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REGULAR PAPER

Soft human–machine interfaces: design, sensing and stimulation

Wentao Dong[1] · Youhua Wang[2,3] · Ying Zhou[2,3] · Yunzhao Bai[2,3] · Zhaojie Ju[4] · Jiajie Guo[2] · Guoying Gu[5] · Kun Bai[2] · Gaoxiang Ouyang[6] · Shiming Chen[1] · Qin Zhang[2] · YongAn Huang[2,3]

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Abstract
Human–machine interfaces (HMIs) are widely studied to understand the human biomechanics and/or physiology and the interaction between humans and machines/robots. The conventional rigid or invasive HMIs that record/send information from/to human bodies have significant disadvantages in practice for long-term, portable, and comfortable usages. To better adapt to natural soft skins, soft HMIs have been designed to deform into arbitrary shapes, and their bendable, stretchable, compressible and twistable properties offer a huge potential in future personalized applications. This paper presents a survey on various soft HMIs in terms of design, sensing, stimulation as well as their applications. Specifically, tactile/motion/bio-potential sensors are categorized for recording various data from human bodies, while stimulators are discussed for information feedback and motion activation to human bodies. It is anticipated that soft HMIs will promote the interaction among humans, machines/robots and environment to achieve desired coexisting-cooperative-cognitive function in a robot system, named as Tri-Co Robot, for the human-centered applications, such as rehabilitation, medical monitoring and human–robot cooperation.

Keywords Human–machine interfaces · Flexible/stretchable electronics · Tactile sensors · Biological healthy monitoring · Stimulation feedback

1 Introduction

Human–machine interfaces (HMIs) refer to the studies of the two-way transmission of information between humans and machines (such as computers or robots) (Liu et al. 2017). Recording and interpreting physical and/or physiological information of humans is a key point to allow the robots interacting with humans. Conventional rigid HMIs have been widely applied in robotic systems, such as rehabilitation robots (Yu et al. 2015; Yi et al. 2017), motion gesture monitoring (Uchida et al. 2004), and biological health monitoring (Brown et al. 2014). However, they generally lead to the uncomfortablity of the human body and unstable signal in motion (He et al. 2015; Kim et al. 2013; Ju and Liu 2017) by directly laminating onto the skin surface (Wang et al. 2015; Hammock et al. 2013). Alternatively, soft HMIs based on flexible/stretchable electronics can fulfil the requirements of the next-generation HMIs that offer the sensing functions of conventional, rigid technologies but also with the ability to be stretched, compressed, twisted, bent, and deformed into arbitrary shapes (Rogers et al. 2010; Huang et al. 2017). They overcome the fundamental mis-match in

✉ Qin Zhang
qin.zhang@hust.edu.cn

✉ YongAn Huang
yahuang@hust.edu.cn

1 School of Electrical and Automation Engineering, East China Jiaotong University, Nanchang 330013, China

2 State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China

3 Flexible Electronics Research Center, Huazhong University of Science and Technology, Wuhan 430074, China

4 Intelligent Systems and Biomedical Robotics Group, School of Computing, University of Portsmouth, Portsmouth, UK

5 State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, China

6 State Key Laboratory of Cognitive Neuroscience and Learning & IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing 100875, China

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mechanical and material properties with human bodies, and thus would realize innovative applications that are impossible for rigid HMIs. It is very important to design the soft HMIs to adapt to the musculoskeletal deformations including local deformation of skin/muscle and global motion of human (Lipomi et al. 2011; Kim et al. 2011). It is beneficial to achieve the expected coexisting-cooperative-cognitive robot (Tri-Co Robot) system for the purpose of rehabilitation, medical monitoring and human–robot cooperation (Ding et al. 2017).

As illustrated in Fig. 1, the soft HMIs for humans interacting with machines/robots or monitoring human health condition can be divided into several categories: (1) soft tactile sensors in E-skin for measuring the pressure and temperature of humans and robots; (2) motion sensors for measuring the joint angles and velocities of natural/artificial limbs; (3) electro-physiology sensors, such as EEG and EMG, for trajectory controlling or health monitoring, as the green and blue arrows; and iv) feedback stimulators for applying electrical stimulations to human bodies, as the red arrows.

The soft tactile sensors are designed as superskins with higher sensitivity and time–space resolution to monitor pressure, strain, and sound information for HMI applications. Soft pressure sensors based on capacitive sensing arrays (Lipomi et al. 2011; Mannsfeld et al. 2010; Tee et al. 2012), piezoelectric materials (Uchida et al. 2004), porous pressure sensitive rubber (Lim et al. 2015), and ionic gels (Sun et al. 2015) are designed to monitor biological signals, which have been widely applied to pressure visualization and reproducing the tactile sensing abilities. Stretchable strain sensors based on piezoresistive materials (Ying et al. 2012), ZnO nanowires (Xiao et al. 2011), metal coils (Kim et al. 2012; Huang et al. 2014), and liquid metals (Jeong et al. 2016) are developed to detect human gestures. Artificial electronic eyes have been extensively applied to robot navigation to assist people for complicated tasks (Ji et al. 2008; Ji and Liu 2009; Guo et al. 2017). Sound signals acquired by piezoelectric materials (Abdeljaber et al. 2015; Rajabi et al. 2015) and EMG electrodes (Shriver et al. 2001) have also been widely adopted in speech analysis and recognition, which show novel interaction ways for playing computer games.

Motion sensing, including measuring joint angles, linear displacements, velocities and accelerations of humans and robots, is critical for the human–machine interaction to accomplish complicated and dynamic tasks (Wang et al. 2012). For example, the artificial limbs integrated with motion sensors can be precisely manipulated and controlled in a closed-loop manner (Watanabe et al. 2006). A large number of soft motion sensors have been designed for HMI applications. Soft joint angle sensors based on graphene, smart gloves, and liquid metal are designed to monitor human gesture and control the robot to reproduce the action (Flynn et al. 2014). Stretchable strain sensors based on carbon-black (Lu et al. 2012), liquid metal (Huang et al. 2014), and ionic gel (Sun et al. 2015) are developed for skin strain, human motion and gestures detection. Velocity and acceleration sensors are widely applied to measure human gestures and positions, and the corresponding algorithms are proposed for classifications for controlling the external machines via human motion state (Park et al. 2016).

Electrophysiology signals from human bodies have also been used in HMI applications, and replaced the conventional electrodes for recordings of electromyography (EMG), electroencephalogram (EEG), and electrooculography (EOG) of biological health (Domazet 2016; Han

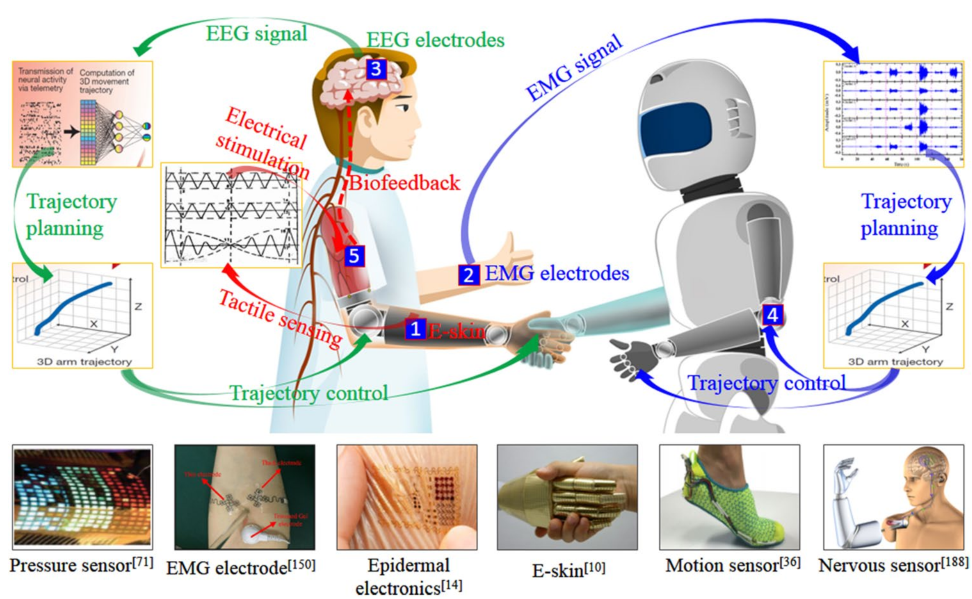

Fig. 1 Schematic diagram for humans interacting with the machines/robots, and various flexible/stretchable devices for soft HMIs

et al. 2016; Saproo et al. 2016; Löhrer et al. 2015; Mavadati 2015). In the state-of-the-art, the flexible/stretchable biopotential electrodes are designed and developed to provide long-term and stable biological signal recordings (Rogers 2013; George et al. 2014; Hu and Wang 2015). The feature extraction and pattern recognition algorithms are proposed to classify the biological signals, and the corresponding control signals are generated through the patterns for controlling the external actuators (Gao et al. 2016; Huang et al. 2016; Lee et al. 2016).

Additionally, stimulations from electronic devices to humans is another kind of important interaction modes that make humans sense external environment or establish closed-loop control between humans and machines/robots via the soft HMIs integrated with stimulators and actuators (Xu et al. 2016; He et al. 2017). Electrical stimulation evokes tactile sensations within the skin at the location of a small, cutaneous electrode by passing a local electric current through the skin to stimulate cutaneous afferent fibers (Haviv et al. 2017; Martin et al. 2017). Feedback to humans via different stimulators can be divided into electrotactile stimulation, sound and light stimulation, braille display, and EEG-EMG stimulation. Electrotactile stimulation is realized with the external voltage supplied from electronic devices (Ying et al. 2012). Sound and light stimulation are designed for biological feedback to improve humans' speech abilities (Calomeni et al. 2013). Braille display based on electroactive polymer actuators (EAP) is designed and developed for visually impaired people to touch and know the outside world more vividly (Marette et al. 2017; Martinez et al. 2012; Bishop-Moser and Kota 2017). EEG-EMG stimulation is proposed for human rehabilitation with the help of robots. Additionally, there are also researches on rendering sense of taste and smell with electronic devices, such as a taste stimulators and artificial noses (Ranasinghe and Do 2016; Löffler et al. 2015; Zou et al. 2015).

Based on different sensing and stimulation techniques, many HMIs have been developed for robots, medical diagnostics, and prosthetic devices. Human–robot interaction based on conventional rigid sensors was firstly studied in 1971 when a prosthetic hand integrated with sensors was designed as a part of body to interact with the surroundings (Nightingale and Todd 1971). At the beginning of the 1980s, a HMI system based on an electronic hand with full sensory perceptions was invented to assist surgeries (Beni et al. 1984). In 1984, Dario reported the ferroelectric polymer tactile sensors integrated in the prostheses through polyvinylidene fluoride (PVF_2) transducers (Dario et al. 1984). It could mimic the human skin to measure contact pressures and hardness. Johansson designed a sensitive skin which could sense its surroundings, and allow the robot arm to avert potential obstacles and effectively maneuver within its physical environment (Johansson 1978). In the 1990s, Jiang et al. proposed one flexible sensor sheet for tactile shear force sensing and integrated them on flexible polyimide foils (Chase et al. 1995). Tzafestas designed a new piezoresistive tactile sensor system for HMI applications, with equally critical mimicing the mechanical properties of human skin to accommodate its various motions, in addition to the ability of an artificial skin to interact with its surroundings (Tzafestas 1994). The soft HMIs increasingly attract much attention recently, including two milestone phases as shown in Fig. 2.

(1) *From 2000 to 2010* Flexible Microprocessors and microsensors were widely designed to flexible HMIs which accelerated the development of electronic skin (E-skin) significantly ranging from robotics to healthcare. Someya et al. developed flexible organic field-effect transistors (OFETs) for large-area integrated pressure-sensitive sheets with active matrix readout (Somarajan et al. 2013; Someya et al. 2004), and the stretchable active-matrix organic light emitted diodes (AMOLED) for large-area integrated pressure-sensitive sheets pressure visualization with pressure-sensitive rubber (Sekitani et al. 2009a, b). A cybernetic hand was integrated with infrared radiation sensors to control hand motions. Rogers et al. designed flexible artificial electronic eyes which provided an effective way for robots to connect and communicate with people (Ko et al. 2008). Bao et al. investigated highly sensitive capacitive pressure sensors with microstructural elastomeric dielectrics for large sensitive mechanical force sensing (Mannsfeld et al. 2010). The flexible optoelectronics including light-emitting diodes (LEDs) and organic photovoltaics (OPVs) were integrated with human skin to show the skin pressure distribution (Wu and Wang 2016).

