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Recent Advances and Opportunities of Active Materials for Haptic Technologies in Virtual and Augmented Reality

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Virtual reality and augmented reality (VR/AR) are evolving. The market demands and innovation efforts call for a shift in the key VR/AR technologies and engaging people virtually. Tele-haptics with multimodal and bilateral interactions are emerging as the future of the VR/AR industry. By transmitting and receiving haptic sensations wirelessly, tele-haptics allow human-to-human interactions beyond the traditional VR/AR interactions. The core technologies for tele-haptics include multimodal tactile sensing and feedback based on highly advanced sensors and actuators. Recent developments of haptic innovations based on active materials show that active materials can significantly contribute to addressing the needs and challenges for the current and future VR/AR technologies. Thus, this paper intends to review the current status and opportunities of active material-based haptic technology with a focus on VR/AR applications. It first provides an overview of the current VR/AR applications of active materials for haptic sensing and actuation. It then highlights the state-of-the-art haptic interfaces that are relevant to the materials with an aim to provide perspectives on the role of active materials and their potential integration in haptic devices. This paper concludes with the perspective and outlook of immersive multimodal tele-haptic interaction technologies.

1. Introduction

Virtual and augmented reality (VR/AR) technology provides interactive visual and auditory experiences in a simulated virtual world or a computer-enhanced real environment. With the aid of technological advancements in graphics and computing technologies, the VR/AR industry has grown rapidly over the past decades. The VR/AR market has also expanded to various industry domains, such as tele-manipulation, medical/military training, virtual collaborative product design, smart manufacturing, gaming entertainment, and product advertising. In addition, it has become a dynamic emerging technology in today's interactive computing with advances in computer graphics, sensors/tracking technologies, and integrated circuit manufacturing techniques. People now connect and meet others virtually in an immersive environment to communicate more effectively.

Haptics technology is also growing rapidly. Considering the continually evolving cutting-edge VR technologies, haptics plays a significant role in providing multisensory feedback to enhance user experience. Instead of using massive equipment to provide kinesthetic feedback, vibrotactile-based haptic actuators such as the eccentric rotating mass (ERM), linear resonant actuator (LRA) and piezoceramic actuators, are widely commercialized. To provide portability and degree-of-freedom in the user's interaction with virtual environments, people demand more compact with high-resolution haptic feedback. In addition to vibrotactile-based haptic actuators, new materials and technologies that can generate high-quality haptic feedback with compact, light-weight, or elastic form factors to deliver comfortable and natural interactions for wearable applications are gaining significant attention. Pneumatic-based devices and actuators provide pressure feedback on the upper body with variable force feedback. Shape memory alloys (SMA) are electromechanical actuators using changes in temperature to generate haptic feedback. SMA

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The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adfm.202008831.

The copyright line for this article was changed on 5 March 2021 after original online publication.

DOI: 10.1002/adfm.202008831

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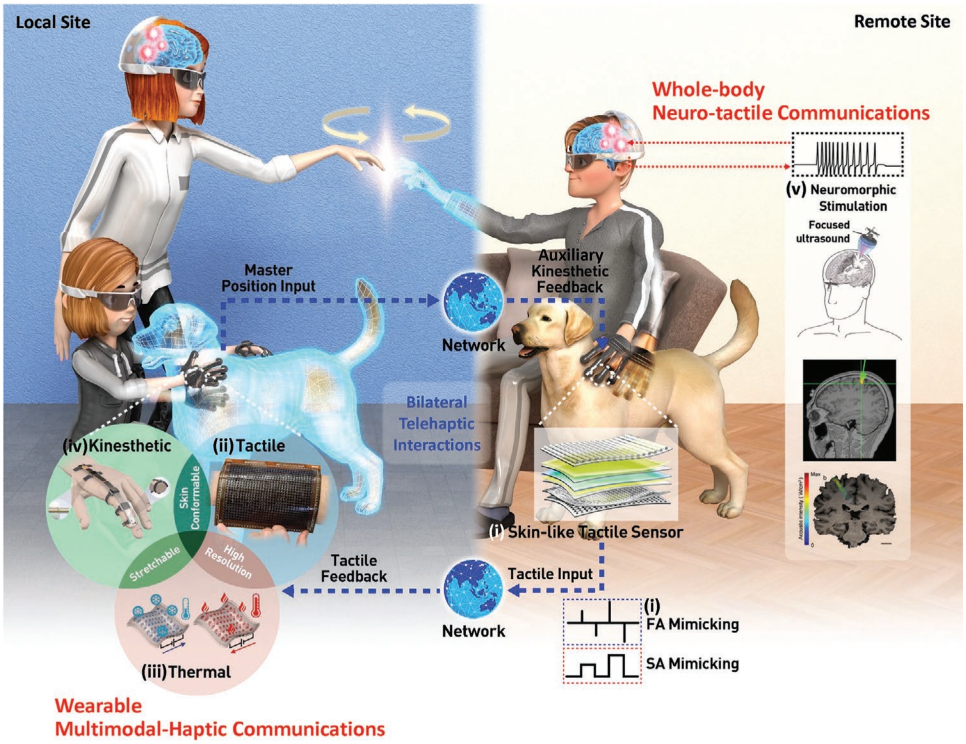

Figure 1. Conceptual illustration of futuristic bilateral and multimodal tele-haptic interaction by combining active material-based haptic technologies and VR/AR interaction system. A young girl and a male are doing haptic interactions while wearing flexible haptic gloves linked to AR glasses. This haptic glove is equipped with skin-like tactile sensors (lower, right) and multimodal haptic feedback modules (lower, left), so that sensing information can be delivered to the counterpart as haptic feedback. A female and a male are interacting with AR glass-linked neuro-tactile modulation devices for whole-body interaction (upper, right) on their heads. i) Reproduced with permission.[1] Copyright 2019, ACS Publications. ii) Reproduced with permission.[2] Copyright 2017, Wiley Online Library. iii) Reproduced with permission.[3] Copyright 2020, Wiley Online Library. iv) Reproduced with permission.[4] Copyright 2020, Wiley Online Library. v) Reproduced with permission.[5] Copyright 2015, Nature Publishing Group.

actuators are light and compact but can provide adequate feedback on the torso[6,7] or skin.[8,9] Magnetorheological (MR) fluid is a smart fluid that increases its viscosity when it is exposed to a magnetic field. MR fluid has been recently used in haptic shoes in VR settings because it can generate considerably large resistive forces with rapid response times.[10–12] MR fluid was also used to provide localized haptic feedback on the touch surface.[13] Furthermore, a number of wearables that adopt machine learning and deep learning techniques were recently introduced to realize the complex gesture recognition in VR/AR applications.[14–16] Electro-active polymer (EAP) films have also been recently used to provide a wide range of tactile stimuli.[17] In addition, flexible and stretchable haptic actuators, including skin-attachable devices, have been analyzed to achieve highly immersive haptic feedback. Soft active materials such as nanocomposites, conducting polymers, and liquid-phase materials have been widely investigated.[18] Microfabrication technologies for stretchable geometries and wireless device platform designs[19] have been utilized to improve the mechanical compliance when haptic devices are attached to the human skin. The mechanical compliance of haptic actuators is critical to provide imperceptible wearing and haptic feedback without disturbing the user's motions.

The next generation of VR/AR technologies calls for telehaptics that enables multimodal and bilateral interactions. The tele-haptic technology strives to realize haptic communications between VR/AR users in remote locations by exchanging haptic sensations transmitted over the network. This is driving the paradigm shift of haptic interactions from the human-to-computer/virtual environment interaction to the human-to-human interaction. It is certainly an exciting future direction for immersive VR/AR interactions, which would offer immense new opportunities for the VR/AR industry (such as, tele-healthcare and contactless haptics) as well as challenges for the development of new devices and technologies (such as, wearable electronics and form factor-free material-based haptic devices). **Figure 1** illustrates futuristic tele-haptic interactions using advanced functional material-based haptics technologies. It shows bilateral and multimodal interactions between the local users (a young girl and a woman) and the physically distant user (a man) in a remote site by transmitting haptic sensations over the network. The users are wearing AR glasses to view each other's environment. The young girl and the man are performing bilateral tele-haptic interactions by means of wearable haptic devices. The compact VR gloves that the girl and the man worn are capable of sensing multiple modes of haptic sensations (such as tactile, kinesthetic, and thermal). Moreover, the gloves can transmit sensing and feedback signals for bilateral interactions. For example, when the man strokes the back of the actual dog, his glove acquires tactile information and transmits it to the girl. The girl then can feel the remotely transmitted tactile sensation, which is regenerated by the built-in tactile and thermal module in her glove while touching the virtual dog. Conversely, the girl can send an input signal to the man through the virtual gloves. Suppose that the girl wants to feel the head of the actual dog, so she pets the virtual dog's head. This local position information is then transmitted to the man's glove, which, in turn, generates auxiliary force feedback by the kinesthetic module embedded in the glove. The force feedback cue is what directs the man to move his glove to the girl's desired position on the dog. This shows an example of bilateral tele-haptic interactions. Furthermore, a tactile sensor with skin-like stretchability and capable of receiving wide-band texture signals is embedded in the conceptual VR glove[1] (Figure 1i). A multimodal haptic feedback device built into the glove is configured to transmit tactile, thermal, and kinesthetic feedback simultaneously to the wearer (a young girl). In the glove, shape memory polymer actuators are embedded to construct reconfigurable arrays of a tactile module with high resolution[2] (Figure 1ii). A highly stretchable thermal module with cooling/heating function is installed using p-type and n-type bismuth telluride thermoelectric pellets[3] (Figure 1iii). Using dielectric materials, high force density textile-based electrostatic clutches are mounted (Figure 1iv), and these can be applicable for kinesthetic haptic feedback in VR/AR systems.[4]

Figure 1 further shows the concept of neuro-tactile communications. The emerging neuro-tactile haptics technology aims to engage the tactile sensory system in the whole-body by neuro-stimulation to generate artificial tactile sensations without traditional haptic devices. Various implantable neural interfaces and non-invasive techniques are being investigated, and soft and bio-compatible materials play an important role in the advancement of neuro-tactile haptics technology. In this figure, the woman and the man are wearing a neuromorphic stimulation headset, which is connected to their AR glasses (Figure 1v). Neuro-tactile stimulation may integrate their brain and body for more intimate tele-haptics interactions.

The core technology for tele-haptics that are more relevant to the material science and engineering community lies in tactile sensing and feedback. For intuitive and immersive tele-haptics experiences, tactile sensors and actuators are expected to offer advanced functionalities and features. For instance, they should possess form factor-free properties to conformably adhere to the wearer's deformable skin surfaces and receive/transmit complex and sophisticated texture information. In recent years, tactile sensor technology has advanced significantly and achieved commercial success. Research results show its skin-like stretchability, high sensitivity, and high reliability. Unlike tactile sensors, there exists a substantial gap between the current tactile actuator technology and the desired technology for tele-haptics. The current tactile actuators are mostly based on traditional electro-mechanical motors, which are too rigid, bulky, or heavy to be used for compact, flexible, and wearable haptics applications. An alternative to electro-mechanical haptic actuator technologies, active or smart material-based device technologies emerge as potential actuators for tele-haptics applications.[20]

This paper's primary goal is to review the current status and opportunities of active materials or advanced functional materials-based haptic technology. This paper also intends to assess the role of active materials for haptic innovations and their potential contributions to the technological needs of emerging haptic technologies, namely tele-haptics. Covering all aspects of the tele-haptics in a review paper is a daunting task, and it may not be desirable as a broader scope diverts the focus and divides the attention. Thus, the current paper aims to review the multimodal sensory feedback technology, which is the core technology for tele-haptics based on functional materials and their integration mechanisms. It also seeks to provide an overview of the current status of haptic interfaces based on active-materials and state-of-the-art haptic devices. This will allow material scientists and engineers to gain perspectives on their potential use for multimodal haptic sensing and actuation and aspire to advanced functional materials to solve technical challenges in realizing fully immersive multimodal tele-haptic interaction in VR/AR.

The next section introduces the technical challenges and recent progress of emerging active material-based sensors and actuators for the fully immersive tele-haptics. After discussing the overall roles of active materials for tactile sensing and feedback, recent advances in haptic interfaces are reviewed in Sections 3-7. These sections are organized according to the interfacing methodology between users and devices. Section 3 provides reviews on touch input-based haptic feedback technology. Section 4 summarizes wearable haptic interfaces, including hand-worn, vest-worn, and foot-worn devices, which are the most common types used to provide haptic feedback in VR and AR. Skin-attachable haptic interfaces are reviewed in Section 5. These skin-attachable interfaces are aiming at more comfortable and imperceptible applications as compared to the wearable haptic interfaces. In Section 6, non-contact haptic systems, which are more advanced concepts, are reviewed. These include mid-air haptic interfaces, which enhance the realism in VR and AR systems by providing direct bare-handed interaction with virtual objects. Section 7 introduces futuristic neuro-haptic interfaces that can directly stimulate tactile sensations through an interface with neurons, which can even stimulate a whole-body as well as part of the body. Section 8 concludes the paper with the current challenges and the future perspective of the immersive tele-haptic interactions.

2. Emerging Active Material-Based Tactile Sensing and Feedback Devices

For more immersive tele-haptic interaction, both sensors and actuators should be practically applied to import and export realistic tactile information. It is obvious that they should be designed to meet the engineering requirements that are laid down by the processes: i) how to "acquire" tactile stimuli; ii) how to "create" realistic tactile stimuli; and iii) how to "deliver" them to the human body. Sensors should accurately detect the tactile stimuli, and actuators should have rendering capabilities for delivering complex and sophisticated tactile feedback, which is close to human perceptive levels, such as a frequency range of 0 Hz to 500 Hz to cover fast adapting and slow adapting mechanoreceptors, including Pacinian corpuscles, Meissner corpuscles and Merkel's disks.[21,22] Their spatial resolution should be higher than human's tactile spatial acuity (≈1.2 mm),[23] and the detection limit of the sensor and minimum actuation force of actuator should surpass the mechanoreceptor's activation threshold force (≈3.6 mN).[24] The interfacing method for delivering tactile feedback efficiently to the human body is also an important factor for VR/AR applications. Enhancing output performance without losing mechanical compliance is another major challenge. The conventional way to apply haptics based on rigid and bulky desktop devices (e.g., PHANToM, 3D systems) remains a drawback for highly immersive virtual

Table 1. Emerging active material-based sensors for tactile sensing.

Mechanism	Key material	Sensitivity (Pressure range)	Frequency range	Spatial resolution	Characteristics	Ref.
Piezoresistive	Graphene nanoplates	1.63 kPa^{-1} (0.1 ~ 6 kPa) 0.04 kPa^{-1} (6 ~ 100 kPa)	<330 Hz	20x20 array (100/cm^2)	Highly sensitive, flexible	[1]
	PEDOT:PSS/PU sphere	10 kPa^{-1} (0.1 ~ 43 kPa)	<72 Hz (14 ms)	10x10 array (100/cm^2)	Flexible, cross talk eliminated	[36]
	Eutectic gallium indium (EGaIn)/PDMS	0.0835 kPa^{-1} (0.1 ~ 50 kPa)	<11 Hz (90 ms)	Radius 1 cm	Stretchable	[39]
Capacitive	Ionic liquid	31.1 kPa^{-1} (<15kPa)	<12.5 Hz (80 ms)	4x4 array (2/cm^2)	Highly sensitive capacitive sensor	[42]
	PDMS micro pyramid	0.2 kPa^{-1} (<4 kPa)	–	13x10 array (11.1/cm^2)	flexible	[68]
	Ag/Ecoflex	22 Mpa^{-1} (<16kPa) 1.25 Mpa^{-1} (16k ~ 360 kPa)	–	10x10 array (25/cm^2)	Stretchable 300%	[52]
Piezoelectric	rGO/PVDF composite	35 uA/Pa (<2.45 kpa) 5 uA/Pa (2.45 ~ 17.15 kPa)	<2000 Hz	Sample size 1 cm^2 (1/cm^2)	Texture perception	[46]
Inductive	EGaIn/PDMS	−13 nH/N (<5 N)	–	Radius 7.5 mm	High SNR 65 dB	[41]
Magnetic	Fe NW/PDMS cillia	60 mΩ kPa^{-1} (<50 kPa) 16 mΩ kPa^{-1} (50 ~ 170 kPa)	–	Sample size 4 mm^2	Shear, vertical force	[69, 70]

haptic interaction. Flexible, stretchable, and form factor-free haptic devices have received significant attention because their mechanical compliance can meet the requirements of minimal motion restrictions, allowing more participation and interaction in VR/AR.[9] These requirements have motivated the studies of material engineering for innovating the form factor of devices and active materials that can significantly improve haptic rendering capabilities with unique material designs and operating mechanisms. Continuous creative research on advanced materials and device structuring technology is required to achieve the high-difficulty specifications for such realistic tactile regeneration. This section presents recent studies and progress regarding design strategies of sensors and actuators for tactile sensing and feedback from critical materials and mechanisms.

