechanical flexibility and stretchability; this could provide an effective and potential platform for further HMI applications.[13–18] Flexible and stretchable sensors, which can be attached to curved and dynamic surfaces, such as human and robotic skins, can continuously monitor the physiological and environmental indicators in real time.[19–25] The sensing process based on flexible sensors is the basis of HMI because HMI requires precise wearable sensors to continuously provide the machine with accurate and real-time external information. Comfortable and advanced wearable sensors largely determine the interactive accuracy and user experience of the interaction process. Similarly, the requirements of deformability and stretchability can be appropriately satisfied via flexible elastic electronic materials, which can help in fabricating soft actuators and robots, thereby creating more comprehensive and fascinating application designs.[26,27] These flexible devices possess great market potential; the number of users of such devices is expected to grow from 125 million in 2016 to ≈900 million in 2021.[28–30] The flexibility and toughness of electronic equipment depend on the development of the materials technology. Electronic devices should be thin enough to withstand deformation, such as bending or folding, while the minimum amount of conformation energy ensures a comfortable wear experience on the skin.[12,31] In contrast, stretchability is mainly realized by 1) designing electric devices with geometrically engineered structures, such as serpentines, wrinkles, and rigid islands,[32–34] and 2) applying intrinsically stretchable materials, such as low-dimensional semiconductor materials and conductive polymer materials.[35–39]

Novel wearable HMI systems must also follow traditional design principles, consisting of four parts, namely users, systems, inputs, and outputs (as shown in **Figure 1**). HMI systems are usually bidirectional,[40] providing a new window to interact with the outside world as well as the possibility of transforming virtual thinking into reality.[41,42] The interaction process can be summarized in the following steps: 1) a

R. Yin, D. Wang, S. Zhao, Prof. Z. Lou, Prof. G. Shen
State Key Laboratory for Superlattices and Microstructures
Institute of Semiconductors
Chinese Academy of Sciences & Center of Materials Science
and Optoelectronic Engineering
University of Chinese Academy of Sciences
Beijing 100083, China
E-mail: zlou@semi.ac.cn; gzshen@semi.ac.cn

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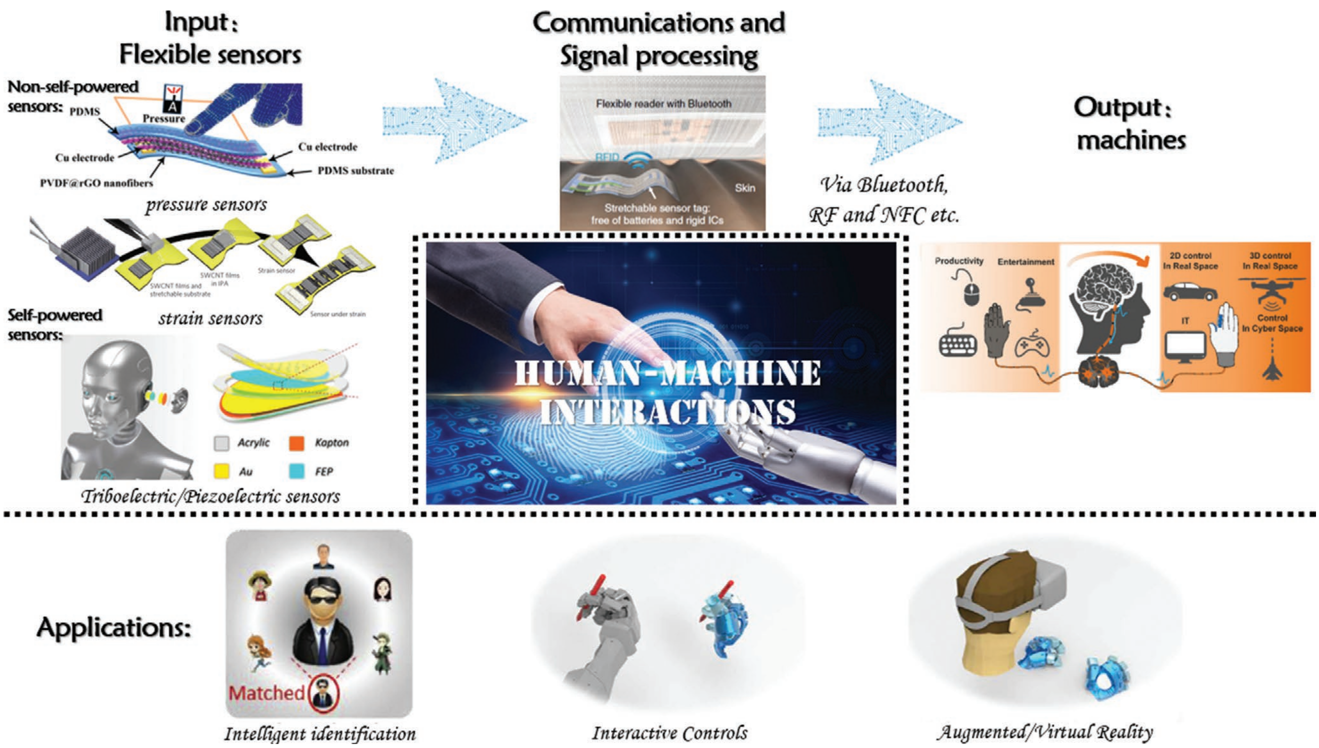

Figure 1. Interactive human–machine interfaces comprising flexible sensors and soft machines, along with their practical applications. Image for "input: flexible sensors": Reproduced with permission.[222] Copyright 2016, Elsevier; Reproduced with permission.[39] Copyright 2011, Springer Nature; Reproduced with permission.[223] Copyright 2018, American Association for the Advancement of Science. Image for "communication and signal processing": Reproduced with permission.[224] Copyright 2019, Springer Nature. Image for "output: machines": Reproduced with permission.[225] Copyright 2019, Elsevier. Image for "applications": Reproduced with permission.[226] Copyright 2019, Elsevier. Reproduced with permission.[171] Copyright 2020, American Association for the Advancement of Science.

user enters a language according to a certain target; 2) the input information is translated into the kernel language; and 3) the system finally executes the kernel language, followed by the customer requirements. For wearable HMI systems, this process can be interpreted as sensing the physical, electrophysiological, and surrounding signals from the wearers; subsequently, the machine performs specific functions.[43] Specifically, the input information relies on flexible sensors (such as pressure sensors and triboelectric nanogenerators (TENGs)) to capture the motion states of the human body as well as the bioelectrical and surrounding signals in real time. Wireless communication and signal processing are added between the input and output to connect the two parts. In the output part, "machine" can be more broadly referred to as a mechanical actuator, robot, or computer; meanwhile, various interactive interfaces are exploited, including the touch screen, electronic skin (e-skin), soft robotics technology, and immersive somatosensory technology.[38,44–49]

The interactive technology has witnessed three major revolutions, from the early mouse to multi-touch, followed by the latest motion sensing. With the continuous update of the Internet of Things (IoT) and the development of artificial intelligence,[11,50] wearable HMI systems have witnessed significant advancements based on the following concepts: 1) personalized safety identification guarantees the creation of a safe and intelligent life; 2) the interactive system perceives all aspects of the customer requirements, including the aspects of life and psychology; and 3) the artificial intelligence analysis system precisely customizes the user habits and preferences based on the users. Although it takes a long time to realize wild imaginations in science fiction movies and literature, some of the actual functions have been gradually realized. HMI systems have been thoroughly developed and introduced various novel experiences, manipulators,[51] and immersive virtual reality (VR) experience.[49]

In this paper, we review the design and development process of wearable HMI systems. We surveyed the recent advances in wearable HMI systems based on flexible sensors and soft actuators. As illustrated in Figure 1, an HMI system can be disassembled and discussed in several parts, including the input, communication, signal processing, and output. The functional mechanism, material selection, and novel design strategies of each part are summarized in detail. Because sensors are fundamentally important, we first focus on the mechanisms and strategies used for designing flexible sensors, including the non-self-powered and self-powered sensors. Then, we review the other parts of an HMI system, including different communication methods and the manufacturing techniques for soft actuators. The applications of wearable HMI systems in intelligent identification and security, interactive controls for robots, augmented reality (AR), and VR are also presented. Finally, we discuss the challenges in this field and share our vision for future trends.

2. Principle and Design Strategy of Wearable Input Devices

The real-time accurate perception of external stimuli is the basis of the entire interactive process.[52–57] Capturing human body signals and external stimuli, such as touch, pressure, tension, and temperature, is similar to human perception somatosensation. Human somatosensation is crucial for humans to complete many daily tasks, such as emotional responses and performance of target actions, that rely on skin afferents to sense environmental changes. Flexible sensors can acquire biological signals, including the blood pressure and body movements, and help inanimate objects to understand "sensations" in interactions.[58,59] Hence, wearable sensors play a vital role in the input terminals of HMIs. Flexible sensors can be divided into non-self-powered and self-powered types according to the different mechanisms including piezoresistive, capacitive, piezoelectric, and triboelectric effects, which both convert external mechanical stimuli into electrical signals.[45,60–62] Non-self-powered flexible pressure/strain sensors (piezoresistive, capacitive types) take advantage of the simple preparation techniques and accurate signal acquisition, which largely depend on the development and utilization of new nanomaterials in novel structures. In contrast, self-powered sensors (such as triboelectric piezoelectric and sensors) can be used in more application scenarios owing to their self-powering capacity and diversified custom design. In this section, we will focus on the basic sensor principles and introduce novel material designs for achieving high performances or specific uses. Moreover, a summary of active materials/constructing strategies of different types of flexible sensors and their practical HMI applications is presented in **Table 1**.

2.1. Non-Self-Powered Sensors

2.1.1. Pressure Sensors

Pressure sensors are the most common type of flexible sensors that mainly rely on four mechanisms, that is, the piezoresistive, capacitive, piezoelectric, and triboelectric effects.[62–67] In this part, we mainly discuss non-self-powered types like piezoresistive, capacitive pressure sensors. Key parameters, including the sensitivity, limit of detection, response time, and stability, are used to describe the performance of a device.

Among them, piezoresistive pressure sensors play a prominent role owing to their simple preparation process, low energy consumption, and excellent sensitivity.[66] The piezoresistive

Table 1. Summary of typical flexible sensors and their applications.

Active materials	Structures	Sensor types	Advantages	HMI applications
Ag nanowires, carbon fabric[52]	Hetero-contact microstructure	Piezoresistive pressure sensor	High sensitivity, fast response time, and reproducible electromechanical properties	Virtual reality
MXene nanosheets[68]	Sandwich structure	Piezoresistive pressure sensor	Highly sensitive, flexible, and degradable properties	Robot control
CNT[73]	Hierarchical textile construction	Piezoresistive pressure sensor	Superlyophobicity, mechanical durability, and highsensitive features	Machine hands controlled by human hand gestures
PVDF dielectric[59]	Convex microarrays	Capacitive pressure sensor	Ultra-high sensitivity, fast response time, and extreme stability	Robotic grabbing objects
Fluorinated ethylene propylene[127]	Sandwich structure	Piezoelectric sensor	Low pressure sensing limitation and high peak output force	Feedback control
Vanadium nitride nanosheets[38]	Metallic sandwiched-aerogel	Resistance-type strain sensor	Excellent structural compatibility, sensitivity, stretchability	Robot hand control
Ag nanowires, polyimide[36]	Kirigami engineered patterns	Resistance-type strain sensor	Digital and rapid process, high optical transparency, stretchability	Quadrotor control
Ag nanoparticle and nanowire[98]	Hierarchical microsized hairy architectures	Resistance-type strain sensor	High robustness, stable performance, stretchability	Virtual shooting game
Monolayer graphene[185]	Layer structure	Triboelectric sensor	Noncontact operating mode	Intelligent noncontact screen control
Liquid metal nanoparticles[109]	Layer structure	Triboelectric sensor	Stable and high open-circuit voltage	Touch interactive keyboard
Fluorinated ethylene propylene[212]	Layer structure	Triboelectric sensor	Effectively capturing eye blink motion	Smart home control
Eco-flex elastomer[171]	Hemisphere shape	Triboelectric sensor	High accuracy realized by machine learning technique	Diversified interactions
Kapton film[117]	Layer structure	Triboelectric sensor	Recognizing more than 156 interaction logics	Gesture control, augmented reality
Gold nanowires[99]	Vertically aligned standing nanowire	Triboelectric sensor	Exceptionally high strain tolerance	Remote controlling light switches and robotic toy vehicle
PET, silicone[48]	Layer structure	Triboelectric sensor	High mobility, suitable for a variety of work environments	Two-factor authentication