(2) *From 2010 to the present* Stretchable HMI has been attracted more and more attentions. The motion features were detected by the soft electronics integrated with multi-strain sensors to control the external actuator (Ying et al. 2012). Javey et al. designed an interactive HMI system integrated with pressure sensitive skin, organic transistor array and LEDs (Takei et al. 2010), and the pressure distribution was provided to interact with external surroundings (Qian et al. 2016). A wearable interactive HMI based on pressure and strain sensors was applied to personal mobile electronics and the Internet of Things (Fan et al. 2014). Stretchable EMG electrodes were designed with serpentine structure to recognize different human gestures, and different control commands were generated to the external actuators (Jeong et al. 2013). The artificial skin integrated with the EMG sensor, strain sensor, and pressure sensor, used as prosthetic skin, was designed to operate complicated tasks, such as grasping the cup, and tapping

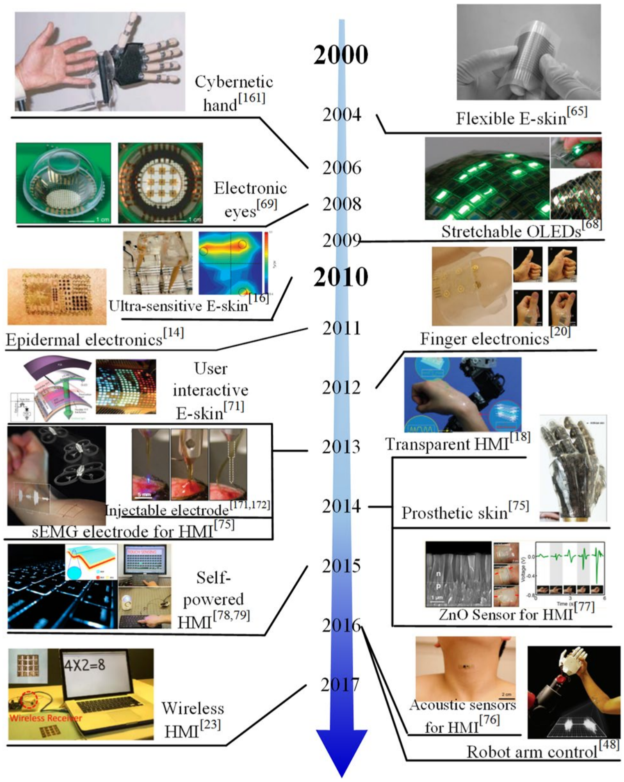

Fig. 2 Evolution of HMI based on flexible/stretchable electronics

on the keyboard (Kim et al. 2014). The acoustic sensor laminated onto the human throat collected the features signal with different speech and generated control commands to control the computer game (Liu et al. 2016). Transparent ZnO sensors were designed and fabricated to recognize the gestures of different fingers without power supply (Pradel et al. 2014). A self-powered HMI with cut-paper-based self-charging power unit was used to practical and medical applications by Wang et al. (Huang et al. 2017; Kim et al. 2014; Pang et al. 2017). Transparent HMI with porous pressure sensitive rubber sensors and strain gauges were designed to control a robot arm remotely (Lim et al. 2015), and the epidermal electronic system with the EMG sensor, strain sensor, humidity sensor, and temperature sensors was also used as an HMI to control the robot arm (Xu et al. 2016).

There were several review articles about the flexible/stretchable electronics which have been applied to soft robot, biological healthy monitoring, electronic skin (E-skin), and detection of human hand motion (Yi et al. 2017; Kim and Rogers 2008; Argall and Billard 2010; Gu et al. 2017; Lee et al. 2017; Zhao et al. 2017; Polygerinos et al. 2017; Xue et al. 2018). Lu discussed flexible and stretchable electronics for soft robot (Lu and Kim 2014). Bao et al. introduced the brief history and development of E-skin, and coexistent problems about its designs and applications (Hammock et al. 2013). Wang et al. reviewed the recent process of E-skin with multi-mode force sensing, temperature, and humidity detection, as well as self-healing abilities (Wang et al. 2015). However, most of these surveys mainly focused on the designs and developments of the stretchable devices in different applications, soft HMIs are not systemically reviewed for the design and applications for human–machine interaction. The stretchable electronics technology enables the next generation of electrodes for soft HMIs (Kim et al. 2014). This paper reviews the development of soft HMIs based on stretchable electronics, including design methods, sensing/stimulation principles, and interaction applications. Material and structural design for stretchability are introduced in Sect. 2. Three typical HMI modes and their applications are reviewed in Sect. 3. Stimulation from electronic devices to humans is introduced in Sect. 4. The whole paper is concluded with remarks in Sect. 5.

2 Structural design of flexible/stretchable components

Material selection and structural design are important to improve the stretchability of HMIs. Recent progresses on the developments of stretchable materials have enabled a number of intrinsically stretchable devices (Sundar et al. 2004; Cheng et al. 2016; Yu et al. 2016; Ding et al. 2017), such as liquid metal, hydrogels and rubber. Epidermal strain sensor based on liquid metal and PEIE-polydimethylsiloxane (S3-PDMS) elastomer substrate could be stretched to 50% and shows excellent compatibility with human skin (Jeong et al. 2016; Chen et al. 2014). PDMS microfluidic devices were also adopted in biomedical applications (Huang et al. 2014; Liu et al. 2015), where PDMS was widely used in the soft devices, due to the advantages of softness, stretchability, transparency, easy fabrication, bio-compatibility, chemical inertness, stability, and adhesive (Yabuta et al. 2003). Organic polymer with mechanical and electrical self-healing properties was applied to electronic skin in soft robotics and biomimetic prostheses (Tee et al. 2012).

On the other side, structural design is critical for stretchable electronics based on inorganic material with extreme strain of 1–2%. It has experienced three symbolic stages: stretchablity, conformability and stability. (1) Geometry design strategies is adopted to improve the stretchability without reducing the electrical performance of the electronic devices. (2) When the soft electronics is laminated onto the skin surface or soft tissue surface, conformability should be taken into consideration for more accurate bio-potential signal recordings. (3) The in-plane deformation interconnect should be more stable during the stretched process.

(1) Several approaches have been utilized to fabricate stretchable interconnect structures (Fig. 3a): patterned thin film on the prestrained substrate to generate nonplanar buckled structures (left frame) (Huang et al. 2010; Su et al. 2017), serpentine film on stretchable substrate, such as wrinkled, serpentine structures (center frame) (Gonzalez et al. 2008; Zhang et al. 2013, b), and self-similar serpentine structure (right frame) (Huang et al. 2017; Zhang et al. 2013; Li et al. 2013; Su et al. 2015; Dong et al. 2017; Huang et al. 2015). The serpentine interconnects were usually designed for large stretchability (Su et al. 2012). However, the freestanding format was a challenge for encapsulation. Soft microfluidic assembly technique is studied to address this challenge (Xu et al. 2014). The self-similar serpentine structure was enhanced version of serpentine design for hyper-stretchable devices, simutaneously with high areal coverage shown in Fig. 3f (Huang et al. 2017; Zhang et al. 2013; Li et al. 2013; Su et al. 2015; Dong et al. 2017; Huang et al. 2015; Son and Kim 2013). Structural optimized strategies were proposed to improve the stretchability of the rectangle electrode (Jeong et al. 2013; Xu et al. 2015). Topology optimization strategies were proposed to optimize the stretchability of electronic devices the with soft mechanism designs (Liu et al. 2017, b).

(2) Beyond the stretchability, the conformability is important for the design of the soft HMIs. The soft HMIs should follow the motion of the soft skin surface for more accurate bio-potential signal recordings. Figure 3b depicted that the soft devices contact with the skin surface conformally for reducing motion artifacts (Jeong et al. 2013; Dong et al. 2017). Stretchable electronics with low bending stiffness and strong adhesion were able to promote conformal contact with human skin, and the criterion was designed for determining the conformability at the skin and soft electronics interface (Cheng, H.Y., Wang, S.D.: Mechanics of interfacial delamination in epidermal electronics systems. Journal of Applied Mechanics-Transactions of the Asme. 81 2014; Wang et al. 2012). In particular, conformability is key for high-performance functioning electronics in HMI applications.

(3) The stability is another important factor for the design of soft HMIs. There were two buckling modes: out-of-surface buckling and in-surface buckling (Duan et al. 2014). The former affected the electrical performance as the stretchable interconnects would be detached from the substrate. The in-surface deformation interconnect was designed for stretchable electronics with thick bar geometries to yield scissor-like deformations modes as shown in Fig. 3c (Su et al. 2017; Su et al. 2015). It was

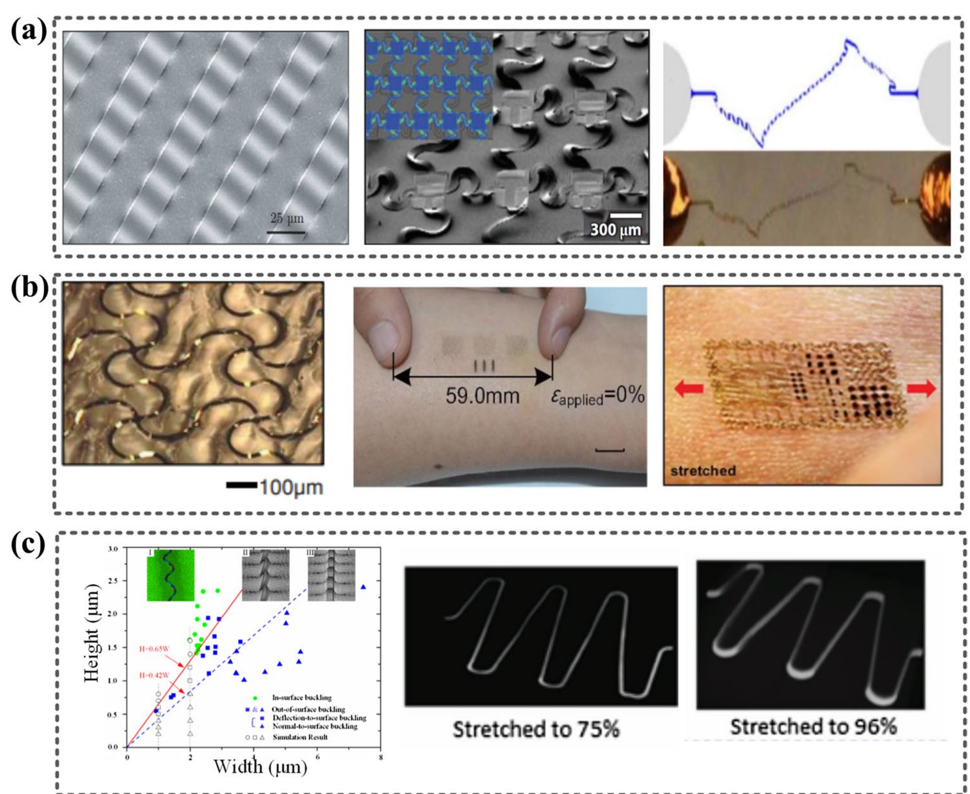

Fig. 3 **a** Stretchability design for HMIs (Gonzalez et al. 2008; Zhang et al. 2013; Song et al. 2008). **b** Conformability (Khang et al. 2009). **c** Stability design for stretchable electronics during been stretched (Duan et al. 2014)

still in surface during the stretching process with thick bar design methods.

3 Sensing from humans via HMIs

The sensing information to human bodies via the soft HMIs are divided into several categories: (1) soft tactile sensor; (2) motion sensors; and (3) electro-physiology sensors. The typical HMI modes based on these three kinds of sensors are reviewed.

3.1 Tactile sensors

Various soft tactile sensors have been designed and categorized by the functions such as pressure sensors, strain sensors and acoustic sensors. Pressure is one of the key physical parameter to evaluate the human sensing ability. Several kinds of pressure sensors have been designed for HMI applications, such as capacitive sensors (Mannsfeld et al. 2010), pressure sensitive rubber (PSR) sensors (Jung et al. 2014), piezoelectric pressure sensors, liquid metal sensors, and ionic gel sensors.

Capacitive sensors were designed to detect the force changes with variable effective area or distance between the two conductive plates via the external pressure (Lee et al. 2008). Bao et al. designed a transparent and stretchable capacitive sensor array based on carbon nanotubes on elastic substrate that was sensitive to both pressure and strain along the directions in length and thickness (Fig. 4a) (Mannsfeld et al. 2010). The sensitivity of the capacitive sensor array depends on the pyramid-structured PDMS which increases the air voids between the PDMS and the organic semiconductor layer. It also provided an effective way of pressure visualization with high sensitivity. Figure 4b depicted a flexible and highly functional capacitive pressure sensor for measuring different kinds of forces in different directions (Pang et al. 2012). It provides an effective method to measure pressure, shear and torsion.