2.1. Recent Tactile Sensing Technologies: Materials and Mechanisms

In recent years, tactile sensor technology has advanced significantly and achieved breakthroughs in robotics, health monitoring systems, and human-machine interfaces with remarkable performance development such as skin-like stretchability, high sensitivity and high reliability.[25–28] The major role of the tactile sensing devices in tele-haptic systems is to collect tactile information from surrounding objects. Thus, integrating tactile sensors into the actuating system is very important for providing precise haptic feedback[29,30] and bilateral haptic interactions.[31,32] Critical characteristics are desired for these tactile sensors, such as having a large number of pixels for detecting distributed force and displacement, a wide dynamic range for covering the human tactile range, and the mechanical compliance for applying devices on skin surfaces. However, simultaneously achieving a high-resolution, wide dynamic range, and mechanical compliance remains a challenge for conventional rigid and bulky devices such as ceramic and metal-based microelectromechanical system technology[33,34] and rigid hardware packaging.[35] To overcome these mechanical mismatches and performance issues, novel functional materials for mechanically flexible and high-resolution tactile sensors have been widely investigated. Soft and stretchable tactile sensors have been developed by various designs of emerging materials such as conducting polymers,[36–38] liquid metals,[29,39–41] ionic conductors,[42,43] carbon nanotubes,[44,45] graphene,[1,46,47] metal nanowires,[48,49] and metal nanoparticles.[50,51] Furthermore, sensor arrays capable of a high spatial resolution,[36,52,53] wide dynamic range,[54,55] and multimodal detection[1,46,52] have also been actively introduced.

From a material perspective for tactile sensing, various detection mechanisms have been exploited. Piezoresistive, capacitive, piezoelectric, inductive, magnetic type sensors accumulate tactile information by converting the physical stress applied to the devices to electrical signals (**Table 1**). Detection types can be chosen depending on the target applications and design flexibility. Piezoresistive sensors transduce pressure or strain to electrical resistance change by increasing conduction pathways. Generally, piezoresistive sensors exhibit high sensitivity and simple readout circuits. Disadvantages include hysteresis and repeatability issues originating from cyclic degradation. Capacitive sensors utilize capacitance change by changing the geometry (thickness and area) in the elastomeric dielectric layer. It has the advantages of a high spatial resolution, low hysteresis, large dynamic range, and high repeatability. Disadvantages include low sensitivity, especially when miniaturized and signal drifts, and noise coming from stray capacitance. Piezoelectric sensors detect tactile stimuli by using the piezoelectric effect of ferroelectric materials, such as piezoelectric ceramics, composites, and polymers. It has a fast response time, which is appropriate for detecting high-frequency tactile stimuli. On the other hand, it is challenging to monitor static pressure and it requires charge amplifier circuits to detect generated charges by the piezoelectric effect. Inductive and magnetic sensors utilize electromagnetic wave change based on the coil's inductance variation to see the deformation. It has the advantages of a significantly high dynamic range, low hysteresis, and high repeatability, but these coils take up space leading to a significantly low spatial resolution.

In general, form factor-free and mechanically compliant tactile sensing devices have been developed using soft materials. Electrical components such as conductors, semiconductors, and dielectric materials are becoming soft and stretchable by using emerging materials and novel structural designs. Among these, conductors are key components for passive and active tactile sensing. However, metals, which are the most widely used conductive material, have higher Young's modulus values based on their respective properties (e.g., Au: 79 GPa, Ag: 85 GPa, Cu: 130 GPa), while the skin has kPa-order modulus values depending on its depth level (e.g., epidermis: 140 to 600 kPa, dermis: 2 to 80 kPa).[56] Strategies for implementing stretchability and softening of conductors include either using geometrical structures or intrinsically stretchable conductors. Geometrical structures such as wrinkles, serpentine, kirigami, and cracks have been suggested for stretchable sensor electrodes. For example, Wang et al. reported skin-like multimodal sensors using highly stretchable geometrical structures, which can be easily attached to curvilinear skin surfaces. Stretchable wirings and non-stretchable islands are connected, and then the sensor array is mounted on the non-stretchable islands. Stretchable wirings are stretchable up to 800% and the pressure sensor array is stretchable up to 300%.[52] Meanwhile, intrinsically stretchable and freely deformable conductors such as nanocomposites, organic materials, liquid metals, and ionic liquids have also been utilized for tactile sensors. For example, stretchable nanocomposites such as silver nanowire (Ag NW) networks dispersed in a polydimethylsiloxane (PDMS) binder matrix are utilized for stretchable electrodes for strain sensors using capacitance change.[49] The conductivity of the Ag NWs reached as 5285 S cm $^{-1}$ at a strain of up to 50%. In addition, a liquid metal film electrode enabled highly stretchable and sensitive capacitive pressure sensor arrays.[57]

Sensing materials are also becoming flexible and stretchable using engineered materials. Metal nanoparticles,[59–61] nanocarbon,[62,63] and conductive polymers[64] based on nanocomposites have been widely investigated as flexible and stretchable sensing materials. These composite materials have percolative conduction networks by conductive fillers in an elastomeric binder matrix to present stress-responsive characteristics when they are deformed. Intrinsically stretchable liquid phase materials are also one of the promising candidates for stretchable sensing components. Liquid metals in elastomer-based microfluidic channels exhibit a piezoresistive response to the applied pressure. Because of the intrinsic stretchability of liquid metal, the sensor can be more soft and stretchable[39] (**Figure 2**e). High-performance piezoelectric materials can be flexible by using 0-3 composites based on piezoceramic particles and a polymer matrix. These composites exhibit much higher piezoelectric constants d_{33} than piezoelectric polymers, maintaining their flexibility.[65–67]

For more sophisticated and multimodal tactile sensing, advanced features such as a high spatial resolution, large number of pixels, and high sensitivity and selectivity have been demonstrated by emerging materials and microfabrication techniques. Recent studies have added functionalities to the tactile sensors, to achieve the challenges that exist in conventional materials and device structures. For example, the selective sensitivity of strain and pressure was incorporated by designing pressure-insensitive porous carbon nanotube (CNT) nanocomposites.[45] A large number of pixels and a wide dynamic range have been demonstrated by mechanoluminescent materials and microfabricated elastomers.[54] And multimodality of the tactile sensor has also been reported by using composite materials with both piezoresistive and ferroelectric properties.[46] More specifically, the bio-inspired microstructured ferroelectric skin was designed to detect static, dynamic pressure, and temperature. The dome-shaped interlocked structure of the polyvinylidene fluoride/reduced graphene oxide (PVDF/rGO) composite functions as both a piezoresistive and a ferroelectric sensor. The sensor is responsive to hot water and static pressure and distinguishes different textures of sandpaper, glass, and paper (Figure 2a). Self-powered tactile sensors that are sensitive to both static pressure and vibration have also been analyzed. The multilayered structuring of the piezoresistive graphene-based sensing layer, the triboelectric sensing layer and the fingerprint patterned passivation layer was introduced[1] (Figure 2b). The bottom piezoresistive sensing layer mimics the slow adaptive mechanoreceptors, and the upper triboelectric sensing layer that produces the electric power by itself mimics the fast adaptive mechanoreceptors. For sensing mechanical compliance and pressure, piezoresistive strain sensors and capacitive pressure sensors are integrated to measure changes in pressure and strain induced by deformed objects[58] (Figure 2c). Sensitivity is also enhanced by soft active materials. Ionic liquid has been used for the high sensitivity of capacitive sensors. Ionic liquid droplets have been introduced as sensing materials, resulting in significant capacitance changes and sensitivity. The pressure sensitivity has been significantly improved up to 31.1 kPa^{-1}, while the sensitivity of the conventional capacitive sensor is 0.2 kPa^{-1}[42] (Figure 2d). By using microfabrication technologies and polymer composite materials, a high spatial resolution tactile sensor array that eliminates cross-talk issues has also been reported. A flexible pressure-sensitive diode was operated by forming a Schottky barrier from the contact of poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and zinc oxide (ZnO)[36] (Figure 2f).

Tactile sensors have been widely investigated for decades and have significantly progressed. They are now evolving to achieve natural and complex tactile sensations similar to the capabilities of human skin. Smart functionalities such as mechanical compliance, selective sensitivity, multimodality, a wide dynamic range, and rapid response time have been added using soft and functional emerging materials. Ultimately, these tactile sensors are highly desirable for fully immersive haptic interactions in VR/AR by collecting realistic tactile information and synchronizing them to the haptic feedback that is delivered to users in real-time.

2.2. Recent Haptic Feedback Technologies: Materials and Mechanisms

Unlike tactile sensors, there is a substantial gap between tactile actuator technology and the desired technology for tele-haptics. Currently, most haptic actuators are based on traditional electro-mechanical motors.[71] In particular, for the latest VR/AR products from the gloves or hand controllers, haptic feedback mainly relies on different types of motors[72–74] because of their stable performance over the years and sufficient feedback

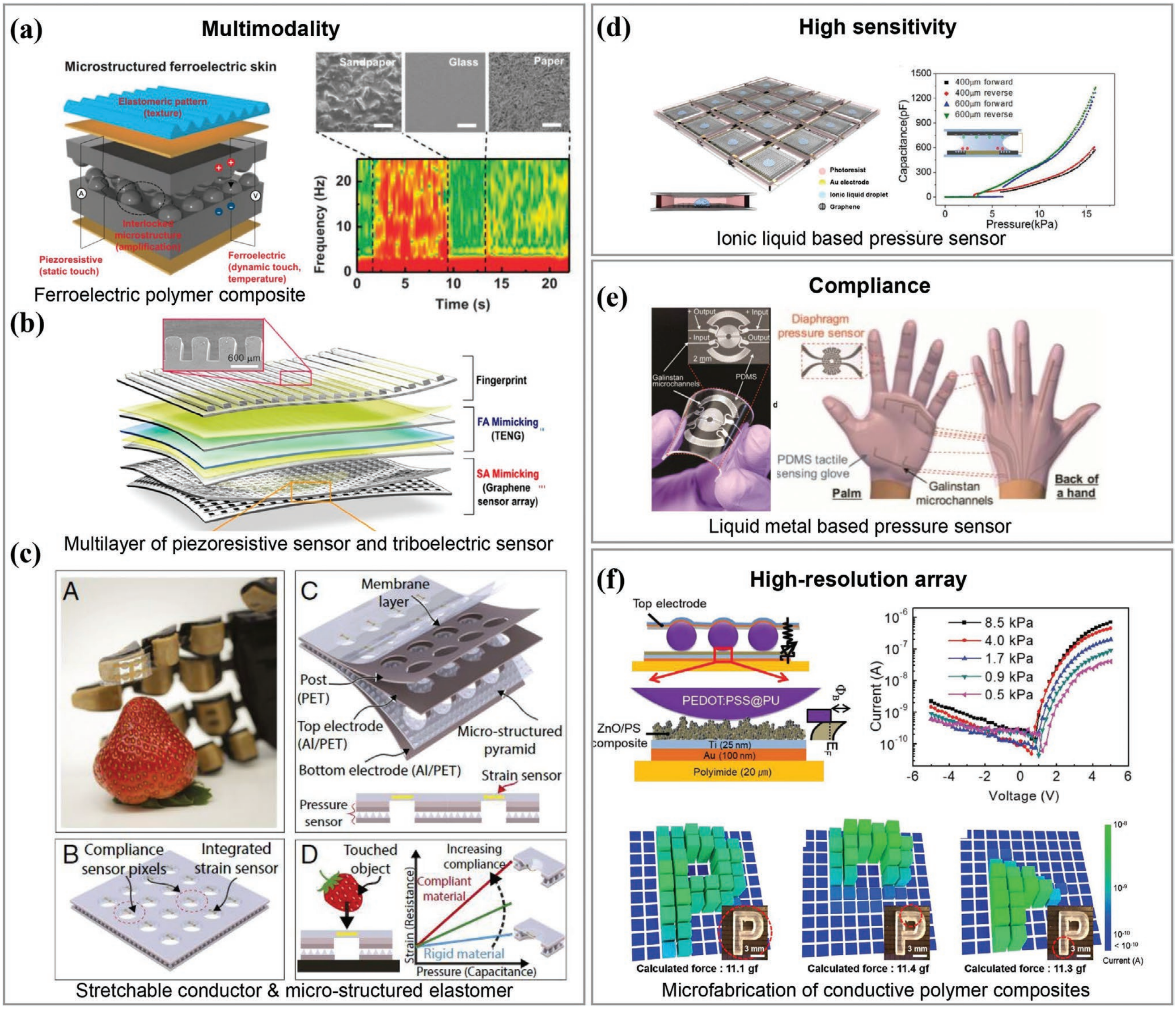

Figure 2. Soft active material-based tactile sensors. a) A bio-inspired microstructured ferroelectric skin. Dome-shaped interlocked structure of PVDF/rGO composite is working as both piezoresistive and ferroelectric sensor. Short-term fourier transformation (STFT) result shows the sensor distinguishes different textures of sandpaper, glass and paper. Reproduced with permission.[46] Copyright 2015, AAAS. b) Self-powered bimodal tactile sensors consist of triboelectric sensor, piezoresistive composite-based sensor, and fingerprint pattern structured layer. Reproduced with permission.[1] Copyright 2019, American Chemical Society. c) A bio-inspired stretchable membrane-based compliance sensor. Compliance of object is measured by strain sensor and pressure sensor. Reproduced with permission.[58] Copyright 2020, PNAS. d) An ionic liquid droplet pressure sensor with large capacitance change. Reproduced with permission.[42] Copyright 2020, Wiley. e) A liquid metal-based pressure sensor using elastomeric microfluidic channels. Reproduced with permission.[39] Copyright 2017, Wiley. f) A flexible pressure-sensitive diode array based on the Schottky barrier formation by the contact of PEDOT:PSS and ZnO. [36] Copyright 2018, Wiley.

intensity. However, these motor-based devices are too rigid, bulky, and cumbersome to be used for wearable haptics and immersive VR/AR applications. Moreover, their high power consumption, which is due primarily to the current-driven mechanisms, is becoming another obstacle for tele-haptic applications. Above all, the most critical issue is that it is difficult to create natural and complex tactile sensations. Actuators need to generate complex tactile feedback such as fine textures, minuscule shapes, and temperature more naturally (beyond the repertoire of conventional haptic feedback) and efficiently deliver them to the human skin. However, it has long been a big challenge for conventional motor-based actuators to meet all of these specifications and requirements (such as large force/displacement, high spatial resolution, a wide dynamic range, fast response time, and multimodality, spatiotemporal acuity). So far, there have been tremendous efforts to fulfill those requirements, especially by utilizing emerging active materials. Various active materials and actuation mechanisms have been exploited to provide vibrotactile and kinesthetic feedback in a flexible and/or stretchable form factor for wearable and skin-attachable applications and multimodal high-resolution haptic feedback for realistic and sophisticated tactile interactions. In this subsection, recent progress in actuators based on various active materials and actuation mechanisms are reviewed. And

Table 2. Emerging active material-based actuators for tactile feedback.