effect is enabled by the changes in current or resistance due to external forces. Piezoresistive pressure sensors are usually fabricated from two parts: flexible polymer substrates and conducting functional materials.[68,69] High sensitivity and detection limit can be realized by two effective ways, that is, developing new functional materials and building "wavy" structures. Functional materials, including low-dimension materials, micro/nanoparticles, textiles, and their composites, play a significant role in constructing and recovering tactile sensation, thereby enabling the dexterous manipulation of machines as well as real-time monitoring of human health.[70,71] Recently, an increasing number of nanostructured materials have been introduced into flexible sensors owing to their excellent solution-processable fabrication, good compatibility, electrical conductivity, and mechanical stretchability, such as carbon nanotubes (CNTs), metal nanoparticles, polymer nanofibers, carbonized nanofibers, and graphene.[72] In addition, electronic textiles equipped with unique features, such as breathability, deformability, sewability, and washability, provide broad prospects for wearable devices.[73] Guo et al.[68] demonstrated a simple and cost-effective way to manufacture versatile flexible wearable pressure sensors. The flexible device could perform a wide range of medical monitoring tasks, covering both small deformations and large movements. Additionally, it could predict the underlying early signs of Parkinson's disease in patients by simulating static tremor. These HMI functions were realized owing to MXenes that functioned as a pressure-sensing functional layer. The functional layer had a large specific surface area and high electrical conductivity owing to its 2D layered structures (**Figure 2**a). The pressure sensor was prepared through a porous MXene-impregnated tissue sandwiched between two degradable polylactic acid sheets; it achieved excellent sensing performance with a broad range (>30 kPa), low detection limit (<10.2 Pa), and fast response (11 ms). This demonstrates the potential of this device in personal healthcare biological monitoring and HMI applications.

In contrast, flexible capacitive pressure sensors (FCPSs) exhibiting the distinct benefits of fast response, high sensitivity, and low hysteresis are also favored by researchers.[74] Similar to piezoresistive pressure sensors, FCPSs usually consist of two parallel flexible conducting flats separated by a dielectric layer (typically polyvinylidene fluoride (PVDF) or methacrylate). The capacitance (C) is determined by the equation $C = \varepsilon A/4\pi kd$, where d, A, and ε represent the distance between the top and bottom electrodes, effective area, and dielectric layer permittivity, respectively. The addition of conductive fillings (such as silver nanowires (AgNWs), metal micro-flakes, and CNTs) and construction of different

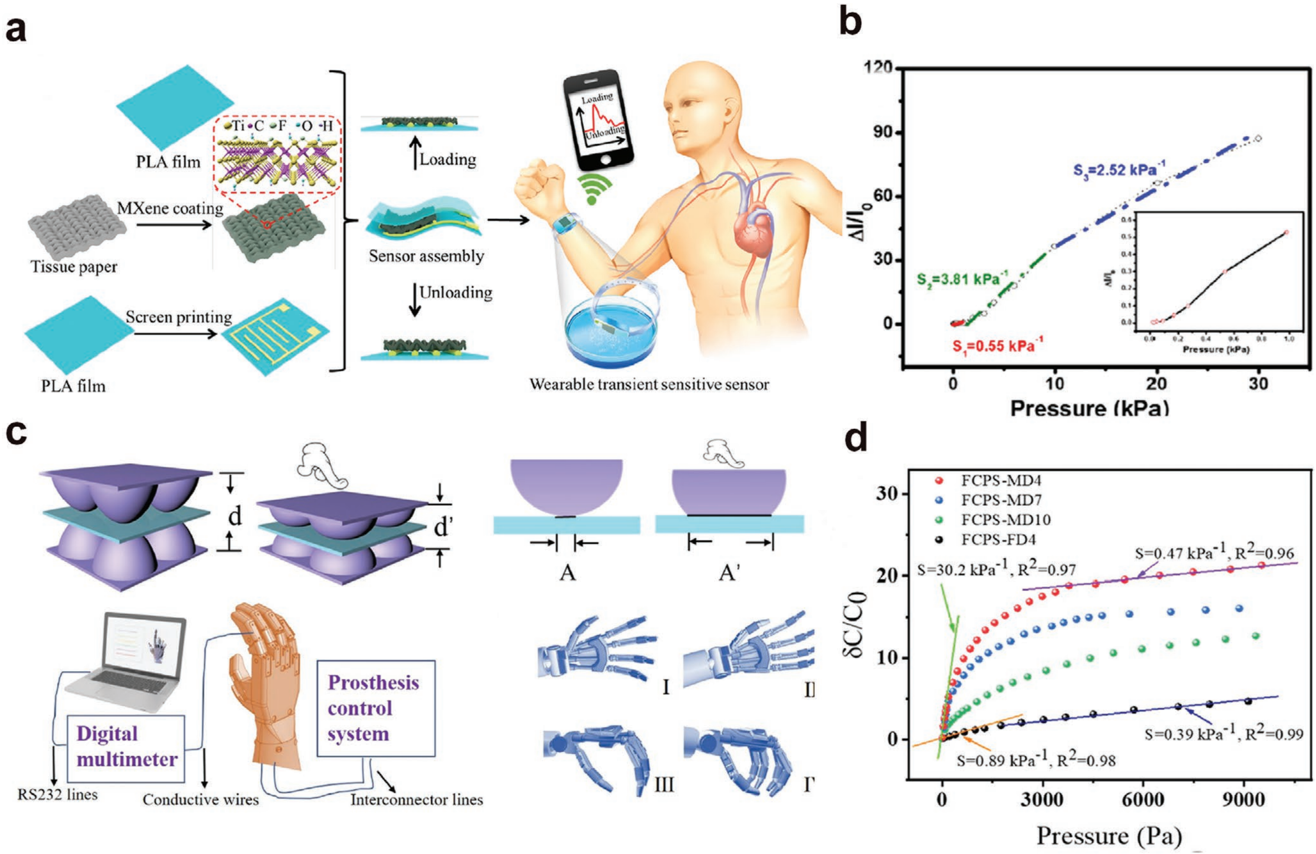

Figure 2. Schematic and pressure sensing performance of three different types of pressure sensors. a) Example of flexible piezoresistive pressure sensors. b) Sensitivity curve of the flexible pressure sensor to pressure. Adapted with permission.[68] Copyright 2019, American Chemical Society. c) Example of flexible capacitive pressure sensors. Schematic of distance and contact area changes when pressure sensor is loaded, and signal recording of robot grasping objects based on pressure sensor. d) Sensitivity curve of the flexible pressure sensor to pressure. Reproduced with permission.[59] Copyright 2020, Elsevier.

microstructures (such as waves, pyramids, and pillars) (to change ε or d) are two effective methods[59,75–77] The addition of conductive materials and the design of microstructures will lead to changes in the contact area and distance between the electrodes, so as to realize the superior performance of the sensor to external stimulation. Xiong et al.[59] developed an ultrahigh sensitive capacitance sensor composed of two polydimethylsiloxane-(PDMS) Au electrodes with surface convex microarrays and an ultra-thin PVDF dielectric layer (as shown in Figure 2b). The FCPS showed ultrahigh sensitivity (30.2 kPa^{-1}), low detection limit (<0.7 Pa), and good stability (>10 000 circles under 15 Pa pressure). Based on its superior properties, it has been implemented for monitoring breathing, pronunciation, and body movements, and controlling robot grippers. These applications for monitoring various human biological signals and controlling robots undoubtedly paved the way for HMI systems, such as intelligent healthcare and automatic speech recognition.

2.1.2. Strain Sensors

Similar to pressure sensors, non-self-powered strain sensors are generally divided into different sensing mechanism types, such as resistive-type and capacitor-type.[78–82] Strain sensors based on resistive changes are contributed to the disconnection of conductive nanomaterials, which play a dominant role among them owing to their simple fabrication process and high sensitivity.[83] Resistive-type strain sensors can be classified into membrane-based and textile-based networks according to the different construction methods.[84,85] The former type of strain sensor is realized by coupling nanomaterials with stretchable substrates. Nanomaterials comprising low-dimension metal materials (such as Ag nanoparticles and AgNWs), metal compounds (such as ZnO and MXene), carbon materials (including CNTs and graphene), and transition-metal nitrides have been extensively studied to further enhance the sensitivity and tensile properties of devices.[86] For example, Zhang et al.[38] developed a novel in situ catalytic strategy for metal aerogel hybrid materials composed of vanadium nitride (VN) nanosheets decorated with well-defined, vertically aligned CNT arrays (schematic of stretching and releasing is illustrated in **Figure 3**a). Benefiting from the main bone structure of 2D VN nanosheets, flexible devices display excellent structural compatibility and flexibility during the repeated deformation process. In addition, aerogel 3D conductive network hybrids guarantee outstanding sensitivity for external strain stimulus. Consequently, excellent sensitivity (gauge factor = 386) and good stability (over 1000 cycles) were obtained (Figure 3b). Strain sensors exhibit excellent performance in detecting human movement, speech, and medical signals, and they have been favorably applied to real-time robotic human hand control systems, thereby proving their significant potential in the field of HMI. Besides, Cheng et al.[87] fabricated an ultrathin strain sensor via a simple yet efficient way. Good sensitivity and wide sensing range ensured real-time monitoring of human body strain signals in situ, which covered from tiny skin stretch to large-scale muscle movements related to various human movements.

Fiber- or textile-based sensors exhibit features that can be easily integrated into daily garments and allow many complex human body motions.[88] Most importantly, fiber- or textile-based strain sensors can effectively avoid the generation of large or even irreversible cracks within a wider strain region in comparison to membrane-based sensors,[89–91] thereby improving their sensing range and long-term stability. In terms of material selection, using polymer composites with high elasticity and conductivity is a classic way to achieve high stretchability and sensitivity. For instance, CNT fibers,[92] carbon-coated PDMS film,[93] AgNW-mixed styrene butadiene styrene solutions,[94] and Ag-reduced fabric materials[95] have been studied extensively. Recently, researchers proved that the integration of fiber- or textile-based strain sensors with multilayers and transistor matrices enables the simultaneous detection of various stimuli (including touch, gesture, and temperature).[96,97] Pang et al.[98] proposed a fiber-based conductive sensor with a graded microcapillary structure (Figure 3c) that demonstrated remarkable stretchability (<200%) and sensitivity (Figure 3d). The device also successfully distinguished between three different types of human gestures (pressure, stretching, and bending), corresponding to unique waveforms. The researchers fabricated a fiber-type sensor for monitoring different electrical signal waveforms (mainly from pressure, tension, and bending movements) by twisting two-layered hairy conductive fibers together. Thereafter, the sensor was woven into smart gloves to serve as pressure and gesture-aware wearable controllers, thereby illustrating the potential of wearable electronics for medical healthcare functions and VR systems. Although fiber- or textile-based wearable electronic devices benefit from their lightweight, high flexibility and can be easily integrated into daily garments, these flexible electronic materials still have unsatisfactory recovery properties under large strains. To address this problem, Gao et al.[99] developed a flexible sensor based on the CNTs and polyurethane (PU) nanofiber composite helical yarn with high stretchability. Figure 3e illustrates the fabrication scheme of the strain sensor. Due to the microscopically interlaced conductive network and macroscopic spiral structure of CNTs/PU spiral filaments, CNTs/PU spiral filaments have good recoverability within 900% of the stretch. Such ultra-elastic and highly stable conductive devices show great prospects for ultra-portable wearable electronic products and multi-function devices.

However, both pressure and tension sensors have many limitations when applied to specific scenarios, which limit their large-scale commercial use. The low detection limit of many existing mature tension sensors impedes the response of subtle strain changes in the human body. The discomfort between the electronic devices and the human body as well as the unintelligibility of wearable devices must be addressed. Won et al.[36] demonstrated a novel fabrication method utilizing the Kirigami approach to pattern a highly conductive and transparent electrode. As illustrated in Figure 3f, the electrode can be designed into various shapes and has multivariable configurability for electronic skin applications. In addition, inspired by rolling friction, Ding et al.[37] proposed a porous fiber strain sensor composed of graphene decorated with nanoballs. The sensitivity of the sensor was improved by reducing the interface area and weakening the interaction (as shown in Figure 3f).

