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# Recent progress in flexible piezoelectric devices toward human-machine interactions

**Jiaqing Liu, Guo Tian, Weiqing Yang, Weili Deng***

Key Laboratory of Advanced Technologies of Materials (Ministry of Education), School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu 610031, Sichuan, China.

***Correspondence to:** Dr. Weili Deng, Key Laboratory of Advanced Technologies of Materials (Ministry of Education), School of Materials Science and Engineering, Southwest Jiaotong University, No. 111, North 1st Section of Second Ring Road, Jinniu District, Chengdu 610031, Sichuan, China. E-mail: weili1812@swjtu.edu.cn

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## Abstract
Human-machine interactions are becoming increasingly required for intelligent sensing and effective manipulation. Recent developments in flexible piezoelectric sensors with short response time and high force-electric interconversion efficiency present a tendency toward facilitating diverse human-machine interactive applications. Here, we review the development of flexible piezoelectric human-machine interactions in the context of robotic control, the Internet of Things, sports coaching and acoustic therapeutics. The synthesis of unique materials, the distinct design of device structures, the typical applications of piezoelectric human-machine interactions and the integration of cutting-edge technologies are elaborated in detail based on recent research. Finally, we highlight the current challenges and directions for the development of piezoelectric human-machine interactions for more advanced application scenarios.

**Keywords:** Piezoelectric devices, human-machine interactions, wearable devices, flexible electronics

## INTRODUCTION
With the rapid development of sensing and information technologies, smart flexible electronics have become a popular research topic, especially concerning cutting-edge technologies like artificial intelligence (AI) and human-machine interactions (HMIs), which greatly facilitate and enrich people's lives[1-4]. Effective

overall design and continuous improvement of user experiences are key to the development of HMI systems[5-7]. Nevertheless, conventional electronic devices are often rigid and unwieldy, restricting their wearability and conformability with human skin, which severely affects the sensing accuracy and user experiences. On this basis, many researchers globally have investigated flexible electronic devices with more eminent stretchability and flexibility for applications such as health monitoring[8-14] and gesture interactions[15-17]. These flexible devices can be fixed to any shape of object[18,19], such as skin[20-23], gloves[24,25] and rackets[26], to continually monitor human behavior in real time. HMIs serve as a bridge for information exchange between users and machines and also represent an indispensable link for next-generation applications, such as virtual reality (VR)[27-29]. Generally, a typical HMI system can be categorized into several parts, including signal perception, information transmission, signal processing and feedback execution. Among these parts, signal perception is the most important part as it detects external stimuli, especially tactile signals, and builds the basis of the whole interaction process.

To date, several principles have often been utilized for sensing in HMI systems, including the piezoelectric[20,26,30,31], piezoresistive[32,33], capacitive[34,35] and triboelectric effects[19,25,36]. Among them, human-machine interfacial sensors based on the piezoelectric effect, which can generate an electric displacement in response to an applied mechanical stimulus, have been widely used for tactile sensing, due to their outstanding performance with high sensitivity, fast response time and self-powered operation[37]. Furthermore, due to the inverse piezoelectric effect, piezoelectric materials can be deformed under an external electric field, which facilitates the preparation of an all-in-one device with both sensing and actuation functions. Moreover, incorporated with various novel technologies like augmented reality (AR), virtual reality and machine learning, piezoelectric HMIs (P-HMIs) are expected to improve people's daily lives to a more intelligent, convenient and interconnected level[38-41].

This review covers the recent progress made regarding smart flexible piezoelectric devices in the field of HMIs. Research concerning flexible piezoelectric electronics is comprehensively summarized and highlighted along with real-life P-HMIs, including robotic control, the Internet of Things (IoT), sports coaching, acoustic therapeutics and machine learning-enhanced P-HMIs [Figure 1][27,42-46]. Finally, the current challenges and prospects of P-HMIs are provided from our perspective, ranging from materials science and structural design to diverse potential applications in the near future.

## HMIS OF FLEXIBLE PIEZOELECTRIC DEVICES

### P-HMIs for robotic control

Recently, with increasing demands for immersion in virtual interactions, the term "metaverse" has become a heated topic in both academia and industry. With the help of smart flexible devices, combined with VR and AR technologies, people can experience immersive interactions in the virtual world, such as playing video games, taking online courses and attending distant conferences[47,48]. In contrast, some extremely harsh environments, such as high temperatures and pressures and confined spaces, make it difficult to approach for manipulation. Therefore, it is of great significance to control robotic systems remotely and interact with robotic systems actively to settle real-life challenges.

The interaction between robots and controllers is a rather complex process that includes highly sensitive sensing, signal and data processing and the execution of control[43,49]. In particular, this process places high demands on response speed and execution accuracy. Thus, a growing number of researchers are devoted to recognizing and mimicking human motions and enabling the interaction with robots by improving the performance of flexible piezoelectric devices. For example, Deng *et al*. designed a flexible self-powered piezoelectric sensor based on unique cowpea-structured PVDF/ZnO nanofibers, which demonstrated

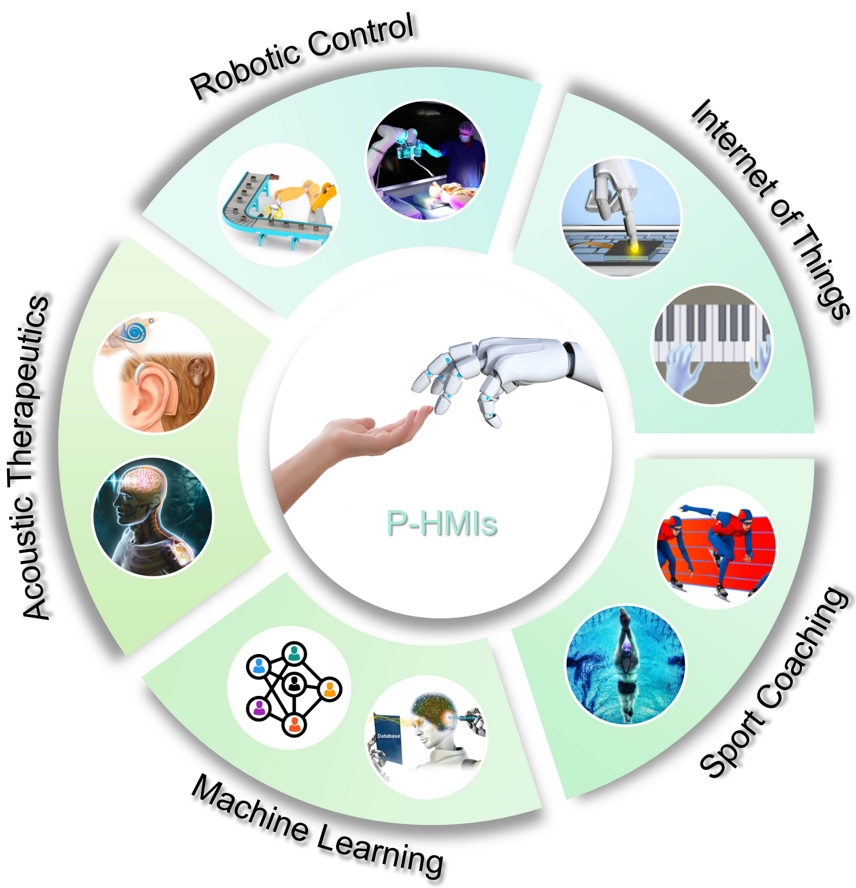


**Figure 1.** Overview of P-HMIs, including robotic control, the Internet of Things, sports coaching, acoustic therapeutics and machine learning. Reproduced with permission from ref.[42]. Copyright 2015, Royal Society of Chemistry. Reproduced with permission from ref.[43]. Copyright 2020, Elsevier. Reproduced with permission from ref.[27]. Copyright 2022, Elsevier. Reproduced with permission from ref.[44]. Copyright 2021, IEEE. Reproduced with permission from ref.[45]. Copyright 2021, MDPI. Reproduced with permission from ref.[46]. Copyright 2019, Wiley.

