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Recent Advances in Wearable Sensors and Integrated Functional Devices for Virtual and Augmented Reality Applications

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The advancement in virtual reality/augmented reality (VR/AR) has been achieved by breakthroughs in the realistic perception of virtual elements. Although VR/AR technology is advancing fast, enhanced sensor functions, long-term wearability, and seamless integration with other electronic components are still required for more natural interactions with the virtual world. Here, this report reviews the recent advances in multifunctional wearable sensors and integrated functional devices for VR/AR applications. Specified device designs, packaging strategies, and interactive physiological sensors are summarized based on their methodological approaches for sensory inputs and virtual feedback. In addition, limitations of the existing systems, key challenges, and future directions are discussed. It is envisioned that this progress report's outcomes will expand the insights on wearable functional sensors and device interfaces toward next-generation VR/AR technologies.

1. Introduction

Virtual reality/augmented reality (VR/AR) is an emerging technology that allows a human to obtain artificial information beyond the natural 2D scene by creating immersive environments, from which users can acquire unique perceptions like the real world. The VR attempts to replace the user's awareness of the surrounding world with an artificial 3D environment. At the same time, the AR allows supplementing the real environment with virtual objects and animations. The VR/AR system is based on computer graphics, which can produce virtual elements that the user can perceive and control through various input devices. Many human sensory systems, such as vision, hearing, touch, and even smell, can be employed through output devices to realize immersive engagement during user interaction.[1–3]

The realization of realistic and vivid human senses in VR/AR systems is one of the key factors to immerse users in the virtual world fully. Most of the available VR/AR systems allow only interactive images and sounds, limiting a level of reality due to the lack of perception feedback. Adding sensory feedback based on motion and haptic interactions can realize a natural user interface, promoting the level of immersion into the virtual world beyond the conventional controls with a joystick, keyboard, or pointer. Implementing the physical comfort and realistic feeling of feedback with multifunctional and high-resolution sensors is essential for seamless and natural interactions with the VR/AR systems. For instance, hundreds of nerve fibers detecting transient mechanical events within a few milliseconds-accuracy were integrated with a hand to interact with small objects.[4] Similarly, recent articles deliver quantitative metrics and comprehensive strategies needed for enhanced user interactions. The requirements of wearable haptic electronics to achieve realistic interactions in the VR/AR include low resistivity and soft interconnects linked over a few hundreds of sensors on large body area,[5] advanced signal processing methods for shorter readout latency within milliseconds,[6] and the wireless power transfer with sufficient distance for motion.[7]

A recent innovation in wearable devices presents a solution to resolving this challenge. For example, the integration with advanced functional materials, miniaturized electronics, and flexible/stretchable substrate enables the artificial sensory modules to be soft and mechanically compliant to the human body, showing their user-VR/AR connection through enhanced wearability.[8,9] Assisted with the wearable technology, various developments such as direct physical interaction to a virtual environment using haptic equipment and the feedback system with human physiological signals are demonstrated in the VR/AR domain.[7,10,11] Material selection in the wearable

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system is critical to offer user wearability and required device functionality.[12] Most wearable VR/AR devices still use rigid and bulky components, which prohibits a natural interaction with the soft human body and limits an accurate detection of body signals to control the virtual world. Ideal materials should offer skin-like mechanical properties that minimize mechanical and thermal loading to the body while maximizing user comfort.[13] In addition, soft materials with enhanced breathability and biocompatibility will provide continuous, long-term device use without causing unwanted skin irritation or allergic reactions. Recently, the impact of the VR/AR in human life has been reviewed in a wide range of applications such as smart home,[14] education and training,[15,16] engineering,[1,2,17] heritage and tourism,[18] medical and healthcare,[19] and usability.[3] However, these works have focused on how the VR/AR technology can be applied in specific fields with limited scopes. Moreover, most recent reviews regarding VR/AR devices have been limited to the topics in visualization techniques.[20,21]

Here, this progress report introduces the recent progress in wearable sensors and integrated functional devices that can enable immersive user interaction with the VR/AR environment. Sections include summaries on various sensory inputs and their feedback system, categorized by vision, motion, touch, physiological signals, and haptic feedback technologies (**Figure 1**). The development of mobile VR/AR systems and their state-of-the-art technology are described according to their overall design, form factor, materials, and interaction mode with the virtual environment. Lastly, outlooks toward the future development of the VR/AR are discussed.

2. Development of VR/AR Environments

Although VR/AR has recently become popular, the technology has been around for a long time. People have been using mirrors, lenses, and light sources to create virtual images in the real world.[22,23] The miniaturization of microelectronics and displays enables the mobile VR/AR on smartphones and tablets.[24] These mobile devices use cameras to detect and track motion, allowing users to experience VR/AR during locomotion. Although most systems are not sensitive enough to register subtle finger movements, the technology is becoming increasingly powerful to allow the user to better connect with the virtual environment and to provide a more immersive experience with intuitive controls.[25,26]

This section summarizes the significant achievements in the development of VR/AR systems. The first computer-generated AR experience was introduced by a computer graphics and immersive interface pioneer, Ivan Sutherland.[27,28] He created the first AR system, which is also the first VR system, as shown in **Figure 2**A. It uses an optical see-through, head-mounted display with a ceiling-mounted tracking system. Later, the sophisticated tracker is replaced by an ultrasonic system. Therefore, the system with the required display, tracking, and computing elements provides an AR experience by creating 3D graphics that appear overlaid on the real world. However, this primitive system can only offer simple wireframe drawings in real-time due to the limited processing power. Also, the system is not portable due to many different components connected by wires. Early wearable VR/AR systems have emerged with the development of