Interfacing Method	Feedback type	Materials	Mechanism	Unit device size (Display area)	Frequency	Intensity of stimuli			Ref
						Displacement	Force (Acceleration) {Friction Coeff.}	Electric/ Acoustic	
Touch-based haptic	Normal/lateral vibration	Voice coil	Electromagnetic Lorentz force	11 x 9 mm^2	≤250 Hz	–	(≤3 G)	–	[82]
	Friction modulation	Transparent electrode (ITO)	Electrostatic force (Electroadhesive surface)	(R ≥ 4.5 mm)	≤1 kHz	≤10 µm	≤ 0.45 N	–	[83]
		Piezoceramic	Squeeze film levitation	(≤198 x 138 mm^2)	27 kHz–225 kHz	0.125 µm – 2.3 µm	Tangential {0.1 – 1.6}	–	[71]
	Shape morphology	MR fluid	MR-based Shape morphing	R ≥ 20 mm	0–200 Hz	–	–	–	[13]
Wearable	Skin indentation (hand-worn)	Molded elastomer, carbon tape, PET	Electro-pneumatic	R ≥ 7.5 mm	0.2 Hz–1 Hz	0.13 mm	–	–	[84]
	Kinesthetic (hand-worn)	High-k dielectric polymer	Electrostatic clutch	100 mm^2	10 Hz	–	21 N· cm^2	–	[4]
	Stiffness modulation (foot-worn)	MR/ER fluid	Rheology	R ≥ 22.8 mm	≤300 Hz	–	Frictional shear stress ≤350 N	–	[11]
Skin-attachable	Vibration	Electroactive polymer (EAP)	Electrostatic	R ≥ 7.5 mm	1 Hz–191 Hz	650 µm	255 mN	–	[17]
		Voice coil embedded in elastomer	Electromagnetic	R ≥ 9 mm	100 Hz–300 Hz	≤300 µm	–	–	[19]
	Skin stretch	Twisted and coiled polymer (TCP)	Thermal contraction	110 x 45 mm^2	–	6.5 mm	650 mN	–	[85]
	Normal, force, shear force, Vibration	Flexible electrode (Metalized Mylar), PDMS, dielectric oil	Electro-hydraulic	1 mm ^{2}	≤20 Hz	≤500 µm	≤300 mN	–	[80]
Mid-air haptic	Skin indentation, Vibration	Flexible ultrasound transducer	Ultrasound Acoustic Pressure	(R ≥ 4.3 mm)	40 kHz/200 Hz (modulation)	–	–	≤257 Pa	[86]
Neurostimulation-based haptic	Electrical stimulation	Biocompatible electrode (AuNM-composite)	Neural electrodes	1 x 4 mm^2	1 kHz	–	–	80 µA Stimulation current	[87]
	Thermal stimulation	Piezoelectric-based Low Intensity Focused Ultrasound (LIFU)	Ultrasound neuromodulation	(R ≥ 3.5 mm)	250 kHz/100 Hz (modulation)	–	–	3–100 W cm^{-2} Acoustic intensity	[5]

we summarized the emerging active material-based actuators that are grouped by the interfacing methods in **Table 2**.

For vibrotactile feedback in a flexible and/or stretchable form factor, soft active materials have been widely utilized based on reliable actuation mechanisms such as electrostatic, electromagnetic, and piezoelectric types. In particular, electrostatic types are adopted for soft and mechanically compliant actuators.[88–90] They have distinct advantages of a rapid response time and high control accuracy despite the smaller displacement compared to pneumatic, hydraulic, and shape memory types. The electrostatic actuators rely on the electric force when an electric field is applied between two conducting electrodes.[91] They have a simple device structure, which is beneficial for realizing mechanical flexibility and miniaturization and can be simply controlled by modulating voltages. As a result, they are relatively easier to fabricate high-resolution actuators array and to design driving circuits than other types. Pyo et al. reported a vibrotactile actuator based on the flexible

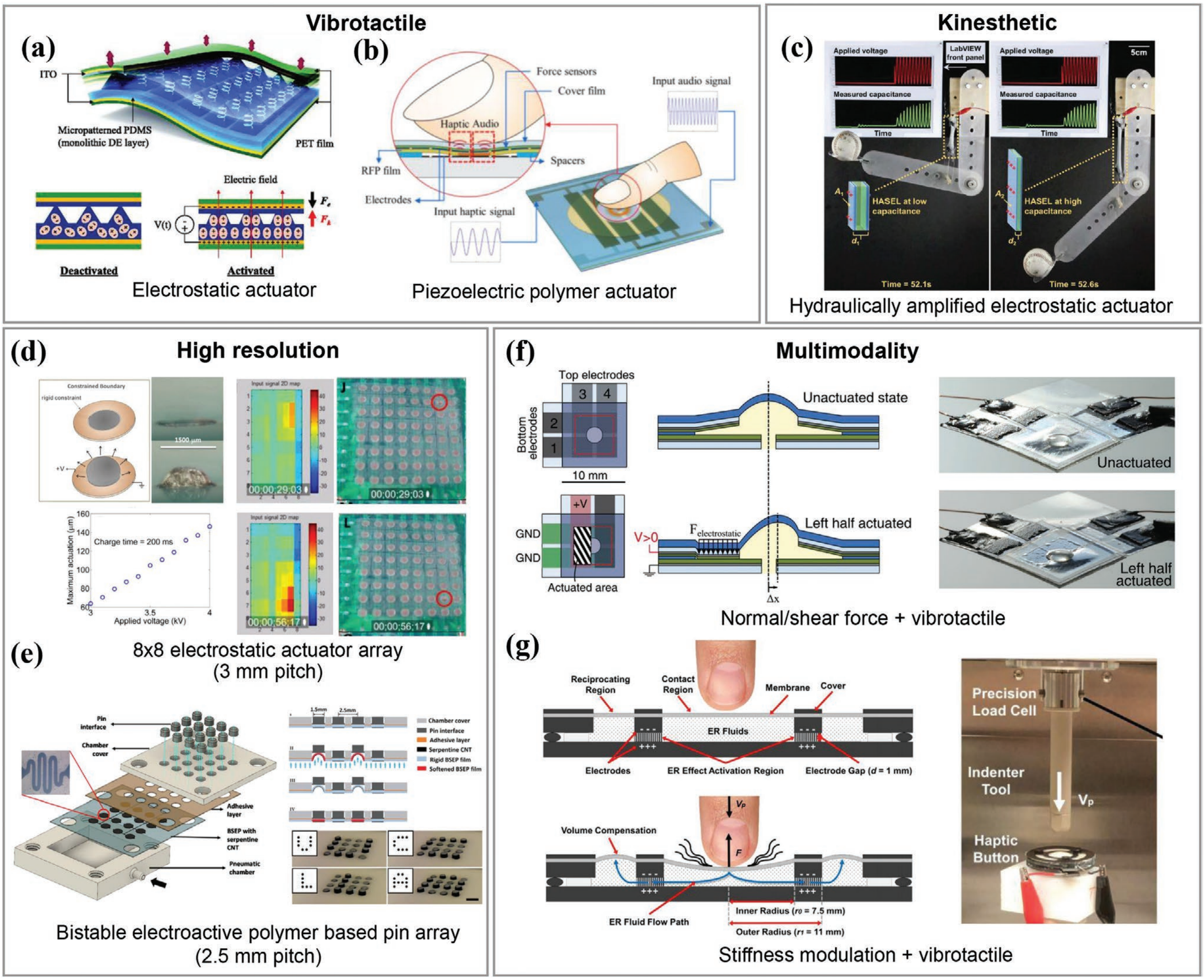

Figure 3. Soft active material-based tactile feedback. a) A robust and flexible microstructured dielectric elastomer-based vibrotactile actuator that can endure high external pressures. Reproduced with permission.[75] Copyright 2018, AIP publishing LLC. b) A relaxor ferroelectric polymer (RFP) actuator for multimodal audio and haptic feedback. Reproduced with permission.[76] Copyright 2019, Creative Commons Attribution 4.0 International License. c) Hydraulically amplified electrostatic actuators using both electrostatic and hydraulic forces. Reproduced with permission.[77] Copyright 2018, AAAS. d) 8 × 8 array of actuators (3 mm pitch) using an acrylic-based dielectric elastomer and CNT-based compliant electrodes. Reproduced with permission.[78] Copyright 2015, CC BY-NC-ND 3.0. e) 4 × 4 bistable electroactive polymer-based tactile display with braille standard resolution (2.5 mm pitch). Reproduced with permission.[79] Copyright 2018, ACS. f) A hydraulically amplified electrostatic actuator generating normal force, shear force and vibrations. Reproduced with permission.[80] Copyright 2020, Wiley. g) The electrorheological fluid–based actuator which provides stiffness modulation and vibrotactile sensation. Reproduced with permission.[81] Copyright 2019, SAGE.

electrostatic type which consists of a pyramidal microstructured dielectric elastomer layer and is capable of enduring high pressures, as shown in **Figure 3**a.[75] The electrostatic actuator shows the high performance of an output pressure up to 25 kPa and a response time of less than 2 ms. Its mechanical output (25 kPa) can be maintained in the notable vibration frequencies (100–200 Hz). It has a simple structure composed of electrodes and the dielectric layer, which can provide its design flexibility. But, it requires kilovolt-order high driving voltages to generate notable haptic feedback.

The electromagnetic type actuators are also widely used to generate vibrotactile feedback. It is controlled by the current applied to the solenoid coils and leads to a 1D motion with a large force and displacement in the low-frequency range. The voice coil motor (VCM) actuator is a representative example of electromagnetic actuators, and is widely adopted in game controllers, mobile phones, and tablets by generating sufficient force and displacement. Rogers et al. demonstrated a coin-size (18 mm) electromagnetic actuator which exhibits a vibrational amplitude of 300 μm in contact with skin phantoms with Young's modulus of 130 kPa just by mili ampere-order current driving.[19] However, it requires coils and permanent magnets which are generally rigid and take up a large volume. For advanced soft electromagnetic actuators, miniaturized coils made of soft conducting materials have also been exploited.[92]

The piezoelectric type actuators utilize the inverse piezoelectric effect, which generates displacements when the voltage is applied. Piezoelectric ceramic materials such as $PbZr_xTi_{1-x}O_3$ (PZT) are widely used for vibrotactile feedback actuators which show sufficient force of 35 N, displacement of 280 µm with the help of displacement amplifier, and a rapid response time less than 1 ms, resulting in high control accuracy (PowerHap, TDK corp., device size: 60 mm × 5 mm × 7 mm). Because of its rapid response time, it is largely adopted for generating high-frequency vibration and rendering texture.[93–95] Piezoelectric polymers have also introduced as attractive active materials to realize mechanically compliant vibrotactile actuators. Duong et al. reported a flexible film-type actuator based on a piezoelectric polymer for multimodal audio and haptic feedback.[76] The Relaxor ferroelectric polymer (RFP) based on poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene) [P(VDF-TrFE-CFE)] was mixed with poly(vinylidene fluoride-trifluoroethylene) [P(VDF-TrFE)] to produce mechanical vibrations via the fretting vibration phenomenon. This PVDF-TrFE-based vibrotactile actuator driven by an input voltage of 200 V with 200 Hz exhibits the maximum vibration amplitude of 2.59 µm when the applied load is 40 mN (Figure 3b). These piezoelectric polymers have the advantage of high flexibility. Still, they have drawbacks of minimal output force and displacement compared to piezoelectric ceramics because they have much lower piezoelectric constants than rigid piezoelectric ceramic materials.

For kinesthetic haptic feedback, pneumatic[96,97] and hydraulic[98,99] type actuators are actively applied due to their performance, such as large strain and large volume change via the movement of fluid within a cavity.[20] Generally, they can generate large displacements even in centimeter-scale and forces of several hundreds of newtons that are difficult to be achieved by electrostatic, electromagnetic, and piezoelectric actuators. However, their major drawback is that the devices should be tethered by tubes connected to bulky air or oil compressor and pressure regulator. To overcome this limitation, Acome et al. developed hydraulically amplified electrostatic actuators, which utilize electrostatic and hydraulic forces to achieve various actuation modes.[77] The elastomeric encapsulation is covered by ring shape electrodes and filled with a liquid-phase dielectric. Six actuators lifted a 4 kg of water (120 kPa) and its strain was 69%. Moreover, by monitoring the capacitance values of the actuators, they also cause self-sensing deformation. This capacitive self-sensing deformation property has been utilized for closed-loop control of robot arms, as shown in Figure 3c. It can be extended to provide highly controllable kinesthetic feedback with a soft wearable form factor applicable for soft robotics.

Furthermore, to realize complex and sophisticated tactile feedback, high-resolution actuator arrays have been demonstrated.[100–102] Vishniakou et al. reported the 8 × 8 electrostatic diaphragm actuator array made of an interpenetrating polymer elastomer network.[78] The array's spatial resolution is 3 mm pitch, as shown in Figure 3d. They also demonstrated a digital replay, which edits and manipulates the touch events recorded by an active matrix pressure sensor array using the electrostatic actuator array with high spatial and temporal resolutions. It is a representative demonstration example concerning the sensor-actuator interconnected system for tele-haptic applications. Moreover, to achieve not only high spatial resolution but also large displacement and high blocking force, Qibing Pei et al. demonstrated a 4 × 4 tactile display with braille standard resolution (2.5 mm pitch) by exploiting a bistable electroactive polymer (BSEP) layer and a pneumatic chamber, as shown in Figure 3e.[79] The BSEP is a stiffness-variable material that shows a 3000-fold stiffness change in the temperature range of 43 ±~3~°C. By controlling the pneumatic pressure and thermal stress, the BSEP layer are softened and each pin can be raised. The device exhibits a displacement of 0.7 mm and high blocking force of 50 g.

Finally, for multimodal haptic feedback, hybrid actuation mechanisms using various emerging active materials are utilized. The above-mentioned electrohydraulic actuator (HAXEL) consists of 4 segmented electrodes that can generate not only normal force for skin indentation but also in-plane shear force by actuating the left half or right half of the actuator, as shown in Figure 3f. By applying an input voltage with 160 Hz, the mean normal force of the actuator is around 220 mN with a ripple of 50 mN. As a result, HAXEL device is able to demonstrate multimodal haptic feedback, including skin indentation, skin stretch, and dynamic vibration by using normal force, shear force, and vibrations.[80] Another promising approach for multimodal haptic feedback is to utilize highly controllable rheology. Electrorheological and magnetorheological types can control the viscosity of fluids by using an electric field and a magnetic field, respectively.[81,103] Mazursky et al. demonstrated an electrorheological fluid-based actuator that provides multimodality of stiffness modulation, and vibrotactile haptic feedback[81] (Figure 3g). By precisely controlling the ER fluid flow with an electric field, the device is expected that it is able to create various haptic sensations such as the shape and texture of virtual objects more realistic.

The design of active materials with various actuation mechanisms is becoming more diverse depending on the types of haptic interface methodologies. Touch-based haptic interfaces (Section 3) are mainly required for touch screen display. It necessitates rendering capability rather than transforming or miniaturizing the form factors of the haptic devices. Material designs and structuring for surface friction control and shape morphing are in high demand to express various textures more precisely on the surface of the display. Wearable (Section 4) and skin-attachable haptic interfaces (Section 5) require device integration in various form factors and even deformable shapes for user convenience. Mechanically compliant and electrically functional active materials are vigorously studied for the wearable and skin-attachable platform. Mid-air haptic interfaces (Section 6) require high-resolution and high-power actuators which can remotely create vibrations in the 3D space by using ultrasound, air-flow, and laser. Therefore materials for mid-air haptics should be designed to transduce the source energy more efficiently. Materials for neuro-haptic interfaces (Section 7) require bio-compatibility, which are chemically stable and mechanically compliant for preventing damage of biological tissue. Further details are discussed in Sections 3– 7.

3. Touch-Based Haptic Interfaces

This section introduces touch input-based haptic feedback technology that has actively reached the stage of commercialization among the numerous tactile regeneration device technologies reported so far, which were discussed in Section 2.