excellent mechanical and electrical properties for gesture interaction with a robotic hand[20]. When the sensor was fixed on a finger knuckle, its bending movements could be converted into electrical signals by the sensor to remotely perform control over the robotic hand via a controlling circuit. In this work, the robotic hand demonstrated its ability to synchronously imitate the same gesture as the human hand, as illustrated in Figure 2A. This self-powered sensor possesses a unique material structure and functioning mechanism, thereby exhibiting promising potential for intelligent HMIs, like gesture recognition and imitation.

Obviously, the effective design of functional materials and device structures enabling the regulation of the overall performance and functionality of piezoelectric devices has played an indispensable role in the development of HMIs. A common strategy is to use thin piezoelectric ceramics with excellent electrical performance to make them more flexible or to dope piezoelectric polymers with good flexibility to improve their electrical output. Recently, many two-dimensional piezoelectric materials have also gained attention due to their lightweight and flexibility[50]. For example, Yang *et al*. reported a piezoelectric device based on tin disulfide ($SnS_2$) nanosheets, which showed excellent energy harvesting and active sensing capabilities[51]. As illustrated in Figure 2B, the device had a conducting channel between 2-5 nm-thick $SnS_2$ nanosheets, electrically connected by multiple Cr/Au electrodes. The $SnS_2$ nanosheets are hexagonal crystals with an

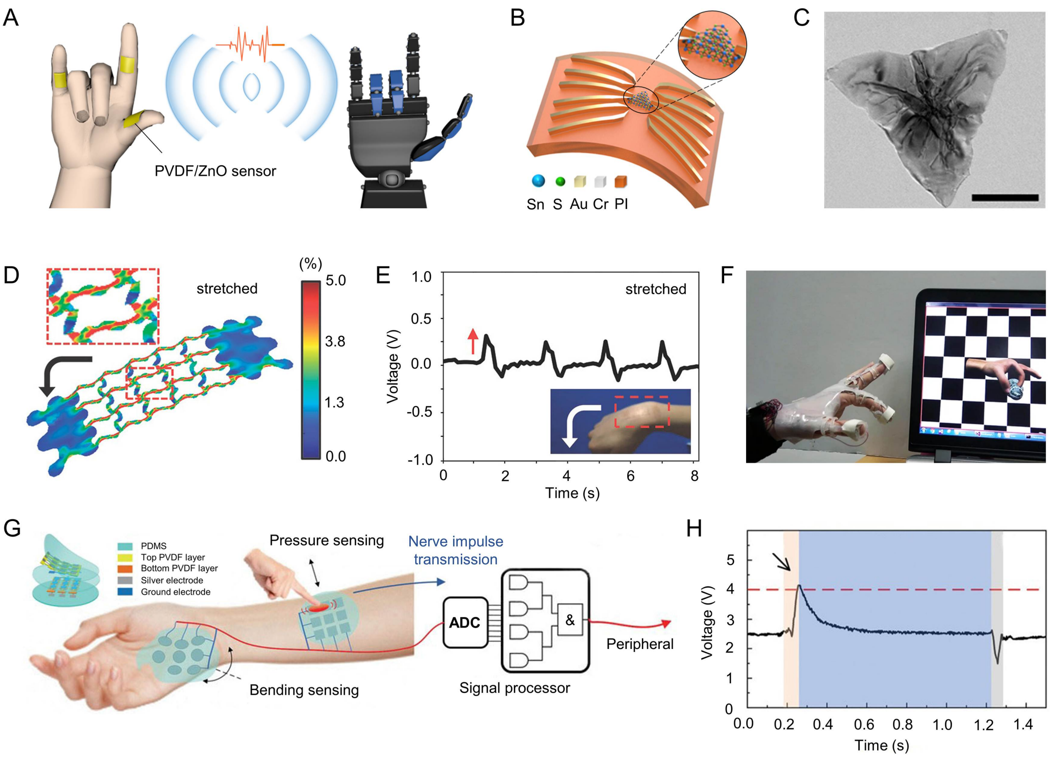


**Figure 2.** P-HMIs for robotic control. (A) Schematic diagram of HMI between a human hand and a remotely controlled robotic hand. Reproduced with permission from ref.[20]. Copyright 2019, Elsevier. (B) Schematic illustration of PENG device with a channel of $SnS_2$ electrically connected by Cr/Au electrodes on a polyimide substrate, where blue and green spheres represent Sn and S atoms, respectively. (C) TEM image with single few-layered $SnS_2$ nanosheets shown in the inset. Scale bar of 1 μm. Reproduced with permission from ref.[51]. Copyright 2020, Elsevier. (D) FEA strain distributions of heterostructure device in stretched mode. (E) Output voltage of sensor in stretched mode as a function of time and an image of sensor in stretched mode. Reproduced with permission from ref.[54]. Copyright 2014, Wiley. (F) Image of using VR to grab an object in virtual space by detecting finger motions in the real world. Reproduced with permission from ref.[40]. Copyright 2019, Springer Nature. (G) Schematic of human-machine interactive sensor array system. (H) Output voltage of sensor as a function of time when using a robotic hand with a feedback module to grasp an object. Reproduced with permission from ref.[55]. Copyright 2021, Wiley.

interplanar spacing of d(100) ¼ 0.32 nm[52,53], as the transmission electron microscopy (TEM) image shows in Figure 2C. In this work, the sensor was successfully demonstrated to achieve the real-time gesture control of a robotic hand by sign language, including a handshake between the robot and the human. The excellent self-powering and dynamic sensing capabilities of the device show rich potential in multidisciplinary fields for future applications, including energy harvesting, intelligent robots and HMIs.

In addition, Lim *et al.* fabricated a transparent and stretchable HMI system with wearable mechanical sensors and stimulators, allowing the feedback to control the movements of a robot[54]. Due to the prominent electrical and mechanical properties of the utilized conductive/piezoelectric graphene heterostructures, the designed piezoelectric sensors exhibited great flexibility and high detection sensitivity, thereby enabling the accurate monitoring of human motions. The strain distribution of the motion sensor stimulated by FEA is displayed in Figure 2D, presenting the strain magnitudes and polarities in the heterostructure of this device. When the wrist was bent, the stretch mode would be triggered and a unique corresponding command signal would be generated to control the robotic hand to move [Figure 2E]. In addition, more complex motion modes, such as radial deviation, ulnar deviation, pronation and supination, could be detected by assembling several sensors into a sensor array. The successful development of the above-mentioned smart devices allows for more sophisticated and intelligent HMIs.