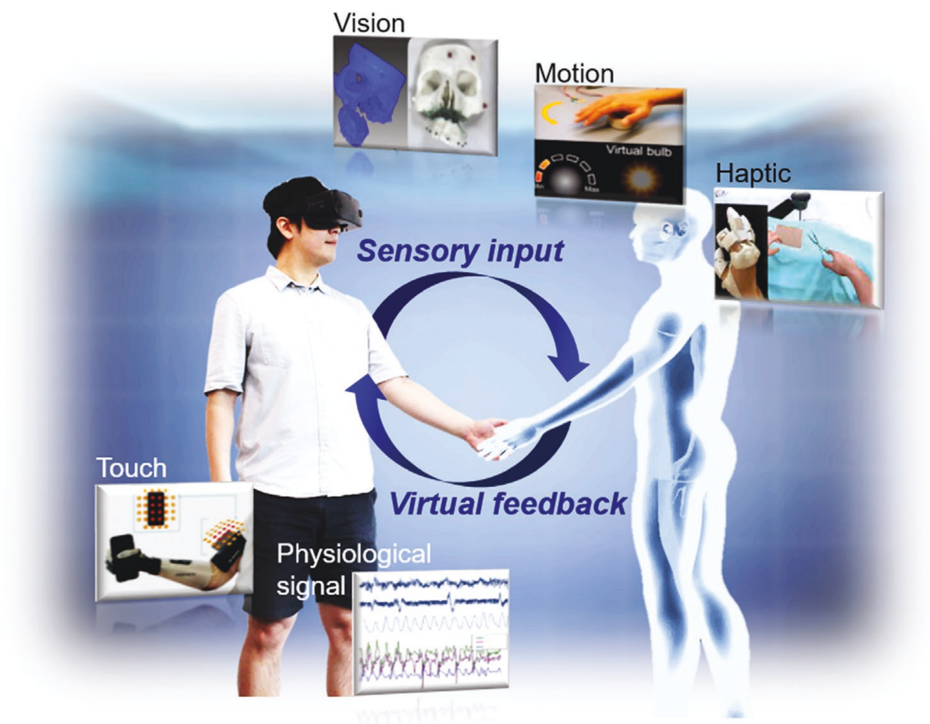

Figure 1. Overview of the applications of wearable sensors and integrated systems in VR/AR. Vision image: reproduced with permission.[33] Copyright 2014, Elsevier. Motion image: reproduced with permission.[25] Copyright 2018, American Association for the Advancement of Science. Haptic image: reproduced with permission.[44] Copyright 2020, American Association for the Advancement of Science. Touch image: reproduced with permission.[7] Copyright 2019, Nature Publishing Group. Physiological signal image: reproduced with permission.[54] Copyright 2019, IEEE.

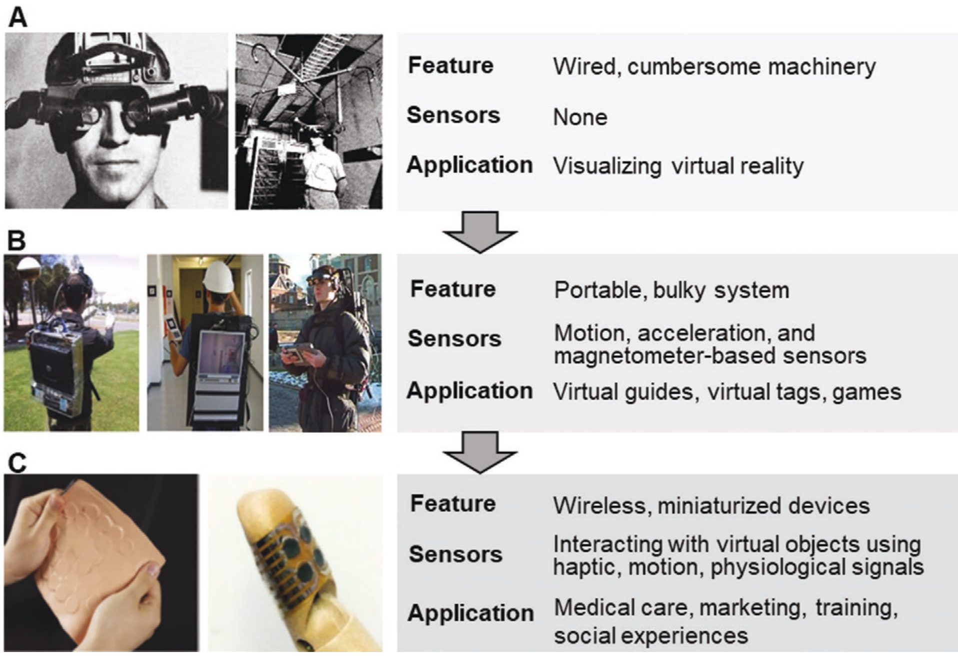

Figure 2. Development of VR/AR environments. A) Initial technologies developed for implementing VR/AR. Reproduced with permission.[27] Copyright 2015, TUG. B) Mobile VR system integrated with a portable sensor system. Reproduced with permission.[27] Copyright 2015, TUG. C) The recent development of smart glasses and soft electronics for VR/AR applications. Left image: Reproduced with permission.[7] Copyright 2019, Nature Publishing Group. Right image: Reproduced with permission.[37] Copyright 2019, Nature Publishing Group.

wearable computers.[22,29,30] With a wearable computer, a head-mounted display is employed for information visualization, and various sensors are integrated for more interactive experiences (Figure 2B). However, these early wearable examples are very bulky and heavy due to the size of the customized computer hardware, tracking sensors, display, and batteries.

Recent advances in functional materials, microelectronics, and electronics packaging have led to portable, user-friendly, and wireless VR/AR devices. The AR smart glasses are eyewear combined with miniaturized electronics to merge what you see in the real world with virtual information. Thus, users can continue to operate within their environment without distractions or obstruction. Although there are many smart glasses available in the market, only a few products have integrated VR/AR with gesture and voice control capabilities.[21] The gesture control makes it possible for the user to interact with the system in noisy environments. As a result, the AR smart glasses have been identified as a vital technology that allows manipulators to conduct various tasks such as assembly, material handling maintenance, and quality control. Figure 2C presents wearable electronic skin (e-skin) for VR/AR applications. The e-skin can enable the users to manipulate software constructed objects that exist in the augmented and virtual world. This system allows for detailed movement detection without the need for extra accessories. Between the e-skin sensor and the VR/AR system, complex interactions can be performed. At the same time, a physical, real-world object is supplemented by the content data appearing in the VR. The smart glasses and wearable electronics combined with VR/AR compatible technologies are becoming more accessible, allowing users to smell, taste, and touch objects in the virtual world.

3. Recent Progress of Wearable Sensors and Functional Devices for VR/AR Applications

This section summarizes the latest, selective literature of wearable devices utilized in VR/AR technology. Unique device designs and development strategies are categorized based on human sensory such as vision, haptic, motion recognition, and physiological signals. **Table 1** summarizes recent examples of wearable systems for VR/AR applications.

3.1. Vision Interactive Devices

Vision detection is the most widely used method in the VR/AR applications. A graphical display system is typically essential for vision-based interactive devices, which is applied on a head-mounted or see-through platform integrated with a global positioning system, accelerometer/gyroscopic sensors, and radiofrequency identification modules.[21,24] A video camera that captures the visual inputs is the main component of a vision-based VR/AR system, providing the correct positioning of virtual objects on the screen.