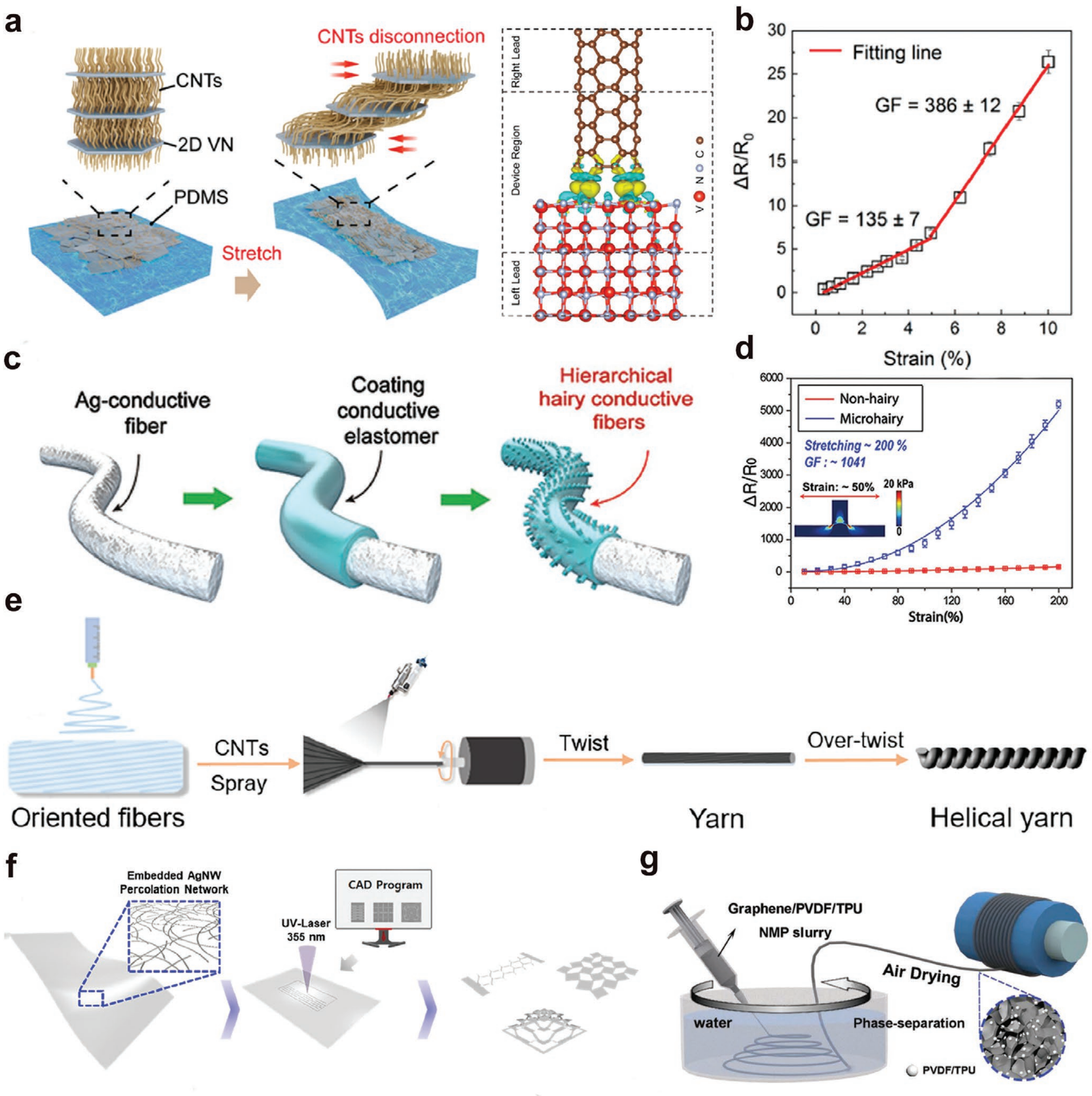

Figure 3. Schematic and sensing performance of strain sensors. a) Disconnection and reversal of the stretch release process of sandwich VN/CNT materials. Adapted with permission.[38] Copyright 2020, American Chemical Society. b) Relative resistance changes versus various strains. c) Schematic of manufacturing a layered pattern conductive fiber for strain sensors. Reproduced with permission.[98] Copyright 2019, Wiley-VCH. d) Variation of resistance relative to lateral strain applied to micro-hairy conductive fibers. e) The fabrication scheme of the helical CNTs/PU yarn for strain sensor. Reproduced with permission.[99] Copyright 2020, American Chemical Society. f) Schematic graph of digital Kirigami cutting process based on ultrathin/flexible NW/cPI nanocomposite. Reproduced with permission.[36] Copyright 2019, American Chemical Society. g) Schematic of the successive fabrication process for porous graphene fibers. Reproduced with permission.[37] Copyright 2019, Wiley-VCH.

2.2. Self-Powered Sensors

2.2.1. Triboelectric Sensors

First invented by Zhonglin Wang in 2012, TENGs are an emerging energy technology.[100–103] Triboelectric devices relying on the coupling of triboelectricity and electrostatic induction converts irregular mechanical energy into electrical energy; they are able to be used as various self-powered mechanical movement sensors, such as vibration sensors,[104] touch/pressure sensors,[105] biomechanical sensor[106] and acoustic sensors.[107] Compared with other types of sensor devices, triboelectric devices have an apparent advantage over diversified custom design and efficient self-powered sensing systems.[108] TENGs generate electricity from almost all types of mechanical movements; thus, they can sufficiently meet all requirements of a human–computer interaction design. Triboelectric devices can also be fabricated into devices with lightweight, structural adaptability, and high flexibility, which are utilized in wearable devices to meet the need for next-generation IoT.[109,101,110]

The working principle of triboelectric devices is illustrated in **Figure 4**a,[100] which was the first TENG device and its device design is still the basis of most current devices.[111] The device, composed of a polyester (PET) film and Kapton film coated with back electrodes, can generate alternating current (AC) when the contact state between the two films changes or, in other words, it undergoes cyclic pressing and- bending motions. Specifically, when PET and Kapton (the two active triboelectric materials) come into contact under extrusion or bending, a triboelectric charge is generated on the surface. After releasing the external force, the charged surface is separated and a potential difference is formed between the two rear electrodes. When they are recontacted by an external mechanical stimulus, the potential difference in the electrode changes. By repeating this cycle, a continuous AC output is obtained. According to the direction of polarization changes and electrode configuration, four different TENG operating modes have been proposed (separation (CS) mode, lateral-sliding (LS) mode, single-electrode (SE) mode, and free-standing triboelectric-layer (FT) mode), as shown in Figure 4b.[112]

The development of material sciences facilitates studies related to TENGs. Permeable conductive composite materials (such as CNTs, AgNWs/nanoparticles, or reduced graphene oxide incorporated into elastic polymers), ionic hydrogel liquid metal (LM), and knitted conductive fibers/yarns, are extensively used as good stretchable energy harvesting electrodes. It should be noted that different materials have different advantages and disadvantages; therefore, it is necessary to select appropriate materials according to specific design requirements. For example, AgNWs and CNTs suffer from a sharp increase in resistance when stretched due to their high Young's modulus. In contrast, although ionic hydrogels exhibit outstanding stretchability, their poor electrical conductivity results in low energy output performance. LM, which represents the dual properties of metals and liquids, seems to suggest a compromise, but it is largely limited by its susceptibility to oxidation and large surface tension, which influences its fluidity. To solve the aforementioned problems, Sun et al.[109] proposed a self-powered tactile interactive interface based on LM nanoparticles. TENGs consist of a Galinstan LM-nanoparticle film and a patterned PDMS, functioning as the stretchable electrode and friction layer, respectively. The device structure and triboelectric principle are shown in Figure 4c. Excellent performance, including stable transferred charge (103.59 nC), short circuit current (12.06 A), and open circuit voltage (268 V), ensures sufficient driving voltage in commercial portable electronics (Figure 4d). Satisfactory and repeatable sensitivity (2.52 $V \cdot kPa^{-1}$) enable its further utilization as a touch interactive keyboard. The intelligent display screen that simulates the trigger of an electronic keyboard shows development potential in human–computer interaction.

Unlike traditional pressure (strain) sensors, which mainly focus on command delivery but lack research on human-readable output,[113–116] triboelectric devices can be potentially implemented for various applications. If a user's interactive electronic skin can spatially map touches through electronic readout and provide a visual output as a human-readable response, the interactive experience will be significantly improved. This functionality can be achieved by using triboelectric devices. Zhang et al.[117] proposed an electronic skin with self-powered, user-interactive characters (shown in Figure 4f). The skin could convert tactile stimuli into electrical signals and instantaneous visible light at trigger pressure thresholds as low as 20 kPa without the need for spare power supply (Figure 4g). Thus, a programmable touch operating platform was built using integrating electric skin with microcontrollers. It could recognize over 156 types of interaction logic and easily control various consumer electronic products (Figure 4e).

2.2.2. Piezoelectric Sensors

Piezoelectric sensors benefit from the ability to act as a sensor as well as an actuator, which is critical for HMI applications. The sensing principle can be explained by the piezoelectric effect, which more specifically refers to the polarization of some dielectric when mechanical deformation (compression or elongation) occurs along a certain direction. The main objective of piezoelectric pressure sensors is to improve the performance by changing different piezoelectric materials, including PVDF,[118,119] lead zirconate titanate,[120,121] and ZnO.[122,123] In addition, the piezoelectret (also referred to as ferroelectret) material is an alternative choice. For instance, cellular polypropylene (PP) exhibits good flexibility, high equivalent piezoelectric coefficient, and light weight.[124,125] PVDF and cellular PP have been successfully integrated into energy harvesting systems and loudspeakers, demonstrating their capacity for sensing and energy conversion.[124,126] For human–computer interaction systems, it is important to utilize the advantages of the energy conversion of piezoelectric sensors to prepare flexible and lightweight devices for perception and response to external stimuli. Zhong et al.[127] designed a sandwich- structured piezoelectret sensor that could simultaneously realize the functions of sensors and actuators. The device consisted of two (top and bottom) fluorinated ethylene propylene (FEP) electret films with gold (Au) and aluminum (Al) electrodes attached to the surfaces, along with an Ecoflex spacer in the middle (as shown in Figure 4h). The function of the actuator could be performed by the action of the electrostatic force, which generated vibration stimulations and provides tactile feedback to the human skin. Similarly, mechanical deformations, such as human movement, and sensors were used to induce electrical output without a power supply. Their equivalent piezoelectric coefficient reached 4050 $pC\ N^{-1}$ with the ability to perform actuating or sensing functions selectively (as shown in Figure 4i). The design principle as well as the sensing and driving characteristics were further developed to meet the requirements of human–computer interaction.