Touch Screen Display (TSD) has become an essential part of modern life as it has been widely applied to various products such as smartphones, tablet PCs, kiosks, information displays, and the panel of the modern home appliances/smart cars. Various haptic technologies have been developed to provide sophisticated texture sensation by interlocking with images visually displayed in the TSD. The tactile experience when touching the display has led to new applications in user interface design, game entertainment, online shopping, education and art.[71]

In Section 3.1, dynamically modulating friction techniques using electrostatic force or ultrasonic wave are first reviewed to generate sophisticated texture sensation in the TSD. Second, the shape-morphing devices rendering physical geometries and shapes are reviewed in Section 3.2. The morphing devices are not yet mature, but they have explosive potential. When connected to VR/AR, multiple users can experience information based on touch and deformation of the surface topology. The devices can be applied to quickly rendering of physical computer-aided design models for industrial designers, physical visualization of a site for urban planners, tactical exploration of volumetric data sets for medical experts, or learning and understanding parametric equations for students.[104]

3.1. Enhanced Touch Panel Devices

To provide sophisticated texture to the user on the touch panel glass of the TSD, a method of controlling the friction force between the touch surface and the finger that slides on the surface was adopted. This friction modulation is accomplished by adopting piezoceramic actuators for conveying ultrasonic vibration waves on the touch surface, as shown in **Figure 4**a.[105] Vibration generated by piezoceramic actuators driven at ultrasonic frequency reduces the coefficient of friction due to intermittent contact between the surface of the touch panel plate and the user's finger pad. Figure 4b shows the experimental change in the coefficient of friction and the results of the finite element method (FEM) simulation with the change in vibration

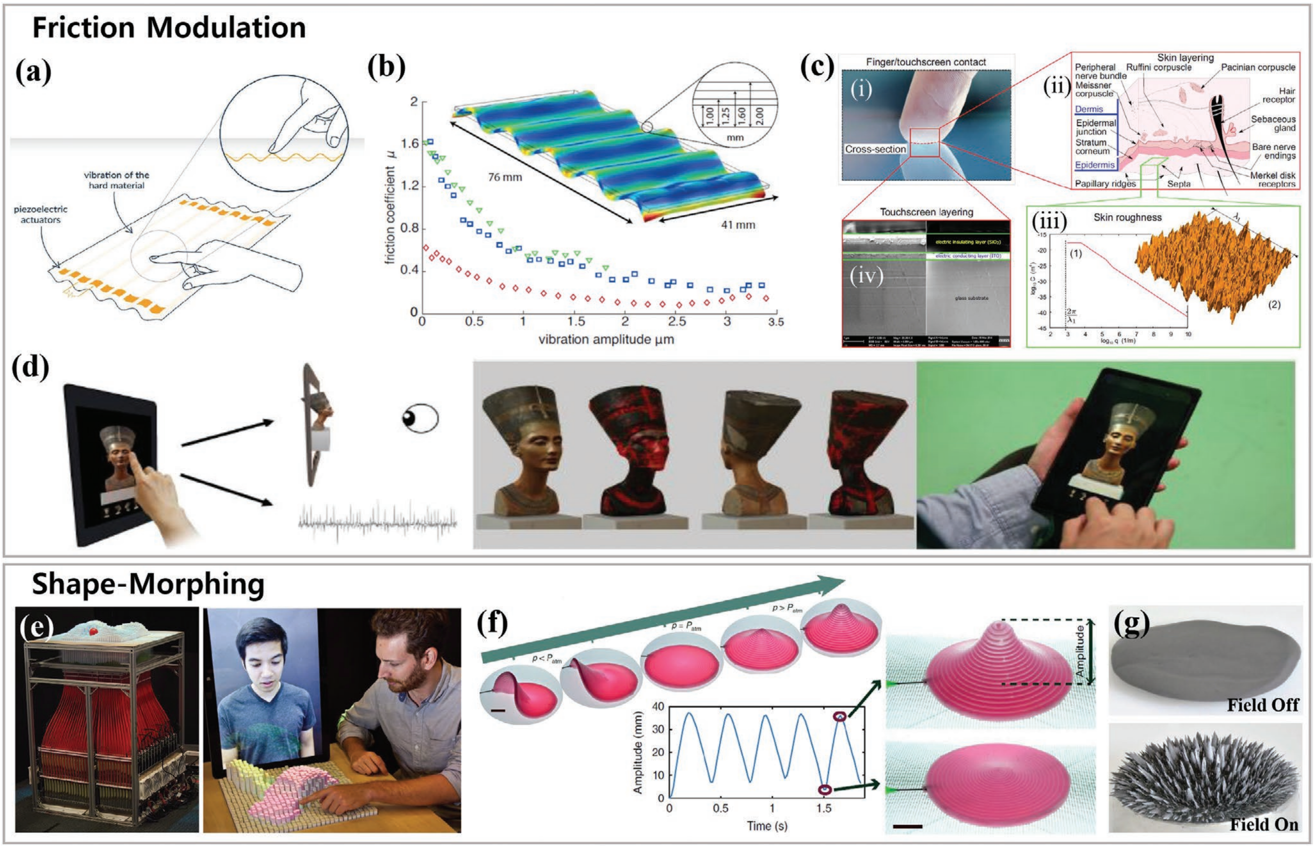

Figure 4. Touch-based haptic interfaces. a) Commercialized variable friction haptic display 'Hap2U' based on piezoceramic actuators for modulating friction coefficient. Reproduced with permission.[105] Copyright 2019, US Patent. b) Experimental evaluation of friction reduction through ultrasonic vibration with FEM simulation. Reproduced with permission.[106] Copyright 2017, IEEE. c) Analysis of contact mechanics between the human's finger pad and a touchscreen plate with electrode under electrostatic adhesion. Reproduced with permission.[107] Copyright 2018, National Acad Sciences. d) Concept of interactive handheld device platform, Touch3D, providing a realistic viewing and touch experience through glasses-free 3D visualizing technology linked to electrostatic vibration. Reproduced with permission.[108] Copyright 2017, ACM SIGGRAPH. e) Shape display 'inFORM' hardware being able to change surface shape with 900 mechanical actuators and its physical telepresence application. Reproduced with permission.[104] Copyright 2015, IEEE. f) Bio-inspired pneumatic shape-morphing device based on meso-structured polymeric elastomer plates capable of fast and complex shape transformations according to the application of pressure. Reproduced with permission.[109] Copyright 2019, Nature Publishing Group. g) Rheological test results of MR fluid with or without applied magnetic field. Reproduced with permission.[110] Copyright 2018, AAAS.

intensity at a frequency of 25.1 kHz, a travelling speed of 17 mm s^{-1}, and an applied vertical force of about 0.1 N.[106] The results show that the ultrasonic wave reduces the friction coefficient as the vibration amplitude increases. Using this frictional force reduction approach, it is possible to reproduce a sophisticated or fine texture by interlocking with the visual image's coordinates displayed in the TSD.

As opposed to reducing friction coefficient, the coefficient of friction can be increased by using an electrostatic adhesion force. To create the effect of electrostatic friction modulation, the device configuration should include a transparent electrode sheet coated with an insulator layer attached to a glass plate.[111] When a sufficiently large voltage signal is applied, the generated electrostatic force increases the friction between the surface with electrodes and the sliding finger pad. For a clear understanding of the contact interaction between the human's finger pad with specific nerve receptors(Figure 4c-ii) and the touchscreen under electroadhesion, Ayyildiz et al.[107] investigated the change in the coefficient of friction as a function of input voltage versus normal force using the mean-field theory derived on the basis of the multi- and full-scale computational contact mechanics research(Figure 4c-iii), and experimental results conducted on a custom-developed tribometer. Their study establishes the prediction model for the electroadhesion phenomenon between human's finger pad and touch plate, and it demonstrates that electrostatic adhesion induces an increase in contact area when viewed at the micro-scale level (Figure 4c-i and 4c-iv), resulting in the increase of the electrostatically vibrating frictional force. The electrovibration device is suitable for application to mobile platforms such as smartphones because of its simple structure and the advantages of being transparent. Kim et al. presented a new interactive handheld device platform that provides a realistic viewing and touch experience through glasses-free 3D visualizing technology synchronized with electrostatic vibration shown in Figure 4d.[108] The interactive mobile platform is designed to incorporate both auto-multiscopic 3D display and electrovibration display for enhancing multi-modal interaction capability.

Despite these strengths of electrovibration technology, the humidity-dependent output performance and the rapid deterioration of the performance due to dust on the touch surface are a big obstacle to commercializing the electrovibration technology. Also, the need for a high voltage input of 2-3 kV causes limitations such as miniaturization, cost reduction, and high voltage shielding (safety issue) of the high voltage amplifier. Due to such limitations of the electrovibration technology, the piezoceramic-based ultrasonic wave generation method is preferred for tactile friction modulation in the market. Hap2U company has successfully developed a haptic information display for automobile center fascia equipped with ultrasonic-based friction modulation technology and is rapidly expanding its business area.[105] Although the friction modulation technology is specialized in texture generation, it still has a limitation. It cannot generate the button feedback sensation, which is the primary function of the touch panel.

3.2. Shape-Morphing Devices

The haptic device of the next step beyond the level of research on the touch panel-based 2D haptic feedback device up to now can be a shape-morphing device capable of delivering haptic deformation of 3D surface topology. The morphing device is still in the early stages of research, but it is a promising technology to enable physical visualization and tactical exploration of remote objects. The shape morphing structures are expected to be key in future applications such as aeronautical area, robotic surgery area, tissue research area, and active material area. The inFORM system, which showed a demonstration linked with the AR environment, presented a variety of possibilities for 3D shape display, as shown in Figure 4e.[104] The inFORM system provides a 3D surface shape change using 900 linear actuators, and the synchronized haptic interaction between the user's hand and the object was achieved using a depth camera located above the head. The Figure(right) demonstrates physical interaction with a 3D automobile model between local and remote users. Even though the challenges of shape display such as resolution, scale, and cost, the extensive spread of VR/AR technology requires additional rich physical interactions. Physical telepresence based on 3D shape display can provide physical implementation, remote operation, and new functions through computer-mediated remote operation. To fundamentally overcome the current electromechanical engineering technology that involves relatively bulky structures, Siefert et al.[109] presents meso-structured polymeric elastomer plates capable of fast and complex shape transformation according to the application of pressure as shown in Figure 4f. The local growth rate and direction are precisely controlled through a specific airway network embedded inside the rubber plate to overcome geometric limitations. The research results demonstrate how to program an arbitrary 3D shape based on an analytical theory model, a simple geometric solution to an inverse problem, and an explanation about the diversity of techniques through a collection of configurations. Such polymer-based research can provide innovative design and flexibility but still has limitations such as low haptic generation output performance and insufficient long-term durability.

Controllable fluids or smart fluids can be another promising candidate active material for surface morphology displays that can exhibit partially controllable apparent softness changes on touch input surfaces. The smart fluid acts as a mechanism to change the evident stiffness by controlling the input of an external magnetic or electric field to change the arrangement of the particles. The magnetorheological fluid is a representative of smart fluids. With the application of the magnetic field to the fluid, the carrier fluid's iron particles are aligned, causing a significant increase in apparent viscosity as described in Figure 4g.[110] When a compressive force is applied from the outside, the chain of particles aggregates into thick columns with solid ends, showing a distinct increase in stiffness. Jansen et al.[13] proposed an enhanced touch surfaces interface adopting Magnetorheological fluid, 'MudPad'.[13] An array of electromagnets actuates a soft and flexible overlay containing magnetorheological fluid to create localized semi-active softness change. Each magnet can be controlled individually, so feedback is generated locally at any point of interaction. Since such a semi-active system does not become unstable, it has the advantage of providing natural haptic interaction feedback to the user even more. However, due to the semi-active type characteristics, the touch surface functions such as protruding and recessing, and the function of providing the 3D shape of the surface is limited.

4. Wearable Haptic Interfaces

Wearable interfaces are the most common sources of VR/AR haptic feedback. Users simply wear the interfaces to receive haptic feedback from the actuators attached to the wearables. Hand-worn haptic devices, including gloves and exoskeleton-type materials, are typical wearable haptic interfaces. Other than hand-worn haptic interfaces, vest- and foot-worn haptic interfaces have been actively applied to provide various tactile sensations across other parts of the body. The benefits of using wearable interfaces are clear that they can provide good interactivity and a large workspace by providing tactile and kinesthetic feedback in 3D space. Since they are the most common VR/AR haptic sources, various materials have been tried, including piezoelectric, pneumatic, shape memory alloy, and magnetorheological fluid actuators, to deliver more realistic sensations. However, such interfaces often became bulky and heavy to wear and suffered from battery issues. This section analyzes three types of wearable haptics, including hand-, vest-, and foot-worn haptic interfaces, to highlight their underlying principles and applications with new materials that have been applied.

4.1. Hand-Worn Haptic Device

Because skin at the fingertips has the most distributed mechanoreceptors, it is a crucial tactile sensory component that allows users to feel even the most sophisticated tactile sensations. The technology for embedding a tactile feedback actuator in a glove-shaped VR interface has been actively analyzed. The well-known commercially available VR gloves of Dextarobotics (left,[74]) and Plexus(right,[73]) companies embed vibration motors for each finger to provide vibrotactile feedback synchronized with the VR environment, as shown in **Figure 5**a. The gloves capture a high degree of freedom hand motion using the built-in sensor at full dexterity, providing intuitive vibrotactile feedback when

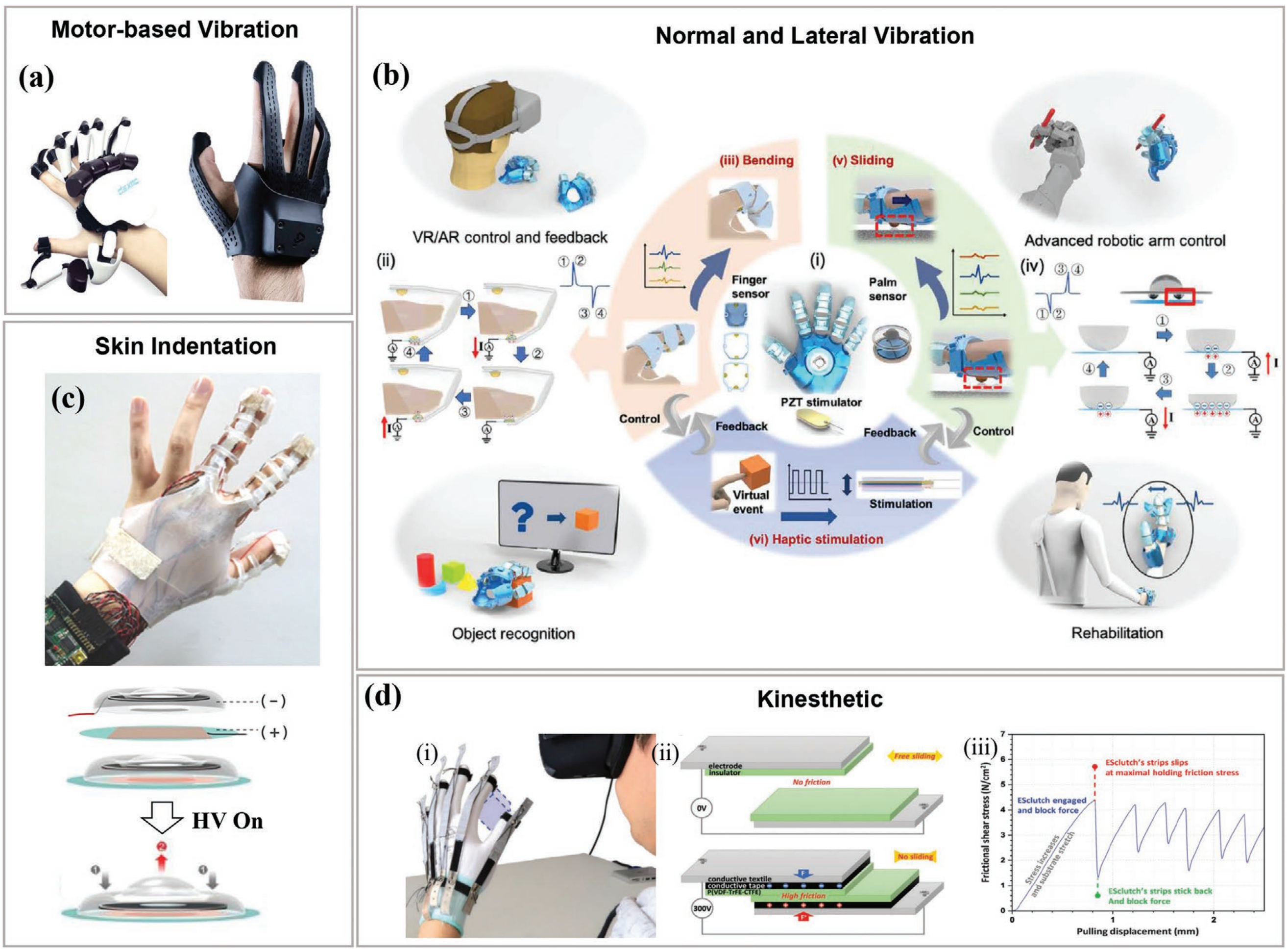

Figure 5. Hand-worn haptic devices. a) Commercialized VR gloves: Dexmo(left) with the function of servo motor-based force feedback and 11 DOF hand motion capturing. Reproduced with permission.[112] Copyright 2021 Dexta Robotics. All rights reserved. Plexus (right) with 21 DOF measurement system and 5 tactile actuators. Reproduced with permission.[73] Copyright 2020, US Patent, and b) Haptic glove consisting of polymer-based triboelectric tactile sensors and piezoceramic-based haptic actuators for intuitive HMI. Reproduced with permission.[113] Copyright 2020, AAAS. c) Fexible virtual reality glove system with pneumatically actuating tactile modules. Reproduced with permission.[84] Copyright 2019, Nature Publishing Group. d) Kinesthetic feedback glove adopting high force density textile electrostatic clutch. Reproduced with permission.[4] Copyright 2020, Wiley Online Library.

the wearer's hand encounters a virtual object. This state-of-the-art VR integrated system can provide an intuitive VR experience; however, owing to the limitation of using a vibration motor, it cannot deliver a sophisticated texture sensation of an object that can provide a more immersive experience.