Figure 3A shows a wearable real-time AR system "AR-Mentor" that offers maintenance assistance and repair works of complex machinery.[31] This system with a wearable display integrates a 6-degree-of-freedom pose tracking sensor, the virtual personal assistant (VPA), and verbal conversational interaction, guiding the user via visual, audio, and locational signs (left image). A microphone captures speech while an inertial measurement sensor monitors a user's position and action. The audio and video feedback is used to identify the user

Table 1. Summary of recently developed wearable systems for VR/AR applications.

Ref.	Interaction type	Input device	Feedback device	Environment	Application
[31]	Vision and audio	6-degree-of-freedom (DOF) tracking sensor and microphone	See-through display	AR	Assist in maintenance and repair tasks of complex machinery with guiding the user in the form of visual, audio, and locational cues
[32]	Vision	Time-of-flight depth sensor	Head-mounted display (HMD)	VR	Detect fingertips with locations, touching the skin, or hovering
[33]		Cameras and image sensor	See-through display	AR	Assist maxillofacial bone surgery by calculating the positions of markers on the object relative to camera data
[34]		Skin-like open-mesh EOG sensors	HMD	VR	Tracking eye movements measuring EOG for vision therapy
[35]	Vision and motion	Eye tracker, handheld clicker, and gyro sensor	See-through display	AR	Demonstrating precise, multimodal selection techniques using head motion and eye gaze
[25]	Motion	Magnetic field sensors with ultrathin foils	Virtual screen	VR	Magneto-sensitive skins with the directional perception that enables magnetic cognition, body position tracking, and touchless object manipulation
[39]		Strain and acceleration sensors on a shirt	Virtual screen	VR	Monitoring and estimating 3D human motions by measuring strain on a shirt
[26]		Triboelectric glove	Virtual screen	AR	Triboelectric human-machine interface for improving readout sensitivity
[38]		Triboelectric glove	Virtual screen	VR/AR	Self-powered triboelectric textile in sweat condition
[37]	Motion and tactile	Flexible, thin pressure and magnetic field sensors	Virtual screen	VR	Electronic skin with tactile and touchless perceptions for the manipulation of real and virtual objects
[7]	Tactile	Touch screen	Skin-like actuators with an elastomer	None	Skin-integrated, battery-free, wireless, 32 independently controlled tactile interfaces
[45]		Optical motion tracking sensor and voltage-induced force	Soft electroactive polymer-based tactile display on a finger and virtual screen	None	Soft wearable non-vibratory tactile displays
[43]	Haptic	Motorized 2-DOF haptic device on the finger	HMD or see-through display	VR/AR	Combination of tangible objects and wearable haptic device for improving the display of stiffness sensations in virtual environments
[44]		Triboelectric-based finger bending sensors, palm sliding sensor, and piezoelectric sensor on smart glove	Virtual screen	VR	Haptic-feedback smart glove
[54]	Physiological signals	ECG, EEG devices, accelerometers, and piezo-resistive fabric sensors	HMD	VR	Detecting meditation levels by physiological feedback
[55]		HMD	EEG, EDA, and heart rate devices	VR	Automatic fear level detection for acrophobia therapy
[56]	Physiological signals and audio	Microphone, eye gaze tracker, and EDA device	HMD and heart rate device	VR	Public speaking training with a multimodal interactive virtual audience

EOG: electrooculograms, ECG: electrocardiograms, EEG: electroencephalograms, and EDA: electrodermal activity.

position with the tool and gaze direction (bottom right image). The user information produced by the VPA on AR interactions is delivered to the virtual rendering system, generating animations that precisely coordinate with the user's perspective view as overlays in the display (top right image).

Figure 3B indicates a novel sensing approach to assist on- and above-skin finger interactions with VR/AR.[32] This system, called WatchSense, utilized a small time-of-flight depth sensor implanted in a wearable device to enlarge the input area to the human skin and the space above it. The authors addressed the limitation of camera-based trackings, such as oblique viewing angles and occlusions. The proposed device showed the detection of fingertips, their locations, and whether they are touching or hovering above the skin (top image). It enabled a 3D input on the hand functioning real-time on conventional mobile devices with several interactive applications, including virtual controls, remote commands to a smartwatch, and joystick control for gaming (bottom image).