With the advent of the metaverse, increasingly more people want to interact in a virtual world since it is not limited by time and space. Sensors and actuators are the necessary bridge between virtual space and the real world. Song *et al*. designed a smart glove consisting of PVDF-based piezoelectric sensors and flexible pneumatic actuators for providing tactile feedback, as shown in Figure 2F[40]. With the gloves on, finger motions could be monitored by piezoelectric sensors and the resulting piezoelectric outputs are transmitted to control the virtual hand. When the virtual hand touches a virtual object, the actuators are activated and give tactile feedback to the finger, thus enabling interaction with the virtual world. In this work, researchers tested this device in a virtual chess scenario, where a tester successfully picked up the pieces in the virtual world.

Furthermore, an active sensor array allows for more complicated and advanced applications of HMI systems compared to single-sensor systems. For instance, Lin *et al*. demonstrated a multilayer skin-inspired piezoelectric tactile sensor array with crosstalk-free row+column electrodes[55]. Integrated with a signal processor and a designated computing algorithm, the e-skin-based sensor array could detect and distinguish the magnitudes, positions and motion modes of external stimuli in real time. As schematically illustrated in Figure 2G, this HMI system resembled the biological response process of human beings. Initially, the mechanical stimuli would be converted to electrical signals by a PVDF-based sensing array due to the piezoelectric effect. The electrical signals were then transmitted to the peripheral devices, such as smartphones, computers and cloud computing platforms. After processing and analysis by specific algorithms, parameters, such as the positions, magnitudes and modes of the stimuli, could be accurately identified in real time. In this work, the authors achieved an interesting application by applying the piezoelectric sensor array with a robotic hand in an industrial scenario. By adjusting the default threshold value (4 V) of the sensor feedback, the robotic hand can correctly control the gripping force during grasping without exceeding the set value, thus protecting the grasped object from being damaged, as displayed in Figure 2H.

Due to the rapid response time and high sensing accuracy of piezoelectric sensors, P-HMIs have proven to be indispensable in real-time robotic control and interactions[56]. Incorporated with 5G technologies, information between humans and robots can be transmitted instantly, enabling many applications that previously seemed impossible. For example, doctors will be able to control medical robotics to conduct remote surgeries regardless of location, making treatment more efficient and reducing healthcare imbalances around the world[57]. However, these precise applications raise serious challenges for the overall design of the system to ensure rapid response time and sensing accuracy. The use of P-HMIs not only makes the interaction with the robot more convenient and efficient but also provides the possibility of realizing the HMI under harsh conditions, thereby reducing the risks that people may suffer.

### P-HMIs for Internet of Things

Benefitting from improvements in advanced sensing and information technologies, piezoelectric flexible sensors for the IoT have been demonstrated in numerous HMIs, such as smart homes[58,59], smart traffic[60] and intelligent healthcare[61,62]. For instance, Song *et al*. reported a piezoelectric device that could be installed as a pavement block on a sidewalk for energy harvesting[63]. This IoT system could be utilized to power walkway signal indicators and enable the collection and processing of environmental data (such as humidity and temperature), as illustrated in Figure 3A. When a person weighing 60 kg stepped on the system ten times, a capacitor (1000 μF) could be charged to 55.6 mJ. Consequently, the harvester successfully turned on a delineator on an actual sidewalk after 4.8 s and powered the IoT system without an external energy supply. This study proves the great durability and energy harvesting capability of the designed piezoelectric device, which shows promising prospects in human motion monitoring and traffic signal control for HMIs.

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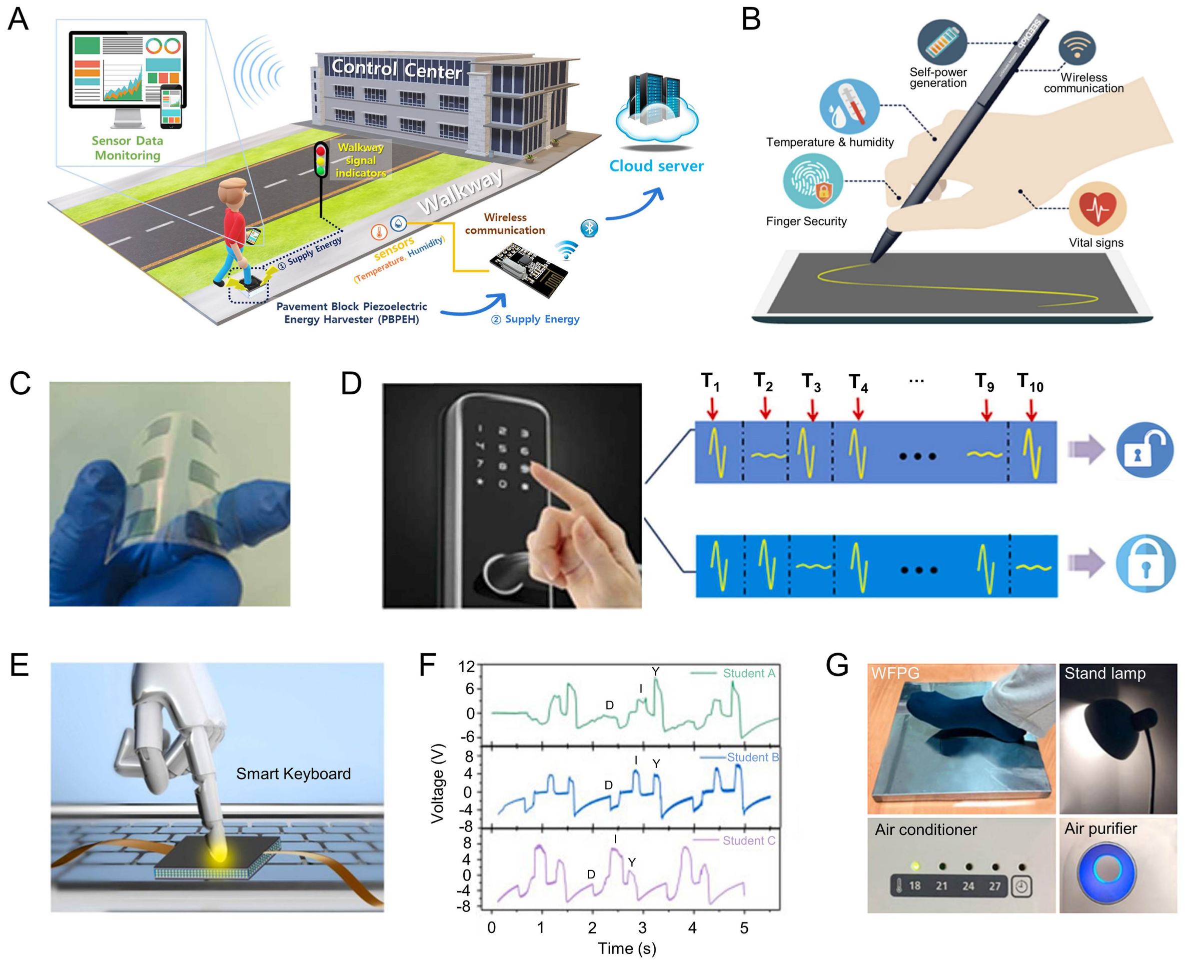


**Figure 3.** P-HMIs for IoT. (A) Schematic diagram of an IoT HMI system controlled by a pavement block piezoelectric energy harvester. Reproduced with permission from ref.[63]. Copyright 2019, Elsevier. (B) Conceptual design and possible applications of a smart pen based on a piezoelectric energy harvester. Reproduced with permission from ref.[64]. Copyright 2021, Elsevier. (C) Photograph of flexible PEH-based sensor arrays for HMI. (D) Working mechanism of flexible tactile sensor-based smart door lock. Reproduced with permission from ref.[65]. Copyright 2022, Elsevier. (E) Schematic overview of a smart keyboard application using flexible piezoelectric sensors. Reproduced with permission from ref.[27]. Copyright 2022, Elsevier. (F) Dynamic voltage output of three adult subjects when typing the word "DIY" on the keyboard attached with PMNP textiles. Reproduced with permission from ref.[66]. Copyright 2021, Elsevier. (G) Photograph of a wireless switch system to achieve the real-time smart home control of a table lamp, an air conditioner and an air purifier. Reproduced with permission from ref.[67]. Copyright 2018, Elsevier.