A vibrotactile actuator based on an active material has been analyzed and applied to provide a sophisticated and realistic tactile sensation by being compactly embedded in a glove-type interface. Zhu et al.[113] presented a haptic glove for intuitive HMI which is composed of polymer-based triboelectric tactile sensors and piezoceramic-based haptic actuators (Figure 5b). The glove housing (Figure 5b-i) is designed to contain the sensors and actuators for detecting multi-dimensional hand's motion and conveying real-time tactile feedback. The major functional units are composed of finger bending sensors and palm sensors. The bending sensor senses the finger's motion with multiple DOFs, and the palm sensor detects the normal and tangential force in eight directions (Figure 5b-i to v). Thus, the presented haptic glove can achieve dexterous joint manipulation.

Song et al.[84] designed an integrated haptic flexible glove for VR application. The proposed glove includes the pneumatic tactile actuators, as indicated in Figure 5c. As shown in Figure 5c (lower), the developed pneumatic flexible tactile actuator is composed of a bottom electrode generating electrostatic attraction force and a grounded contact part in the center. When voltage signals are applied to the bottom electrode, the contact part vibrates up and down by electrostatic attraction. When interacting with a target object in a virtual environment, both tactile sensation and kinesthetic information (object shape, physical properties, etc.) are important factors for natural interaction. The dextarobotics' glove (Figure 5a, left) embeds servo motors built into each side of the finger. The glove's direct-drive method powered by highly customized servo motors offers precise force feedback with a maximum of 5 kg. cm. Despite the dexterous design of this VR glove, the use of electro-mechanical servo motors could not overcome the device's limitations, becoming larger, heavier, and consuming significant power. Figure 5d demonstrates a kinesthetic feedback glove using textile electrostatic clutches (ESclutches) for VR applications.[4] The ESclutches are small and light, making them especially suitable for wearable applications. They are variable capacitors in which the frictional force between the electrodes creates a frictional shear stress of 21 N cm^{-2} at 300V, proportional to the square of the applied voltage.

4.2. Vest-Worn Haptic Device

Vibrotactile actuators and motors are the most common types of vest-worn haptic devices used to generate tactile feedback. They generally utilize several vibrotactile actuators to create and deliver tactile sensations across other parts of the torso. **Figure 6**a presents a haptic vest that generates tactile and

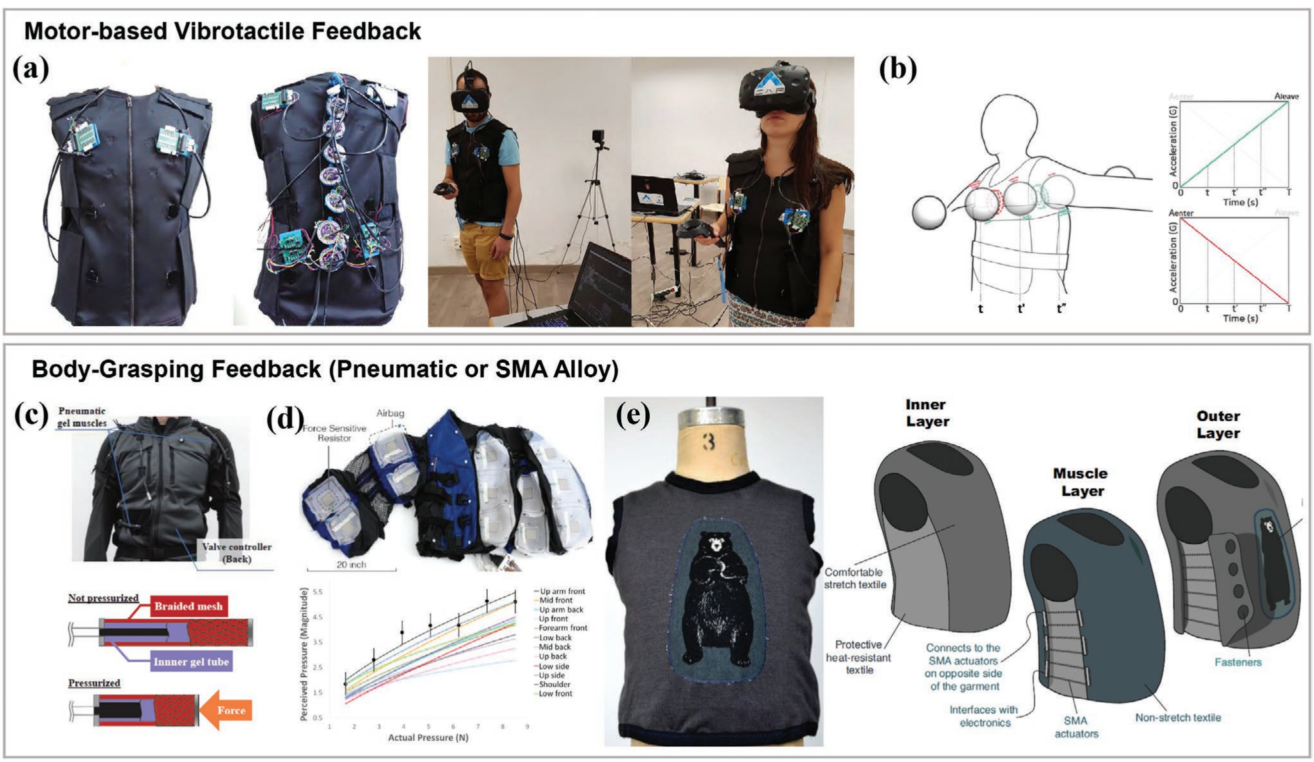

Figure 6. Vest-worn haptic devices. a) Haptic vest for evaluating presence in virtual environment. Reproduced with permission.[114] Copyright 2017, IEEE. b) Concept of body-penetrating tactile phantom sensations through the torso. Reproduced with permission.[115] Copyright 2020, ACM. c) Muscleblazer suit with a set of pneumatic gel muscles to provide pressure feedback. Reproduced with permission.[96] Copyright 2019, IEEE. d) Force Jacket is pneumatically actuated jacket to provide variable forces to the upper body. Reproduced with permission.[97] Copyright 2018, ACM. e) Hugging vest uses shape memory alloy (SMA) to provide pressure sensations. Reproduced with permission.[7] Copyright 2016, ACM.

thermal stimulation using vibration motors and thermoelectric actuators.[114] They investigated the effects of tactile and thermal feedback when interacting with a virtual environment. The vest was equipped with several vibration motors having a frequency ranging between 0 and 350 Hz to generate vibration patterns during interactions. Heat and cold sensations were also provided using thermoelectric actuators based on Peltier cells. The cells were fitted with 3D-printed supports attached to the vest. One side of the Peltier cell was in contact with the user, and a heat sink was placed to avoid overheating of the cell. A total of 12 Peltier cells were placed on the vest. The synesthesia suit provides vibrotactile sensations over the entire body for VR experiences.[116] The suit uses 24-channel voice-coil actuators with various body sizes. The suit consists of the Synesthesia software engine that controls the 24 tactile channels. The engine reproduces several haptic effects by recording tactile signals from the real environment or modulating prerecorded sound. The suit was designed to distribute haptic sensations throughout the entire body using a spatial pattern.

Kim et al.[115] provided body-penetrating tactile phantom sensations using two vibrational actuators attached to opposite locations of the torso (Figure 6b). They used two voice-coil actuators with stereo audio amplifiers to activate the actuators. The signal amplitude was initially the greatest at the entrance. However, it decreased over time. The amplitude gradually increased from 0 at the exit. The TIKL Suit[117] is a wearable vibrotactile outfit designed for human-motor learning. The system consists of optical tracking devices, haptic actuators, software, and hardware for output control. This system investigates the effect of tactile feedback on motor learning. Users mimic target postures, and real-time tactile feedback is delivered to the joints that do not match the target-posture configuration, enabling users to correct their posture rapidly. Tacsuit from bHaptics[118] is a commercialized haptic vest that provides various patterns of tactile effects for VR experiences. It uses 40 ERM actuators with low latency (less than 20 ms) to provide feedback to the upper body in real-time. The vest system also offers real-time audio-to-haptic features that automatically turn audio signals into haptic ones.

Muscleblazer[96] is a pneumatic vest that uses pneumatic-gel muscles to provide pressure feedback on the upper body (Figure 6c). The pneumatic-gel muscles are lightweight and flexible, and they contract and expand based on the air pressure coming from the sides, controlled by solenoid valves. The vest is further connected to the VR system to provide pressure feedback in a virtual environment. The force jacket[97] is another pneumatic vest that provides an embodied haptic VR experience (Figure 6d). The jacket contains 26 airbags, each made from a polyurethane film, fabricated by using a computer numerical control heat-sealing machine. The polyvinyl-chloride (PVC) tubing is attached to each air compartment, further connected to the corresponding solenoid valve's outlet ports. One of the solenoid valves is connected through PVC tubing to the air compressor, and the other is connected to a vacuum to control the air release. The authors confirmed that the perceived pressure changed linearly based on the actual pressure.

Another source of the actuator technology for the haptic vest is the SMA. SMAs are significantly light and compact but can generate a force large enough to provide haptic feedback onto a human torso. Jones et al.[6] developed a tactile vest using an SMA. The SMA actuator consists of a pin, a pivot rod, the SMA, and super-elastic wires. When current is applied to the SMA wire, the pin near the pivot rod rotates, which subsequently presses against the skin to provide feedback. The active-hugging vest[7] is an SMA device designed for pressure therapy (Figure 6e). The vest consists of an inner layer for comfort and insulation, a muscle layer that performs the hug, and an outer layer for protection. The SMA springs contract when a current is applied to create compression for pressure sensations.

4.3. Foot-Worn Haptic Device

Figure 7 presents various foot-worn haptic devices. The Gilded Gain[119] from Sony emulates physical ground textures using vibrotactile feedback (Figure 7a). The wearable insole contains six vibration panels that provide various haptic patterns according to the desired ground textures. Furthermore, it contains a push-down switch and an accelerometer to detect user footsteps. SoleSound[120] is a footwear system that simulates various ground surfaces based on audio-tactile feedback (Figure 7b). Vibrotactile actuators are integrated inside the shoes to activate the actuators with audio signals. The system uses several components, including four piezoresistive force sensors, three two-channel audio amplifier boards, a loudspeaker, an IMU, and five vibrotactile transducers to deliver tactile feedback through a feedback engine. The signal is generated based on the inertial and piezoresistive sensors. Taclim[121] is a commercialized pair of haptic shoes that adopt built-in vibrotactile actuators to emulate various ground textures. These can also detect footstep and sense movements using a nine-axis sensor with market-available trackers. Vibrotactile actuators have several benefits, including portability and simple application. However, they cannot express certain ground textures, such as mud and sand, and are also limited in emulating ground deformations.

Level-ups[123] are stilts that can be worn similar to a boot. It allows users to walk around and experience virtual elevation effects. It consists of a lift table and operates based on a scissor mechanism. A DC motor is activated to control and actuate the lift table, driving the axle to prevent it from rotating. The HapticWalker[122] is a haptic device comprising three-DOF two-foot platforms (Figure 7c). The equipment contains six-DOF force and torque sensors. The system uses a special switched override filter cascade to manipulate the velocity profile and provide anti-stumbling training. The Snow Walking is a boot-shaped haptic device[124] and it can generate the sensation of snow walking. A slider-magnet mechanism is used to simulate vertical locomotion. In fact, these approaches present the feasibility of ground-surface deformation simulations. However, it is challenging to apply them to real-world applications due to their complicated structures.

As shown in Figure 7d, RealWalk[10–12] is a pair of haptic shoes that use MR fluids to create VR ground textures and deformation sensations. The MR-fluid actuators were designed to allow users to depress the actuators while adjusting the MR fluid's viscosity, creating various ground-texture sensations. In an MR fluid actuator, several discs are stacked together in the

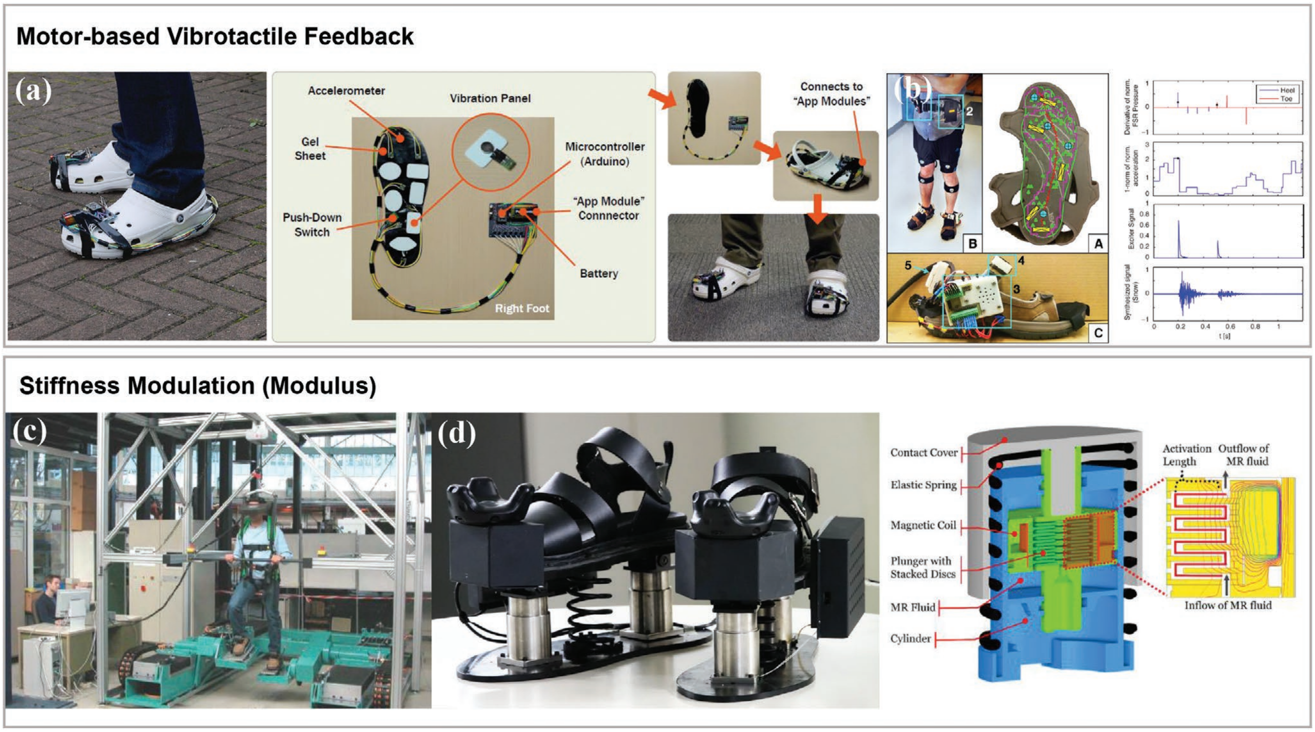

Figure 7. Foot-worn haptic devices. a) Gilded Gait from Sony. It's a pair of insoles with embedded actuators to simulate the feelings of a range of different ground textures by utilizing vibrotactile feedback. Reproduced with permission.[119] Copyright 2010, ACM. b) SoleSound is a foot-wearable system to deliver audio-tactile underfoot feedback. Reproduced with permission.[120] Copyright 2014, IEEE. c) HapticWalker is a haptic locomotion interface that allows user to walk for gait rehabilitation using six DOF force/torque sensors. Reproduced with permission.[122] Copyright 2005, ACM. d) RealWalk is a pair of haptics shoes for VR and it is designed to provide realistic sensations of ground surface deformation and texture through MR (magnetorheological) fluid actuators. Reproduced with permission.[12] Copyright 2020, IEEE.

center of the plunger. A magnetic coil is wound around the discs to maximize the resistive force caused by the MR fluid. This design allows the MR fluid to maximize the fluid flow path length by forming a zigzag pattern.