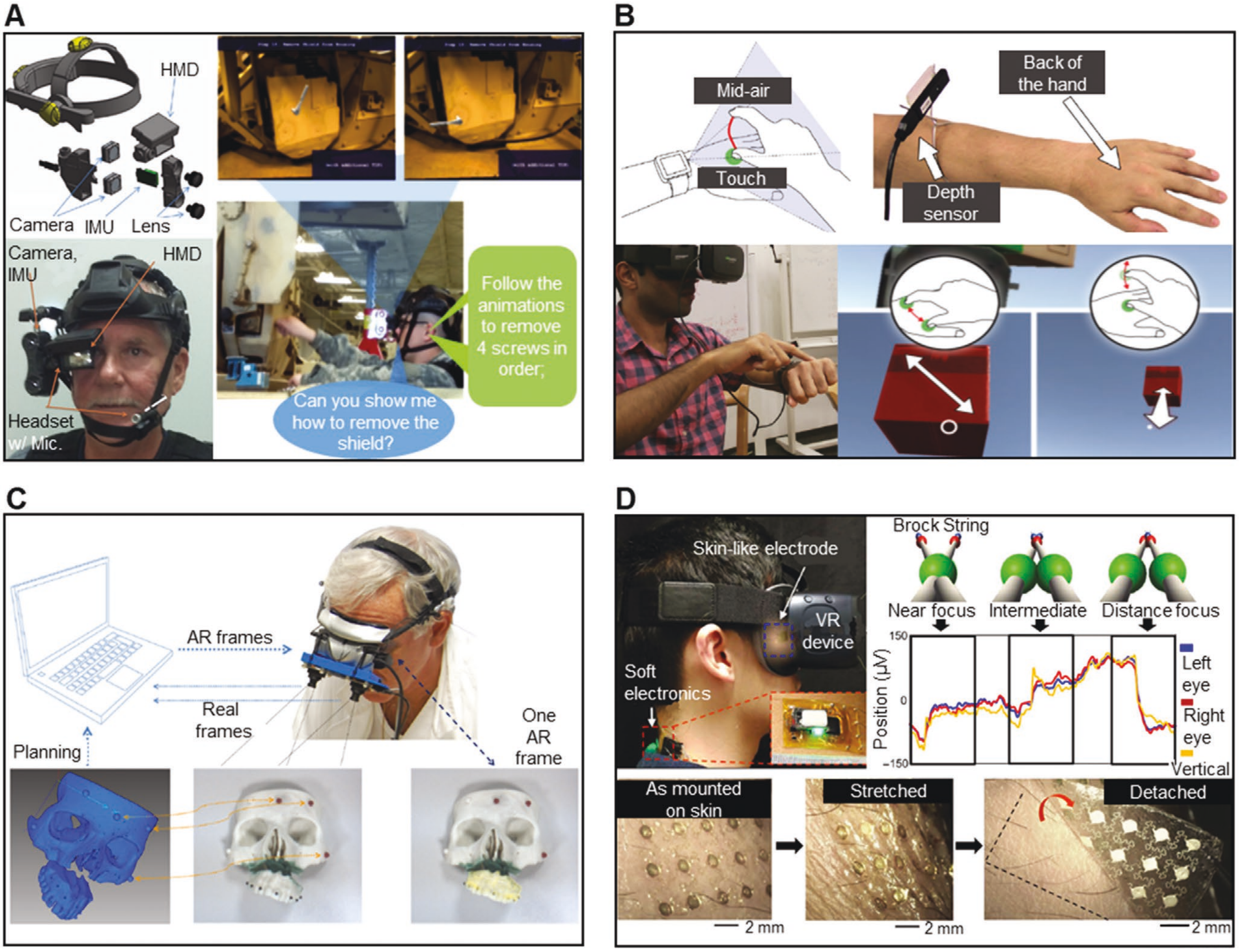

Figure 3. Vision interactive wearable devices for VR/AR applications. A) Wearable real-time AR system that is configured to assist in the maintenance and repair tasks of complex machinery. Images showing the wearable (HMD), including camera and microphone (left). The audio and video feedbacks as overlays on display (right). Reproduced with permission.[31] Copyright 2014, IEEE. B) On- and above-skin finger input for interaction on VR/AR. Working principle of 3D input space on the back of the hand (top) and the virtual operating control (bottom). Reproduced with permission.[32] Copyright 2017, Association for Computing Machinery. C) Localizer-free, head-mounted wearable system facilitating AR as a video-based wearable device to assist maxillofacial bone surgery. Reproduced with permission.[33] Copyright 2014, Elsevier. D) EOG-recording wearable soft electronics for periocular therapeutics. Images of the wireless soft electronic system (top left) with operating VR and EOG signals (top right). Skin-like electrodes that are attached to the skin (bottom). Reproduced with permission.[34] Copyright 2020, American Association for the Advancement of Science.

Figure 3C shows a localizer-free, head-mounted wearable system with AR as a video-based device, assisting a maxillofacial bone surgery.[33] A lightweight, stereoscopic head-mounted display consisted of two cameras, and an image sensor was located in front of the user's eyes. Surgical accuracy was monitored with the navigation system's support recorded the matches of three beacons located on the repositioned maxilla in the AR system. Precise alignment between the real and virtual objects was achieved without an external tracking system by calculating colored beacon locations compared to camera data and computerized tomography images.

Figure 3D introduces a fully portable, wireless soft electronics that enables a sensitive tracking of eye movements (vergence) for vision therapy via the combination of wearable ocular sensors measuring (EOG) and VR.[34] The VR system visualized continuous movements of multiple objects in three varying depths of near, intermediate, and distance of eye motions, allowing portable ocular therapeutics without utilizing physical apparatus. A flexible circuit, encapsulated in a soft, adhesive elastomer, was attached to the user's neck without adhesives or tapes (top left image). The EOG system consisted of mesh-like electrodes mounted on the skin near the eyes, which enabled noninvasive eye potentials. Due to the remarkably thin feature, the electrodes could cover with the human nose's contoured surface and nearby eyes and secured under a VR headset (bottom image). The wearable AR device that simultaneously monitors multimodal signals can provide a more precise manipulation of virtual objects using a second input mode for refinement. For example, using eye gaze interactions as an input mode has excellent potential for its innate ability without the need for extra carrying equipment; however, the need to carry systems necessary for physiology monitoring and motion tracking still remains. Such a drawback was addressed by adapting multimodal pointing refinement techniques for precision target selection in the AR by combining the eye gaze and head pointing with hand gestures, handheld clicker devices, and scaled head movement.[35] The authors explored "pinpointing" techniques consisting of a primary pointing motion and secondary refinement using the presented layout, including target markers, feedback cues, and viewing field. Their functional demonstration showed that the eye-based techniques leveraged concentration and convergence signs when interacting with smart objects or 3D visualizations. The achieved precision of pinpointing allowed deep menu structures in a browser to be compressed in a small space, enabling the control of humidity and temperature sensors selected with the little yellow dot.

3.2. Motion Interactive Devices

Motion interactive VR/AR devices can have tactile and touchless interaction for manipulating real and virtual objects in the gaming industry, business, safety, and medical applications. Recent advancements in the e-skin study of artificial receptors, multimodal sensors, and human-machine interfaces technologies have enabled complex interactions toward prospect personal appliance without numerous regulation knobs and physical "clicks."[36] Assuring the user experience for interfacing between such wearables and supplemented reality requires the e-skin devices to be soft, lightweight, and mechanically compliant and selective in their response to objects of interest, capable of discriminating the desired interaction modes in real-time. Here, we introduce representative examples of the motion interactive devices for promising applications. Conventional optical-based VR/AR systems have an insufficient resolution, in that they rely on optical detection of moving body parts via camera arrays, accelerometers, and image processing.

Touchless manipulation of virtual objects was recently realized by developing magneto-sensitive skins using finger/palm motions instead of optic-based somatic manipulation (**Figure 4**A).[25] The e-skin system was combined with magnetic field sensors, i.e., proximity sensors, imitating both the touching and turning functions. The ultrathin, skin-like sensors (top images) were mechanically imperceptible and temperature stable, designed by a 2D magnetic field sensor. Transfer printing and aligning in two Wheatstone bridges of the sensors, of which multilayer spin valve stack comprises heterostructure, allowed for discriminating between the x and y in-plane components of the magnetic field. No crack or layer stack delamination was observed within the layers upon mechanical bending. Such remarkable mechanical performance assures the device conformability required for on-skin applications. As a demonstration, the authors realized a light-dimming application of a virtual bulb (bottom images). The virtual dialing pads were based on a plastic ring-like support with a permanent magnet in the middle using one of the angle sensors fixed to a user's palm. Moreover, the devices operate at low power in conjunction with permanent magnets. Possible motion-light translation applications include motion tracking in robotics, regenerative medicine, navigation, sports, and gaming interaction.