3. Principle and Design Strategy of Communication and Output Devices

Three parts, that is, humans (input devices), machines (output devices), and communications constitute HMI systems,

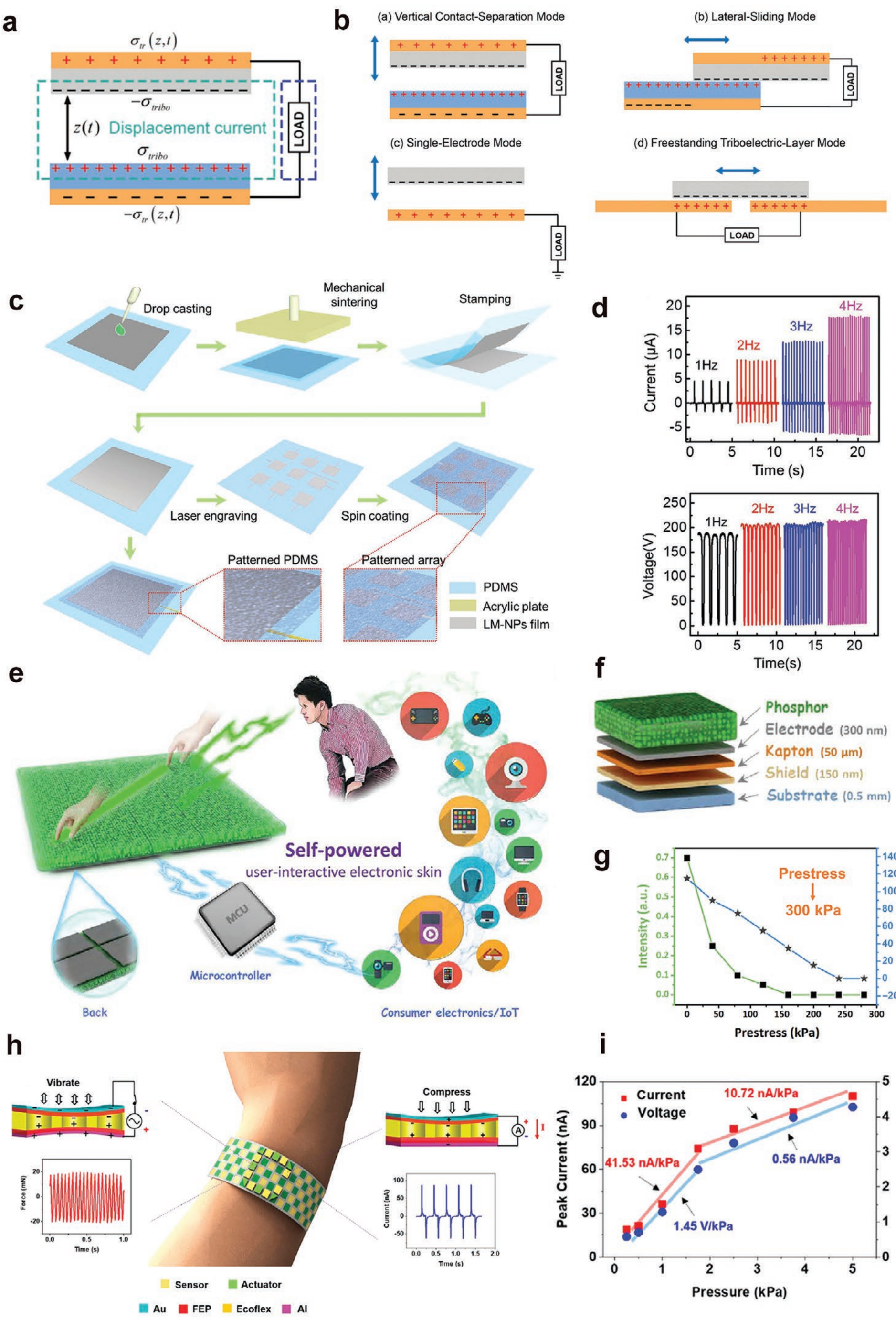

Figure 4. Schematic and example of TENGs. a) Theoretical models of TENGs. Reproduced with permission.[100] Copyright 2012, Elsevier. b) Four working modes of TENGs (vertical CS, LS, SE, and FT modes). Adapted with permission.[112] Copyright 2014, Royal Society of Chemistry. c) The fabrication process of tactile triboelectric interactive interface. d) Open-circuit voltage and short-circuit current of TENG device under different frequencies. Reproduced with permission.[109] Copyright 2020, Wiley-VCH. e) Schematic of the skin that can convert tactile stimuli into light signals (visible to the human eye) and electrical signals simultaneously controlled by the machine. f) Graph of device structure. g) Skin light intensity and output voltage under different pressure. Reproduced with permission.[117] Copyright 2020, American Association for the Advancement of Science. h) Example of flexible piezoelectric pressure sensors. Schematic describing the piezoelectret sensor structures. i) The peak short-circuit current and open-circuit voltage under different applied pressures. Reproduced with permission.[127] Copyright 2019, American Chemical Society.

achieving the processes of giving feedback to humans and instructing the machines.[44,128,129] After capturing the human-perceivable signals, the data processing and communication processes between humans and machines are crucial to give commands to electrical readouts (output devices).[130,131] For example, **Figure 5**a presents a simple robot control HMI

Figure 5. Different parts of the HMI system are connected via wireless communication. a) Schematic of the HMI system for robot control. Reproduced with permission.[132] Copyright 2020, American Association for the Advancement of Science. b) A 3D structure of a unit in wireless pressure sensor array comprising fabric spacers sandwiched between the antenna (top) and a ferrite film (bottom). Reproduced with permission.[136] Copyright 2019, Wiley-VCH. c) Schematic and photo of integrated HIMI multi-functional materials on the hand model. Reproduced with permission.[137] Copyright 2016, Wiley-VCH. d) Photograph of library management system realized through document movement and a paper calculator triggered by the touch of a finger, enabled by the wireless receiver. Reproduced with permission.[138] Copyright 2020, Elsevier. e) Schematic of a tactile interaction interface based on self-powered optical communication. f) Graphene touch switch controlling the custom minute city. Reproduced with permission.[142] Copyright 2020, Elsevier.

system based on a tactile sensor.[132] In this section, we will illustrate other components of HMI system, except for input sensors. Wireless (even self-powered) communication satisfies the requirements of flexible and convenient interactions, whose design strategies and several examples are presented in Section 3.1. As a bridge between the input and output parts, wireless communication is mainly established through Bluetooth and the radio frequency technology. New communication measures can introduce some new features, but they also require the development of new encoding/decoding and adaptation. When the external information is transmitted from the input information, the computer analyzes and processes the information and transmits it to the output part for execution (the information processing section will not be emphasized in this article). Then, we introduce different actuators/machines (so-called output devices) that execute different customer requirements in Section 3.2. As the actual undertaker of the final man–machine interaction function, the types of mechanical actuators vary according to the customer requirements. In addition, the increasing demand for soft machinery and robots requires the research and development of new materials such as memory polymers.

3.1. Communication

Wearable electronics that use wireless transmission technologies (such as the Bluetooth technology, radio frequency identification, and near field communication) provide a concise and effective bridge between the input and output devices.[133,134] The low-power communication platform helps the external stimuli, collected by the sensors, to be further analyzed and processed; then, the processed data can be passed to actuators reacting accordingly, which enables real-time HMI processes. Most communication methods are passive components based on inductors (L) and capacitors (C). They communicate via electromagnetic fields in response to changes in the external stimuli.[135] Such design architecture enjoys advantages including simplified electrical connections, no need for preparing power supply, long service life, and easy miniaturization, thus facilitating the wearable HMI process. For instance, a wireless pressure sensor array was demonstrated by Chen et al.[136] The passive antenna consisted of an inductance coil (L_s) and an interfinger capacitor (C_s) connected in series, and LC resonators (as explained in Figure 5b) were manufactured. The ferrite film assembled below had high permeability and low resistance to magnetic flux over a wide frequency range. In addition, the wireless detection of the resonant frequency depended on the near-field electromagnetic communication between the induction antenna and external receiver. The mechanical compression of flexible fabric diaphragms under external pressure resulted in inductance changes that could be further converted to a detectable resonant frequency offset. Consequently, high sensitivity (-0.19 MHz kPa^{-1}) and quality factor (over 35) were obtained. It was used in multiple systems to monitor human movement characteristics and it demonstrated strong potential in the field of human–computer interaction. Bartlett et al.[137] integrated multiple soft material layers and rigid components, and presented wearable biomonitoring multifunctional devices (Figure 5c). Wireless communication commendably strung each part of the entire system. As another example, we introduce a self-powered system based on ultrathin papers.[138] By integrating single electrode paper TENGs with signal processing circuits, the TENG (finger touch)-generated output voltage could easily operate the wireless sensor system to produce infrared (IR) signals to set off the integrated circuit system. The signal processor received the remote IR signal, which was then analyzed and recognized by the computer. Utilizing this signal processing circuit, they successfully achieved a wireless human–computer interaction system that focused on managing documents (Figure 5d).

Unlike traditional radio frequency communication, various novel communications with their own advantages have emerged. Among them, optical communication takes advantage of quickly and efficiently transmitting large amounts of data over a long distance without radiation.[139,140] However, specific optical transmission mediums and complex encoding/decoding techniques are essential for optical communications to realize efficient and secure communication processes.[141] Complicated encoding/decoding techniques might be a common problem when adopting new communication technologies. To address this problem, Huang et al.[142] reported a self-powered stable and universal tactile interactive system (TIS) triggered by triboelectronic signals. The TIS system comprises a TENG, an light-emitting diode (LED), a photoresist serving as an optical communicator, and signal processing parts. The signal collector delivered signals produced by the TENG to drive the LED and photoresistor. Irregular/imperfect triboelectric electrical signals were corrected in the process that could serve as the trigger signal for various functional terminals. As shown in Figure 5e, this system extended HMI applications to various scenarios, such as intelligent control, pattern recognition, intelligent robotics, and IoT. Figure 5f presents a demo application of a customized small city scene. The system was induced by the triboelectric signals generated by the electrostatic induction between the finger and PET to turn on/off the LED and color fan.

3.2. Actuators (Machines)

Machines are responsible for reacting to external stimuli and performing corresponding functions, which are the last link for completing HMI tasks. The definition of the last link "machine" is relatively broad, which may include a series of electronic equipment such as robotic hands, robots, and computers. Here, we use "actuators" to refer to all the machine concepts. The design strategy of the soft actuator is largely inspired by the process of human neural reflex.[143] Different actuation mechanisms have been studied for robotics and artificial intelligence.[144–147] Specifically, actuators are triggered by certain stimuli (such as mechanical movements, steam,[148,149] light,[150–152] photoheat,[153,154] electric, and magnetic[155,156]) to produce shape changes or motions. Soft and flexible actuators benefiting from their excellent biocompatibility, great deformability, and high tolerance of defects show unique advantages over traditional stiff actuators when dealing with HMI applications. For example, soft grippers were fabricated to grab fragile objects such as fresh fruits and eggs.[157–159] Similarly, different stimuli-responsive material-based soft lenses exhibited excellent performance.[160] To fulfill the versatile interactions between humans and these soft machines, specific compatibilities and adjustments (different from conventional hard robots) must be redeveloped and redesigned. For instance, the low Young's modulus of soft materials cannot perform high