In addition, many researchers are also interested in embedding smart P-HMI devices into daily items. For example, Kim *et al.* designed a smart pen-based piezoelectric energy harvester, which could generate energy in both the $d_{31}$ and $d_{33}$ modes during writing[64]. Two piezoelectric devices, a cantilever and an impact-type device, were installed in the pen. The designed device showed excellent energy-harvesting abilities and was able to generate sufficient power to operate a wireless sensor. It was also capable of detecting the users' writing movements. Based on the above functions, this pen-based IoT device may be applied to many HMIs in the future, such as information security, wireless communication and the detection of various environmental and biological signals, as shown in Figure 3B.

Recently, Lv *et al.* successfully demonstrated a piezoelectric IoT device for smart door locks[65]. They first fabricated an all-inorganic transparent Sm-doped $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (Sm:PMN-PT) film on a mica substrate via a simple one-step sol-gel process. The synthesized soft film showed an ultrahigh piezoelectric coefficient $d_{33}$ of 380 pm $V^{-1}$ and superior flexibility. Furthermore, a 3 × 2 piezoelectric sensor array was fabricated to detect the spatial distribution of exerted forces, as shown in Figure 3C. When the passwords were entered on the sensing array, the corresponding output voltage would be detected by a multichannel signal collector and then compared with the preset password in the system. If the input numbers matched the password in the memory, the door would be unlocked and vice versa, as illustrated in Figure 3D. Such flexible PMN-PT films are proving to possess significant potential for the authentication of smart unlocks.

Similar to locks, the keyboard is another common and popular device, eligible for information exchange between humans and machines. With the escalation of computer-related security issues, criminals can easily bypass security authentication systems by hacking passwords, causing serious problems for the privacy of personal information. On this basis, Zhou *et al*. demonstrated a smart keyboard-based personalized recognition system, as depicted in Figure 3E[27]. In this study, several volunteers were asked to type the same words on the smart keyboard, with piezoelectric sensors attached to its keys. From the results of the piezoelectric output, the authors found that the amplitudes, intervals and waveforms of the outputs varied with volunteers, showing individual personal features. Therefore, it is possible to identify the user through analyzing the signal patterns collected by the smart keyboard. Likewise, Su *et al*. conducted a thorough study regarding a smart keyboard based on barium titanate-doped polyvinylidene fluoride (BTO/PVDF) piezoelectric nanocomposite fibers[66]. In their study, polydopamine-modified nonwoven piezoelectric (PMNP) textiles were constructed based on the BTO/PVDF fibers, whose unique structure endowed the textiles with prominent piezoelectric output and mechanical stiffness. The PMNP textiles were then attached on a keyboard to detect the patterns of finger tapping. As shown in Figure 3F, three sets of voltage output were measured when each student entered the same word "DIY" on the keyboard attached with the PMNP textiles. As can be seen from the plot, there are significant differences between the three collected waveforms. Several biometric features could be obtained by analyzing the data, such as typing forces, finger sizes and typing patterns. All the additional information from P-HMIs can be used as a valid identifier for the personalized interactive authentication system, proving its advantages over traditional devices.

Furthermore, Kim *et al*. investigated an excellent piezoelectric material (optimized PZN0.25C ceramic) for smart-home sensors that could be attached to floor tiles[67]. When stepping on the floor, a peak output voltage of 42 V and a current of 11 μA were generated by the PZN0.25C ceramic. This energy could power a wireless sensor unit to control the on/off of home appliances, such as stand lamps, air conditioners and air purifiers in real time, as schematically shown in Figure 3G. Furthermore, such piezoelectric devices can easily be placed on floor tiles at a large scale, which provides more possibilities for HMIs.

To conclude, in the era of the IoT, flexible piezoelectric sensors can be attached to numerous daily necessities to realize HMIs and make life more intelligent in a vast amount of scenarios[68,69]. At present, we have already experienced the convenience of P-HMIs in smart homes, including voice-controlled or tactile-sensing devices, such as smart curtains, voice assistants and automatic lights. With the further advancement of IoT technologies, including sensing, signal transmission and information feedback, perhaps newly developed smart IoTs could be controlled by facial expressions, muscle gestures or even emotions, which will make our daily lives more convenient and efficient.

### P-HMIs for sports coaching

As the era of AI approaches, advanced technologies have been integrated into many aspects of our lives[70]. Various wearable sensing and interactive information systems are widely used for physical fitness monitoring and training instruction in sports. Traditionally, the training of athletes is judged and recorded primarily through visual observations from coaches or camera-type equipment, which often lacks immediate or precise feedback. With the aid of P-HMIs, sports training can be more scientific and efficient due to the real-time monitoring and sports data analysis[71-73]. Recently, Tian *et al*. designed a distinct self-powered piezoelectric sensor with a rich lamellar crystal baklava-structured PZT/PVDF for guiding table tennis[74], as shown in Figure 4A. Based on the outstanding performance of the designed sensors (sensitivity of 6.38 mV/N and response time of 21 ms), the fabricated table tennis racket, attached with a 6 × 6 sensor array, could accurately detect the hit location and the magnitude of the contact force. On this basis, coaches would be able to provide customized guidance for the training of athletes from the data collected in real time. The design of this smart racket offers promising prospects for the application of P-HMIs in individual sports guidance and intelligent sports equipment.

In addition to racket games, like tennis and table tennis, P-HMIs can also be used in other sports concerning continuous motion monitoring. Lu *et al.* designed a flexible self-powered piezoelectric sensor for speed skating motion monitoring[45]. This sensor mainly consists of polarized PVDF, silver electrodes and a flexible polyester substrate, which could be attached to the hip joint of skaters and the blades of skating shoes [Figure 4B]. When skating, the device could generate corresponding piezoelectric voltages with different amplitudes and durations in response to body movements, such as joint bending angles, motion frequencies and skate blade vibrations, as shown in Figure 4C. These data are then stored and analyzed to provide individual guidance for skaters.