In another application, bio-functional e-skins were developed by equipping with a compliant magnetic microelectromechanical system (m-MEMS) capable of transducing both tactile and touchless simulations in a single wearable sensor platform (Figure 4B).[37] The complexity involved with perceiving both inputs was successfully decreased by a distinguishable bimodal sensing principle that allowed the discretion of signals from both interactions into two non-overlapping regions. In specific, the magnetic touchless sensing enabled a signal-programmable manipulation of the magnetic items of m-MEMS. Also, m-MEMS allowed for complex interactions with a magnetically functionalized physical object. Two major components of m-MEMS include: i) a soft frame based on a PDMS rubber accommodating a thin compliant magnet with a pyramid-shaped extrusion, and ii) a high performance flexible magnetic field sensor, depending on the giant magneto-resistive effect, presented on a 20 µm-thick flexible foil (left images). In this way, the resistance from tactile and touchless interactions was separated by adjusting the magnetic beacons′ field in polarity and strength. The authors demonstrated the m-MEMS platform to detect an object of interest and to arouse a pop-up menu, interacting with its content depending on a combination of gestures and physical pressing. The interactive e-skin device is compact and soft enough to wrap around the skin of the fingertip, enabling complex interactions with a functionalized region on a glass in the VR as well as swiping over the virtual knob in a touchless way (right images). The presented e-skin with the multimodal interaction capabilities are expected to bring benefits for highly compliant human-machine interfaces, healthcare, and humanoid robots.

High power consumption of wearable devices that require the continuous operation of sensors and onboard electronics limits the period of device operation. Independent and self-sustainable systems are possible solutions for the continuous use of wearable devices. Figure 4C shows a triboelectric human–machine interface (THMI) using high-speed nanophotonics for sensitive readout.[26] The authors propose the THMI system with nanophotonic aluminum nitride (AlN) modulators, composed of a micro parallel-plate capacitor sandwiching of AlN, enabling stable, real-time human–machine interaction and motion recognition. The mechanical deformation, caused by an applied force, is converted to an electrical signal through triboelectrification and then transduced into a photonic signal for human–machine interactions (top image in Figure 4C). This work demonstrates an AR-enabled flower planting with smart THMI gloves. Discrete actions in the flower planting process are defined by different gestures (bottom image in Figure 4C), which shows the device performance with high temporal resolution. The same research group reported a self-powering wearable glove that is composed of conductive superhydrophobic textiles for gesture recognition.[38] The triboelectric textile was designed to harvest biomechanical energy from human motion. The wearable glove with an integrated superhydrophobic textile demonstrated a highly accurate control of VR/AR by finger motions with machine learning. The accuracy of recognition was slightly declined in sweat conditions (99.4% to 96.9%) due to the device's superhydrophobic capability.

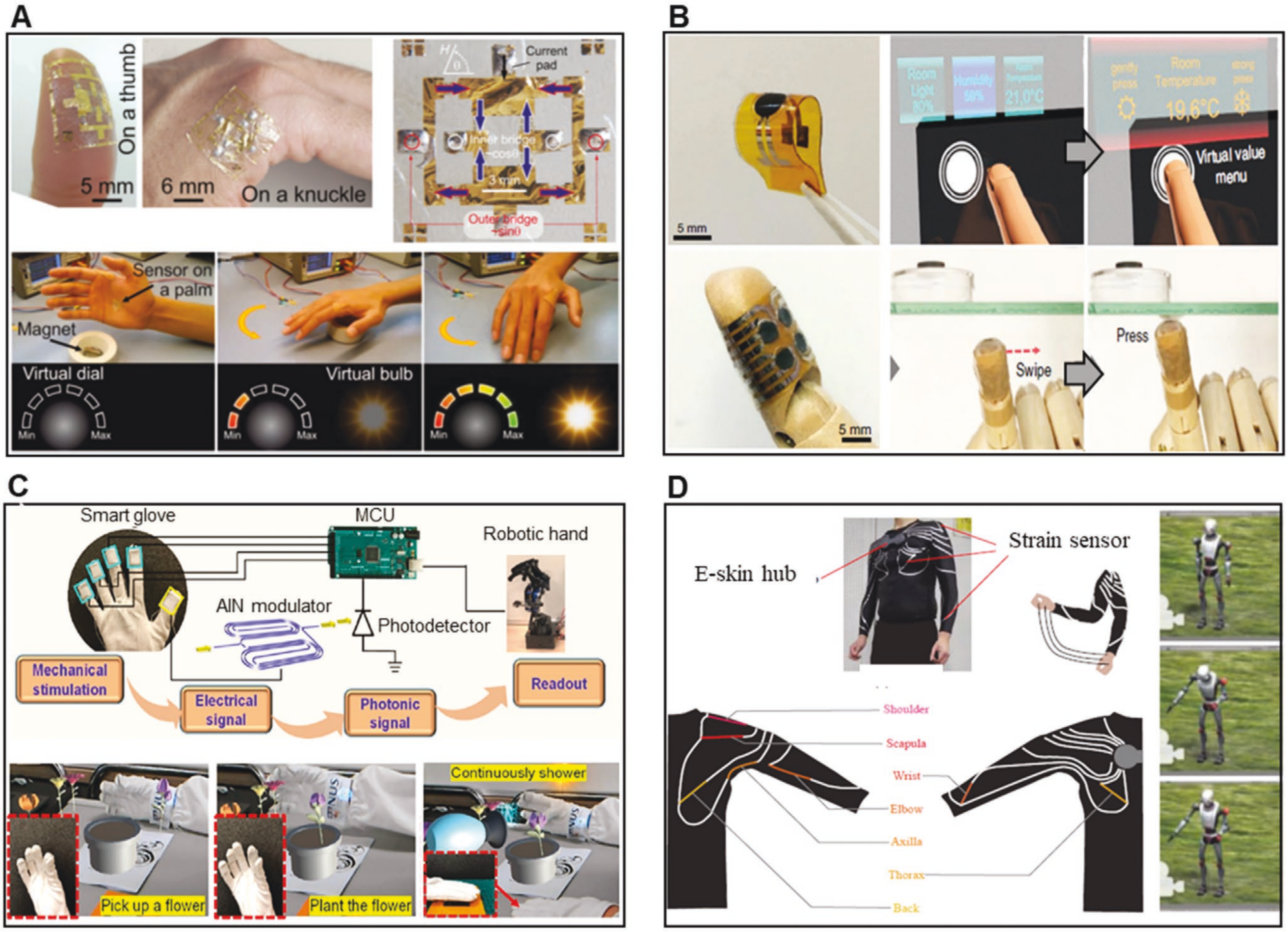

Figure 4. Motion interactive wearable devices for VR/AR interactions. A) Touchless manipulation of virtual objects by developing highly compliant magneto-sensitive skins. The ultrathin, skin-like sensors combined with magnetic field sensors (top). Demonstration of a light-dimming application of a virtual bulb (bottom). Reproduced with permission.[25] Copyright 2018, American Association for the Advancement of Science. B) Proximity and pressure sensing with flexible on-skin device for tactile and touchless simulations. Biofunctional e-skins equipped with a compliant magnetic microelectromechanical system (top left) mounted on finger replica (bottom left). Demonstration to activate a pop-up menu and interact with its content relying on a combination of gestures and physical pressing (right). Reproduced with permission.[37] Copyright 2019, Nature Publishing Group. C) Wearable triboelectric human-machine interface using robust nanophotonic aluminum nitride modulators (top) and AR flower planting with smart gloves (bottom). Reproduced with permission.[26] Copyright 2020, American Chemical Society. D) Strain sensors-mounted wearable shirt-type e-skin device (left). Demonstration of a visualized care-working motion (right). Reproduced with permission.[39] Copyright 2019, IEEE.