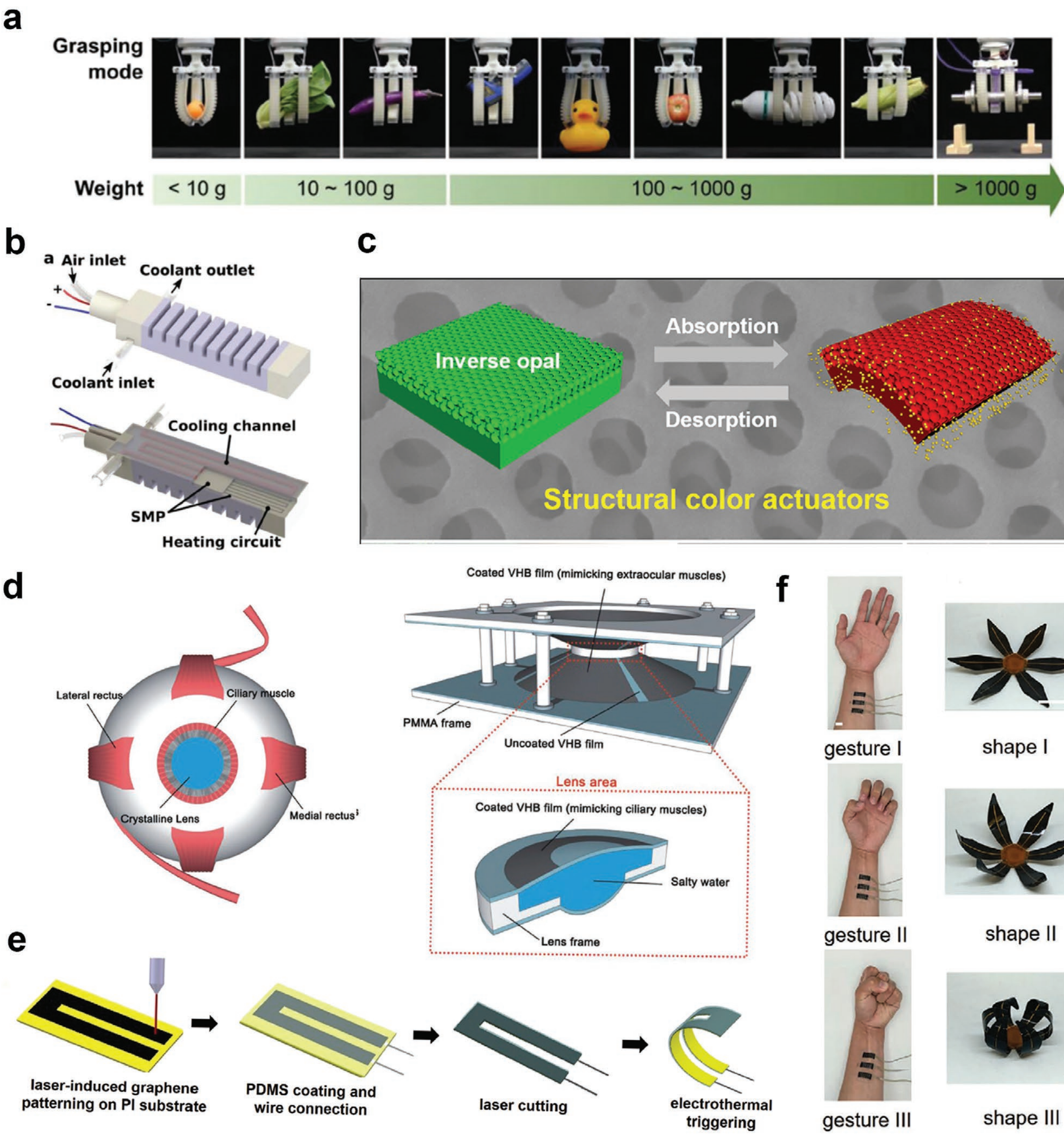

Figure 6. Design and fabrication of different actuators. a) Demonstration of a versatile gripper grabbing objects of any shape and various weights. b) FRST soft actuator fabricated by multi-material 3D printing techniques. Reproduced with permission.[180] Copyright 2019, Wiley-VCH. c) Schematic of structural-color actuators inspired by chameleons. Reproduced with permission.[143] Copyright 2019, Elsevier. d) Design and production of biomimetic soft lens imitating the structure of the human eye. Reproduced with permission.[51] Copyright 2019, Wiley-VCH. e) Fabrication process of soft electrothermal, LIG-based actuators. f) 3D assembly of flower-like structures controlled by human gestures. Reproduced with permission.[170] Copyright 2020, Wiley-VCH.

load capacity tasks. To address this problem, Ge et al.[180] presented a stiffness-tunable (FRST) soft actuator utilizing hybrid multi-material 3D printing technologies. They combined a shape memory polymer (SMP) layer and a fully printed actuator body, whose stiffness could be increased over 120 times without harming the adaptability and flexibility. **Figure 6**b shows a schematic of the FRST soft actuator composed of an embedded SMP inextensible layer and a pneumatic body. SMP materials become hard at room temperatures but soft at 70 °C, which enabled the weights to be adequately supported and become soft under different conditions (Figure 6a). Furthermore, the FRST actuators showed fast response rates for the heating and cooling processes reversibly, switching their stiffness from 10 MPa to 1 GPa in 32 s. Finally, a robot grip with three first actuators verified the high load capacity and shape adaptability of the FRST actuator.

To achieve different functions, specific flexible actuators for different application scenarios have been developed. Li et al.[51] developed a novel human–machine interface utilizing electrooculographic (EOG) signals to control the motion and focal length of the bionic soft lens. Inspired by the working principles of the eyes of humans and most mammals, the deformation and motion of the soft lens were realized by activating different regions of the dielectric elastomer (DE) film, as shown in Figure 6d. The EOG signal reflected the changes in the electric potential between the cornea and fundus of the eyes, which are closely related to eye movements. Deformation of the soft lens could easily be synchronized with eye movements. The system could be introduced in future prosthetics, remotely operated robots, and adjustable glasses. Additionally, researchers drew inspiration from nature to design the actuators. By introducing dye materials into the actuator system or using the physical interaction of light with the inherent periodic nanostructure, the actuator could not only change its shape, but also adapt to the environment by displaying specific colors (Figure 6c).[143]

As for the choice of materials, a serious of materials such as electrorheological materials,[161] elastomers filled with electrically/magnetically active liquids,[155,162] SMPs,[163] material structures of granular or laminar jamming,[164,165] and low melting point alloys,[166] are utilized to achieve high load capacity while not sacrificing their compliance. Thermally activated SMP is one of the most promising stiffness adjustable materials due to its reversible change over three orders of magnitude during the transition from soft rubber state to hard glass state. Recently, it has been reported that the 3D assembly of mechanical guidance is necessary for many emerging HMI applications (like soft robots, tunable optical devices, and responsive metamaterials) thanks to its compatibility with plane manufacturing technology and suitability for various geometric shapes and length ratios.[167–169] There are many promising actuating materials meeting the requirement of shape transformation from 2D to 3D triggered in HMI, which can be driven by optical, electrical, humidity, thermal, and multiple stimuli.[170–172] For example, Yan et al.[170] developed a soft electric actuator based on laser induced graphene (LIG) and explored their usages in mechanically oriented 3D assembly HMI. The actuator composing of a LIG, polyimide film, and PDMS trilayer worked by using the LIG as a flexible heater, introducing temperature differences through heating. Subsequently, the stress derived from significant thermal expansion differences between PI and PDMS will fold globally or bend locally in a reversible and on-demand way, resulting in successfully morphing 2D precursors into a programmed 3D architecture (as shown in Figure 6e). With the help of finite element analysis which can quantitatively control the key point of the electro-thermal transformation of 2D to 3D shapes, more than 20 complex 3D architectures with predetermined geometric shapes have been built (Figure 6f). Based on this application, they demonstrated the interaction between two types of human and LIG-based soft actuators including human gestures controlling band gap behavior and soft manipulator fingers with integrated bioelectronic sensors.

4. Applications of Wearable HMI

With the rapid development of wearable devices and the modern information technology, mankind has never stopped pursuing a more convenient and fascinating life. Soft robots and digital computers have been more closely integrated into people's daily lives. In the process of gradual adaptation between humans and machines, a rich variety of interaction methods have been derived, which provide new possibilities in the fields of education, medical care, security, and entertainment. Evidently, HMI is a new communication channel between people and electric devices; it is also an effective way to transform virtual thinking into real action. Flexible and portable wearable devices greatly increase the application scenarios and user experience of HMI, which is also the trend of future development. In this section, we divide the HMI applications of wearable devices into three aspects: identification and security, mechanical control, and AR/VR. The build strategy for intelligent applications is briefly described herein, followed by several specific examples.

4.1. Intelligent Identification and Security

The intelligent recognition technology is becoming increasingly popular and mature in the field of HMIs; it has made considerable breakthroughs in the fields of image, voice, gesture, face, and integrated biological recognition. **Figure 7**a presents a schematic graph of object recognition by touching gloves.[171] The category of recognition can be extended from object recognition to the recognition of human movement state, health state, and authentication. Evidently, the intelligent recognition technology has garnered significant attention by humans to better understand the world. Accurate identification activities depend on the real-time acquisition of external information and subsequent feedbacks, which utilize sensors,[173,174] electrical transducers,[175] communication tools, and mechanical controllers[176,177] as mentioned in the earlier chapters. In addition, the robustness and wearing comfort of the identification devices largely determine the application scenario and user experience of interactive activities. Owing to previous research on various flexible material systems, identification and surveillance are more convenient and universal in our daily lives.[178] How to manufacture highly flexibly, conveniently portable, and multifunction electrical sensing arrays on a completely transparent substrate is an urgent need for HMI identification.[179–181] To address this problem, Yuan et al.[179] introduced a flexible, transparent, and self-powered triboelectric A TSA comprising an elastic adhering PDMS layer, an electrification FEP film layer, and a transparent PET substrate was used to perform spatial mapping and trajectory monitoring (Figure 7b). The device demonstrated excellent performance, including high sensitivity (2.79 mV Pa^{-1}), fast response time (50 ms), and good operational stability (over hundreds of cycles). These basic sensing properties ensure that the sensor can easily sense multi-touch stimulations and track the trajectory of the touch motion. The proposed TSA could spatially map the pressure and record complex information about the touch behavior, which is ideal for building advanced secure access capabilities in human–computer interaction and private communications.

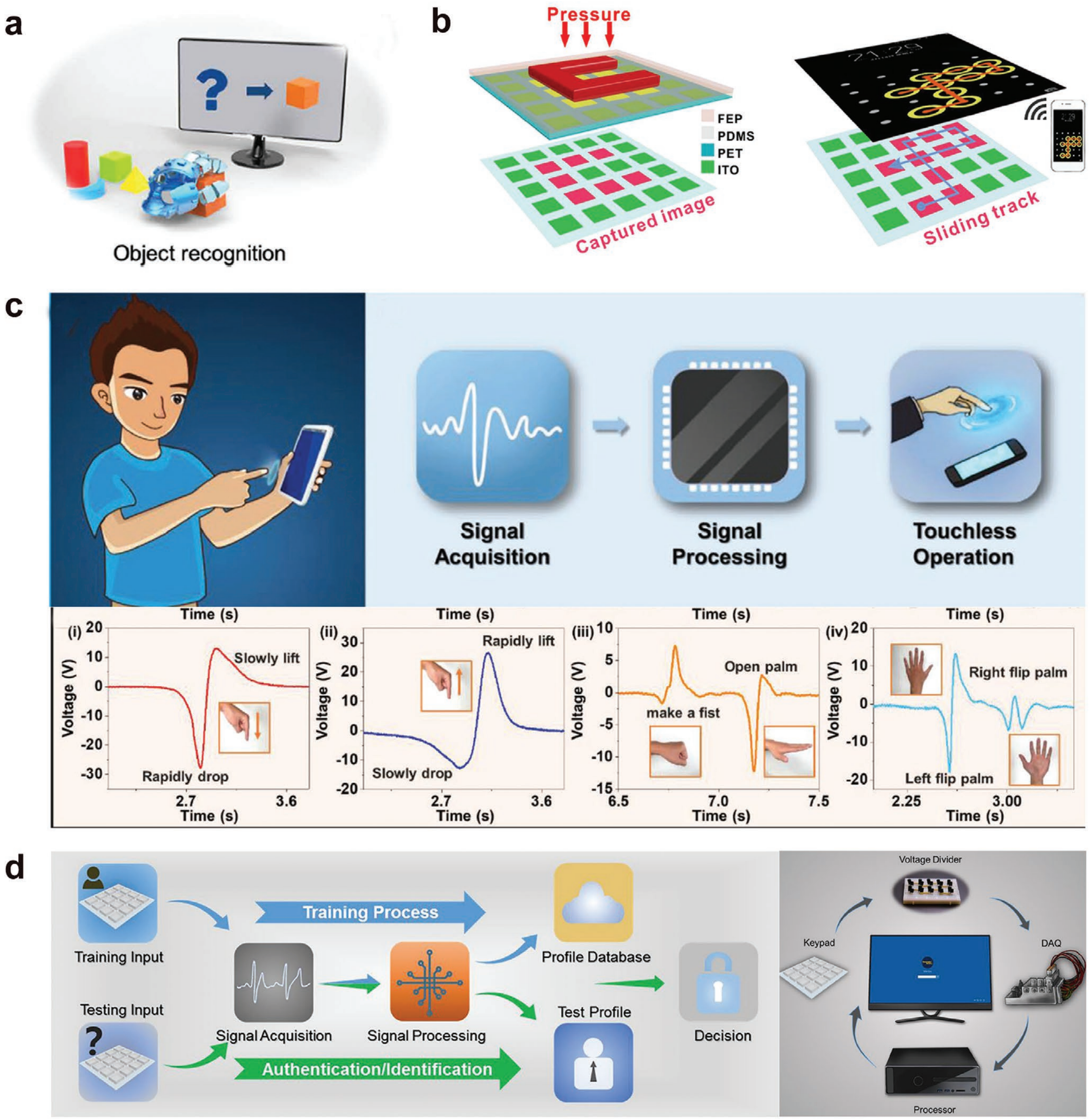

Figure 7. HMI applications of intelligent identification and security. a) Object recognition HMI function based on gloves. Reproduced with permission.[171] Copyright 2020, American Association for the Advancement of Science. b) Pressure mapping and intelligent sliding unlock based on the TSA. Reproduced with permission.[179] Copyright 2017, American Chemical Society. c) Schematic graph of the intelligent noncontact screen control system and electric signals change corresponding to different gesture movements. Reproduced with permission.[185] Copyright 2019, Wiley-VCH. d) Schematic graph and photo of the two-factor authentication and identification system. Reproduced with permission.[48] Copyright 2018, Elsevier.