Soft PSR sensors were another important way for the pressure sensing to HMI applications. Javey et al. developed a tactile sensing glove for capturing a variety of comprehensive hand motions, such as holding, gripping, grasping, squeezing and so on (Fig. 5a) (Takei et al. 2010; Takei et al. 2010). To realize the visual display of pressure distribution, a user-interactive E-skin based on PSR sensor was also developed for pressure visualization. The OLEDs were laminated between the active matrix transistors and the PSR layer, which could be turned on with a decrease in resistance of the rubber. Thus, it provided a promising application in the force visualization for any pressure applied to the smart glove. Wearable PSR-based pressure and strain sensors were developed on a commercial elastomeric patch for control the mobile robot motion as shown in Fig. 5b (Jung et al. 2014). The strain gauge was composed of two channels and the pressure sensor consisted of four channels for designating directions and control speeds. The commands were remotely delivered by mechanical motions through the six channels. Each signal measured by the pressure sensors or strain gauges would generate different control command for the motion of the robot (Dong et al. 2017).

Piezoelectric materials have been widely applied to monitor the pressure of the human motion for HMI applications. Figure 6a introduced the transparent and self-powered ZnO nanowire sensor for gesture recognition and HMI applications without power supply to the electronic system (Wang

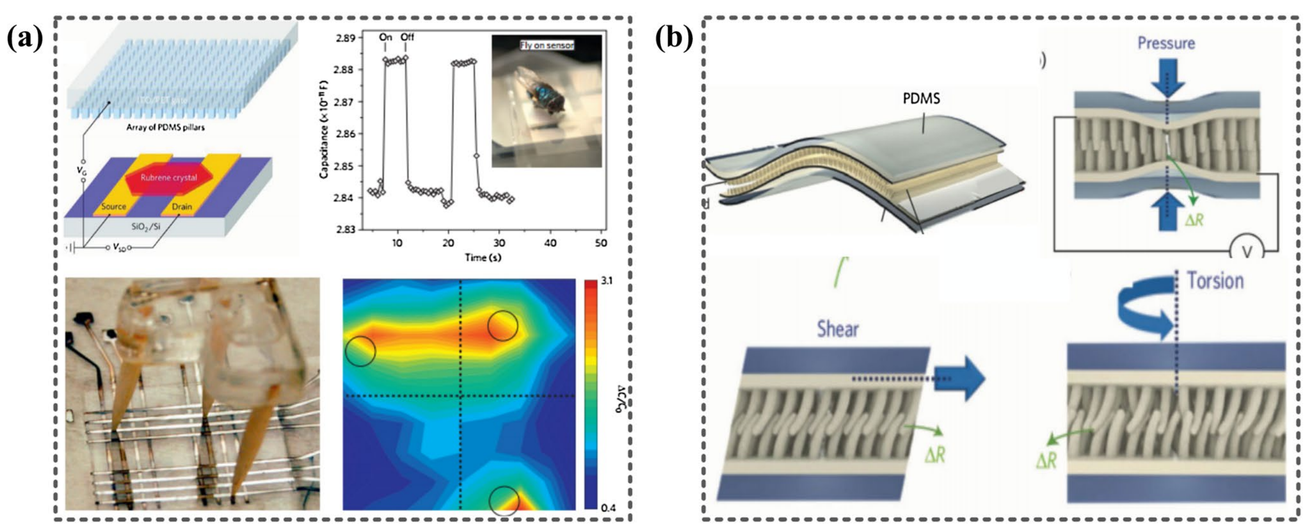

Fig. 4 Soft HMIs based on capacitive pressure sensitive sensors. **a** Ultra-sensitive pressure sensor with PDMS microstructure (Mannsfeld et al. 2010). **b** Mutli-functional capacitive pressure sensor (Pang et al. 2012)

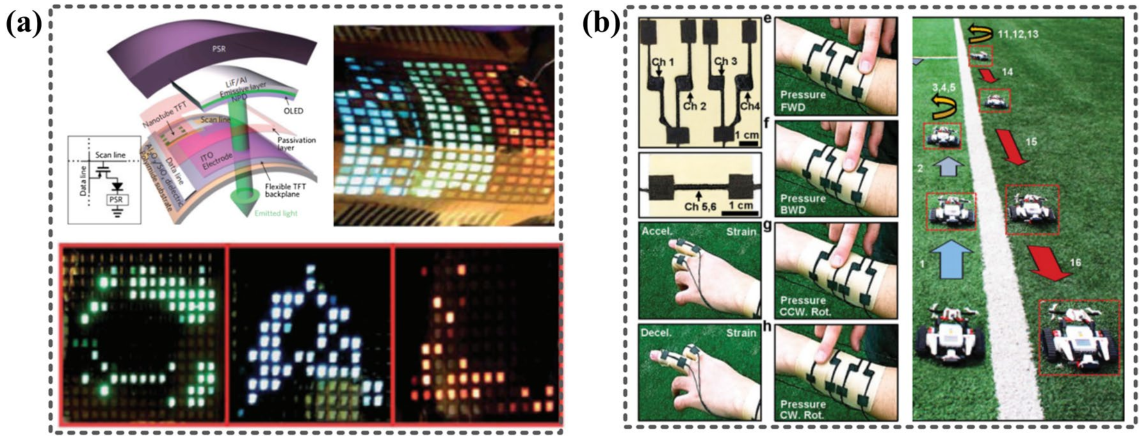

Fig. 5 Soft HMI based on wearable PSR-based pressure sensor. **a** User-interactive E-skin (Takei et al. 2010). **b** Wearable PSR-based pressure sensor (Jung et al. 2014)

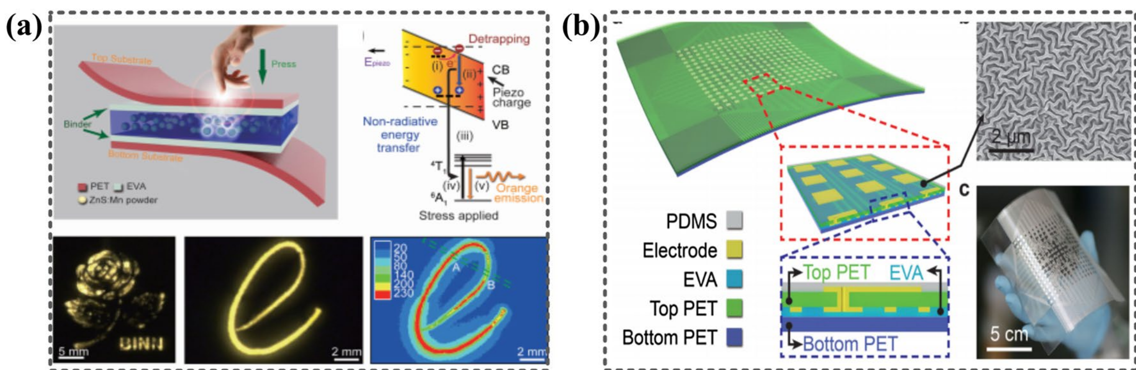

Fig. 6 Soft HMI based on wearable piezoelectric pressure sensor. **a** Transparent and self-powered ZnO nanowire sensor (Wang et al. 2015). **b** Self-powered pressure-sensitive triboelectric sensor (Wang et al. 2016)

et al. 2015). The piezoelectric ZnO sensors were designed with high sensitivity which could map the pressure distribution (Wu et al. 2013). Self-powered pressure-sensitive triboelectric sensor matrix was designed and developed for real-time tactile mapping, and it had the potential to HMI applications (Wang et al. 2016) as shown in Fig. 6b. A stretchable triboelectric–photonic smart skin was reported to enable multidimensional tactile and gesture sensing for a robotic hand (Bu et al. 2010). Piezoelectric sensors are more sensitive for dynamic motion, and can realize self-powered systems for wearable and soft HMIs.

Conductive ionic hydrogels were also used to pressure monitoring which could satisfy the soft property of the skin surface. Hydrogels were soft like tissue and very stretchable, where ions could be dissolved into water as ionic conductors (Hong et al. 2010). A flexible transparent touch panel based on conductive liquid channels was developed to detect the load which is mounted on the round surfaces (Shikida and Asano 2013). Kim et al. constructed a novel ionic touch panel with one conductor layer and four electrodes with one at each corner, as shown in Fig. 7 (Kim et al. 2016). This touch panel could measure continuous plane locations, which is different from the conventional multi-electrode arrays. Utilizing the touch panel, people could write words, play music and chess. The pressure sensory sheet based on ionic conductors ("ionic skin") with highly stretchable, transparent, and biocompatible properties was designed to measure pressure and strain information (Sun et al. 2015).

Strain sensor was designed to monitor the deformation of the human body for human–machine interaction (Dong et al. 2017; Gang et al. 2018). Strain sensors were utilized to catch multi-finger gestures, as shown in Fig. 8a (Pradel et al. 2014). Through the motion of different fingers, various control commands can be generated for external actuators. Figure 8b depicted the stretchable Si gauge was designed as a tube to detect the finger motion (Ying et al. 2012), which contacts with finger conformally. A wearable force sensor array, where the touch signal was detected by conducting

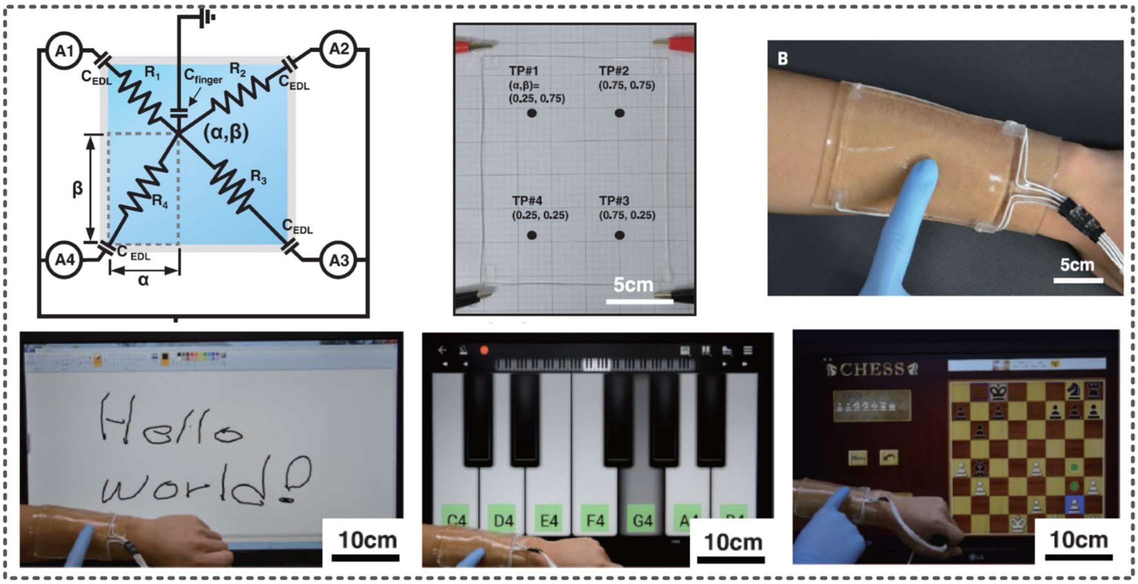

Fig. 7 Soft HMI based on transparent ionic gel pressure sensor (Kim et al. 2016)

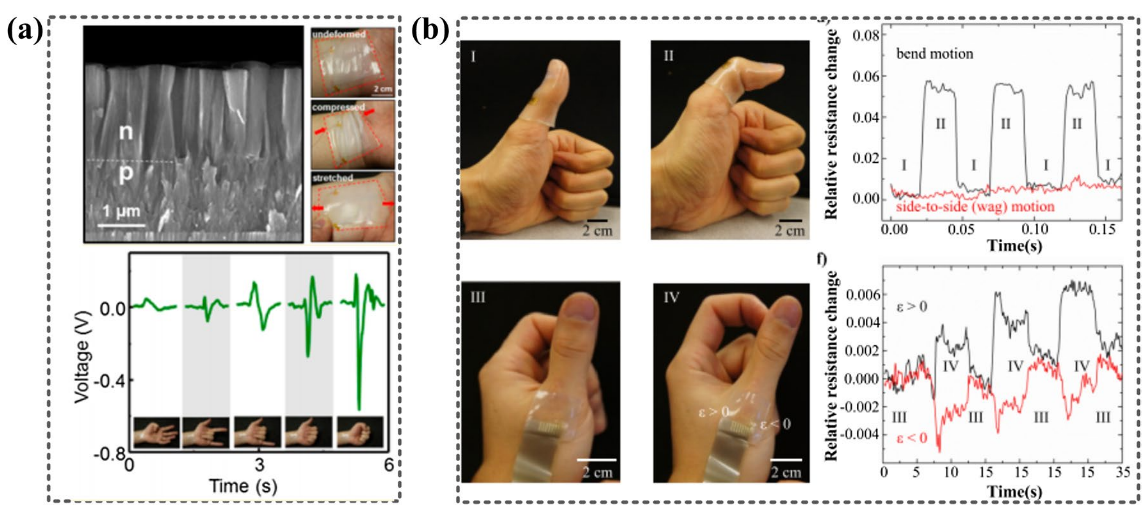

Fig. 8 Strain sensor for HMI. **a** Self-powered strain sensor (Pradel et al. 2014). **b** Strain sensor based on semiconductor silicon ribbon (Ying et al. 2012)

two transparent electrodes when the pressure was acquired by Si strain gauges. The liquid metal was encapsulated by elastomer channels for monitoring skin strain, which had excellent electrical and mechanical properties, such as the approximate conductivity with solid metal, and stretchability due to the soft elastomers and liquidity of the liquid metals.