Moreover, P-HMIs have also proven their potential in coaching other kinds of sports, such as boxing and swimming. As shown in Figure 4D, Yao *et al.* embedded a 3D-printed flexible piezoelectric lattice into a boxing glove to detect the magnitude and spatial distribution of punch force[75]. The obtained piezoelectric signals could be instantly transmitted to cell phones via a WiFi module and paired with a graphical display. When a person hit the wall with this glove, whether it was a direct hit or a right hook, the corresponding spatial distribution of the force could be displayed on the cell phone, as shown in Figure 4E. As a result, users can obtain feedback regarding their boxing performance simply from their mobile phones and use the information to hone their boxing skills. Interestingly, Mao *et al.* demonstrated a flexible self-powered biosensor based on ZnO nanowire arrays and a flexible polyethylene terephthalate (PET) substrate for the real-time monitoring of swimming[76]. Due to the piezoelectric effect of polar ZnO nanowires, the sensor could convert the biomechanical energy of swimming into electric energy without the need for an external power supply in the water. As illustrated in Figure 4F, the sensor could be easily fixed on the skin to monitor motions like joint moving angle and frequency during swimming. The sensor mainly consisted of the planar electrode and flat ZnO nanowires, as shown in Figure 4G. The output voltage waveform of the sensor allowed us to obtain and evaluate different swimming patterns [Figure 4H]. Likewise, the collected signals could be transmitted to a specific terminal for further analysis to help people improve their swimming skills.

It is generally believed that wearable P-HMIs will be applied to many forms and carriers, including but not limited to gloves, shoes and e-skin. With the fast advancement of flexible electronics and AI, there will be more state-of-the-art signal processing and machine learning algorithms to analyze sports-related data. These advanced algorithms are expected to be integrated with expertise in sports science and medicine to make sports training more scientific and personalized.

### P-HMIs for acoustic therapeutics

With the surging need for personal medical treatment and rehabilitation, various therapeutic devices have been developed. In particular, for implantable devices, power supplies, information exchange and feedback

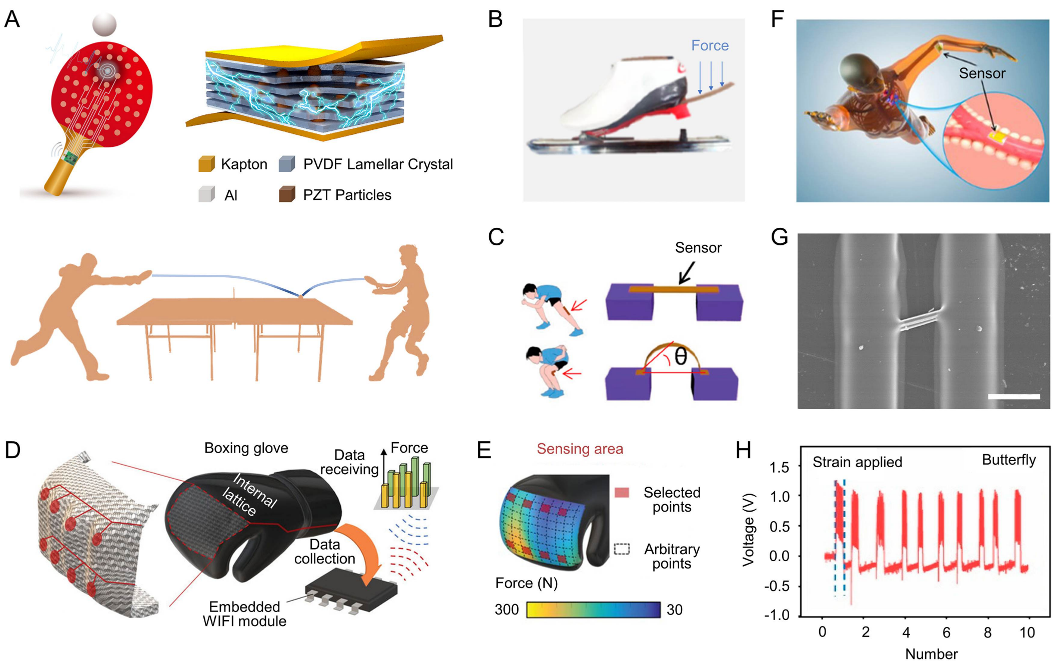


**Figure 4.** P-HMIs for sports coaching. (A) Schematic diagram of smart racket and sensor structure for interactive table tennis coaching. Reproduced with permission from ref.[74]. Copyright 2019, Elsevier. (B) Photograph of piezoelectric sensor attached to an ice skate blade. (C) Measurement system for mimicking the motion of a knee joint. Reproduced with permission from ref.[45]. Copyright 2021, MDPI. (D) Schematic diagram of P-HMI system based on a boxing glove. (E) Spatial distribution of force magnitudes obtained from electrodes attached to boxing glove. Reproduced with permission from ref.[75]. Copyright 2019, Wiley. (F) Schematic diagram of monitoring swimming athlete's elbow joint angle and heart rate. (G) SEM image of a single ZnO nanowire crossing a pair of electrodes. Scale bar of 10 μm. (H) Waveform of piezoelectric voltage output of butterfly stroke. Reproduced with permission from ref.[76]. Copyright 2021, MDPI.

control are crucial challenges that need to be addressed. In this process, acoustic waves not only transmit energy wirelessly for therapeutic devices implanted in human bodies but also act as carriers to exchange information for HMIs, which is an important medium recognized by researchers[77-81]. Piezoelectric devices play an extraordinary role in the field of acoustic therapeutics due to their efficient bidirectional electromechanical coupling capability. For example, Zhang *et al.* reported a piezoelectric ultrasound energy-harvesting (PUEH) device that could be implanted underneath the skin for deep brain stimulation by converting ultrasound energy to electrical energy [Figure 5A][82]. As schematically illustrated in Figure 5B, the designed harvester was a multilayer structured device with a Sm-doped $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (Sm-PMN-PT) single crystal as the functional layer. The Sm-PMN-PT crystal was laid at a thickness of 380 μm and then divided into small pieces with dimensions of 1 mm × 1 mm. These pieces were then integrated with several flexible electrodes to form a 6 × 6 array and encapsulated in PDMS for excellent biocompatibility and flexibility. In the experiment, the device implanted in a rat brain could generate an output power of 280 μW under ultrasound stimulation, which could instantly stimulate the periaqueductal gray brain area for analgesia.

In addition to analgesia, a plethora of people are also suffering from disabilities such as blindness and the significance of electronic ocular prostheses to restore vision through neural electrical stimulations has become apparent. Jiang *et al.* reported a flexible ultrasound-induced retinal stimulating piezo-array (F-URSP) for evoking visual perception in blind individuals[83]. The prepared F-URSP, as an artificial ocular prosthesis, had a two-dimensional piezo-array with 32-pixel stimulating electrodes to perceive images. Each piezo-element could be respectively activated by ultrasound, which was individually transduced by