Another requirement for the VR/AR is to monitor 3D human motions for extended periods. Although acceleration sensors and optical capture systems have been used to measure behavioral patterns, it is hard to estimate the detailed motion patterns for monitoring of human life without cumbersome setups. As one of the promising methods, a suit-type e-skin fits the human body with strain sensors without impeding movements. Figure 4D shows an overview of the suit-type device, where 14 strain sensors are located around the scapulae, shoulders, elbows, axillae, wrists, thorax, and back (left image).[39] By establishing and evaluating the regression model of a convolutional neural network, the e-skin could estimate the joint angles of the upper human body. The authors demonstrated the measurement of a care-working motion and visualized the movements (right images). The participant stretched the arms to pull a person to the bedside (transfer task 1) and placed his arms in front of his chest to hold the body (in task 2 and task 3). Despite its high error values in moving joints, the wearable textile e-skin is a noteworthy approach for estimating the human body motion in caretaking and healthcare applications.

3.3. Haptic and Force Feedback Devices

Haptic and force feedback interface is one of the essential components to receive a tactile response when interacting in VR/AR.[40–42] This section summarizes recent work in haptic and force feedback VR/AR systems, whose key functionalities are enabled by various wearable sensors and their applications as a smart glove, prosthetic control, and tactile display.

Figure 5A shows the wearable haptics to improve the display of stiffness sensations in virtual environments.[43] The haptic device comprises two servo motors, a fabric belt, and a strap

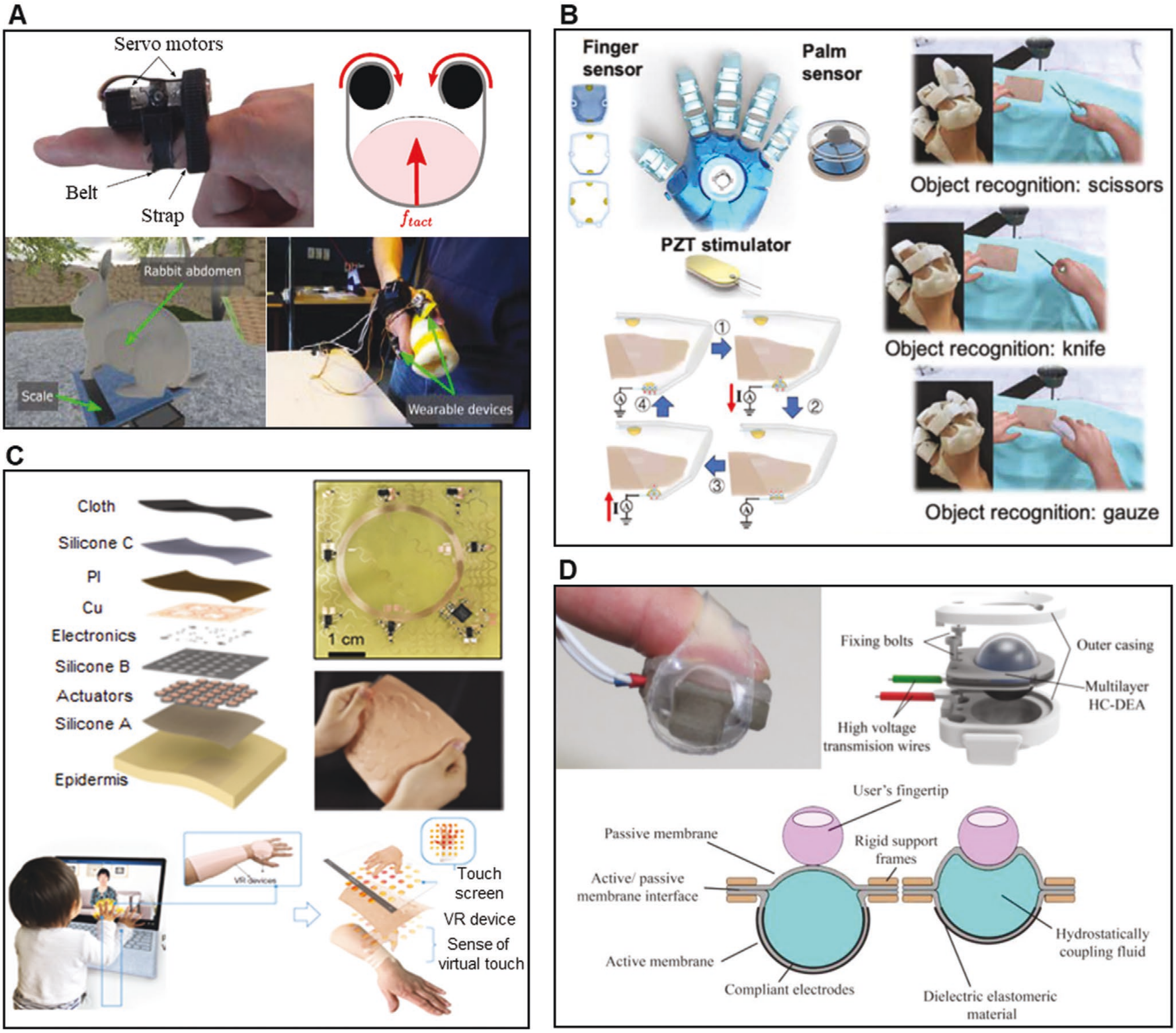

Figure 5. Haptic and force feedback wearable devices for VR/AR applications. A) Wearable tactile modules interacting with tangible objects. Images showing the prototyped wearable haptic device (top left), the actuation principle (top right), VR scene (bottom left), and the interaction between the tangible object and the haptics (bottom right). Reproduced with permission.[43] Copyright 2018, IEEE. B) Triboelectric and piezoelectric haptic-feedback glove. Schematics of wearable haptic glove (bottom left) and working principle (bottom left). Developed device applied to the surgical training program (right). Reproduced with permission.[44] Copyright 2020, American Association for the Advancement of Science. C) Wireless epidermal haptic system. Design and architecture of an epidermal VR system (top left). Optical image of an epidermal VR device under twisting (top right). Example of application of epidermal VR system to the social media (bottom). Reproduced with permission.[7] Copyright 2019, Nature Publishing Group. D) Soft wearable non-vibratory tactile displays. Side view of the fingertip mounted display (top right). Schematic illustration showing the HC-DEA tactile display with the outer casing and the high voltage supply wires (top right). The bottom image shows the principles of basic HC-DEA tactile display with voltage on (left) and the rest (right). Reproduced with permission.[45] Copyright 2018, IEEE.