Touch screens are widely used in identifying and interacting applications based on the principle of resistive or capacitive sensing,[182] infrared radiation (IR) rays, and surface acoustic waves.[100,183] Although the touch screen technology is well developed, the input of the touch screen sensor greatly relies on the contact between the finger and screen, which limits the versatility and possibility of human hand movements to a certain extent (only limited gestures such as touch and sliding can be detected).[184] To address this problem, Mao et al.[185] proposed a triboelectric touch-free screen sensor operated by triboelectric contact. They used the charges that are naturally generated by the human body. The graphene/ITO/PET three-layer structure, which can be easily integrated into wearable intelligent devices, can detect various gestures, including making a fist, opening palm, flipping palm in different directions, and dropping and lifting of fingers at different speeds (Figure 7c). Moreover, they developed an intelligent contactless screen control system that could display the process of unlocking the smartphone interface through contactless operation mode. Based on this innovative touch-free design concept, this screen sensor provided users with greater freedom of movement, which can make human–computer interaction more efficient and engaging.

With the internet penetrating every corner of our lives, network security has become a serious problem. The network/digital security of authentication in traditional HMI systems has become more critical owing to the rapid development of decoding and hacking techniques.[48] This also implies that the traditional keyboard and touch-screen based HMIs are vulnerable to password leakage; thus, there is an urgent need to develop an effective and continuous HMI certification solution.[186] Wang et al.[48] proposed two-factor authentication utilizing the triboelectric system as the identification system. The system adopted a triboelectric keystroke device to implant the progress of converting human movements (including typing force and the influence of contact areas) into electrical signals. By continuously collecting the inherent behavior of users reflected in the keystroke dynamics, a platform for user classification based on the support vector machine (SVM) algorithm and a custom signal processing scheme for feature extraction were successfully constructed (shown in Figure 7d). The two-factor authentication system can effectively eliminate the effects of external factors (such as involuntary touch) and provide higher levels of complete network verification by integrating the effects of typing power. In addition, the SVM platform provides a more reasonable training design stage and the ability to deal with nonlinear characteristics in keystrokes, which helped achieve an accuracy of up to 98.7% in identifying different users. The application of this identification system as an input device in the finance and computing industry is of great significance for user identification and information protection.

4.2. Interactive Control Applications

The wearable human–machine interface acts as a direct communication path between humans and machines, which involves obtaining physical or electrophysiological signals from consumers and further driving the machine to perform specific functions accordingly.[187–189] Voice control for executing verbal commands,[190] executing verbal commands for facial feature recognition,[191] wrist bands recording hand gestures, and electrophysiological signals (such as electrocorticogram, neuron signals, electromyogram (EMG), electroencephalogram (EEG), and electrooculogram signals[192–194]) are widely applied to HMIs. Traditional solutions of control terminals include keyboard, touchpad, and joystick, while more diverse and innovative alternatives satisfy the additional requirements of the development of technology. For example, glove-based wearable HMI devices can realize subtle emotion interactions between people and machines.[195,196] Specifically, several important motion physiology parameters are required to capture all information related to the hands and transmit it to subsequent actuators. Relying on the high sensitivity of micro-electromechanical system sensors, smart gloves can achieve motion tracking functions with high sensitivity. The aforementioned acquisition of mechanical and physiological signals of the human body is the basis for the real-time and accurate performance of machine control and specific functions. Microfluidic or pneumatic chambers,[197] vibration motors,[198] wire actuators,[199] and piezoelectric mechanical stimulators[200] are types of common actuators. The large size and power consumption of the traditional actuation system will give rise to portable and continuous use problems; thus, various soft machines have been designed and fabricated in recent years. For instance, the soft gripper was developed to grab fragile objects such as eggs,[158,159] and the soft lens has better wearing compatibility compared with the traditional lens.[201–203]

Real-time control of a robotic arm by capturing human gestures and movements is a fundamental application.[204] Gestures are perceived as an interactive technology that potentially provides a more intuitive, natural, and creative way to communicate with our machines. Huang et al.[38] presented a real-time robot control system relying on VN/CNT flexible strain sensors. They obtained metallic sandwiched-aerogel hybrids composed of VN nanosheets decorated with well-defined vertically aligned CNT arrays. The conductive 3D network sensor exhibited excellent strain sensitivity. **Figure 8**a shows the application of the VN/CNT strain sensor in finger motion interaction. The bending of the finger caused a change in the sensor resistance and converted it into an output voltage signal, which was transferred to the micro-control part. Then, the rotation of the motor and robot finger bending was controlled by the microprocessor. Instant controlling robot hand demonstration was also outperformed by imitating human gestures from "five" to "one" in Figure 8a(ii), which showed the accurate and fast interaction between a human and machine. Analogously, Chen et al.[73] proposed a self-protective and reproducible e-textile (SPRET) by synthesizing a "steel-concrete" structured nanocomposite in a hierarchical manner. The SPRET-integrated pressure sensor could detect a wide range of motor and physiological signals accurately and reliably under wet conditions (even underwater). They integrated the SPRET glove, a custom-made data acquisition (DAQ) system that records and processes the changes in the voltage signal from the sensor, and a robot hand that communicated with the DAQ system via Bluetooth (Figure 8b). The robot hand was demonstrated to be synchronously controlled by human hand gestures and further proved to be capable of more complex actions and environments.

Beyond the basic gesture control, Sim et al.[43] introduced temperature interactions between human and robot hands and demonstrated the viability of a closed-loop HMI system. The HMI system was based on a sol-gel-on-polymer processed indium ZnO semiconductor nanomembrane. Ultrathin imperceptible and stretchable wearable sensors paved the way for wearable HMI applications, and the interaction worked similarly as the robot hand control systems described earlier. The sensor resistance worn on the shoulders changed when the shoulder moved, which drove the robot to simulate

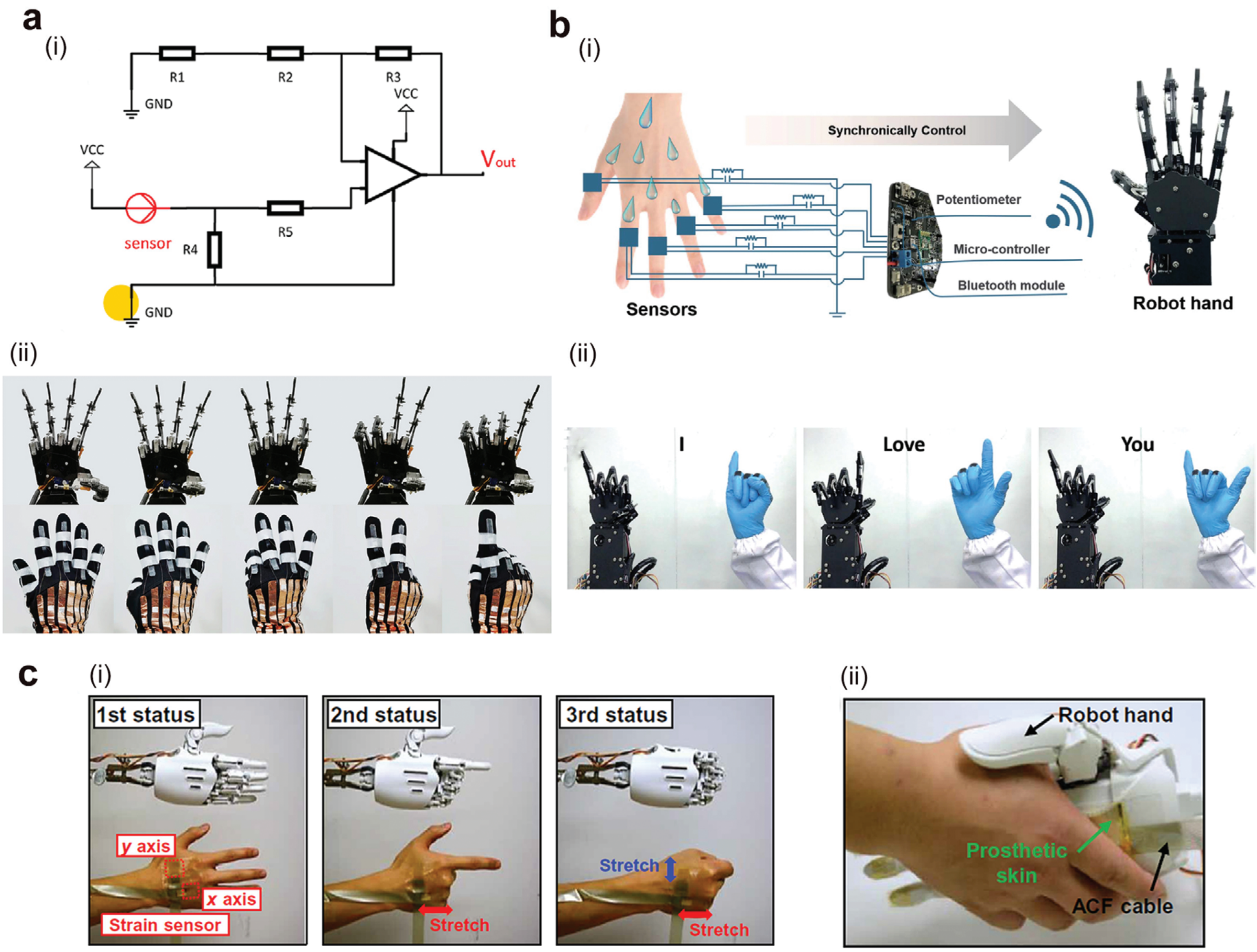

Figure 8. Real-time control of robot hands. a) i) The signal acquisition circuit of real-time controlling of robot hand. ii) Real-time control photos of robot gestures from "five" to "one." Adapted with permission.[38] Copyright 2020, American Chemical Society. b) i) Intuitive human–computer interaction diagram. ii) A sign language representation of a robotic hand controlled by human gestures. Adapted with permission.[73] Copyright 2019, Royal Society of Chemistry. c) i) Wearable closed-loop man–machine interface simulates human movement. ii) Image of HMI device integrating temperature sensor when touching the human hand. Reproduced with permission.[43] Copyright 2019, American Association for the Advancement of Science.

human motion and control the virtual character. As shown in Figure 8c, two strain sensors placed in different directions on the back of the tester's hand guaranteed the precise control of 2D motion. Simultaneously, the indium zinc oxide temperature sensor attached to the mechanical hand detected the environmental temperature or the captured object, and then applied it to the human skin through a soft micro heater. The closed-loop HMI system was realized by a combination of ultra-thin wearable sensors, prosthetic skin, and wearable temperature transfer devices.

Noninvasive bioelectrical signals, including EEG,[205,206] EMG,[207] and EOG signals, are useful for more diverse and complicated HMI applications.[193,208] Cai et al.[51] designed an interface between human eyes and a soft adjustable lens composed of electroactive polymer films. The biomimetic lens involved multiple separated DE films that were controlled by human EOG signals. Owing to the rapid reaction to DE, the movement and deformation of the soft lens can easily synchronize with the movement of the human eye. **Figure 9**a shows the performance of the soft adjustable lens controlled by the EOG signal. Moving the eye in four directions can control the flat movement of the adjustable lens in real time, while blinking can trigger the focal length change in the lens. The EOG system can be utilized in remotely operated robots, future prosthetics, and adjustable glasses.