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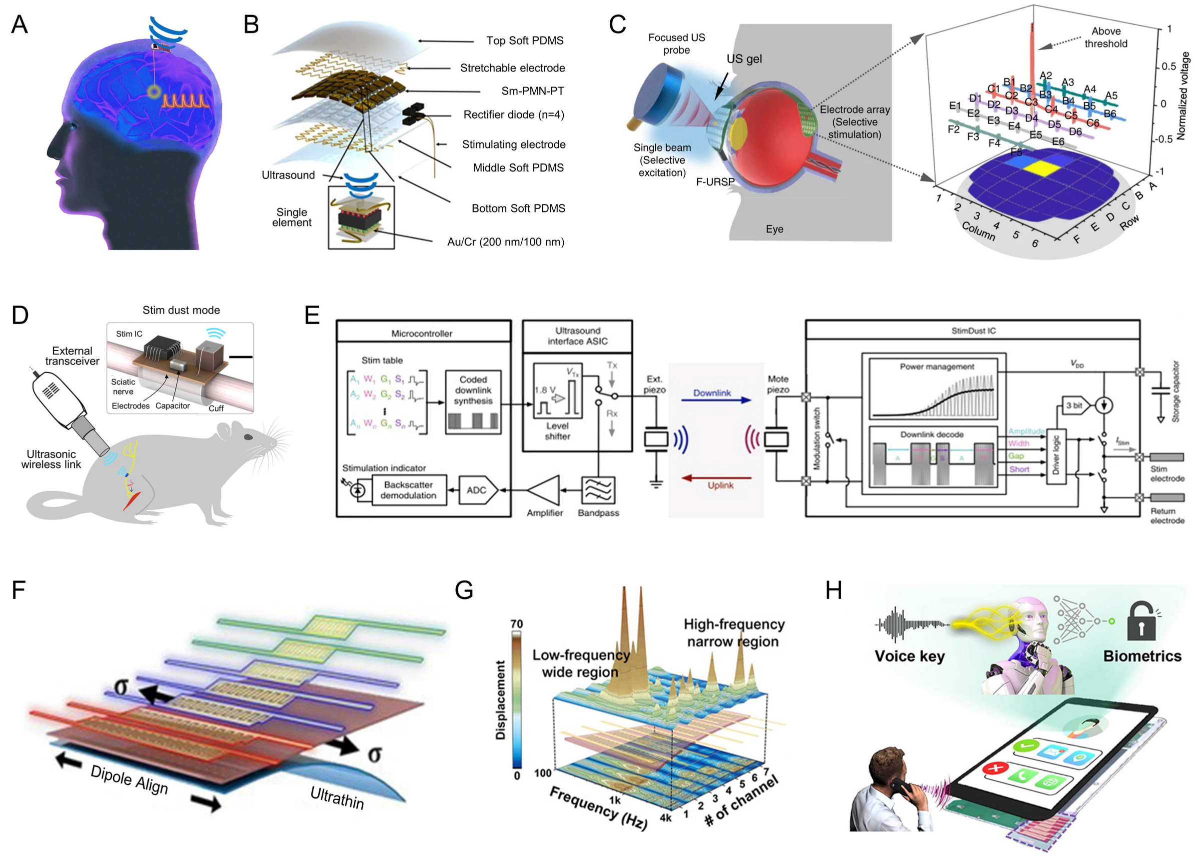


**Figure 5.** P-HMIs for acoustic therapeutics. (A) Schematic diagram of Sm-PUEH device for deep brain stimulation and analgesia. (B) Structural diagram of Sm-PUEH. Reproduced with permission from ref.[82]. Copyright 2022, American Association for the Advancement of Science. (C) Schematic diagram showing working model of F-URSP, in which a focused ultrasound probe was used for selective excitation of the piezo-array and the output voltage magnitude of each element in the array under the excitation of a single focused probe. Reproduced with permission from ref.[83]. Copyright 2022, Springer Nature. (D) Diagram of StimDust system implanted in a rat to stimulate its sciatic nerve. Scale bar of 1 mm. (E) Block diagram overview of neuro-stimulating system. Reproduced with permission from ref.[84]. Copyright 2020, Springer Nature Limited. (F) Highly sensitive frequency response of PMAS for full-cover phonetic spectrum using an ultrathin polymer, a piezoelectric membrane and a multichannel electrode. (G) Multiresonant displacements of ultrathin PMAS membrane measured by an LDV under frequency sweep from 100 Hz to 4 kHz. (H) Smartphone biometric authentication using machine learning-enhanced acoustic module integrated with mini PMAS, machine learning processor and wireless transmitter. Reproduced with permission from ref.[85]. Copyright 2021, American Association for the Advancement of Science.

programmable beamlines, resulting in particular piezoelectric patterns. As illustrated in Figure 5C, the piezo-element in perpendicular contact with the ultrasound beam exhibited a high output voltage above the threshold with a high signal-to-noise ratio of ~32.6 dB, while the other piezo-elements displayed discernable diminution in the magnitude of output voltage because of the lower intensities of the received ultrasound. As a consequence, the ultrasound-induced pattern reconstruction was successfully demonstrated in murine retinal tissue. Such modes of operation, which link ultrasound acoustic induction and retinal electrical stimulation via piezoelectric devices, exhibit great potential in the field of restoring vision to the blind through visual reconstruction.

Recently, Piech *et al*. demonstrated a wireless ultrasonically powered implantable neural stimulator, which could be used for interactive communication between human beings and machines[84]. As illustrated in Figure 5D, the designed system consisted of a piezoceramic transducer, an energy-storage capacitor and an integrated circuit, which directly attached to the sciatic nerve of a rat to fulfill electrical stimulation. A single ultrasonic link provided power to both the mote and bidirectional communication, achieving the interaction between the mote and the external transceiver, as shown by the functional diagram in Figure 5E. The uplink data could be demodulated to indicate whether a stimulus had occurred and the downlink data could send programmed commands to control the generation of the stimulation pulses through decoding. When implanted into the sciatic nerve of several rat models, the device engaged repeatable stimulation according to a series of physiological responses, successfully achieving the closed-loop nerve stimulation therapy.

In addition, flexible piezoelectric acoustic sensors have attracted substantial attention as essential components for human-machine interactive applications, such as the voice user interface. For example, Wang *et al.* designed a highly sensitive piezoelectric mobile acoustic sensor (PMAS) for biomimetic frequency band control[85]. Figure 5F illustrates the device structure of this PMAS, which consisted of an ultrathin PET substrate, a piezoelectric membrane and several multichannel interdigital electrodes. The internal residual stress of the PZT membrane was customized to reinforce dipole alignment among the interdigital electrodes, which greatly increased the sensitivity of the device. As a result, the multiresonant band of PMAS exhibited an eminent sensitivity to the frequency of sound. As seen in Figure 5G, the multiresonant displacements of the PMAS membrane varied distinctly with frequencies from 100 Hz to 4 kHz, as measured by a laser Doppler vibrometer (LDV). On this basis, the multichannel data obtained by PMAS embedded into the smartphone were transmitted to the processor, where the input signals were compared with information in the built-in database with the help of the Gaussian mixture model algorithm to complete the machine learning-based biometric verification, thus allowing or denying access to the phone [Figure 5H]. The authors hypothesized that acoustic P-HMIs will not only play an important role in clinical therapeutics, such as curing diseases and helping people with disabilities, but will also be used in other areas, such as biometric authentication, due to the high sensitivity of piezoelectric devices to acoustic waves. The promotion of acoustic therapeutic HMIs still faces many challenges, such as the miniaturization of implanted devices competing with force-electric conversion efficiency and higher requirements for biocompatibility and stability, which are critical issues that need to be addressed in the future.

### Machine learning-enhanced P-HMIs

As a cutting-edge technology conducive to the enhancement of HMIs, machine learning has captured the attention of researchers from various disciplines, especially those focusing on smart flexible electronics. Incorporated with machine learning algorithms, the data obtained from flexible piezoelectric sensing systems can be better utilized to provide appropriate guidance for a plethora of applications, including, but not limited to, emotional detection[86,87], interactive displays[30,88,89] and sign-to-speech translation[90].