band to attach the device on the finger (top left image). When two servomotors spin in opposite directions, the belt is pulled up or down, applying a varying force normal to the finger (top right image). In contrast, the belt provides a shear force to the finger when motors rotate in the same direction. The bottom pictures show the example of the haptic device's stiffness perception showing the interaction between the VR scene and tangible objects. The user wearing two tactile devices on the fingers can move a rabbit from a basket to a scale (bottom left image) and pet it by holding the tangible object (bottom right image). As the rabbit breathes, the shape and stiffness of tangible objects vary, allowing the users to feel these changes through wearable tactile devices.

Figure 5B introduces the haptic feedback smart glove with triboelectric-based finger bending sensors, palm sliding sensors, and piezoelectric mechanical stimulators (top left image).[44] The contact electrification generates the triboelectric output for both finger and palm sensors during the interaction between the positive skin and negative elastomer. The sensor is in a neutral state at the original state. Simultaneously, the positive skin surface neutralizes the negative sensor surface at the contact and causes the previous positive charges on the electrode to be repulsed to the ground (bottom left image). Eventually, the detection of multidirectional events (sliding and bending) of the haptic-feedback glove is visualized in the VR/AR. Right images in Figure 5B describe an example of VR demonstrations showing the surgical training program. The classified hand gestures from the haptic device allow the intended object recognitions, including the scissors, knife, and gauze.

Figure 5C reveals wireless, battery-free platform of electronic systems and haptic interfaces for the VR/AR.[7] The soft electronic device for an epidermal VR interface includes the functional multilayer: 1) a thin elastomeric layer as a soft, adhesive interface to the human skin, 2) a silicone-encapsulated functional layer that supports a wireless control system, power, and actuators, and 3) a breathable, stretchable fabric as a skin-conformal supporting substrate with strain-limiting mechanics to avoid damages. The fabricated epidermal system shows mechanical compliance under twisting (top right image). Bottom images summarize a potentiality in virtual social interactions. A girl virtually touches her grandmother's hand by wearing the VR device through an interface on the laptop screen. The grandmother experiences a haptic sensation on a spatiotemporal pattern of the touch, which matches that of the girl's fingertips on the touch screen's image.

Figure 5D provides the wearable fingertip tactile displays with a hydrostatically coupled dielectric elastomer actuation (HC-DEA) technology.[45] The tactile display can be secured to the fingertip with a silicone strap (top left image). The active and passive actuators are multi-layered with an acrylic elastomer film biaxially pre-strained by 350% and integrated within a plastic outer casing (top right image). The bottom image shows HC-DEA's schematic structure to provide the stimuli to the finger pad. When a voltage is applied to the active membrane's electrodes, the consequent surface expansion causes it to buckle outward (bottom left), compared to at rest (bottom right).[46] These achievements would make VR/AR systems possible implementations to mimic tactile interactions with virtual soft bodies.

3.4. Physiological Signal Interactive Devices

Human physiological signals include brain activity (EEG), cardiac systole-diastole cycle (ECG), muscle health (EMG), skin conductance (EDA), and breathing patterns. Recording of these signals can provide clinical cues about the physical activities and health conditions of the subjects.[47,48] For example, EEG shows the complex neural activity for studying neurological disorders.[49] ECG signals from the heart give the information of normal cardiac function.[50] EMG data offers the recognition of the nerve and muscle activity,[51,52] and EDA provides clinical insight such as the sympathetic arousal and cognitive states.[53] A recent VR/AR system based on the sensors for measuring the physiological parameters allows the subject to treat and train numerous disorders or therapies by providing the neurofeedback.[54–56]

Figure 6 shows a collection of examples of the physiological signal interactive wearable device for VR/AR systems. Four different sensors, including EEG, ECG, breathing, and motion activity, can measure relaxation, focus, and meditation levels of the subject in conjunction with real-time VR/AR technologies (Figure 6A).[54] Noninvasive EEG activity indicates the change in the subject's concentration level during relaxation and meditation. The electrical activity of the heart allows the monitoring of the heart rate and variability, leading the relaxation. The respiration rate measured by the piezo-resistive fabric sensors is one of the clear indications of relaxation, which is directly correlated with the meditation level. Activity monitoring based on the accelerometers provides useful information in focus level during the meditation. The measured physiological signals are wirelessly transmitted, extracted, and dynamically mapped to real-time meters that reveal concentration and relaxation levels. The estimated concentration and relaxation levels are then fed back into a central controller unit. Finally, the subject experiences the optimized scenic visual feedback for the meditation through a VR headset and the final score on the overall quality of the meditation.

Figure 6B captures the use of the VR/AR system and wearable bio-potential sensors for treating acrophobia.[55] Previous treatment for the phobias is focused on drugs and cognitive behavior therapy to modify the patients′ destructive behavior patterns.[57] However, this VR system combined with wearable multimodal sensors of EEG, EDA, and heart rate serves precise treatment of acrophobia by automatically adapting the exposure scenarios according to the subject's fear ratings: 0—relaxation, 1—low fear, 2—medium fear, and 3—high fear. Top images in Figure 6B show the user wearing a VR headset during virtual exposure equipped with the physiological signals monitoring. Deep learning algorithms predict the personal fear scales based on the multimodal sensory data through the virtual environment views from the ground floor to the building rooftop (bottom image). This system for treating the acrophobia can be used in clinics, for home- and self-therapy. Figure 6C introduces public speaking training with a multimodal interactive virtual audience framework.[56] Nonverbal communication, including speech tone, posture, and eye contact, is a crucial communication skill for many professions and in everyday life.

4. Conclusions and Outlooks

This progress report summarizes the most recent technology updates in wearable sensors, integrated electronics, and functional VR/AR systems. We review various techniques that offer human sensory feedback while enhancing user interactions with virtual content. Wearable sensory devices to receive cognitive and affective feedback allow new opportunities for real-time and continuous interfacing with VR/AR environments. Although various methods tracking physiological signals have been utilized to detect vision, they still need additional voice recognition for accurate control of VR/AR functions. The embodiment of a natural and realistic feeling of sensing feedback is essential for seamless interaction in the VR/AR systems.

