Introduction to consumer Electronic

Haptics and Multi-touch Devices: Introduction to Touch panel, Capacitive Touch screen, Light pen.

Users are given the illusion that they are touching or manipulating a real Physical Object. ‘Haptics’ is a technology that adds the sense of touch to virtual environments.

The term haptic originated from the Greek word ἁπτικός (haptikos) meaning pertaining to the sense of touch and comes from the Greek verb ἅπτεσθαι (haptesthai) meaning to “contact” or “touch.

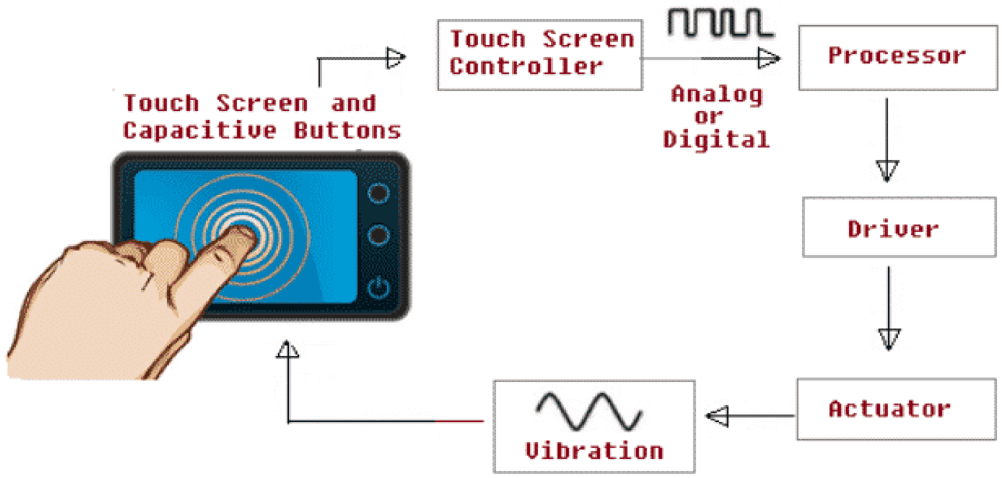
What is ‘Haptics’?

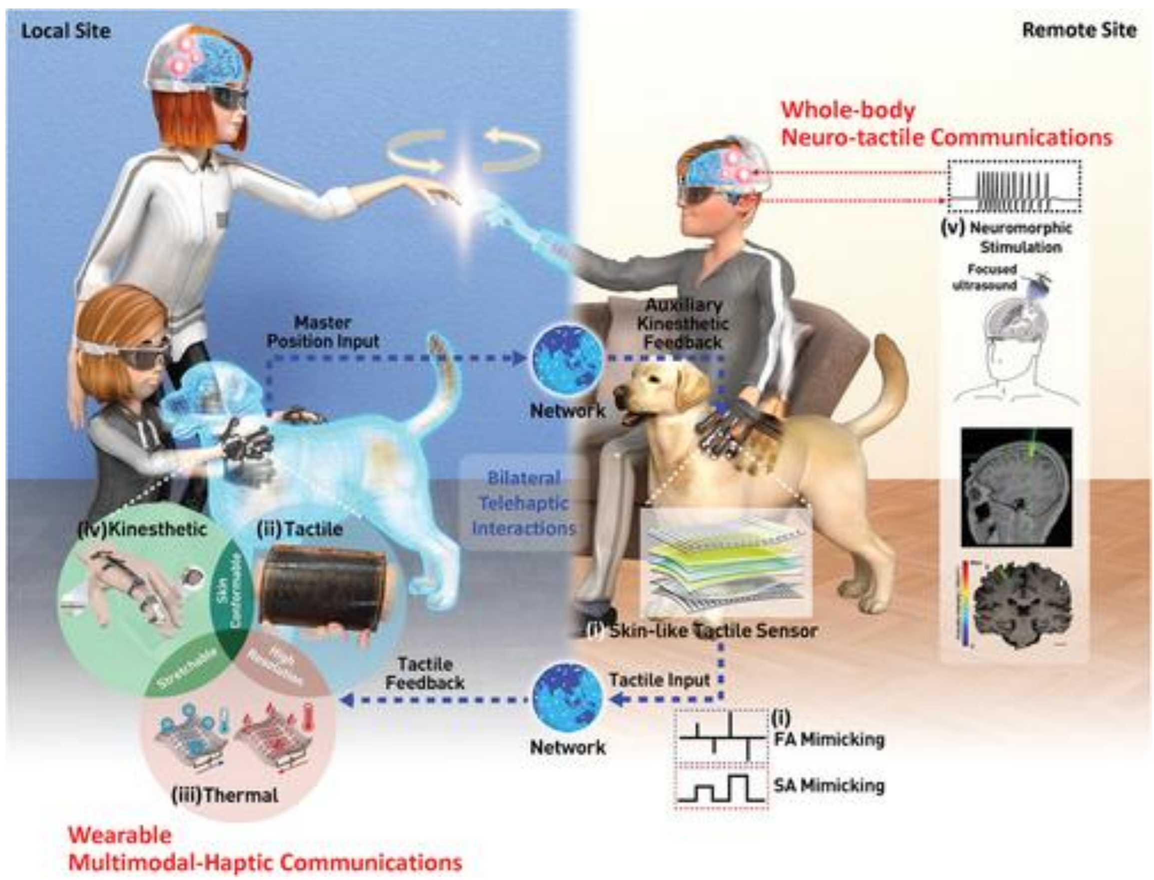
Haptic technology refers to technology that interfaces the user with a virtual environment via the sense of touch by applying forces, vibrations, and/or motions to the user.