Acoustic sensors were integrated into E-skin, to provide a function of sound recording. The epidermal mechano-acoustic devices with multiple sensors were compatible with the soft curvilinear skin, which captures and recognizes the speech via the voice-activated HMI. Figure 9 depicted an epidermal mechano-acoustic sensor which recognized the human voice and controls the motion of the robot via different voices (Liu et al. 2016). The devices could simultaneously capture acoustic vibrations from the vocal cords, such as speaking "left," "right," "up," and "down". This feature could allow the epidermal acoustic sensor to be used for communication in noisy environments. Acoustic sensors based on piezoelectric nanofibres with high sensitivity was fabricated by electrospinning for recognizing human voices (Lang et al. 2016). Acoustic sensors provide an innovative method for wearable sound recorders and voice interaction with robots/machines.

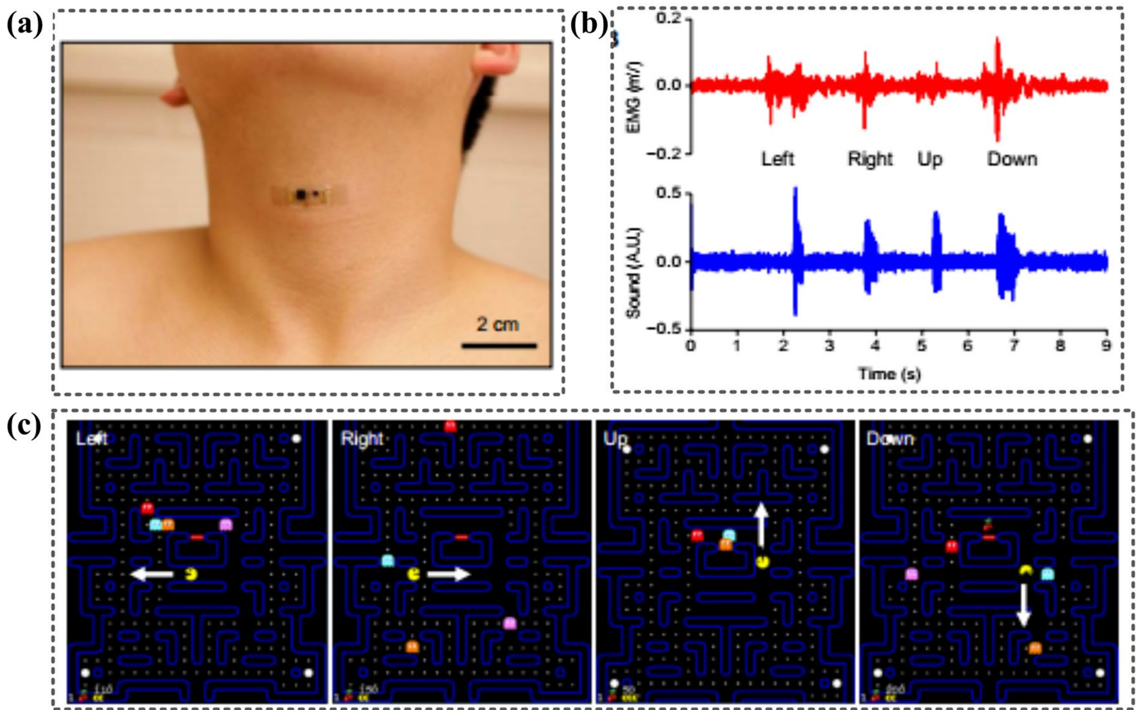

Fig. 9 Mechano-acoustic sensor for HMI application (Liu et al. 2016). **a** Epidermal mechano-acoustic sensor laminated onto the throat. **b** Classification signals from different speech via the acoustic sensor; **c** control the computer game

3.2 Motion sensors

Coordination and collaboration between humans and robots require motion sensing for complicated tasks. Soft sensors producing signals conforming to limb/joint rotations or soft-tissue deformations can be used to interpret human body motions from aspects of kinematics (angle, velocity and acceleration) (Menguc et al. 2014), kinetics (pressures and forces) (Trkov et al. 2017) and energy/power (muscle forces and deformations), which can be employed for motion intent recognition and robot control (Chen et al. 2013; Zheng et al. 2017).

A wearable sensing system based on capacitors was designed in soft cuffs to monitor the shape changes of leg muscles during walking for locomotion mode recognition (Chen et al. 2013) and gait phase estimation (Zheng et al. 2017) of transtibial amputees. The robust capacitive signals provided a promising alternative for the control of exoskeleton/orthosis. Figure 10a depicted a rehabilitation system which enables patients with muscular dystrophy to perform repetitive rehabilitative tasks and regain hand functions. Joint angle sensors were embedded into the rehabilitative system to offer better patient outcomes through therapies (Qi et al. 2014). The patients could regain hand functions with the help of the HMI therapy based on joint angle sensors. A prosthetic hand integrated with artificial skin was highly compliant, and mechanically coupled to the curvilinear surface of the prosthesis shown in Fig. 10b (Kim et al. 2014). The prosthetic hand integrated with motion joint angle sensors could monitor strain and joint angle information during the hand movements. With the help of the sensors, the prosthetic hand can perform like a human hand for grasping, fisting, and writing, which demonstrated a good example in the HMI application.

Human motion generally induced the skin deformation, and strain sensors are widely designed to detect the human skin deformation. Deformation information from different parts of the body (wrist, fingers, hands and so on) were sensed by stretchable sensors. Figure 11a depicted the interactive HMI system with the ultrathin, lightweight, and stretchable nature of devices which were developed to control the motion of the robot arm (Lim et al. 2015). The wrist deformation were measured to control the motion of the robot. The finger joint motion angles were detected by an epidermal strain sensor with the liquid metal (Fig. 11b), and several features were extracted with the different bending angles for the potential HMI application (Jeong et al. 2016). Figure 11c depicted a PDMS "smart glove" with multiple embedded microfluidic diaphragm pressure sensors monitoring human joint angles. The smart glove was capable of providing dynamic responses toward a variety of hand motions such as holding, gripping, grasping, squeezing, lifting, moving or touching objects (Chossat et al. 2015). Additionally, a sensitized garment with 52 channels of signals derived from

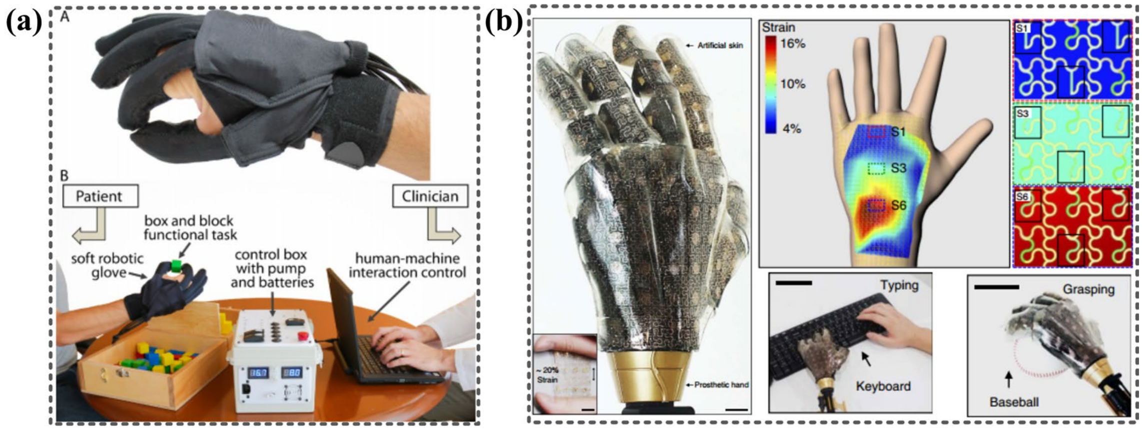

Fig. 10 Joint angle sensor for HMI application. **a** Rehabilitative system with joint angle sensors (Qi et al. 2014). **b** A prosthetic hand with multi-functional sensors (Kim et al. 2014)

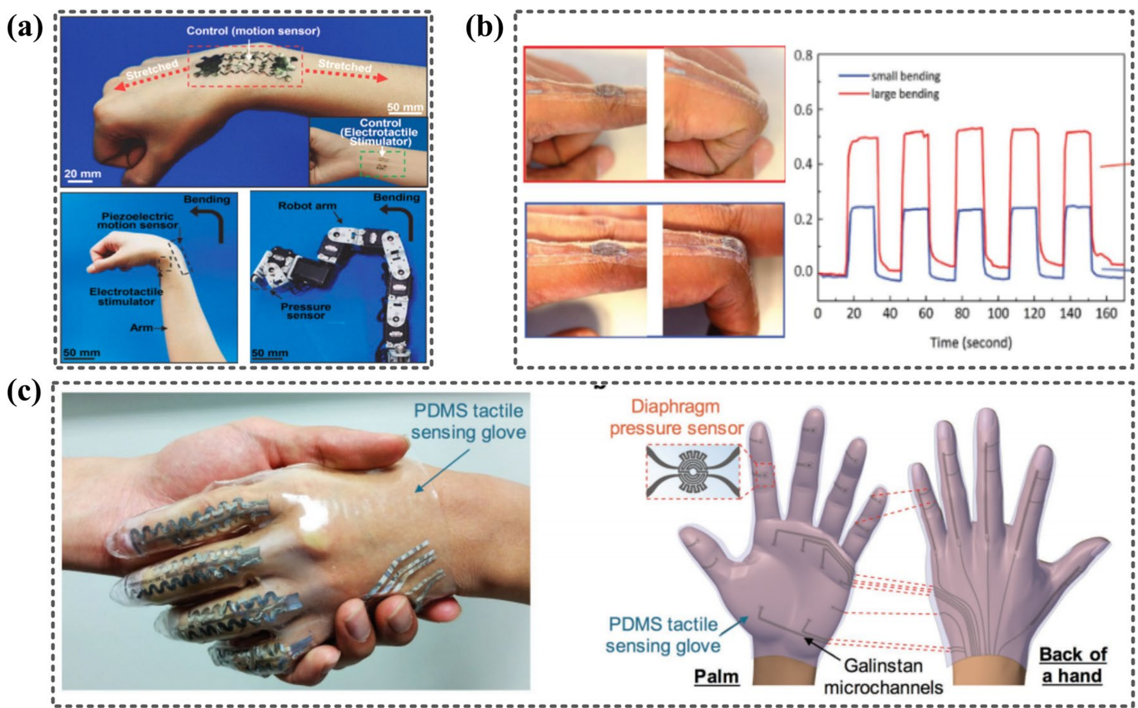

Fig. 11 Joint angle sensor for HMI application. **a** Interactive human machine interface for robot arm control (Lim et al. 2015). **b** Epidermal strain sensor with liquid metal for finger motion detection (Jeong et al. 2016). **c** A PDMS "smart glove" with embedded microfluidic pressure sensors (Jeong et al. 2015)

a user's shoulder and elbow movements was developed to control a virtual robotic wheelchair (Gulrez and Tognetti 2014).