In addition, Won et al.[36] proposed an HMI application of controlling a drone by real-time measuring the surface EMG (sEMG) on human forearms. Monitoring physiological signals in real time without skin irritation relied on the development of a new concept of stretchable and transparent electrodes comprising a flexible, ultra-thin laser-patterned Kirigami structure. Benefiting from the transparent, soft, ultrathin, and stretchable properties of Kirigami electrodes, curved and irregular skin surfaces were covered in a conformal manner, which enabled the real-time measurement of forearm motions. As shown in Figure 9b(i), specific gestures

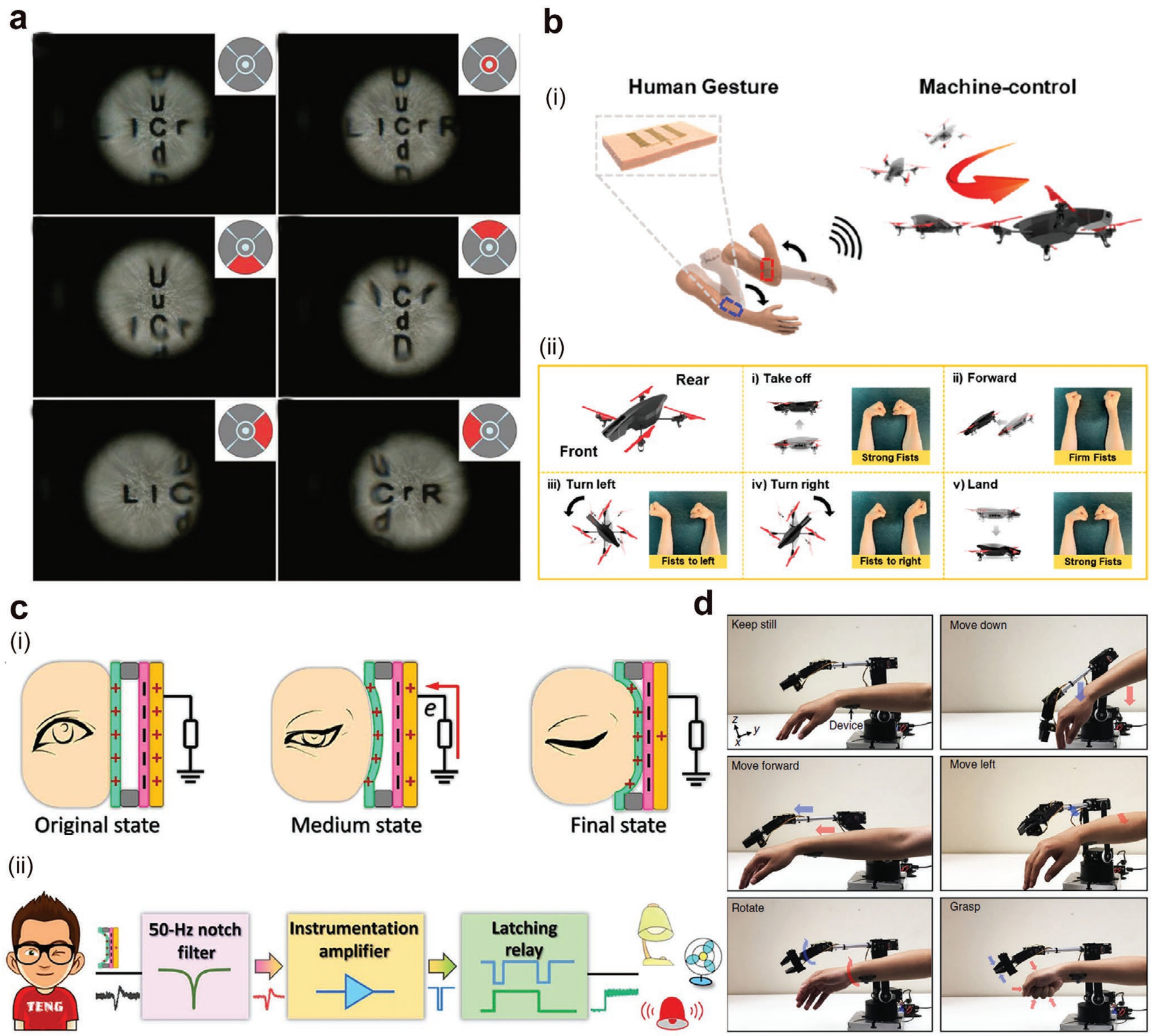

Figure 9. Applications of HMI control based on human physiological signals. a) A biomimetic soft lens controlled by EOG Signals. Reproduced with permission.[51] Copyright 2019, Wiley-VCH. b) i) Human–machine interface based on transparent Kirigami electrode to control the quadrotor UAV via sEMG signals. ii) Description of controlling UAV through different gestures. Adapted with permission.[36] Copyright 2019, American Chemical Society. c) i) Schematic of the eye movement-triggered, self-powered mechanosensational communication system. ii) Diagram of a mechanosensational smart home control system. Reproduced with permission.[212] Copyright 2017, American Association for the Advancement of Science. d) Wireless robotic arm control enabled by EMG signals. Reproduced with permission.[209] Copyright 2018, Springer Nature.

and Wi-Fi network connections were used to control the quadrotor UAV (unmanned aerial vehicle) in real time. SEMG produced by the potential difference between the flexor and carpal muscles was used to control drones. Figure 9b(ii) shows several different commands for drones corresponding to bimanual gestures. Additionally, Xu et al.[209] reported a 3D-integrated scalable system with electronic connections between layers, which achieved a higher integration level. The angular velocity (G_x and G_y), acceleration (A_x, A_y, and A_z), and EMG data were obtained to control the translational movement, rotational movement, and grasping of the robotic arm, respectively. Figure 9d demonstrates the wireless, real-time, and high-degree imitation of the robotic arm controlled by human actions.

However, bioelectrical signals commonly suffer from a low signal-to-noise ratio, leading to a lack of effective resolution when modeling. Moreover, electrodes for sensing bioelectrical signals commonly require complex preparation processes.[210,211] To compensate for this shortcoming, Wang et al.[212] demonstrated that the mechanical micro movements of the skin around the corners of eyes could serve as good signal triggers. They fabricated a novel TENG-based micromotion sensor utilizing an indium tin oxide electrode and two opposite tribomaterials, which could swiftly transfer eye motions such as winks into HMI commands (Figure 9c). In contrast to the traditional electrooculogram approach, the proposed sensor signal level was remarkably increased (from ≈1 to 750 mV), thereby effectively capturing the eye movements. Two actual HMI applications, namely hands-free typing systems and smart home control systems are presented as well. TENG-based microsensors are unique in their basic principles and provide novel design concepts for the intelligent sensor technology.

4.3. AR and VR

The AR and VR technologies integrate computers, electronic information, and the simulation technology to fulfill the purpose of a clever fusion between virtual information and the real world as well as a sense of environmental immersion simulated by a computer. Widely used commercial AR and VR systems adopt head-mounted displays, loudspeakers, and accelerometers as the basic foundation for a 3D environment generated by computers to replicate real-world human experiences, such as auditory and visual stimuli.[49] However, more comprehensive and immersive AR and VR technologies require multi-sensory functions such as touch and warmth, instead of interactive images and sounds, that can dramatically overturn the fields covering clinical medicine, social media, rehabilitation, recovery, and the entertainment industry.[213,214] Human feeling is a very complicated process, including the process of external stimuli coded to electrical signals, electrical signals transmitted to the brain via nerves, and sensory information eventually decoded by the brain; the construction of the virtual world needs to imitate and perfect this process.[215–217] Thus far, the incorporation of touch into VR and AR has been a huge challenge. While researchers have attempted to enrich the senses of the virtual world, AR and VR devices have been made into portable and highly compatible wearable devices to optimize the user experience.[95,218–220]

As a proof-of-concept, a series of studies have attempted to simulate the sense of touch with pressure or strain sensors. Zheng et al.[52] proposed a hetero-contact microstructure (HeCM) sensing mechanism, which was inspired by the cooperative sensory mechanism of mammalian tactile mechanical receptors (**Figure 10**a). The cooperative perception of HeCM enabled the device to significantly enhance its mechanosensational range, fast response, and stable reproducibility. Thus,

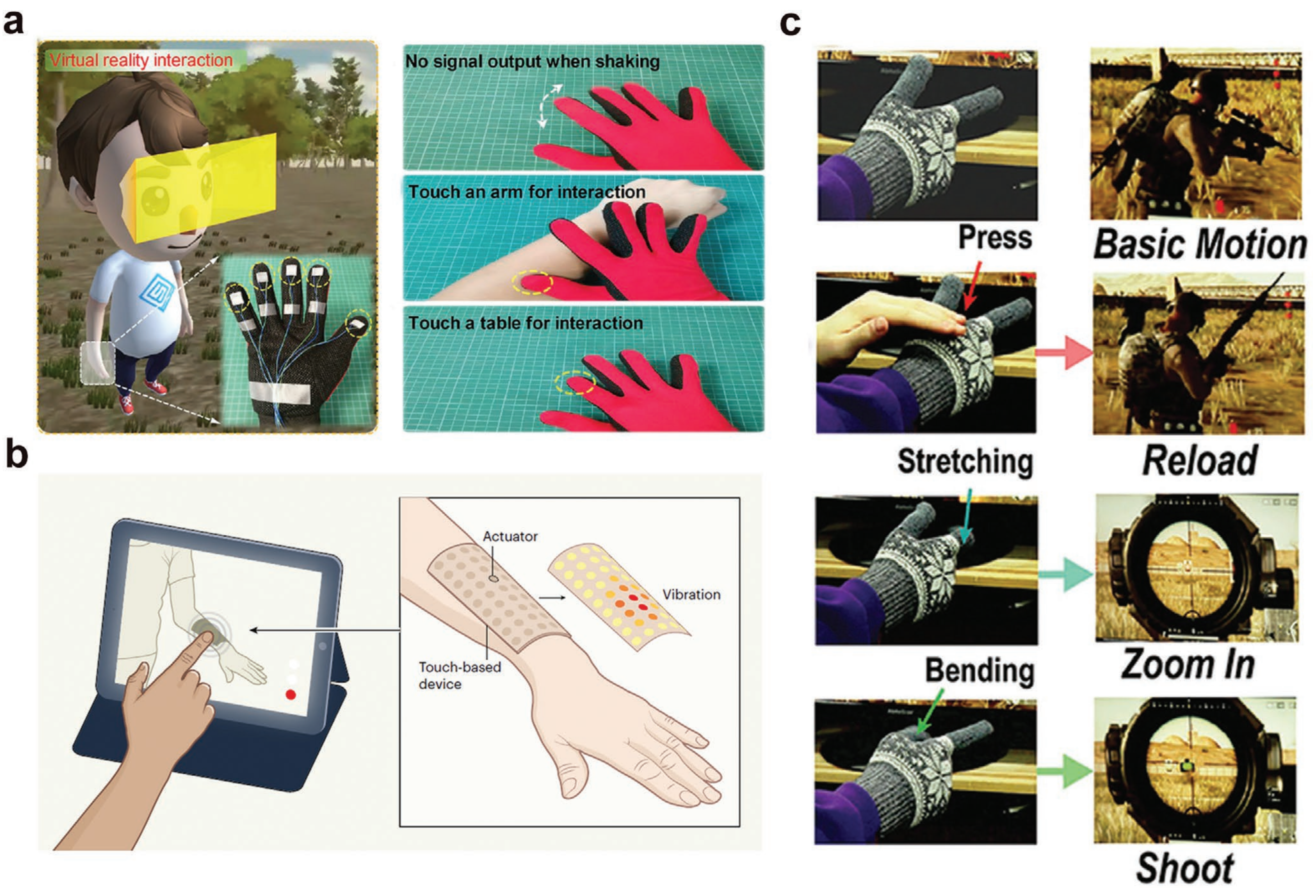

Figure 10. Applications of AR and VR. a) VR interaction configuration of the glove. The circles of yellow dotted line show the layout of tactile sensors. Virtual interactions are realized by touching the arm or table. Reproduced with permission.[52] Copyright 2019, Elsevier. b) Device for incorporating touch-based sensations in VR and AR. Reproduced with permission.[49] Copyright 2019, Springer Nature. c) Photos and virtual images of intelligent wearable gloves for external stimulation control actions within the game interface. Reproduced with permission.[98] Copyright 2019, Wiley-VCH.

the wearable 3D haptic panel with an auxiliary analog-to-digital conversion circuit utilizing HeCM sensors proved to have potential applications in the AR and VR fields. They assembled five HeCM sensors on a glove to obtain real-time force data feedback. By utilizing the multi-channel microprogram control unit to recognize and code HeCM's tactile electrical signals, the glove achieved precise virtual navigation control, controlling cursor position for wireless typing, and visual force feedback. As shown in Figure 10b,[49] it is a common way to integrate touch-based sensations into VR and AR devices. Analogously, conductive sensors based on conductive hierarchical hairy fibers exhibit remarkable stretchability, sensitivity, and distinguishability for three different human gestures (pressure, stretching, and bending).[98] Researchers created an advanced glove that could control the virtual interface by detecting hand movements and developed a shooting simulated game that responds to the movements of hands in real time through a virtual game interface. As shown in Figure 10c, testers applied pressure and bent stress onto the first joint to reload the bullet and zoom in a target while folding the index finger stretching the pressure to fire on the target. These conceptual attempts gradually improve the construction of the virtual world and enable the precise and free transformation of thought into desired control.