Recent wearable sensors that detect motion, touch, and force can provide advanced user engagement with the virtual world. The acquisition of simultaneous feedback from multiple

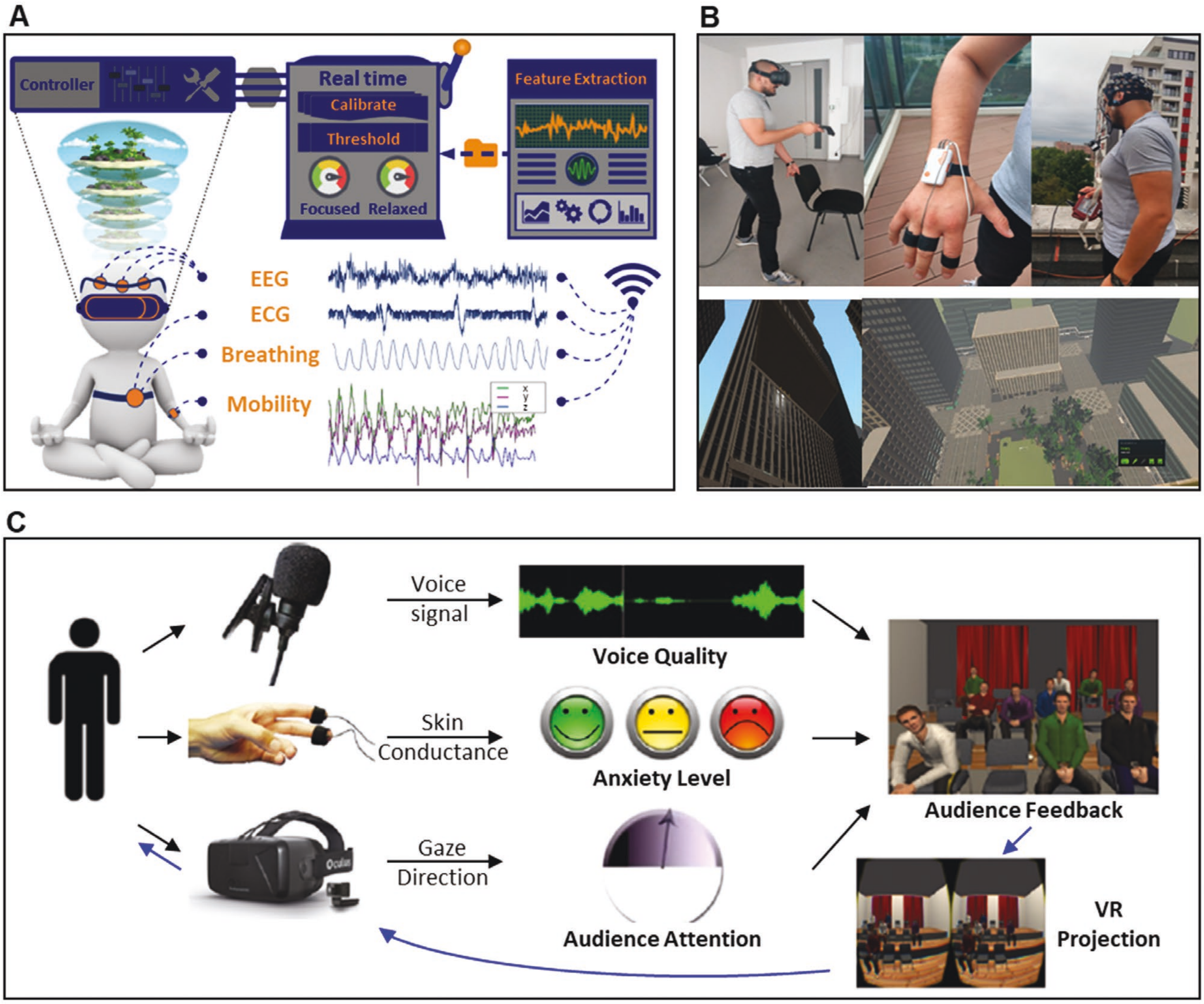

Figure 6. Wearable sensor systems that record physiological signals for VR/AR interactions. A) Real-time extraction of EEG, ECG, breathing, and mobility for detecting meditation levels. Reproduced with permission.[54] Copyright 2019, IEEE. B) Automatic fear level detection for acrophobia virtual therapy. Photos showing the users wearing the wearable physiological sensors and VR headset (top). Visualized scenes from the VR device (bottom). Reproduced with permission.[55] Copyright 2020, MDPI. C) An interactive virtual audience platform with multimodal wearable sensors, including the voice, skin conductance, and gaze. Reproduced with permission.[56] Copyright 2015, ACM Publications.

multifunctional electronics sensors will improve the consensus with the VR/AR. Development of miniaturized computing, more efficient wireless powering, and intelligent data processing methods will require wiring across multiple sensors, allowing continuous and long-term usage of the portable system. Recent work[6] shows a neuro-inspired artificial peripheral nervous system that enables simultaneous transmission of thermotactile information with low readout latencies and rapid tactile perception for scalable e-skin. For example, a recent report[58] demonstrates a wireless body-sensor network based on metamaterial textiles, which shows efficient wireless communication and power transfer. The wearable system integrates conductive fabrics to enhance data transmission efficiencies by three orders of magnitude higher than conventional radiative networks. Recent examples[59,60] that use the wireless powering based on the energy harvesters and magnetic resonant coupling show implantable biosensors with battery-free, wireless, and multimodal sensing capabilities.

The ergonomics approaches, considering numerous human factors, could become critical elements in wearable VR/AR devices. Integration with soft material-based sensing components will intensify the functionality and applicability for the VR/AR, providing a natural interactive interface. Future works should focus on the collaborative, multi-user VR/AR environments such as virtual gaming and meeting scenarios, where users can share and interact with multiple people similar to the physical environment. The barrierless world between the virtual and real environment will be implemented to the next-generation human life to advance wearable functional technologies.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

augmented reality, integrated functional devices, virtual reality, virtual sensory feedback, wearable sensors

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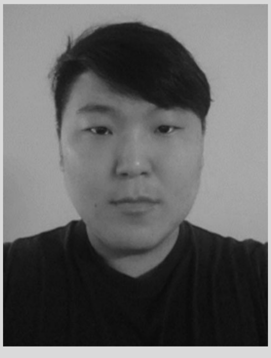

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