Wearable, skin-mountable, and printed strain sensors can be used to detect the body deformation signals at different parts of body in a precise manner. Figure 12a depicted the sensors attached to the wrist and elbow to record human deformation signals during the sporting process. Muscle activities were detected by recording muscle bulging in the forearm using a flexible tactile sensor, through which Gaussian process regression was carried out to predict wrist, hand and single-finger activation for controlling prosthesis and assistive robots (Jaquier et al. 2017). Figure 12b depicted that thin carbon-black-doped PDMS was designed as the strain gauges featured with its high resistivity and strong dependence on strains, which

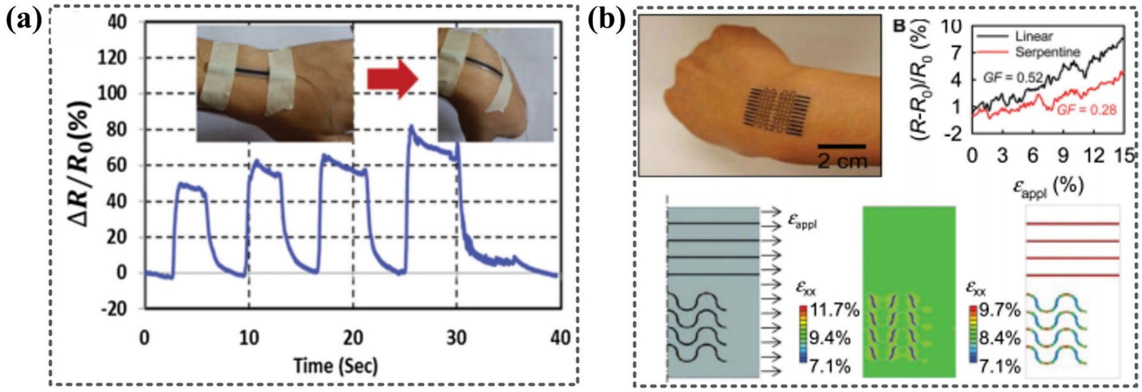

Fig. 12 Soft strain sensor for HMI application. **a** Wearable strain sensors (Jaquier et al. 2017). **b** CB-PDMS based strain gauge (Lu et al. 2012)

was used for human gesture detection (Lu et al. 2012). Microfluidic stretchable strain sensor based on printed liquid alloys was designed to monitor human gestures which provides large deformation ability (Jeong et al. 2014). This kind of strain sensors could stick on skin to measure deformation without mechanism.

The velocity and acceleration sensors are designed to sense the kinetics of human bodies. Figure 13a depicted a smart shoe integrated with velocity sensor for detecting human motions. Different characteristic signals were classified with different human motion modes, and different human gestures are generated to interact with surroundings (Park et al. 2016). A printed flexible multiplexed physical sensor was mounted onto the skin surface for human motion signal recordings as shown in Fig. 13b. The flexible sheets integrated with chemical sweat pH sensor and ion sensitive field-effect transistor were demonstrated in real-time human motion monitoring. A skin-inspired highly stretchable and

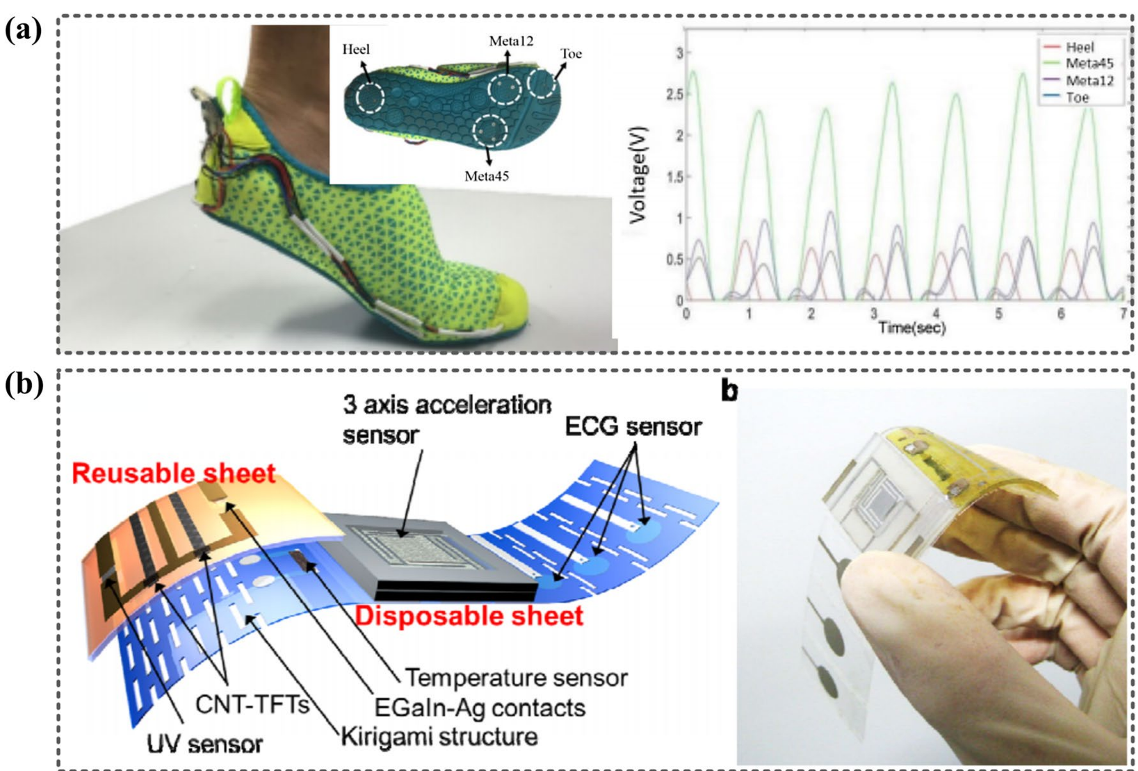

Fig. 13 Motion sensor for HMI application. **a** A smart shoe integrated with velocity sensor (Park et al. 2016). **b** Printed flexible three-axis acceleration sensor (Hua et al. 2018)

conformable matrix network (SCMN) was developed multi-sensing functions including but not limited to temperature, in-plane strain, humidity, light, magnetic field, pressure, and proximity. It was incorporated on a personalized intelligent prosthesis to demonstrate its capability in real-time spatial pressure mapping and temperature estimation (Hua et al. 2018). A sensing system was developed for real-time monitoring the fastening-strap pressure between human bodies and exoskeletons to reduce risks of skin ulcers, necrotic tissue (Tamezduque et al. 2015).

3.3 Electrophysiology sensors

EMG signal reflects the activation of muscle fibers innervated by motor neurons. It can be noninvasively acquired by the surface electromyography (sEMG) electrodes (Jeong et al. 2013; Wentao et al. 2018; Han et al. 2016; Yokus and Jur 2016). Signals obtained during bimanual gestures such as ‘squeeze fists’, ‘bend wrists to the left’, ‘bend wrists to the right’, and ‘bend wrists outward’ generated four characteristic sEMG patterns, as shown in Fig. 14a. Linear discriminant analysis (LDA) method was used to classify the features into discrete gestures (Zhang and Jia 2007), and it demonstrated that the motion of the four-rotor aircraft is controlled by the EMG sensor. Figure 14b depicted a stretchable sEMG patch which could realize the robot hand mimicking human gestures for robot manipulation via eight gestures of a human hand (Zhou et al. 2018). The sEMG signals were captured from different hand gestures as shown in Fig. 16b. The collected signals from the eight gestures were used for training and classification for robot manipulation.

The EOG sensor mounted on a region of the forehead that was prepared by exfoliating the stratum corneum with tape yielding reproducible and high-quality results, as demonstrated in alpha rhythms recorded from awake subjects with their eyes closed (Kim et al. 2011; Jin et al. 2015; Sigari et al. 2014). The expected feature at 0–10 Hz could be seen in the Fourier-transformed data as shown in Fig. 15a (Mishra et al. 2017). The signal-to-noise ratios were comparable with those of conventional, rigid bulk electrodes with conductive coupling gels. Figure 15b depicted the EOG systems with three modules: the sensor for EOG acquisition, the acquisition instrument, and the host computer control system (Guo et al. 2016). The signals were recorded by a commercial amplifier system, including data processing and a graphic user interface. EOG signals of eye movements (blink, upward, and downward) were recorded for obtaining high classification performance by the Fourier transform method. The bioelectronics system with a high-quality recording of EOG signals shows a great potential application in long-term, wearable, and clinically applicable HMIs.

The brain-computer interface (BCI) technology is a radically new communication option for those with neuromuscular impairments that prevent them from using conventional augmentative communication methods (Rothschild 2010). Current BCIs use electroencephalographic (EEG) recorded at the scalp single-unit activity from cortex to control cursor movement, select letters or icons, or operate a neuroprosthesis (Wolpaw et al. 2000). An EEG sensor mounted on the head was designed to record EEG signals for controlling computer games shown in Fig. 16a (Kim et al. 2011). Fast fourier transform (FFT) method was adopted to extract features of these words (Güneysu et al. 2013). As an example, dynamic time-warping pattern recognition algorithms applied to throat-based EMG data enable the control of a computer strategy game (Sokoban). The EEG sensor had the capabilities as a HMI to control the computer game (Norton et al. 2015). The results from a BCI for a text speller were shown in

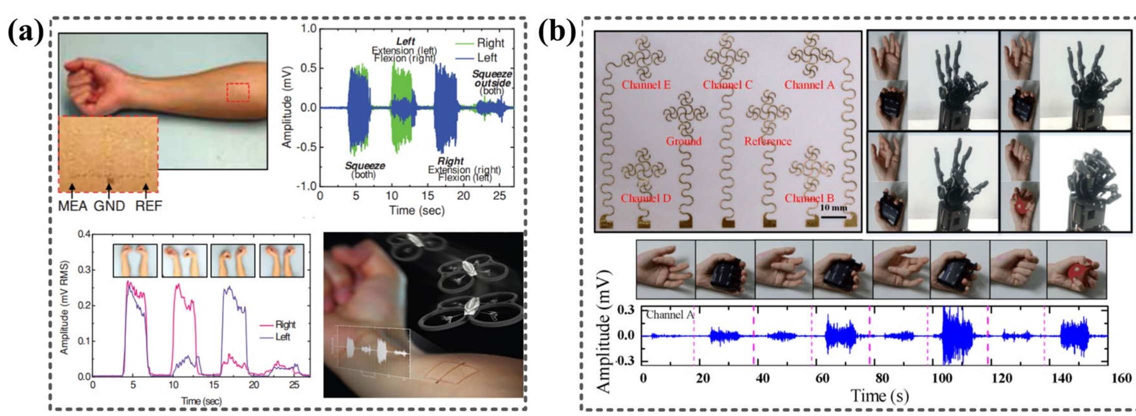

Fig. 14 Stretchable EMG electrode for HMI to control the robot motion. **a** Motion control of the four-rotor aircraft via the electrode placed on the forehand for extracting feature signal from different gestures (Zhang and Jia 2007). **b** Stretchable multichannel sEMG patches for robot manipulation via eight gestures of the hand

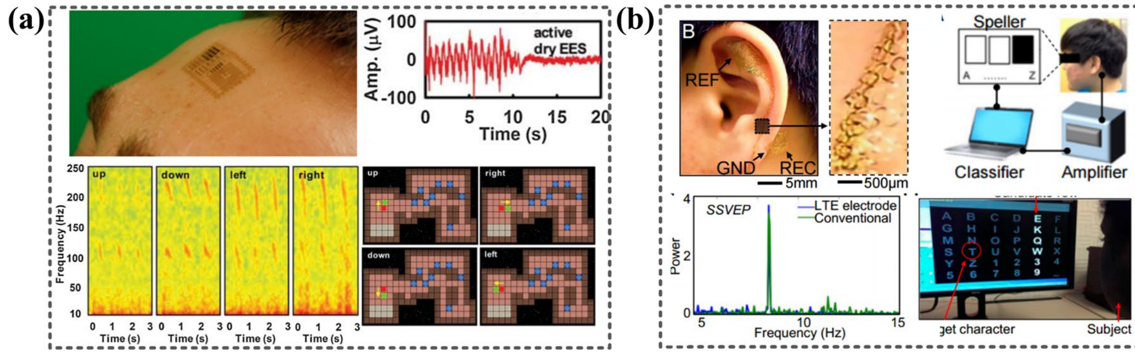

Fig. 15 Stretchable EOG sensor for **a** Eye motion detection (Mishra et al. 2017). **b** EOG signal recordings and feature extraction with different eye motion (Guo et al. 2016)