As an example of AR and VR system integration, Rogers et al.[49] proposed a skin-integrated, wireless-controlled, and wireless-powered haptic interface. They integrated wireless communication coils, integrated circuits, system-on-a-chip (SoC), and large arrays of vibrators into soft electronics, which were laminated into a simple, noninvasive wearable skin (as shown in **Figure 11**a). The touch-based interface was capable of communicating information through spatio-temporally programmable patterns of localized mechanical vibrations, which established methods to extend the AR/VR experience beyond human auditory and visual interaction. Figure 11b,c systematically introduce several applications of epidermal VR systems, including social media, prosthetics, and entertainment applications. Taking social media applications as an example, a little girl and her grandmother successfully performed the remote virtual touch process by wearing a skin VR device. These practical application demonstrations represent a wide range of potential applications of the system.

In addition to traditional sensors and research efforts related to touch, state-of-the-art AR and VR systems depend on ultrasonic generator arrays or the optical detection of moving body parts to manipulate virtual objects.[27] Nevertheless, these systems either encounter the inflexible and bulky problem or apply VR glasses and gloves, which have numerous constraints.[218] To overcome the aforementioned problems, Makarov et al.[221] first introduced an e-skin utilizing magnetic functionality to track human movements. The system was based on magnetic fields to provide underexplored complementary information channels. Unlike optics-based devices, there is no need to form a direct line of sight between the object and sensor. Owing to the low operating power and low wearing limitations, the system can enjoy a wide range of potential applications, ranging from motion tracking, navigation, and medical health to sports and game interactions. As shown in Figure 11d, the device monitors hand movements in non-contact situations considering the interactions of a 2D magnetic field sensor with a stray magnetic field. Two preliminary applications were demonstrated in the geomagnetic field. The authors also created a device that converts local magnetic fields into discrete values depending on the angle of hand rotations. Similarly, they adjusted the brightness of the virtual light bulb relying on the interaction with the magnetic field to control the physical properties of objects in VR. In addition, they coded the angles from 0° to 180°, replicating the typical hand movements when operating a true dial.

In addition to the applications of AR and VR systems in the entertainment, sports, and social fields, the AR/VR technique also opens new paths for diversified training programs. The programs can significantly save cost and are observably beneficial to the industrial, medical, and educational fields. Lee et al.[171] proposed a triboelectric-based haptic feedback smart glove and piezoelectric mechanical stimulator. In the virtual space, the self-generated friction electrical signal had various degrees of freedom in human hands, which successfully detected the multidirectional bending and sliding events. The virtual space provided by HMIs facilitates the realization of various specific operational learning needs. As shown in Figure 11e, the use of glove-based HMI enhanced the interactive capabilities of various VR training projects and social activities.

5. Summary and Outlook

HMI is a window to communicate between users and particular equipment, robot, or even virtual world, which is becoming increasingly influential in various fields of medical care, motion detection, entertainment industry, social media, and training programs. A variety of strategies and materials have been established and intensively investigated to achieve effective, intuitive, and seamless manipulation. In comparison to traditional rigid and heavy interactive devices, flexible and wearable human–computer interaction is an inevitable future trend that can provide better user experiences and fascinating applications such as fictitious renditions. In this article, we discussed the construction strategies of HMI systems based on wearable sensors and specific advances for HMI applications. Wearable sensors, wireless communication, data analysis, and functional actuators together constitute lightweight, user-friendly HMI systems. We emphasize the concept of flexible and wearable devices, and summarize the attempts made to improve material systems and architectural designs. Specifically, flexible sensors that can perceive the state of the human body and its surroundings are the primary component of the HMI system. Pressure sensors and strain sensors benefiting from their simple fabrication process and excellent sensitivity are the most common types, while TENG devices enable diversified custom design and efficient self-powered systems. The implementation of intrinsically flexible materials such as low-dimensional conductive materials (e.g., AgNWs and MXenes) and stretchable polymer materials, or compositing conductive and stretchable components are two effective ways to realize wearable sensors. After obtaining the external stimulus signals from humans, the processing and transmission of signals is the next step in the interactive process. Wireless communication technologies, such as radio frequency identification and near field communication, serve as a bridge between the input

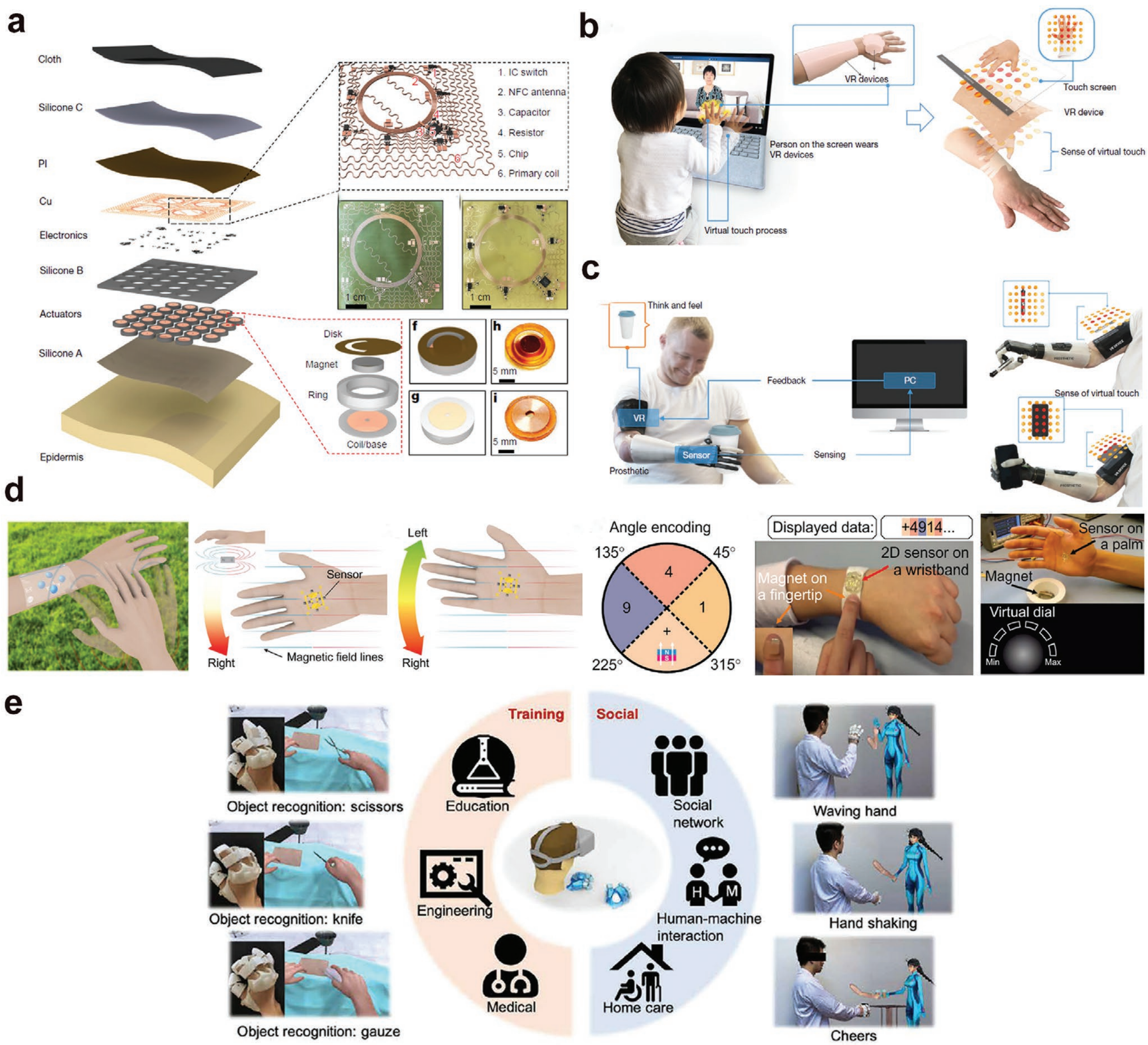

Figure 11. Entertainment, social, and training applications of AR and VR. a) Design architecture of an epidermal VR system. Epidermal VR system application examples of b) social media application and c) prosthetics application. Reproduced with permission.[49] Copyright 2019, Springer Nature. d) Touchless operation based on objects interacting with magnetic fields, enabling interaction with objects in AR/VR. Interactive control of the virtual keypad and virtual light bulb dimming in a touch-free manner Reproduced with permission.[221] Copyright 2018, American Association for the Advancement of Science. e) Universal applications on diversified scenarios, including social activities and training programs based on the glove Reproduced with permission.[171] Copyright 2020, American Association for the Advancement of Science.

and output devices; moreover, they facilitate portable interacting methods and remote controls. The exploration of new means of communication (such as optical communications) has opened up more possibilities; however, it requires the development of new communication protocols as well. With the increasing demand and technological developments for HMIs, novel functional actuators and interactive modes are required. Soft, human-friendly machines and real-time remote control of the devices are two major trends in HMIs. Based on these strategies and concepts, HMI applications can be widely developed for recognition, manipulation, and VR.

In terms of commercialization potential, portable and wearable HMI devices are promising owing to their scalable fabrication processes, broad application areas, exceptional performances, and user-friendly features. Although there is a large range of portable HMI devices that are either already available commercially or being developed in academic laboratories, with the rapid development of biomaterials, digital communication networks, and artificial intelligence, the field of disposable sensing still has much room for growth. The impending translation from research discoveries to large-scale commercial products still needs to solve the following main challenges, which will be realized through interdisciplinary collaborations.

1) Technological development of voice, face, gesture interaction, and multi-channel fusion interactions is required to provide a more natural interactive experience and satisfy the requirements of more abundant application scenarios.
2) Devices with adequate miniaturization and flexibility need to be mass produced to meet the needs of daily applications.
3) HMI devices are integrated with IoT and artificial intelligence development to provide more advanced interactive applications.
4) The matching degree of each link of human–computer interaction needs to be strengthened to realize the interconnection of smart devices and multiple scenarios.
5) New features, such as low-cost, self-healing biocompatibility, and biodegradability, guarantee improvements in convenience, user comfort, and device robustness.

Despite such challenges, the field of flexible sensors for HMI applications is becoming increasingly popular. Future efforts in the development of portable HMI devices will evidently tackle these challenges. With the vigorous development of wearable devices in recent years, we believe that these devices will have explosive growth in the near future. By then, humans and machines will begin to move toward deep collaboration, and people's lives will be extremely convenient and colorful.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

flexible/stretchable sensors, human–machine interfaces, integrated systems, wearable electronics

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Ruiyang Yin received his bachelor's degree (major in physics) from Shandong University in 2018. Currently, he is a graduate student at the Institute of Semiconductors, Chinese Academy of Sciences. His current scientific interests focus on the design and synthesis of flexible gel materials and the investigation of their wearable sensing performance.

Zheng Lou is a professor in the Institute of Semiconductors, Chinese Academy of Sciences. He received his B.S. degree (2009) and his Ph.D. degree (2014) from Jilin University. His current research focuses on flexible electronics based on low-dimensional materials, including pressure sensors, electronic-skin, transistors, and photo-detectors.

Guozhen Shen received his B.S. degree (1999) in Chemistry from Anhui Normal University and Ph.D. degree (2003) in Chemistry from the University of Science and Technology of China. He joined the Institute of Semiconductors, Chinese Academy of Sciences as a professor in 2013. His current research focuses on flexible electronics and printable electronics, including transistors, photodetectors, sensors and flexible energy storage, and conversion devices.