Machine learning not only improves the accuracy of results while reducing the volume of sensory information that needs to be obtained, but also uncovers the hidden features in the data. Generally, there are three types of machine learning models: supervised learning, unsupervised learning and reinforcement learning, all of which can be utilized to enhance P-HMIs and boost the accuracy and efficiency of their applications[57]. In particular, for stimuli identification and feature analysis in HMI devices, which require training with real data, supervised learning algorithms are the most popular because they ensure fast and efficient performance. For example, Lee *et al.* focused on the integration of machine learning with flexible piezoelectric acoustic sensors, showing huge potential for speech recognition[91]. Figure 6A briefly illustrates the process of machine learning-enhanced P-HMIs and their potential applications in HMIs concerning human voices. The incorporation of novel piezoelectric acoustic sensors and optimized machine learning algorithms is regarded as a key role of voice-controlling HMIs, such as biometric authentication, AI secretaries and the control of smart home appliances.

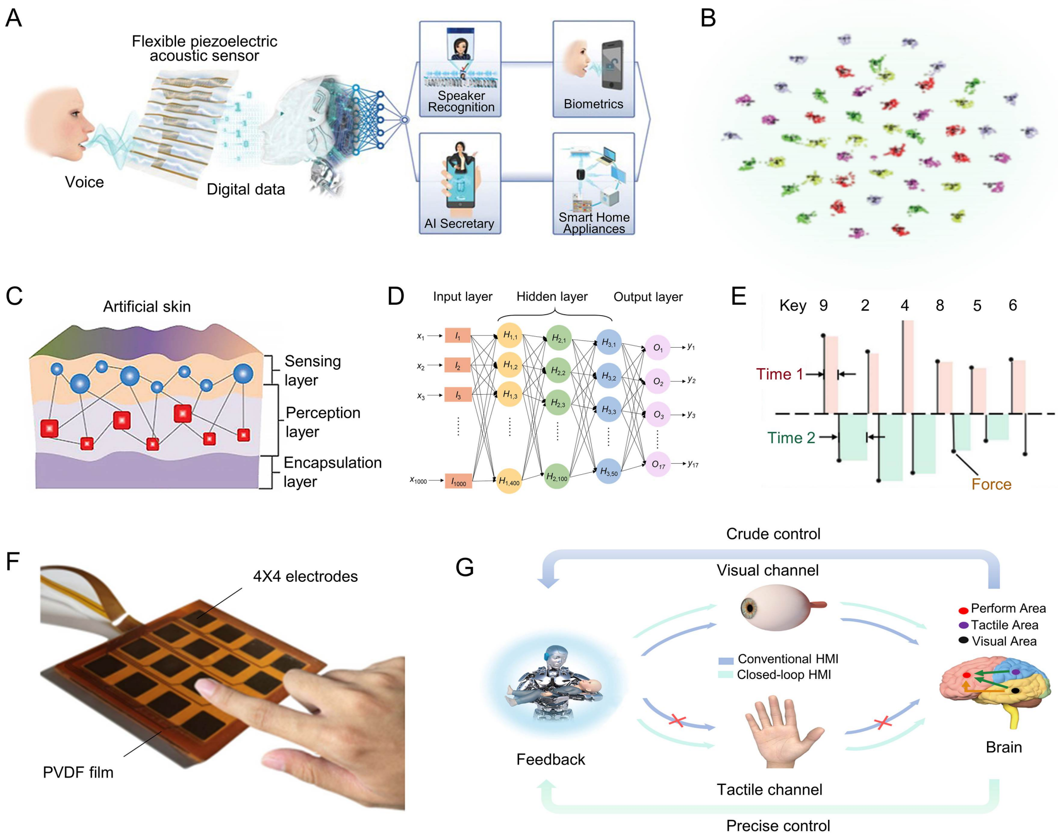


**Figure 6.** Machine learning-enhanced P-HMIs. (A) Overall illustration of process and potential applications of machine learning-enhanced piezoelectric acoustic sensors. Reproduced with permission from ref.[91]. Copyright 2019, Wiley. (B) Visualized speaker embeddings with t-SNE. Each speaker is marked by its color and the text indicates pronounced digits. Reproduced with permission from ref.[92]. Copyright 2018, IEEE. (C) Artificial skin consisting of sensing, perception and encapsulation layers. Reproduced with permission from ref.[93]. Copyright 2020, Wiley. (D) Architecture of neural network model for the classifier used for object recognition. Reproduced with permission from ref.[94]. Copyright 2020, IOP Publishing Ltd. (E) Schematic diagram of piezoelectric output voltage signals when a password is entered. (F) Image of piezoelectric panel for user authentication. Reproduced with permission from ref.[95]. Copyright 2021, IEEE. (G) Schematic illustration of HMIs with traditional and closed-loop HMI systems. Reproduced with permission from ref.[97]. Copyright 2022, American Association for the Advancement of Science.

Novoselov *et al*. analyzed the performance of a speaker recognition system based on convolutional neural networks (CNNs)[92]. A single high-level feature extractor was trained with human voices through deep CNNs to distinguish speakers and digits simultaneously. With five randomly selected speakers, the same digit pronounced by different people or different digits pronounced by the same person were projected on two principal axes with t-distributed stochastic neighbor embedding (t-SNE), as displayed in Figure 6B. The developed CNN system with multitask learning surpassed the classical algorithms, achieving an equal error rate of 2.85%.

Furthermore, the combination of machine learning and e-skin has resulted in many interesting applications. As depicted in Figure 6C, artificial skin usually consists of three layers: a sensing layer, a perception layer and an encapsulation layer[93]. Combined with machine learning, Chung *et al*. successfully achieved object classification with a piezoelectric actuator-sensor pair[94]. When the robotic hand grasped the objects, the data obtained by the actuator-sensor pair was used as the input for machine learning after several preprocessing steps. On this basis, a real-time object recognition system was successfully demonstrated with a neural network classifier and the accuracy was above 90%. The classifier model for the object classification task is schematically shown in Figure 6D, with the neural network at a scale of 1000 × 400 × 100 × 50 × 17. This work successfully fulfilled object classification with flexible piezoelectric sensors and machine learning algorithms, showing the significant potential of P-HMI systems for information exchange.

In addition to e-skin-based HMIs, machine learning can also be utilized for IoT devices, such as smart interactive touch panels for door and mobile phone locks, making authentication more secure and reliable. Researchers discovered that keystroke behavior varies significantly from person to person, an aspect that was usually overlooked. Herein, Jia *et al.* demonstrated a keystroke authentication system with a piezoelectric touch panel coordinated with a machine learning algorithm[95]. When a password was entered, the keystroke datasets with force and time features could be obtained by the piezoelectric touch panel [Figure 6E], which contains a 4 × 4 electrode array, as shown in Figure 6F. The machine learning algorithms were then used to perform the authentication comparison, where the random forest classifier demonstrated an accuracy of 96.40% due to the differences in individual keystroke behavior, which prevent intruders from passing the authentication even if they enter the correct password.