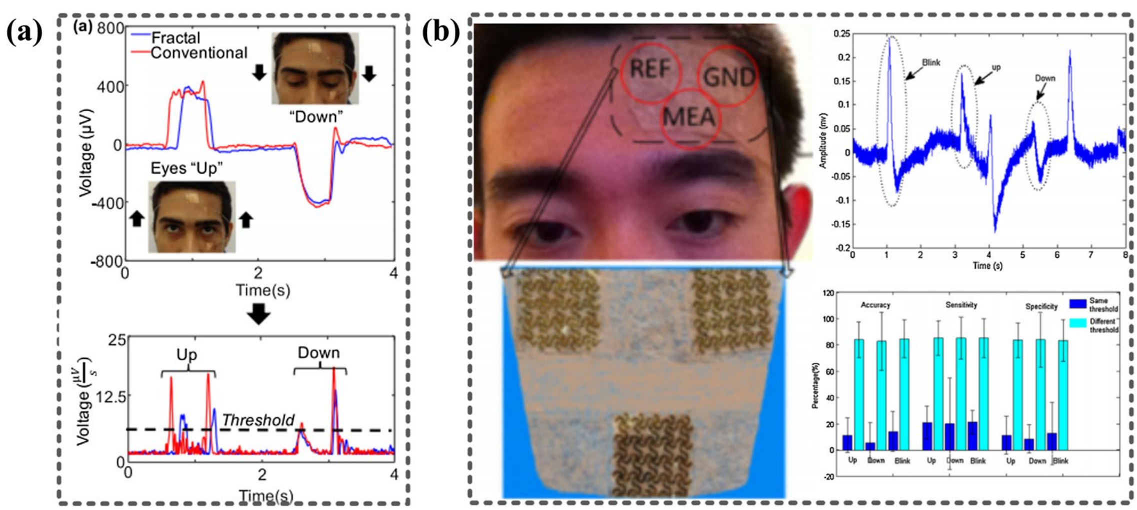

Fig. 16 EEG signal via epidermal electronics for BCI application. **a** Stretchable epidermal electronics to control the computer game (Kim et al. 2011). **b** Interact with computer for character recognition (Norton et al. 2015)

Fig. 16b. The results exhibited similar patterns and amplitudes, where event-related potentials provided an additional example.

4 Feedback to humans

Stimulations based on soft tactile sensation from the physiology of the human skin to tactile sensing techniques have been studied in recent years. Several categories of stimulation to human bodies are designed, including electrotactile stimulation, sound and light stimulation, braille sheet display, and EEG-EMG biofeedback.

4.1 Electrotactile stimulation

Electrotactile stimulation evokes tactile sensations within the skin at the location of a small cutaneous electrode by passing a local electric current, through the skin to stimulate cutaneous afferent fibers. An electrocutaneous display system composed of three layers was implemented for the augmentation of skin sensation, where visual images captured by the sensor were translated into tactile information and displayed through electrotactile stimulation (Kajimoto et al. 2003). Integrating distributed sensing (E-skin) and stimulation (matrix electrodes), an electrotactile feedback system was proposed in Ref. (Franceschi et al. 2016) that helped user subjected to recognize dynamic movement patterns. It embodies closed-loop artificial devices into the user body scheme.

The human tongues could be employed as an illustrative example of HMI applications. The Tongue Display Unit (TDU, Brain Port similar to USB port) was developed for stimulating the tongue surface (Kercel and Bach-Y-Rita 2006). TDU was connected to a flexible-printed-circuit for the stimulation of the dorsal surface of a tongue as shown in Fig. 17a (Kaczmarek 1476). The electrical stimulus to each electrode was individually controllable in real time. The block diagram of TDU comprised five 8-bit microcontrollers, electrode driver output, power and communications circuits. A type of electrotactile stimulation was designed with multiplexed using silicon nanomembrane (Si NM) diodes (Fig. 17b (Ying et al. 2012). The multiplexed electrotactile array was outside the freestanding finger-tube and the required voltage for sensation decreases as frequency increases, consistent with equivalent circuit models of skin impedance that involve resistors and capacitors connected in parallel. This technology could be used in applications ranging from HMIs to 'instrumented' surgical gloves (Kim et al. 2012).

4.2 Sound and light stimulation

Sound and light stimulation to the human body is helpful to people's therapy. The visual stimulation occurs through strobe lights, while auditory stimulation is made by binaural beats. The brain stimulation by light and sound between the biofeedback techniques was pushed forward by Calomeni et al. (Calomeni et al. 2013). Vieira defined the biofeedback as an immediate return of information through sensitive electronic equipment capable of capturing sensory responses, amplifying and transforming physiological signals (Vieira et al. 2007). The synthesis of brain waves fitted the definition well because the technology was able to stimulate the brain externally. Photo stimulation that highly corroborated with the possibility of brain waves could be induced through externally stimulated frequencies. The frequencies changed the state of consciousness depending on external factors such as time of stimulation, culture, and expectations of the individual (Budzynski 2009).

Júnior et al. observed the effect of photic and auditory stimulation in the variable reaction time and skilled motor-cognitive efficiency of 20 football players (Da et al. 2015). Zhang designed a kind of stimulation device aiming at alleviating brain fag (Zhang et al. 2012). Meanwhile, the specific stereo signal which is expected to induce alpha-wave of human brains was programmed and encoded into audio files, as shown in Fig. 18a. Barnett-Cowan et al. measured the perceived timing of galvanic vestibular stimulation (GVS) relative to tactile, visual and auditory stimuli (Barnett-Cowan et al. 2011). In Fig. 18b, participants sit inside a plastic hemisphere receiving a diffused flash of light and

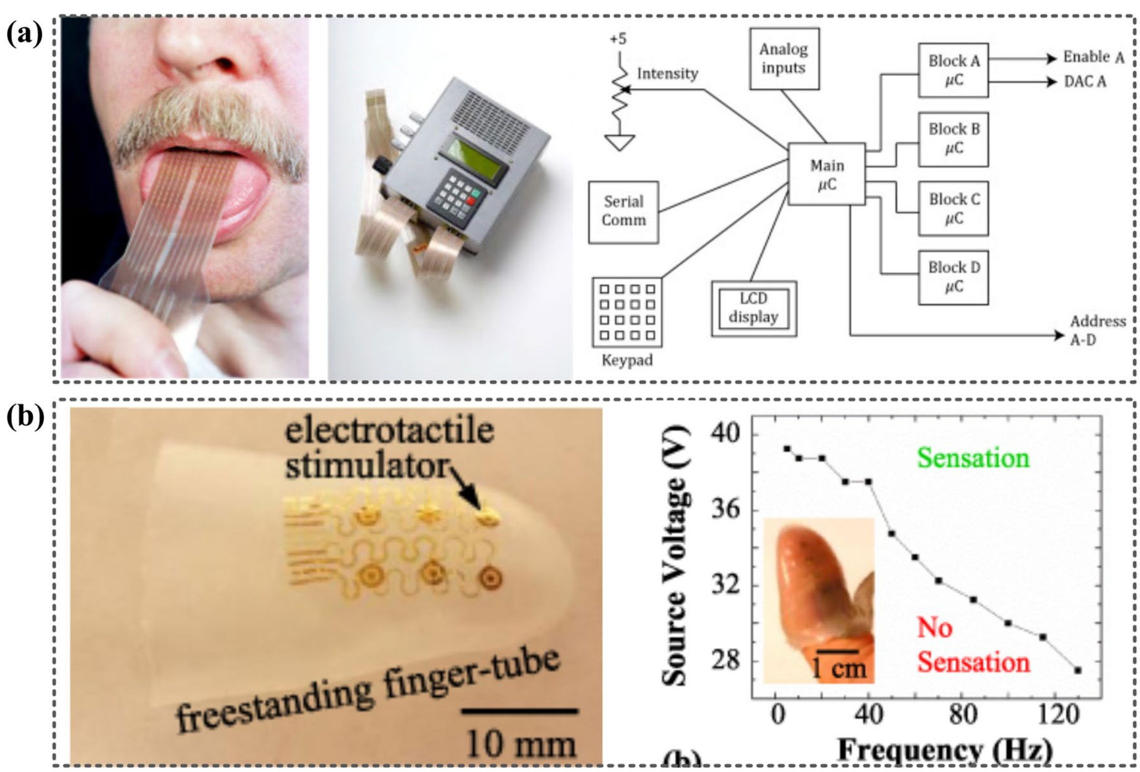

Fig. 17 Electrical stimulation on tongue and fingertip for HMI. **a** Electrical stimulation to the surface of a tongue (Kaczmarek et al. 2011). **b** Electrotactile stimulation with electrode arrays (Ying et al. 2012)

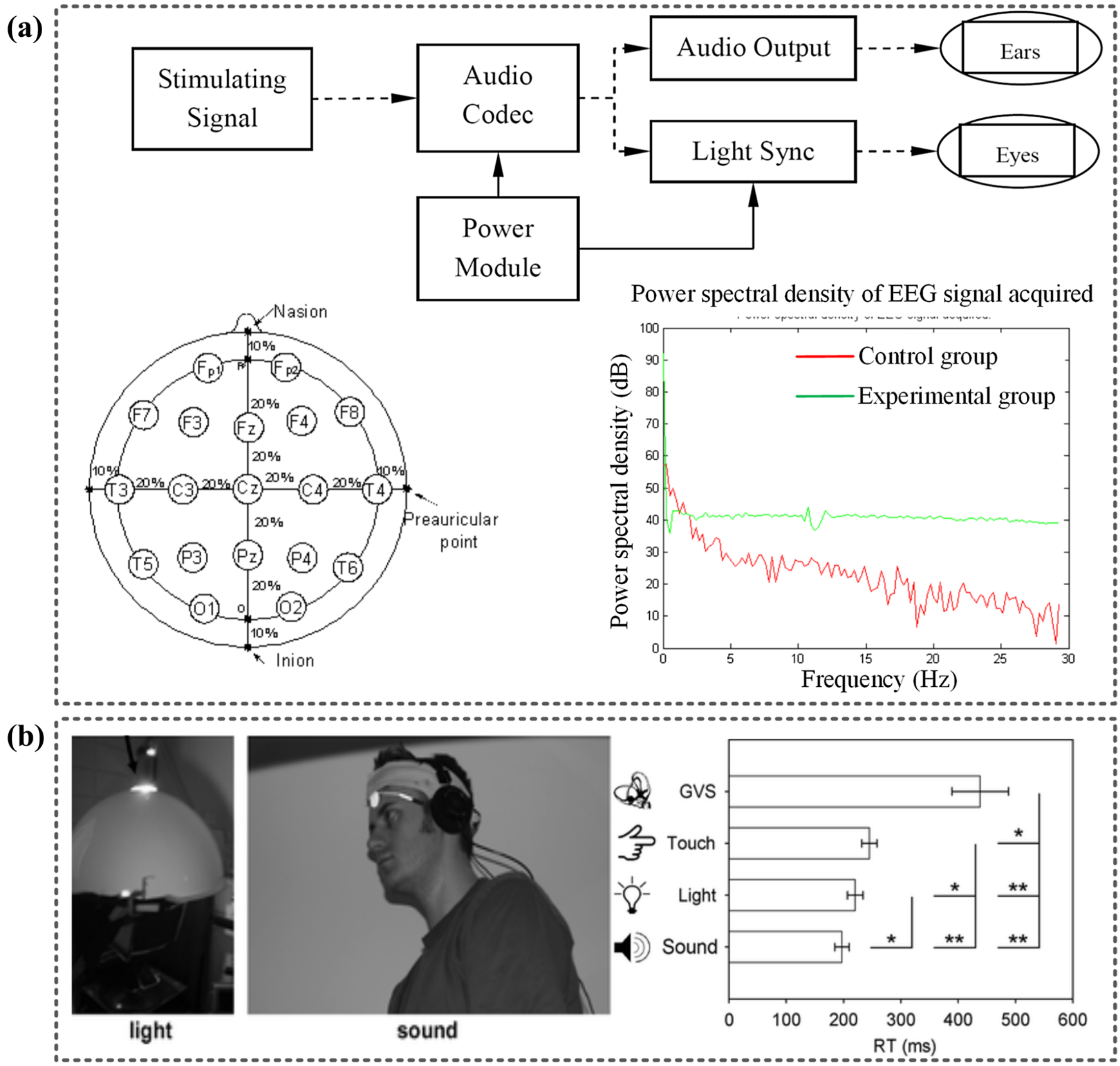

Fig. 18 Sound and light stimulation for HMI application. **a** Schematic graph for stimulation to the human body (Barnett-Cowan et al. 2011). **b** Experiment setup of sound and light stimulation (Young et al. 2012)

sound stimulation respectively. A middle ear microphone was developed based on MEMS capacitive accelerometer for middle ear hearing aids as well as future fully implantable cochlear prostheses, where the sensor was interfaced with a custom-designed IC chip over a flexible substrate (Young et al. 2012).