5. Skin-Attachable Haptic Interfaces

In addition to wearable haptic interfaces with the forms of garments, researchers are pursuing more comfortable and even imperceptible form factors that can seamlessly adhere to the human skin for applications such as human-machine interfaces, soft robotics, and VR/AR.[125] By mimicking the modulus and thickness of human skin, haptic devices are becoming soft, flexible, and conformably attached to the skin surface so that they keep providing haptic feedback without disturbing users' motions. Also, improved adhesion between skin and haptic devices would significantly enhance tactile feedback delivery. However, it is a challenge to make active actuating parts soft and stretchable. There is a tradeoff relationship between the output performance and the mechanical compliance of actuating devices. Strategies related to the design of functional materials such as nanocomposites and the hybrid integration of actuators make breakthroughs on these challenging issues. This section reviews the status and roles of emerging active materials for skin-attachable haptic devices. Skin-haptic actuators using active materials are expected to efficiently provide tactile feedback (e.g., vibration, shear force, thermal feedback, skin indentation, and skin stretch) with imperceptible user convenience. Moreover, high resolution and multimodal skin-haptic actuators have also been developed by hybrid integration strategies for realistic and natural multi-point user interactions.

5.1. Soft Skin-Haptic Actuators for Vibrotactile and Kinesthetic Feedback

To generate normal vibration feedback with skin-attachable devices, rubber-like soft active materials are of significant interest. Stretchable and conductive nanocomposite materials such as silver nanowire (Ag NW) embedded PDMS,[128] CNT-elastomer composites,[129] composites with PEDOT:PSS and polyurethane,[130] are key materials for soft actuators to generate the vibrational tactile feedback. Mun et al. reported a soft tactile actuator using compliant silver nanowire electrodes. The soft actuator was fabricated by multi-layered electroactive polymer (EAP) films and dielectric layers. The multi-layered actuator is designed to produce convex protrusive deformation by applying electric field, which can be programmed for a wide range of tactile stimuli and provide normal vibration feedback[17] (**Figure 8**a). These EAP actuators can be made with thin and soft membranes so that all device area become mechanically compliant like rubber, which is an ideal condition for skin-attachable haptic interfaces and very low power consumption

Figure 8. Skin-attachable haptic interfaces. a) An electroactive polymer-based soft actuator array attached on fore-arm which can produce convex and protrusive deformation. Reproduced with permission.[17] Copyright 2018, IEEE. b) Design and architecture of an epidermal VR system by using independently controllable 32 channel haptic actuators. Reproduced with permission.[9] Copyright 2019, Springer Nature. c) A matrix built of 15 shape memory alloy (SMA)-based plasters that can generate shear forces on the skin. 8 touch gestures were created. Reproduced with permission.[8] Copyright 2020, ACM. d) Ultra-thin conformal array of filamentary metal structures that simultaneously function as both thermal sensors and actuators. Reproduced with permission.[126] Copyright 2015, PLoS ONE, CC BY 4.0. e) 5 × 5 array of high resolution hydraulically amplified taxel for wearable haptics. It exhibits a low-profile, flexible array which can be integrated on a textile sleeve. Reproduced with permission.[80] Copyright 2020, Wiley. f) A multimodal skin-haptic interface device for virtual tactile feedback of roughness, hardness and temperature. Reproduced with permission.[127] Copyright 2020, CC BY 4.0.

because of almost negligible current flow. However, these kinds of EAP actuators require kilovolt-order high operation voltage to produce a high electric field, which is a drawback for skin-attachable applications because of their safety issue. Another promising approach for the typical vibration feedback with skin-attachable interfaces is to embed rigid high-performance actuators with soft materials. J. Rogers et al. demonstrated skin-integrated haptic interfaces by using wireless electromagnetic actuators embedded in a skin-like silicone elastomer layer. The novel design and architecture of the electromagnetic actuators, embedded in an elastomer, enabled wireless epidermal VR systems. Figure 8b presents an device schematic with 32 channel of independently controllable actuators. The device produces haptic patterns that correspond to the shape features of objects held in a robotic prosthetic.[9]

To create shear force feedback on the skin surface, shape memory alloys (SMA) are also promising candidates. Its 1D geometry enables mechanically compliant integration with elastomers and textiles, despite it being a rigid metal. It generates tensile force, which is desirable for shear force and kinesthetic feedback. Nanayakkara et al. demonstrated a matrix composed of 15 shape memory alloys (SMA)-based plasters.[8] SMA wires in the plasters generate shear forces on the skin. Eight touch gestures were created as follows: (1) grabbing the arm, (2) grabbing the wrist, (3) three taps down the arm, (4) three taps up the arm, (5) stroking down the arm , (6) stroking up the arm, (7) encircling/rolling on the arm, and (8) encircling/rolling on the wrist (Figure 8c). A major drawback of SMA actuators is slow operation speed because it relies on thermal conduction and contraction.

With vibration and shear force feedback, thermal feedback, which is highly desirable in VR/AR applications, can also be implemented using skin-attachable thermal actuators. Intrinsically stretchable composite materials and geometrical structures have been used. For example, wearable skin-like thermal actuators using Ag-Au nanocomposites have been demonstrated.[131] The heating element is stretchable up to 100%, and its heating performance is stable under deformation. By using geometrical structures, an ultra-thin conformal 4×4 arrays of thermal sensors and actuators mounted on the cheek have been demonstrated, as shown in Figure 8d. A thin polyimide film of less than 3 µm encapsulates the electrical interconnects. The silicone elastomer thin film (as small as 5 µm) of a low modulus (35 kPa) provides a conformal contact and intimate thermal interface on the skin. To generate skin stretch with skin-attachable actuators, the muscle-like actuation mechanisms are presented. Twisted and coiled polymer (TCP)-based actuators exploit ultra-high molecular weight polyethylene (UHMWPE) fibers to render the sensation of skin stretch. These actuators are made of polymeric fibers that have a negative linear thermal coefficient. The length of these fibers contract when they are heated.[85]

5.2. Soft Skin-Haptic Actuators for High Resolution and Multimodality

To generate high-resolution skin indentation with a device that has a thin, compact form factor, functional polymer materials have also been utilized. High-resolution electrohydraulic actuator arrays have been introduced based on hybrid actuation mechanism with hydraulic and electrostatic types. Figure 8e shows 5×5 array of 1 mm-pitch high resolution hydraulically amplified tactile pixels.[80] The actuator consists of a liquid-filled pouch with a central elastomer region and a polymeric perimeter electrode. When a electric field is applied, the electrode layer pushes the fluid rapidly into the stretchable center and forming a raised bump. The output force and displacement of the actuator are respectively up to 300 mN and 500 µm, with a response time of less than 10 ms.

Hybrid integration of soft active material-based actuators and rigid components on a soft matrix platform can be a compromised solution to realize multimodal and sophisticated haptic feedback. Lipomi et al. demonstrated a conformable haptic device which can produce multimodal sensations, including hardness, temperature, and roughness.[127] Three haptic actuators including vibrotactile, thermoelectric, and electrotactile types are integrated to provide complex and multimodal tactile stimulation, as shown in Figure 8f. To express hardness of virtual objects, lower and higher amplitude vibrations were generated, corresponding to softer and harder objects. The surface temperatures of virtual objects were controlled by using thermoelectric devices. The polarity and magnitude of the voltage determined a heating or cooling sensation. For rendering of the surface texture, the electrotactile effect has been utilized. Electrical input signals generate action potentials on the nerve endings of the skin that is recognized as tingling. These devices allow participants to discriminate complex tactile sensations in VR/AR.

Skin-attachable soft haptic interfaces are promising approaches for generating realistic virtual haptic feedback and augmenting the tactile sensations. Design strategies using intrinsically soft active materials and hybrid integration with rigid components have been tried to provide vibrotactile, kinesthetic feedback, high resolution, and multimodality on a soft membrane or textile, making intimate contact with the skin surfaces. Nevertheless, further improvements in spatial resolution and output intensity of tactile feedback, such as the extruding forces and displacements of soft polymeric actuators, still remain technical challenges of skin-attachable haptic interfaces. Therefore, innovations of the actuation performances based on material engineering and novel structuring designs are highly expected.

6. Mid-Air Haptic Interfaces

Non-contact haptic systems are part of an emerging technology that aims to realize high tactile applications in near-future interaction systems. They are hands-free and unencumbered, compared with bulky worn contact haptic systems. Recently, with the popularity of VR/AR systems,[132–134] direct bare-hand interactions with virtual objects have been deemed necessary to improve the sense of reality and engagement of VR/AR systems. Mid-air haptic technologies can provide this advanced immersive experience by delivering a well-designed non-contact tactile sensation to an interaction space in the air space surrounding the user.[135] Such a technique would enrich immersive experiences with digital objects and also improve the performance of the non-contact input. In particular, non-contact interaction is expected to circumvent unwanted physical contact with various dangerous applications and situations, such as contaminated environments. An appropriate mid-air tactile sensation would be critical to the application. In this section, an overview of the multiple types of mid-air haptic devices is provided by analyzing recent studies and applications, considering their device operation mechanisms, performances, and uses.

6.1. Ultrasound Haptic Device

The ultrasound haptic system is a promising non-contact tactile technology that can be used for sophisticated mid-air haptic stimulation. The ultrasound stimulation system, which focuses on 40 kHz ultrasound waves emitted from multiple ultrasound actuators onto a focal point by accurately positioning haptic cues around a large spatial region, renders various stimuli at a high resolution. When the focal point meets the human skin,

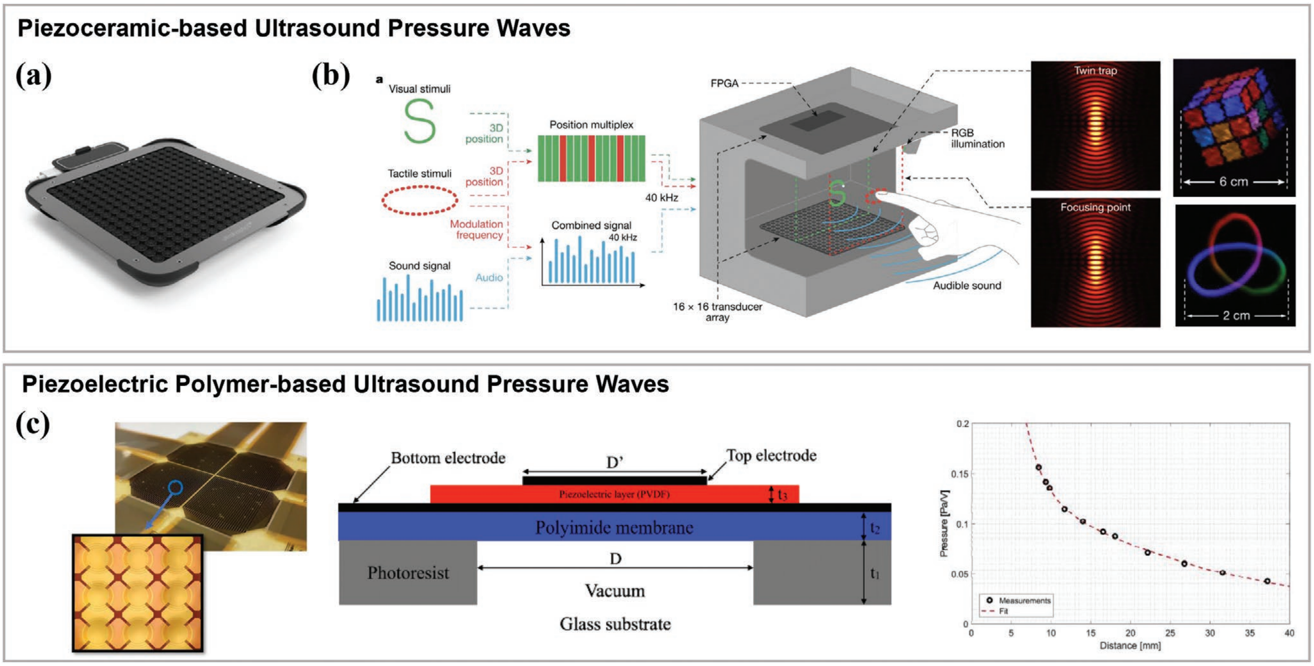

Figure 9. a) Ultrasound haptic system having high resolution and large spatial region for non-contact, sophisticated in-air haptic stimulation. Ultraleap device delivers mid-air tactile sensations around 300 mm above from the haptic display by generating focal points using the multiple ultrasound waves. Reproduced with permission.[136] Copyright 2020, Ultraleap. b) Multimodal acoustic trap display (MATD). A levitating volumetric POV display can simultaneously deliver haptic feedback with visual and auditory feedback as a multimodal interaction system using ultrasound stimulation. Reproduced with permission.[137] Copyright 2019, Nature Publishing Group. c) The compatible Piezoelectric Micromachined Ultrasonic Transducer (PMUT) array for mid-air haptic feedback. Due to its relatively miniaturized size compared with other ultrasound transducer technologies, a polymer-based PMUT array can be adopted for mid-air haptic feedback above 10mm, near the display. Reproduced with permission.[138] Copyright 2019, IEEE.

a nonlinear phenomenon of ultrasound waves occurs with increased acoustic radiation pressure,[139] generating the tactile sensation on the skin. Controlling ultrasound intensity and its modulation frequency varies the tactile sensation.

Iwamoto et al. introduced an ultrasound haptic prototype as an interaction system for a 3D stereoscopic display.[139] It achieved an output force of 0.8 gf and a spatial resolution of 20 mm. This initial exploration confirmed the feasibility of using an ultrasound haptic device as a tactile display. The dynamic phase control of an ultrasound haptic was investigated to display 3D haptic animations by individually manipulating both phase and intensity of each ultrasound transducer.[140] The effective range of the modulation rate was analyzed to target the most sensitive area on the palm per frequency and enlarged the focal point by increasing the device power.[141] Carter et al. explored a method of producing multiple localized points of ultrasound haptic stimulations having a cue size of 8.6 mm.[86] The study indicated that users could feel two separate tactile stimuli and distinguish between the different vibration frequencies during psychophysical experiments. The compatible PMUT array is another type of ultrasound haptic display that adopts a polymer-based piezoelectric micromachined ultrasonic transducer (PMUT) array for mid-air haptic feedback; this was proposed by Halbach et al.[138] (**Figure 9**c). It produced a relatively minuscule haptic feedback above 10 mm from the display.

Studies on ultrasound haptic displays have extended the design space of haptics and HCI. Several studies have explored ultrasound haptic systems for rich interaction experiences of VR, AR, and 3D stereoscopic displays. A mid-air haptic feedback system for an head-mounted display (HMD) was built by mounting an ultrasound array on its front surface.[142] It focused on unobtrusive haptic feedback as the user touched virtual objects. The AirPiano enhanced a music playing system to provide touchable experiences for a virtual instrument in VR with mid-air haptic feedback.[143] Refinity allows users to explore realistic virtual products for a futuristic retails shopping experience using ultrasound haptic display combined with an autostereoscopic 3D display.[144] A feasibility study for future AR glasses was conducted, considering localization and movement perception of ultrasonic haptic feedback on the face.[145] Recently, Hirayama et al. introduced a multimodal acoustic trap display (MATD) using a twin levitation trap with ultrasound stimuli, which is a levitating volumetric 3D persistence-of-vision (POV) display that can simultaneously deliver haptic feedback with visual and auditory feedback using acoustophoresis in the air[137] (Figure 9b). MATD levitates and manipulates a particle using primary ultrasound traps and displays perceived color information on it for volumetric visual contents. Using a secondary trap, MATD delivers simultaneous auditory and tactile feedback synchronized with visual content. The maximum pressure level of the tactile points is 158.5 dB.