With the rapid development of flexible electronics and machine learning, increasingly more applications that once seemed impossible, such as brain-computer interactions, will become a reality. In recent studies, soft piezoelectric sensors have been implanted into rodent nerves to detect nervous impulses[96]. With the aid of machine learning, the obtained data can be effectively interpreted and then targeted instructions can be issued. The study of machine learning-enhanced P-HMIs is still currently a budding research area. Among all the machine learning algorithms, neural networks (NNs), with high robustness and fault tolerance, have been the most popular in recent studies on P-HMIs, such as acoustic signal processing[91]. By constructing a closed-loop HMI with both precise sensing and feedback [Figure 6G], it is expected that people with disabilities, such as paralysis, will be able to control wheelchairs, TVs and even computers by means other than their hands, and even convey thoughts for people with diseases, such as amyotrophic lateral sclerosis, which will greatly improve their quality of life[97].

## SUMMARY AND OUTLOOK

Since the discovery of the piezoelectric effect, researchers globally have been inspired to find approaches to improve the performace and enrich the applications of piezoelectric devices. In this review, the recent progress in P-HMIs has been presented around the applications in robotic control, the IoT, sports coaching, acoustic therapeutics and machine learning. Given the latest trend in academic research on P-HMIs, we have depicted a comprehensive diagram to explicate the summary and perspectives of P-HMI[98-103], as shown in Figure 7. As the cornerstone of piezoelectric devices, piezoelectric materials largely determine their comprehensive performance, such as sensitivity and response range. How to improve the electromechanical coupling efficiency of piezoelectric materials, including organic materials, inorganic materials, composite materials and biological materials, is the focus of future research, especially considering both mechanical flexibility and piezoelectric output[98,100,104-110]. In addition, the effective design of device structures also plays an important role in P-HMIs. Planar, sandwiched and three-dimensional structures are three of the most popular architectures for HMIs[101-103,111]. The development of high-performance piezoelectric devices by improving structural designs for scenario-specific application requirements is another important research direction.

With the rapid development of various advanced technologies, such as VR/AR, cloud computing, 3D printing and so on, the incorporation of P-HMIs with these technologies will be the focus of both academia and industry. For instance, with VR/AR integrated P-HMIs, people will be able to chat with their friends, watch movies or play video games more interactively and immerse themselves in the virtual world[40,41,44].

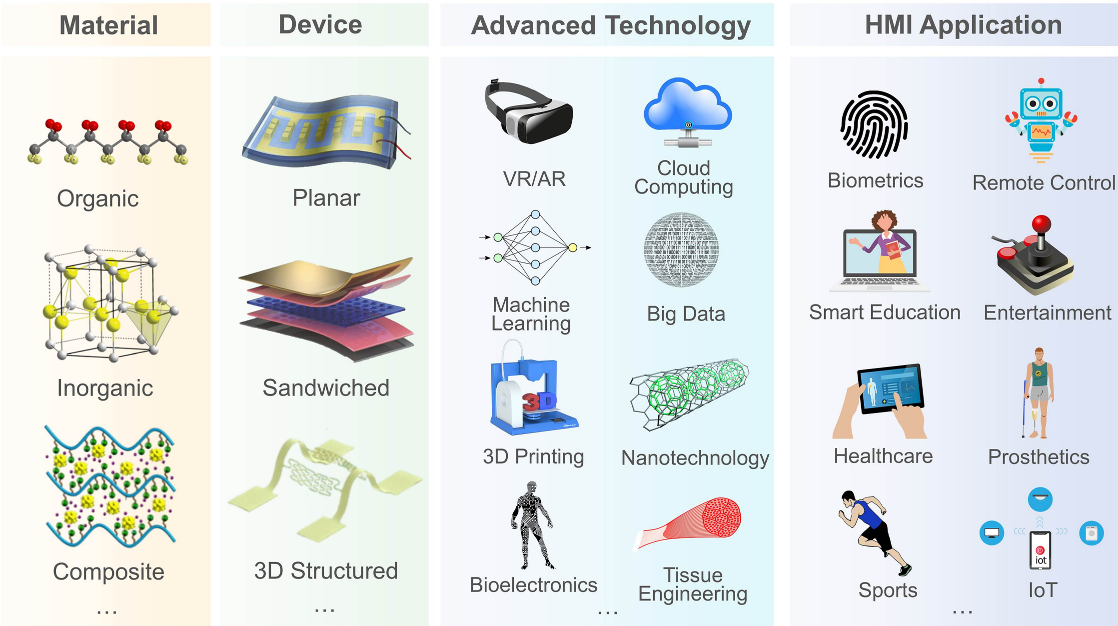


**Figure 7.** Outlook for P-HMIs: from piezoelectric materials to future applications. Reproduced with permission from ref.[98]. Copyright 2008, Elsevier. Reproduced with permission from ref.[99]. Copyright 2009, AIP Publishing LLC. Reproduced with permission from ref.[100]. Copyright 2020, Elsevier. Reproduced with permission from ref.[101]. Copyright 2019, Elsevier. Reproduced with permission from ref.[102]. Copyright 2018, Wiley. Reproduced with permission from ref.[103]. Copyright 2019, Springer Nature.

With the development of cloud computing and big data, wearable P-HMIs can collect human health-related physiological and behavioral information. On this basis, massive amounts of data would be processed and computed on cloud platforms, which could extract more detailed information. Moreover, with high-efficient data analysis on the cloud, applications such as remote smart medical care would be better facilitated in the future[112,113]. Furthermore, benefiting from cutting-edge nanotechnology and tissue engineering techniques, P-HMI will become even more miniaturized and friendly for human bodies. Combined with machine learning and other algorithms, P-HMI with large-scale sensing and feedback shows enormous promise in many fields, such as intelligent diagnostics, smart education, biometrics and so on, which is of great significance for improving the quality and convenience of our daily lives. However, there are still many challenges that must be addressed for P-HMIs to fulfill the above-mentioned smart applications:

(1) The competitive relationship between mechanical flexibility and piezoelectric output has been the focus of research on flexible piezoelectric devices for a long time. How to balance their relationship to obtain high performance for P-HMI needs to be further explored, especially considering the piezoelectric effect for sensing and the inverse piezoelectric effect for actuation in an integrated manner.

(2) Many different working principles can be used for sensing and actuation of HMIs and the fusion of multiple principles is an important development trend. The coupling of different principles expects hybrid flexible HMI devices to exhibit better sensitivity, wider detection range and higher signal-to-noise ratio.

(3) To obtain more accurate and higher-resolution monitoring information, the number of sensors used for HMIs will continue to increase. Along with this, it poses higher challenges for the large-scale preparation of piezoelectric devices and the processing of massive amounts of information.

(4) P-HMIs usually involve multidisciplinary intersections, including materials science, mechanical engineering, electronic technology, biomedical engineering and so on. In the future, scientists and engineers will need more interdisciplinary knowledge to engage in the complicated R&D processes of P-HMIs to advance their practical applications.

In summary, flexible piezoelectric human-machine interactive devices have sparked numerous ideas and thoughts in both academia and industry. Although the fantasies in science fiction would not come true all at once, increasingly more meaningful applications will be realized with the development of P-HMIs. Intelligent HMIs will bring convenience and efficiency to all aspects of our daily lives, raising them to a level we could never have imagined.

## DECLARATIONS

### Authors' contributions

Conceptualization, investigation, wrote the original draft: Liu J
Reviewed and revised the manuscript: Tian G, Deng W
Supervision, project administration, funding acquisition: Yang W, Deng W

### Availability of data and materials

Not applicable.

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### Conflicts of interest

All authors declared that there are no conflicts of interest.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Copyright



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