Figure 19 depicted an implantable wireless optoelectronics sensor to manipulate animal behavior via the optogenetics technologies (Kim et al. 2013; Shin et al. 2017). Implantation of the wireless optoelectronics was very similar to that of traditional optic fiber ferrules and previous wireless devices. Once the region of interest was located and a hole drilled through the skull, the device could be lowered using the custom mounting fixture. The wireless optoelectronics had a red LED indicator easily visible through the skin, and used as an implantable optogenetic device for changing the behavior mode of the animal with the red light stimulation to the animal (Park et al. 2015; Mccall et al. 2013). A skin-inspired mechanoreceptor was developed with a flexible organic transistor circuit that transduces pressure into digital frequency signals directly, whose output was used to stimulate somatosensory neurons of mouse cortex in vitro (Tee et al. 2015).

4.3 Electroactive polymer actuator for braille sheet display

Braille sheet display is used for the visually impaired people to communicate with the outside world through touching the EAP actuators. A flexible, shock-resistant, and lightweight braille sheet display was successfully fabricated on a plastic film by integrating a plastic sheet actuator array

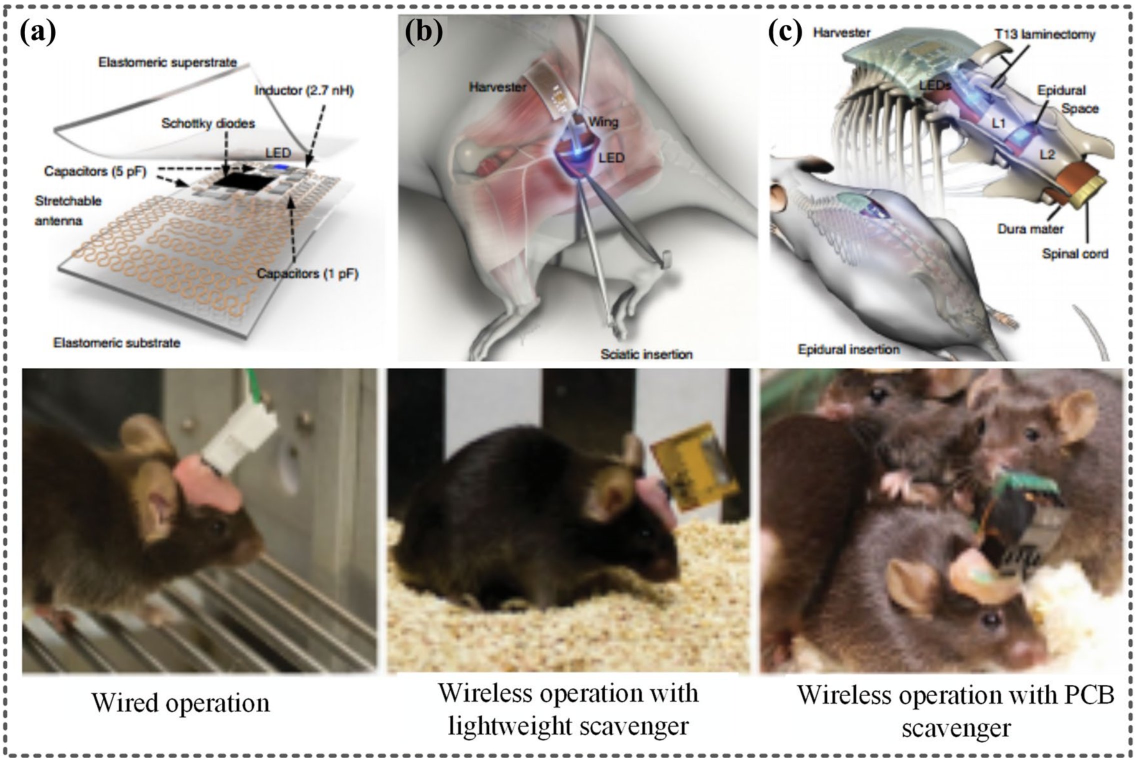

Fig. 19 Wireless optoelectronics for HMI application to change animal behavior (Park et al. 2015)

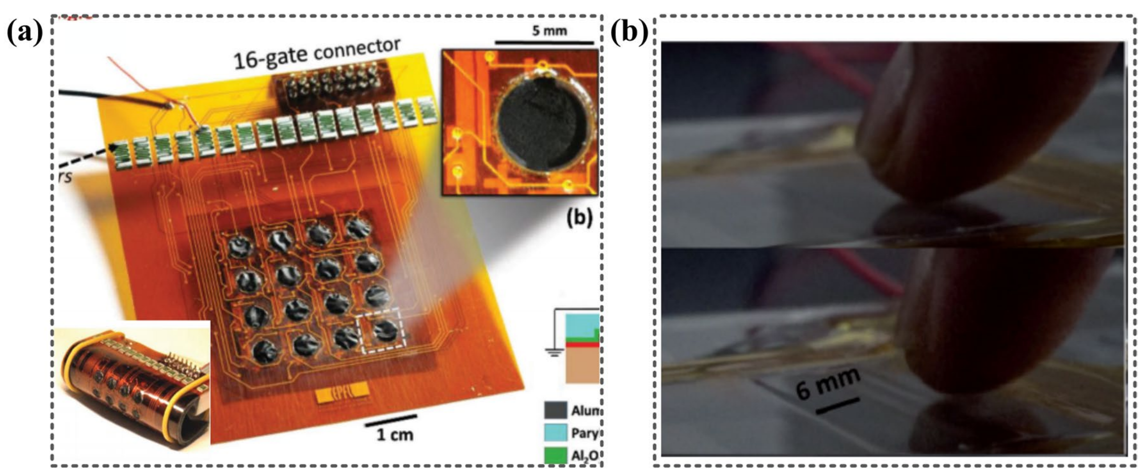

Fig. 20 Stimulation to the body via EAP actuator for HMI applications. **a** Flexible EAP actuator (Marette et al. 2017). **b** Flexible braille sheet display (Takamiya et al. 2006)

with a high-quality organic transistor active matrix shown in Fig. 20a (Marette et al. 2017). The plastic MEMS actuators with organic transistor active matrices had new versatile possibilities for flexible, large-area electronic applications including tactile displays (Kato et al. 2005). This demonstration of low-voltage control of a matrix of kV actuators paved the way to be used in many degrees of freedom for soft robotics, haptic displays, and flexible braille displays. When a hand touches the braille sheet display, the response information could be transformed to the subject. It provided an effective HMI for the subject to interact with the outside world via braille sheet display. Figure 20b depicted unprotected fingers probing the surface under the actuated condition indicating that the surfaces were electrically insulating and safe to touch (Takamiya et al. 2006). 1 mm thick soft insulating layer on the top provided insulation from direct contact of fingers with electrodes (Ankit, N., Tiwari, M., Rajput, N.A., Chien, Mathews, N.: Highly transparent and integrable surface texture change device for localized tactile feedback. Small 1702).

The soft pneumatic actuators based on composites consists of flexible elastomers with embedded sheets or fiber structures which are inexpensive, simple to fabricate, light in weight, and easy to actuate (Wei et al. 2017; Gu et al. 2017). These soft pneumatic actuators could manipulate objects with moderate performance which they can lift loads up to 120 times their weight (Martinez et al. 2012; Bishop-Moser and Kota 2017). Soft robots were essentially more compatible for human interactions as their soft and easily deformable bodies ensured a minimal damage and load exerted to humans and environment (Lee et al. 2017). Soft robots with ability to adapt the curved and irregular surfaces allowed overcoming the shortcomings of rigid robots (Polygerinos et al. 2017). Soft robotic glove for hand rehabilitation performed specific tasks for training. There were many other works on hand rehabilitation by soft exoskeleton systems (Menguc et al. 2013). Embedded with nickel nanostructured microparticles, a organic polymer performed mechanical and electrical self-healing properties at ambient conditions, and it was pressure- and flexion-sensitive, and therefore suitable for electronic skin applications in soft robotics and biomimetic prostheses (Tee et al. 2012).

4.4 EEG-EMG biofeedback to human bodies

EEG-EMG biofeedback training has become a useful tool for rehabilitation of impingement syndrome. It allows patients a better sense of muscle activations involved in the movement of the shoulder girdle. Contingent visual and proprioceptive feedback about the user's EEG and EMG activity is provided in the form of velocity modulation during functional task training. Participants started the real-time operation task with their paretic arm and hand relaxed in a comfortable rest position to reach one of the three targets around the workspace (Fig. 21a, b), while supinating the wrist and opening their hands (Cui et al. 2017; San Juan et al. 2016). It helped the patients accomplish complicated target task with the EEG-EMG biofeedback system and enhance the motion ability of patients.

Figure 21c depicted that the closed-loop system could facilitate functional neuroplastic prosthesis and eventually elicit a joint brain and muscle motor rehabilitation (Sarasola-Sanz et al. 2017). Its usability was validated during a real-time operation session in a healthy participant and a chronic stroke patient, showing encouraging results for its application to a clinical rehabilitation scenario. The calibration session was divided into an EEG screening and an EMG calibration. The EMG calibration was performed with the healthy upper limb. Information from different aspects with multiple methods about the process of EEG-EMG signals and modeling of human motion was extracted and

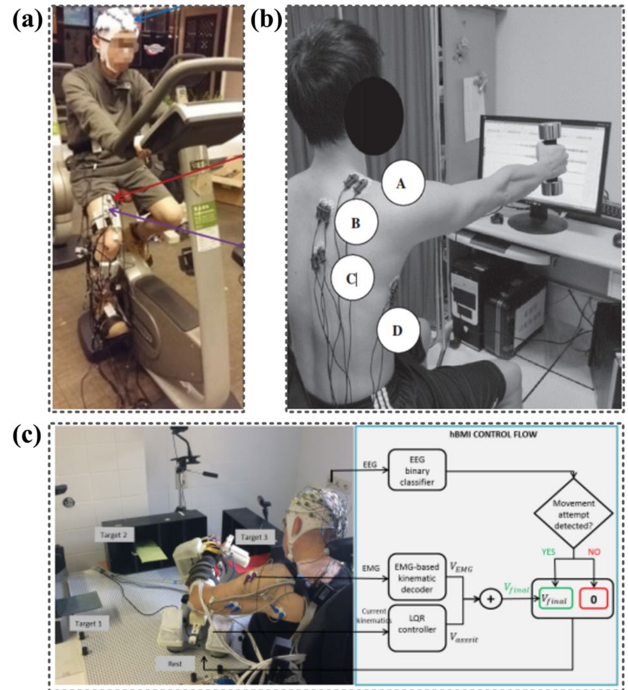

Fig. 21 EEG-EMG Biofeedback training for stimulating humans. **a**, **b** Biofeedback system based on EEG-EMG electrode (Cui et al. 2017; San Juan et al. 2016). **c** The closed-loop system based on EEG-EMG biofeedback (Sarasola-Sanz et al. 2017)

recognized. Generally speaking, HMI based on EEG-EMG biofeedback was an effective media to establish natural connections between humans and robots.

Paralysis of hands and arms in persons with paraplegia or stroke reduced their dexterity, daily living skills, self-sufficiency, and vocational potential (Schenk 2013). Therefore, many researchers focused on how to restore normal motor functions of upper limbs like elbow/wrist flexion and extension, hand grasp/release (Westerveld et al. 2012). Since elbow motions were very important in upper limb movements, different control strategies were designed to incorporate into flexible electrical stimulation (FES) systems, inducing desired elbow flexion/extension by stimulating the specific muscles. The surface electrode array had been applied in FES systems to induce more precise stimulation control, realizing more accurate and diverse arm and hand movements (Fig. 22a) (Freeman 2014).