With the benefits of localization and a high resolution, ultrasound haptic devices have also been applied for industrial uses, such as VR/AR automotive interfaces.[146,147] One successful commercial product is the Ultraleap device, which provides a sensation editor to render haptic patterns with an adjustable modulation rate and intensity[136] (Figure 9a). This allows

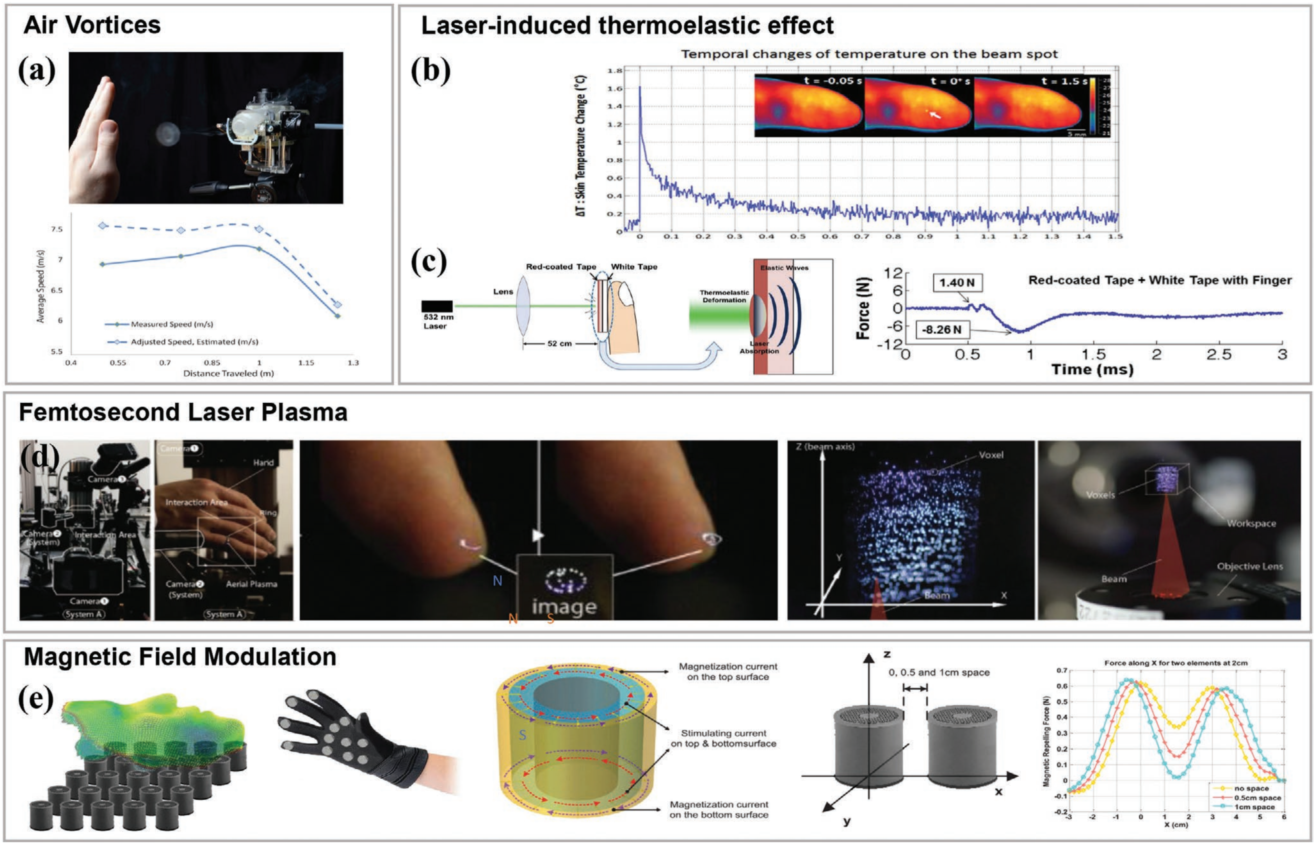

Figure 10. Potential mid-air haptic devices have been explored to enrich the mid-air interaction experience. a) AIREAL mid-air haptic system using by multiple woofer speakers generates discrete air vortices that can travel significant distances over 1 m. Reproduced with permission.[150] Copyright 2013, ACM. b) Laser-induced thermoelastic effect system using low-power radiation. It delivers maximum 1.63 °C of mid-air thermal feedback by the thermoelastic waves making a mechanical displacement in the tissue. Reproduced with permission.[151] Copyright 2015, Nature Publishing Group. c) The indirect laser radiation evoking a thermoelastic effect to the elastic medium through the air. It provides mechanical vibrations to the skin. Reproduced with permission.[152] Copyright 2015, IEEE. d) Femtosecond laser-plasma generating shock waves on the skin which delivers mid-air haptic feedback with volumetric holographics. Reproduced with permission.[153] Copyright 2016, ACM. e) Magnetic field from an electromagnet array and hand-attached magnet disks which generates the volumetric shapes of mid-air haptic feedback. Reproduced with permission.[154] Copyright 2016, IEEE.

developers to easily access the mid-air haptic system to create new types of VR/AR applications. Another commercial product is the PMUT-based haptic device from Imec.[148] This is a miniaturized micro-electromechanical system based on structures that enable portable solutions.

Despite the state-of-the-art mid-air ultrasound haptic system, drawbacks are arisen for driving noise and safety issues by increasing ultrasound haptic stimuli' intensity. The noise generated by the ultrasound transducers can be hazardous, although the noise levels meet safety requirements.[149] The noise can also spoil the quiet and comfortable environment expected with their daily use. The spread of acoustic output to the air, in addition to the focal point, can interfere with surrounding sound-input devices. The issues must be handled for their sustainability and reliability.

6.2. Potentially Applicable Mid-Air Haptic Technologies

A variety of mid-air haptic systems has been explored to deliver non-contact tactile feedback. The straightforward method generates an airflow on the skin. It can display relatively strong stimuli on the skin at a distance. The large distance of the airflow system is well suited for large-scale scenarios in VR, AR, or 3D displays. Air-vortex systems can deliver pressure stimuli over 1 m with 90% accuracy, generated from multiple subwoofer speakers[150,155,156] (**Figure 10**a). It is a discrete haptic feedback system with considerable force on the skin. When air is ejected from an aperture, the speed difference between the edge and center of the aperture makes the air rotate around the aperture to generate an air vortex.[157] The air-vortex system can also be implemented using an air jet.[158–160] The compressed air from the air tank is ejected toward the surface of the air cannon. An air-jet system beneficially delivers long-term haptic feedback during an interaction.[159] Another type of mid-air VR/AR haptic system uses HMDs to enrich the user experience by emitting short- and long-term airflows (winds) using fans[161] and air nozzles.[162]

Weiss et al. explored a magnetic field for delivering mid-air haptic feedback.[163] A prototype using electromagnetic actuation produced both magnetic attracting and repelling forces with magnets attached to the hand to deliver vibration patterns around 35 mm above the display. A magnetic rendering system using a specialized cylinder-ring electromagnet array and hand-attached magnet disks was developed to render volumetric shapes in the air[154] (Figure 10e). It produced a magnetic force of 0.11–0.49 N 20 mm above the surface. Another mid-air magnetic-field haptic device used a time-varying magnetic field to induce current flows within the body.[164] The current from the magnetic field activated the mechanoreceptors of the skin, generating a tactile sensation. In another feasibility study, a mid-air tactile sensation was delivered through body hair stimulated by a magnetic field.[165] Passive magnetic cosmetics were applied to the body hair, and the hair movement delivered the tactile sensations by activating the tactile neurons in the skin.

A laser-induced thermoelastic effect using low-power radiation was recently analyzed as a novel mid-air haptic system[151] (Figure 10b). The system caused a physical sensation from a photo-mechanical effect of the instantaneous heating of tissue by pulsed-laser radiation, producing thermoelastic waves that caused a mechanical displacement in the tissue, activating mechano-receptors.[151] This non-contact haptic stimulation delivered maximum thermal feedback of 1.63 °C 10 mm over the display using low-power radiation. The spatial resolution was 0.14 x 0.14 mm^2, and the diameter of the heated region was approximately 0.59 mm. A mid-air haptic system using the indirect laser radiation on an elastic medium was explored to provide continuous moving tactile sensations on the skin[152,166] (Figure 10c). The laser radiation delivered mechanical vibrations by evoking a thermoelastic effect on the PVC tape (the elastic medium). A femtosecond laser delivered mid-air haptic feedback with volumetric holographic by emitting light at an arbitrary 3D position[153] (Figure 10d). A nanosecond laser-plasma induced by a femtosecond laser-generated shock waves when the plasma voxels were touched.

The potentially applicable mid-air haptic technologies by various mid-air haptic actuators can create their specialized tactile sensation on the skin. Even so, potentially useful mid-air haptic technologies have been explored to display tactile sensations. First, the technologies proposed by studies must ensure the safety of skin exposure. Then, they must improve their performance, including both magnitude and spatial resolution. In the future, it is expected that they can generate more sophisticated sensation for virtual objects in VR/AR.

7. Neuro-Haptic Interfaces

Advances in neuroscience have evolved to transmit tactile sensation directly through neural interfaces in our bodies. By stimulating peripheral nerves or the area of sensory perception in the brain cortex, primitive studies regarding the creation of artificial feelings have been reported.[172–174] These neuro-haptic interfaces are actively analyzed in the field of robotic prosthetics providing tactile feedback for the impaired. The neural interface requires soft and biocompatible materials to prevent chronic inflammation near the interface between the device and living tissues. Moreover, requirements such as stability over time, low invasiveness, and high selectivity in neuro-haptic interfaces are highly desirable for restoring the tactile sensation of the impaired, or augmenting the tactile information of the normal and even communicating with them. These neuro-haptic interfaces have the potential to achieve whole-body accessible haptic feedback without restricting the physical limit of hardware. It also enables highly efficient tactile transmission without any motors or a bulky power supply. However, the challenge is to develop safe and reliable neural interface devices that do not cause chronic damages to the nerves. In this section, the neural interface of peripheral neurons and the brain cortex, as well as the non-invasive neural modulation methods for neural-haptics, are presented.

7.1. Implantable Neural Interfaces for Haptics

Generally, the neurostimulation in peripheral nerves and the brain cortex has been analyzed to deliver tactile information for the impaired who cannot feel tactile sensations through their skin.[175] In this case, tactile sensing signals or artificially regenerated tactile signals can be transmitted to their nervous system through a neural interface.[176]

Peripheral nerve stimulation has been demonstrated for the sensory feedback of a prosthetic hand. Schiefer et al. reported the restoration of the natural pressure perception on the hand by implanting cuff electrodes in the forearm of a subject[177] (**Figure 11**a). The cuff electrode interfaces enabled the sensory feedback that is synchronized with the forces applied on the thumb, index, and middle fingers of the robotic prosthetic hand during object manipulation. The cuff electrodes contained either four or eight independent stimulation channels in a 4 mm diameter cuff (electrode pitch: 3 mm or 1.5 mm) and the exposed contact area per electrode is 0.45 mm^2. The stimulation channels are evenly spaced around the circumference of the peripheral nerve. The cuff electrode is advantageous to secure stability and safety of implantable neural interface because it is less invasive, although it has a lower spatial resolution (1.5 mm pitch) compared to needle-type electrodes (400 μm pitch). A large number of cuff electrodes chronically implanted on human peripheral nerves can be biologically stable and consequently work up to 10.4 years.[178] On the other hand, the needle-type electrode can provide high-resolution microstimulations although it has higher invasiveness. George et al. demonstrated a bidirectional neuromyoelectric prosthetic hand which can convey biomimetic sensory feedback and control the reaction behavior by implanting needle-type electrode to the peripheral nerves.[168] The signals acquired from the pressure sensors of the prosthesis triggered the microstimulation of sensory nerve fibers through chronically implanted Utah Slanted Electrode Arrays (standard electrode pitch: 400 μm), providing tactile sensations on the phantom hand (Figure 11b). The closed-loop sensory feedback significantly improved precise control of grip force and handling of fragile objects. Furthermore, the participant was also able to distinguish size and softness of the objects with additional training. Currently, these implantable peripheral nerve stimuli are still limited to nerve rehabilitation and sensory restoration of the impaired, but they are expected to be expanded to deliver and share the tactile sensation of the normal people in the future.

Along with the peripheral neural interface, the brain-machine interface on the sensory cortex is also a promising approach to

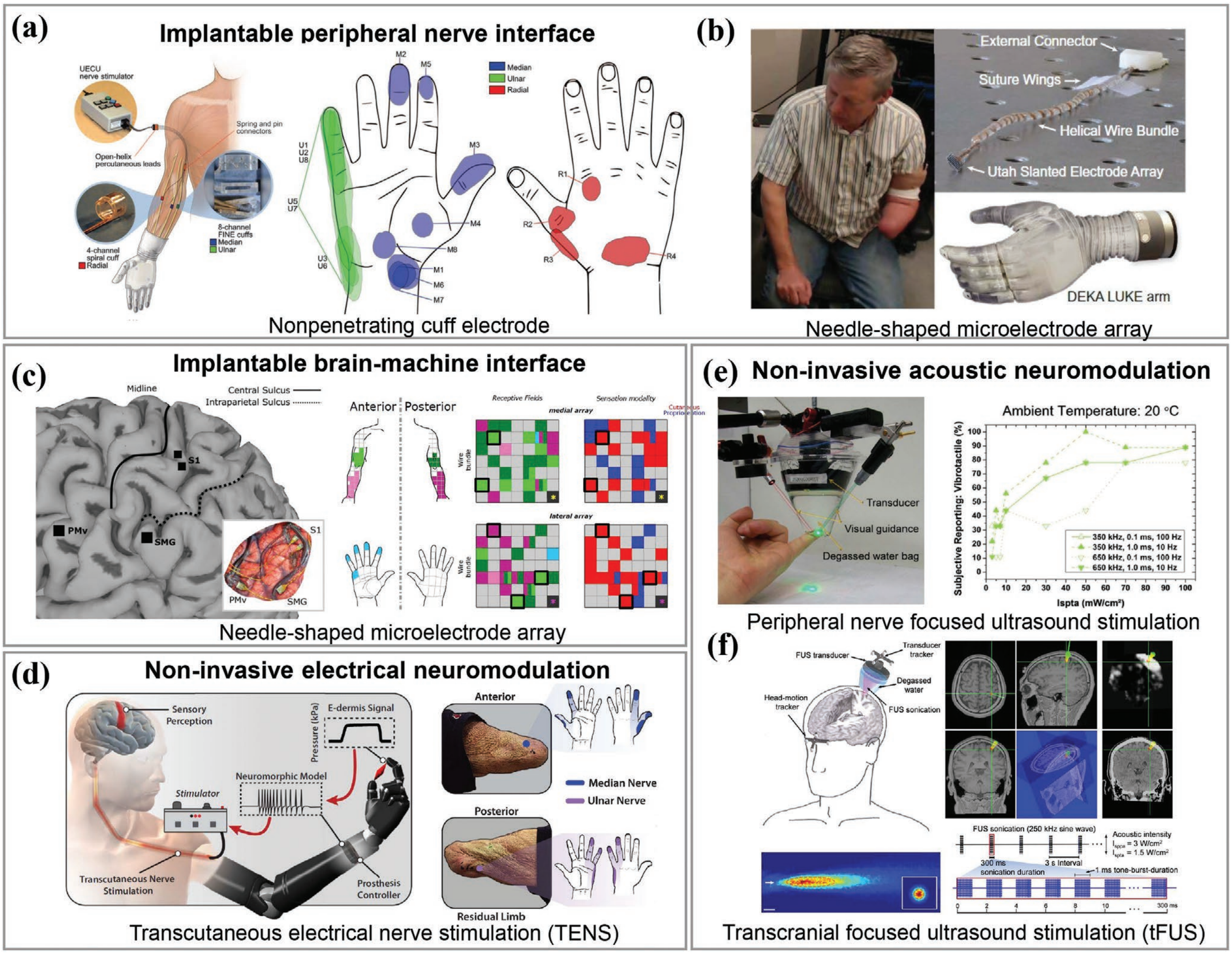

Figure 11. Neuro-haptic interfaces for tactile sensory feedback. a) Implantable peripheral neural interface for natural pressure perception on hand. 20 channels of nonpenetrating cuff electrodes for peripheral nerve were implanted in the forearm. Reproduced with permission.[167] Copyright 2014, AAAS. b) A bidirectional neuromyoelectric prosthetic hand that conveys biomimetic sensory feedback using a needle-type slanted electrode array. Reproduced with permission.[168] Copyright 2019, Science Robotics. c) Implantable brain-machine interface for sensory feedback. 96-channel platinum-tipped microelectrode recording array (Neuroport) were implanted into supramarginal gyrus (SMG) and ventral premotor cortex (PMv). And two stimulating arrays (48 Channels) were implanted into primary somatosensory cortex (S1). Reproduced with permission.[169] Copyright 2018, eLife Sciences Publications Limited. d) A prosthesis with pressure sensor and transcutaneous electrical nerve stimulator to recognize both touch and pain. Reproduced with permission.[170] Copyright 2018, Science Robotics. e) Ultrasound focused to skin surface for inducing various peripheral sensations by modulating the sensory receptors. Reproduced with permission.[171] Copyright 2014, Wiley Online Library. f) Image-guided transcranial focused ultrasound. Focused ultrasound (FUS) was transcranially transmitted to the somatosensory cortex with the guidance of neuroimage data. Reproduced with permission.[5] Copyright 2019, Nature Publishing Group.

regenerate tactile sensation. Tactile signals from the peripheral nerves are eventually centralized to the brain. Therefore, a direct neural interface on the brain's sensory cortex might be an more efficient way to provide truly realistic whole-body tactile information. There has been a tremendous effort to access tactile sensation via neural interfaces in the brain, also called brain-machine interfaces (BMI) or brain-computer interfaces (BCI). Anderson et al. analyzed brain microstimulation for a discriminable artificial sensation. 400 µm-pitch microelectrode arrays (96 channels) were implanted into the ventral premotor cortex and supramarginal gyrus, and two stimulating arrays (48 channels) were implanted into the primary somatosensory cortex.[169] Reproducible elicitations of sensations in the cutaneous and proprioceptive feedbacks on the arm were demonstrated, depending on both the amplitude and frequency of the stimulation (Figure 11c). The brain neural interface has an unrivaled advantage that it is potentially accessible to all parts with the tactile sensation. But the brain has very complicated 3D morphology, which is difficult to interface with a stimulating device without sophisticated penetration surgery. And there are also risks such as brain damage caused by inflammation of electrodes implanted into the brain.