Figure 22b depicted a multi-pad electrode based functional electrical stimulation system for restoration of grasping. Since patients with low-level hemiplegia retained partial volitional muscle contraction ability, researchers attempted to extract information from muscle activities that remained under voluntary control sufficient to predict appropriate stimulation levels for several paralyzed muscles in the upper extremity (Malešević et al. 2012). Considering the difficulties of producing enough joint torque and dynamic control

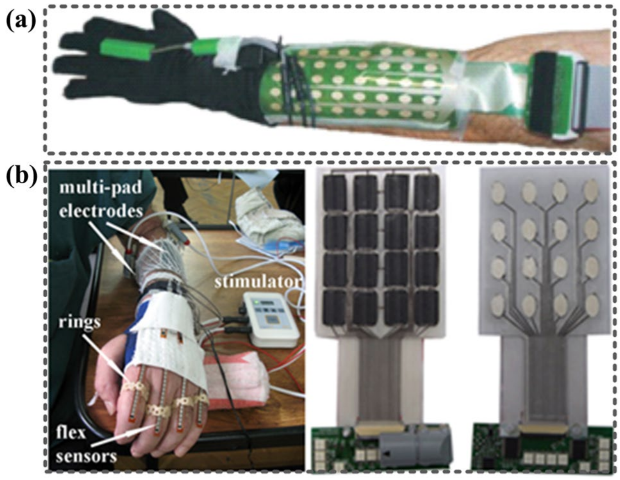

Fig. 22 **a** Electrode array with data glove and electrogoniometer (Freeman 2014). **b** sensor system for the assessment of the effects of stimulation (Malešević et al. 2012)

by using FES alone, EMG-driven electromechanical robot system integrated with FES was developed for wrist training after stroke. The performance of the system in assisting wrist flexion/extension tracking was evaluated on five chronic stroke subjects, which showed the FES-robot assisted wrist training could enhance the hand, wrist, and elbow functions.

Surface FES systems can be safely used by clinicians, but accurate placements of the electrodes may be difficult and time-consuming. Figure 23a depicted an EMG-based implanted FES upper limb system. A great number of stimulation channels/electrodes allowed activation of greater number of muscles, which resulted in better upper limb function, for example, better grasping and releasing. And additionally FES upper limb system could provide forearm pronation and reaching by elbow extension (Ethier et al. 2012). Figure 23b depicted a brain-controlled FES system that had been also developed to restore grasping function following paralysis. It extracted brain neural data of monkeys to predict muscle activity, and used it to control grasping action by implanted intramuscular electrodes for stimulation of hand and forearm muscles (Melo et al. 2015). During the early phases of rehabilitation, most persons hoped for restoration of lower limb neurological function sufficient at least to allow standing and walking. Therefore, there were researches aiming to apply FES inducing joint movements of lower limbs. In addition, FES had also been used as rehabilitation like correcting drop foot. Figure 23c depicted a hybrid system of exoskeletal bracing and multichannel FES to facilitate standing, walking, and stair climbing after spinal cord injury based on implanted electrodes (Chai et al. 2015). Moreover, FES were used to induce sensory feedback, for example, tactile sensation, which was significant for non-invasive neural interface that could feed back finger-specific tactile information from the prosthetic hand to forearm amputees.

5 Conclusion and discussion

This paper has highlighted the development of soft HMIs based on flexible and stretchable electronics technologies, including flexible/stretchable tactile sensors, motion

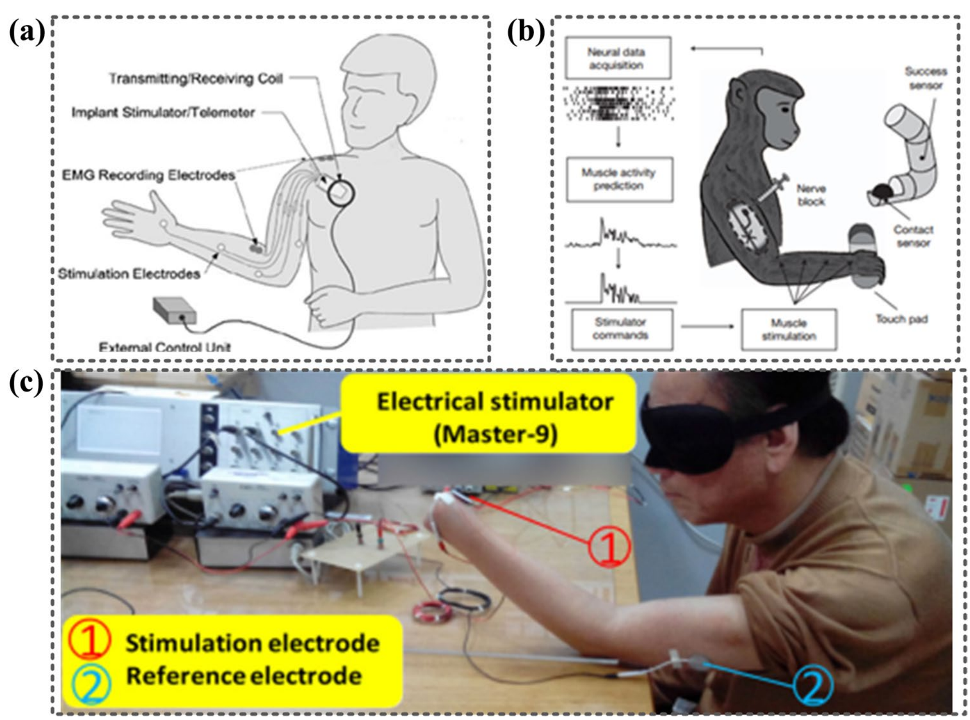

Fig. 23 EMG-based implanted FES upper limb system. **a** FES upper limb system (Ethier et al. 2012). **b** Brain-controlled FES system (Melo et al. 2015). **c** A hybrid system of exoskeletal bracing and multichannel FES (Chai et al. 2015)

sensors, biological sensors, and stimulation feedback to human bodies. Soft HMIs will play a key role in human-centered applications including robotics, sports, automobiles, textiles, and many other fields. Flexible/stretchable motion sensors are critically important for the robot and humans to accomplish complicated and dynamic tasks. Electrophysiology sensors have been developed as HMIs for EMG, ECG, and EOG signal recordings. The flexible electronic devices can stimulate human bodies for enhancing manual ability. Highly integrated electronics for the detection of multiple stimuli are the subject of many investigations. With the aid of newly emerging technologies, such as wireless sensor networks and ultrathin sensors, these efforts have received substantial attention in the field of health monitoring, medical implant services, and HMIs.

Recent developments in material science, nanotechnology, micro-/nano-fabrication techniques can improve HMI technologies in terms of performance, reliability, and miniaturization. (1) Conformal HMIs are designed and fabricated with flexible and stretchable electronics to provide a more friendly interface between human bodies and machines. Artificial skins with tactile sensors designed to mimic human skin in structural, functional, physiological and mechanical attributes, are promising in HMI applications. Flexible electronic devices have been used in many applications in recent tactile sensing technologies for their biocompatibility and excellent mechanical properties. (2) Soft tactile and bio-potential sensors are developed to improve human body rehabilitation as one type of HMIs, where flexile and stretchable electronics can be connected to a human nerve as part of human body. Stimulations to human bodies are generated by feedback information from the soft electronic devices integrated with soft tactile sensors or bio-potential sensors. (3) Soft HMIs promote interdisciplinary researches, such as flexible hybrid electronic manufacturing in the range of physics, material science, chemistry, informatics, manufacturing and so on. It would give an effective solution to fully flexible systems with soft sensors, soft printed circuit boards, and soft processors for improving the biocompatibility with human bodies.

However, there still exists some difficulties for the development of soft HMIs in the field of service robot and healthcare: (1) High manufacturing cost of soft HMIs among the critical issues to be considered in development. The low-cost materials and simple fabrication processes are desired to reduce cost. In a similar way, devices with low-power consumption or self-powering ability are worthy of in-depth studies. (2) More advanced intelligent sensing and congestive technologies are needed. Very large information and data must be exchanged between the human and machine for interacting more effectively. New algorithms are required for recognizing sensor signals to improve the communication and interaction efficiency, by mimicking real human skin which can adjust and provide feedback in real time according to the different types of external stimuli via the peripheral nervous systems. Future HMIs will also intelligently respond to variations in the external environment based on novel information transmission technology. (3) Coexistence safety could be a problem between the humans and machines. Multi-sensory and intelligent electronic devices should be thoroughly studied for future HMI applications, such as Tri-Co Robots. This provides an effective means for humans to interact with robots or machines in a similar way as human-to-human interactions. So soft HMIs provide a promising solution for a safe and friendly interaction between humans and robots.

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Wentao Dong received the B.S. and M.S. degrees in mechanical engineering from Wuhan University of Technology (WUT), Wuhan, China, in 2009 and 2012, respectively, and he received the Ph.D. degree in mechanical engineering with the School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, China in 2017. He joined East China Jiaotong University in 2017. His current research interests include the manufacturing and applications of flexible and stretchable electronic device.

Youhua Wang received his B.S. degree at Tsinghua University, Beijing, China, in 2014. He is currently a Ph.D. Student at School of Mechanical Science and Engineering of Huazhong University of Science and Technology, Wuhan, China. His research interests include soft materials, human-machine interface, and epidermal electronics.

Ying Zhou graduated from the Ocean University of China in 2016 and now is a graduate student at School of Mechanical Science and Engineering of Huazhong University of Science and Technology. Recent research interests include acquisition of biological signals and electrotactile for feedback with epidermal electronics.

Yunzhao Bai received the B.S. degree in mechanical engineering from Wuhan University of Technology, Wuhan, China, in 2017. He is currently pursuing the Ph.D. degree in mechanical engineering with the School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, China. His current research interests include the manufacturing and applications of flexible and stretchable electronic device.

Zhaojie Ju received the Ph.D. degree in intelligent robotics from the University of Portsmouth, Portsmouth, U.K., in 2010. He is currently a Senior Lecturer in the School of Computing, University of Portsmouth. He previously held research appointments at University College London and University of Portsmouth, UK. His research interests include machine intelligence, pattern recognition, and their applications on human motion analysis, human-robot interaction and collaboration, and robot skill learning.

Jiajie Guo received the B.S. degree from the Department of Engineering Mechanics and Science, Peking University, Beijing, China, in 2006, and the M.S. and Ph.D. degrees from the Department of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA, in 2009 and 2011, respectively. He is currently an Associate Professor in the School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan, China. His current research interests include compliant mechanisms, mechatronics, and system dynamics/control.

Guoying Gu received the B.E. degree in electronic science and technology, and the Ph.D. degree in mechatronic engineering from Shanghai Jiao Tong University, Shanghai, China, in 2006 and 2012, respectively. He was a Visiting Scholar at Massachusetts Institute of Technology, USA, National University of Singapore, Singapore and Concordia University, Canada. He was as a Humboldt Fellow at University of Oldenburg, Germany. Since October 2012, he has worked at Shanghai Jiao Tong University, where he is currently appointed as an Associate Professor with School of Mechanical Engineering. His research interests include soft robotics, high-precision motion control, design of soft sensors and actuators.

Kun Bai received his B.S. degree in Control Science and Engineering from Zhejiang University, China in 2006 and earned his M. S. and Ph. D. degrees in Mechanical Engineering at Georgia Institute of Technology, Atlanta, US in 2009 and 2012 respectively. Currently, he is an Associate Professor with the State Key Laboratory of Digital Manufacturing Equipment and Technology and the School of Mechanical Science and Engineering at Huazhong University of Science and Technology, China. His research interests include smart actuators/sensors and human-machine interfaces.

Gaoxiang Ouyang received the B.S. in automation and the M.S. in control theory and control engineering both from Yanshan University, China, in 2002 and 2004, respectively, and the Ph.D. degree at the Department of Manufacturing Engineering, City University of Hong Kong in 2010. He is an associate professor in the State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing, China. His research interests are bio-signal analysis, neural engineering, and dynamics system.

Shiming Chen received the Ph.D. degree in control theory and control engineering from Huazhong University of Science and Technology in 2006. He is currently working with the School of Electrical and Electronic Engineering, East China Jiaotong University, where he is a Dean and a Professor. His current research interests include multiagent systems, swarm intelligence, and complex network.

Qin Zhang received the Ph.D. degree from University of Montpellier, Montpellier, France, in 2011. She was a JSPS Fellow at the Tokyo University of Agriculture and Technology in 2012. Since 2013, she has been an Associate Professor at the Huazhong University of Science and Technology. Her research interests include human-robot interaction, rehabilitation robotics, and bioechatronics.

YongAn Huang received the B.S. and M.S. degrees in structural engineering in 2001 and 2004, and Ph.D. degree in Engineering Mechanics in 2007, from Northwestern Polytechnical University, Xian, China, respectively. He was a Visiting Scholar at Northwestern University (USA) in 2012. He is a Professor with the State Key Laboratory of Digital Manufacturing Equipment and Technology and the School of Mechanical Science and Engineering at Huazhong University of Science and Technology. His research interests are focused on Flexible/Stretchable Electronics, human-machine interaction, and Electrohydrodyanmic Printing.