For long-term stability and reduced inflammation of implanted neural interfaces, biocompatible materials and mechanical stability characteristics are critical. Biocompatible electrodes mainly consist of chemically stable metals, such as platinum, gold, and tungsten, and all except for the contact pads which should be left open for neural interfaces are also covered with a non-cytotoxic insulating material.[179,180] The difference in mechanical stiffness between rigid electrodes and soft tissues results in damage of living tissues originated from micromotions of the electrodes.[181,182] Thus, the mechanical compliance of neural interface electrodes is another technical challenge. Microwires[183] and micromachined electrodes on thin plastic substrates[184] are used to reduce the mechanical mismatch issue. Electroactive nanomaterials, such as conductive polymers,[185] CNTs,[186] graphene,[187] metal nanowires,[188] and hybrid nanomaterials,[189] have also been analyzed for mechanically compliant neural electrodes. In the future, achieving both long-term stability and high-spatial-resolution of neural interface electrode would be highly desirable for sophisticated sensory feedback, but it is a big technical challenge.

7.2. Non-Invasive Neuromodulation for Sensory Feedback

Another promising approach for neuro-haptic interfaces is a non-invasive neuromodulation method that can stimulate neurons without electrode penetration into the skin or brain. In addition to implantable methods, peripheral nerves can be stimulated via the skin, which is called transcutaneous electrical nerve stimulation (TENS).[190,191] Kajimoto et al. demonstrated an electrotactile display that directly stimulates the nerves within the skin by an electrical current via the surface electrodes.[192] To produce natural tactile sensation, they have tried selective stimulation of 3 different mechanoreceptors, RA, SA-I, and PC by using depth-selective stimulation. As a result, pressure sensation, vibratory sensation and sensation of soft material have been demonstrated by applying different stimulation modes of the electrotactile display. It is preferable to conventional mechanical actuators in several aspects. The electrotactile display can be manufactured in a small form factor, energy efficiently, and free from mechanical resonance issues. However, it also has issues that the tactile sensation is rather electrically tingling and it is affected by thickness and moisture of the skin, which can only vary from individual to individual. Osborn et al. demonstrated the transmission of touch and pain via the neural skin interface.[170] Tactile information generated during the object grasping is converted to a neuromorphic signal, and it is used to stimulate peripheral nerves via the skin to generate sensation of touch and pain (Figure 11d).

Current forms of clinically applied non-invasive neuromodulation methods such as transcutaneous electrical nerve stimulation (TENS), transcranial current methods (tACS, tDCS), and transcranial magnetic stimulation (TMS) have been studied extensively.[193] However, high-definition stimulation focused by ultrasound, magnetic field and electric current inside the human body is still challenging. Recently, neuromodulation by focused ultrasound (FUS) is highlighted as a promising approach that combines noninvasiveness with a focus that can be sharp and deep in the biological tissue.[194] Chung et al. reported the stimulation of peripheral neurons by the focused ultrasound.[171] The ultrasound wave focused on the skin surface can elicit various sensations by modulating sensory receptors' activity. In the experiment, pulsed focused ultrasound was applied to the finger for 10 s using two frequencies of 350 kHz and 650 kHz, and various acoustic intensities (3–100 mW cm^{-2}). Volunteers reported the feelings such as cool, warm, vibrations, and mild pain, while there was no escalation of skin temperature. However, continuous stimuli were not effective. Only the pulsed focused ultrasound temporarily affect to the activity of the sensory receptors and indicate potential applications in the field of non-invasive neuro-haptic interfaces (Figure 11e).

In addition to peripheral neurons, the brain has also been stimulated by the focused ultrasound. In the last decade, low-intensity transcranial focused ultrasound (tFUS) has been widely adopted for neuromodulation. The tFUS possesses a 3D high spatial resolution penetration characteristics as a non-invasive neuromodulation tool.[195] Lee et al. reported elicitation of explicit somatosensory sensations by focused ultrasound-based neuromodulation.[5] Focused ultrasound (FUS) was utilized for the transcranial stimulation of somatosensory cortex corresponding to the hand area. In the experiment, EEG recordings revealed the elicitation of sonication-specific sensation evoked potentials (Figure 11f). In the future, further neurological studies on an explicable mechanism analysis and safety verification of the artificial sensory regeneration based on these tFUS brain simulation are needed.[196] And for user convenience, development of miniaturization and flexible form factors of tFUS devices to be conformably attachable to the skin is also highly required.

Neuro-stimulation for haptics has been conducted via implanted electrodes interfaced with nerve and skin surfaces, as well as noninvasive electro and acoustic neuromodulations. However, in order to realize truly immersive neuro-haptic feedback, these above-mentioned interface techniques as well as researches on interchangeable algorithms between the devices' electrical signals and in-body biological sensory signals are also essential. Eventually, these neuro-haptic methods, including neural interfacing devices and algorithms for regenerating biological tactile patterns, will promise an efficient whole-body haptic feedback and tactile communications without being limited to the physical performance of the previous actuators. Advanced biocompatible materials and flexible form-factor design of high-resolution simulators will become more important key technologies to secure human safety and long-term stability.

As above, developing a safe and reliable neural interfacing device is a fundamental task for neuro-haptic interfaces. For the next step of neuro-haptics, we have to find solutions to demonstrate realistic tactile sensation by the electrical stimulation signal waves. Firstly, delivering stimulation signals accurately to target neurons with the discriminated high spatial resolution is essential. So, tracking technology of target neurons and knowledge of neuroscience and cognitive science for mapping the effective neurons for sensory feedback are highly required. Secondly, algorithms that translate tactile sensing signals to appropriate spike signals for activating the neurons are crucial for precisely controlled tactile pattern generation and sensory recognition. Recently, neuromorphic models have been exploited to deliver tactile sensations through nerve stimulation to discriminate various textures using slow adapting receptors (SA)-like dynamics for the stimulation procedures[197] and to provide tactile feedback to a robotic prosthesis for enhancing grip control.[198] When the stimulation signals were modeled to imitate human sensory signals, the participant could differentiate the objects faster than the traditional encoded algorithms based on stimulating intensity. Thus, biologically inspired tactile signals induced more intimate and natural percepts.[168] Furthermore, technological innovations related to neural interface, neural tracking, sensory cognitive mapping, and sensory signals translating algorithms will be essential to realize ultimate immersive whole-body tele-haptic interactions.

8. Challenges and Outlook

This paper has presented the recent progress and innovations of haptic interfaces and devices for the current and future AR/VR applications. It has striven to highlight technological advances of active material-based haptic interfaces as well as haptic actuation methods and devices for key tele-haptic technologies, focusing on touch-based, wearable, skin-attachable, mid-air, and neuro-haptic interfaces. As the scenario presented in Figure 1, the future of AR/VR world demands bilateral, multimodal tele-haptic interactions, allowing people in physically distant locations to communicate or share the sense of touch beyond the current audio-visual interactions. In other words, tele-haptic interactions entail acquiring the "input" tactile sensations using sensing elements from one user and subsequently regenerating the "output" tactile sensations in order to provide the tactile feedback to the other user at a remote location. Thus, among many technologies that are required to implement tele-haptics, sensing and reproducing realistic tactile sensations play a significant role in fully immersive tele-haptic interactions. The five haptic interface technologies reviewed in this paper represent most up-to-date core tactile actuation technologies. The level of technological development of each of technologies shows a wide range of variation, and there exist gaps between the current and desired performance, which present challenges. Conventional haptic actuators may not be suitable or impossible to address the challenges. On the flip side, the challenges present opportunities to explore novel materials and mechanisms to offer solutions to the challenging problems, leading to technical advancements and innovations. These perspectives and potential applications of the core haptic interface technologies are discussed next.

The touch-based haptic interfaces are one of the widely used haptics technologies in the industry (**Figure 12**a). Their commercial success, particularly in mobile devices, are attributed to their ability to produce vibrotactile feedback with high spatial resolution, dynamic range, and output intensity. For the next generation AR/VR applications, touch-based haptic interfaces need to offer more advanced features, such as haptic localization, multi-point stimulation, and shape-morphing function. These features will enable touch-based haptic interfaces to generate a localized tactile stimulus at a target point or an area of the surface (rather than the entire touch surface or display), multi-point tactile feedback, and haptic feedback with surface and shape differential topology. To implement the advanced features in touch-based haptic interfaces, more sophisticated force modulation and stretchable and transparent display modules are necessary. Friction and tangential force modulation based on electrostatic and ultrasonic waves that incorporate transparent Indium tin oxide (ITO) electrode and piezoceramics are being studied for texture reproduction, multi-point tactile stimulation, and large touch display applications. Advanced polymeric materials with excellent light transmission properties and stretchable electrodes with high conductivity are desirable for advancing conventional touch-based display modules or extending from 2D to 3D shape topology display. Enhanced touch-based haptic interface technologies can be applied to mid to large size displays, such as table PCs, automotive dashboard display, and kiosks.

Wearable haptic interfaces have gained the popularity in the virtual 3D industry in recent years with various commercially-available devices (Figure 12b). Wearers experience greater freedom due to the embedded power/controller and wireless connectivity of the wearable devices while perceiving haptic sensations such as normal/lateral vibration, skin indentation, stiffness modulation, and kinesthetic feedback. The weight and the size of the wearables are most critical factors in designing wearable devices as wearing the cumbersome device will degrade user experiences. To increase portability and wearability as well as performance, reducing bulky and restrictive haptic equipment, including heavy and potentially hazardous batteries, and constraining form factors while integrating actuators with different modalities, it is inevitable to develop and apply a polymer-based actuator composed of a combination of light polymer materials, stretchable electrodes, and fluid medium. The light and flexible properties of the polymer material greatly improve the wearability enabling development as a skin-attachable type, and the introduction of a multi-layered polymer structure makes it possible to easily combine with the wireless power receiving layer and provide multimodal haptic feedback.

Skin-attachable devices are highly sought-after haptic interfaces, and by far the most actively studied currently for commercial applications (Figure 12c). Built on light-weight and flexible polymers, wearable skin haptic interfaces can generate tactile sensations such as the normal vibration, the skin indentation, the shear/stretch force, and thermal feedback individually or simultaneously and deliver them for unconstrained and natural VR interactions. Moreover, versatile designs are possible to have the interfaces in stackable and array forms, which can increase the multi-point stimulations and tactile patterns or shape generations. The main challenges include enhancing the durability of the interfaces for long-term use, and delivering battery-free power to the interfaces. To enhance the long-term reliability of the polymer actuator, researches are being conducted to lower the driving voltage through the development of a highly dielectric polymer,[199] or to improve the stability of the electrode by pre-cracking the flexible electrodes.[200] The wireless battery-free configuration is an essential factor in designing a skin-attachable haptic interface. For example, the study of wireless haptic interfaces for VR/AR with a large primary coil for near field communication (NFC)-based power harvesting and an intermediate coil to increase magnetic field strength

Figure 12. Summary of challenges and Opportunities of haptic interfaces for VR/AR technology. a) Touch-based Haptic Interfaces. Reproduced with permission.[111] Copyright 2010, Association for Computing Machinery. b) Wearable Haptic Interfaces. (left) Reproduced with permission.[84] Copyright 2019, Nature Publishing Group. (right) Reproduced with permission.[113] Copyright 2020, AAAS. c) Skin-attachable Haptic Interfaces. (left) Reproduced with permission.[9] Copyright 2019, Springer Nature. (right) Reproduced with permission.[3] Copyright 2020, Wiley Online Library. d) Mid-air Haptic Interfaces. Reproduced with permission.[136] Copyright 2020, Ultraleap. e) Neuro-haptic Interfaces. Reproduced with permission.[201] Copyright 2016, BMC Neuroscience

has been highlighted.[9] The development and application of the wireless powered haptic actuator is being focused as an important technology for fully immersive VR/AR interaction.

Contactless haptic technologies (such as, mid-air haptic interfaces) are emerging in AR/VR. For mid-air haptics, users can perceive haptic feedback on their bare hands and fingers without wearing any devices or any contact (Figure 12d). The acoustic radiation force generated by ultrasound transducers allows free-form interactions in mid-air. Being in its early-stage of development, the mid-air haptic interface technology possesses several challenging as well as opportunities. Currently, mid-air haptic interfaces show poor performance (low special resolution and output intensity) along with synchronization issues between hand gestures and the feedback focal points. Miniaturization and reduction of unwanted noises induced by driving ultrasound transducers are other significant challenges need to be addressed. Nonetheless, potential impact of non-contact interfaces on the AR/VR industry is substantial. Combining non-contact haptics with holographic and digital contents (such as, holo-haptics) will revolutionize AR/VR experiences as it enables intuitive interactions of 3D contents in visual-haptic workspaces.

The neuro-haptic interface is the least explored emerging haptic technology, yet it has huge potentials in providing most natural and realistic haptic interactions (Figure 12e). It strives to tap into the human's somatosensory cortex by accessing to the neuro circuitry for neurostimulation to induce haptic sensations. For neuro-haptic interfaces, maintaining a long-term stability of invasive neural electrodes is a significant challenge. Thus, soft and biocompatible materials can contribute to development of neuro-haptic interfaces that can minimize inflammation and chronic damage of nerve cells. For non-invasive neuromodulation, devices integrated with a skin-attachable platform are highly desirable for maximizing the benefit of non-invasive neurostimulation and improving spatial accuracy of stimulation by fixing on the skin. Currently, studies regarding the neurostimulation-based haptic interface have been vigorously investigated to achieve the ultimate goal of whole-body neuro-tactile communications.

Figure 12 summarizes the above-mentioned challenges of the five core haptic technologies for tactile sensations. It is clear that advanced functional materials can play a crucial role in advancing the haptic technologies. In particular, polymeric materials that are light and form factor-free have made possible for the shift of haptic technologies from traditional, electromechanical actuators to wearable or skin-attachable type interfaces. The existing and novel material design and fabrication technologies are anticipated to produce active materials with prescribed material properties for haptic applications. Recent advancements of 3D printing technology and microfabrication process as well as material design leveraged by artificial intelligence and machine learning are quite impressive and promising for the design and production of materials tailored for specific purposes. Unequivocally, novel active materials will greatly contribute to breakthrough haptic technologies for AR/VR applications.

Acknowledgements

T.-H.Y., J.R.K., and H.J. contributed equally to this work. This work was supported by Institute for Information & Communications Technology Promotion (IITP) grant funded by the Korea government (MSIT, Grant No. 2020-0-00003, Development of high piezoelectric coefficient composite and ultra-low power multilayered piezoelectric sensor/actuator multi-functional module).

Conflict of Interest

The authors declare no conflict of interest.

Keywords

active materials, bilateral, immersive, multimodal, tactile actuator, tele-haptic interaction, virtual and augmented reality

Received: October 16, 2020
Revised: January 18, 2021
Published online:

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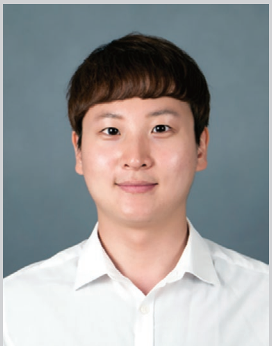

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