This mechanical stimulation may be used to assist in the creation of virtual objects (objects existing only in a computer simulation), for control of such virtual objects, and to enhance the remote control of machines and devices (teleoperators).

This emerging technology promises to have wide-reaching applications as it already has in some fields.

For example, haptic technology has made it possible to investigate in detail how the human sense of touch works by allowing the creation of carefully controlled haptic virtual objects.





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.

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

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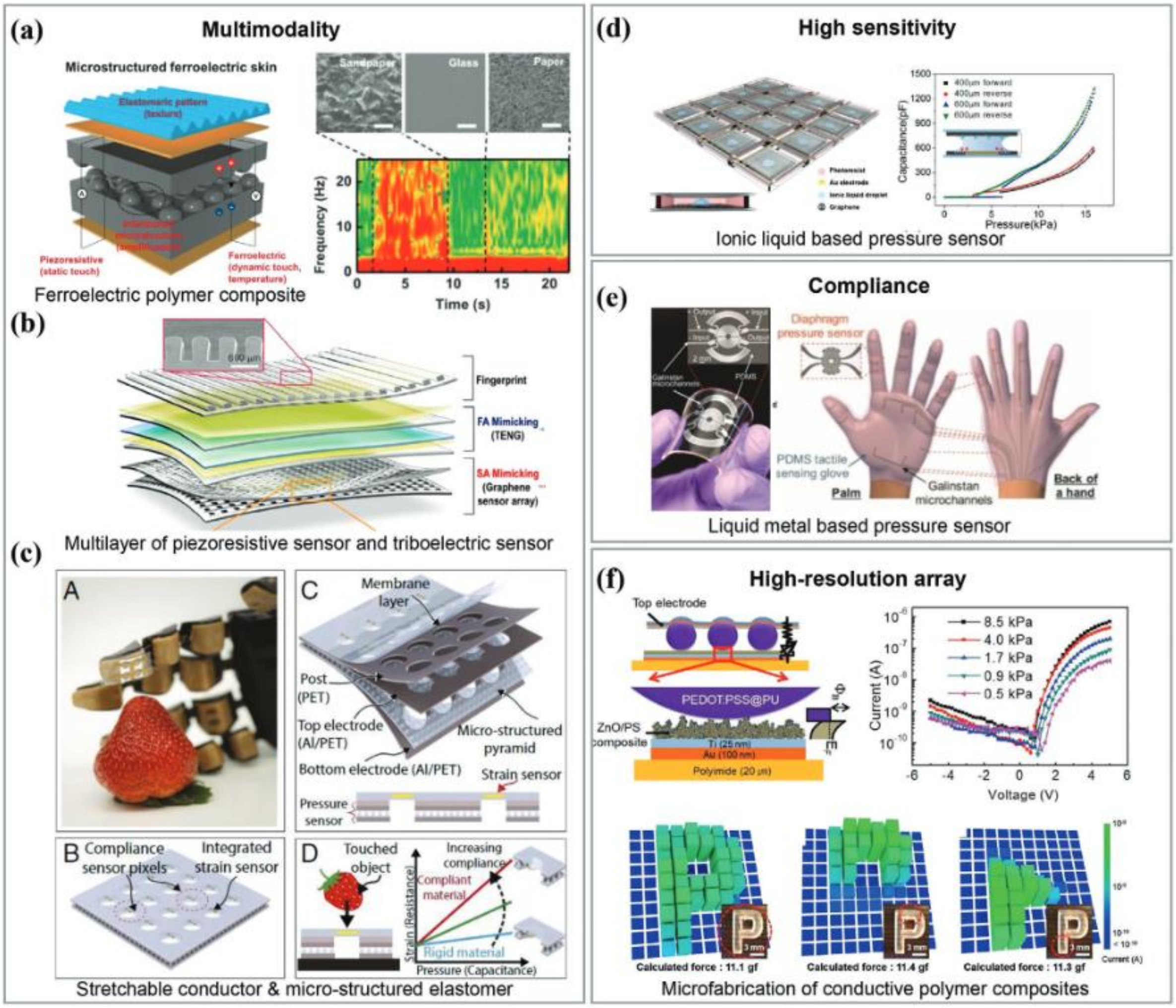
Mechanism	Key material	Sensitivity (Pressure range)	Frequency range	Spatial resolution	Characteristics	Ref.
Piezoresistive	Graphene nanoplates	1.63 kPa^{-1} (0.1 ~ 6 kPa)	<330 Hz	20x20 array (100/cm^2)	Highly sensitive, flexible	[1]
		0.04 kPa^{-1} (6 ~ 100 kPa)				
	PEDOT:PSS/PU sphere	10 kPa^{-1} (0.1 ~ 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)	–	10x10 array (25/cm^2)	Stretchable 300%	[52]
		1.25 Mpa^{-1} (16k ~ 360 kPa)				
Piezoelectric	rGO/PVDF composite	35 uA/Pa (<2.45 kpa)	<2000 Hz	Sample size 1 cm^2 (1/cm^2)	Texture perception	[46]
		5 uA/Pa (2.45 ~ 17.15 kPa)				
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)	–	Sample size 4 mm^2	Shear, vertical force	[69, 70]
		16 mΩ kPa^{-1} (50 ~ 170 kPa)				

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: Displacement	Intensity of stimuli: Force (Acceleration) {Friction Coeff.}	Intensity of stimuli: Electric/ Acoustic	Ref
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]



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.Adv. Funct. Mater.2021, 31, 2008831.

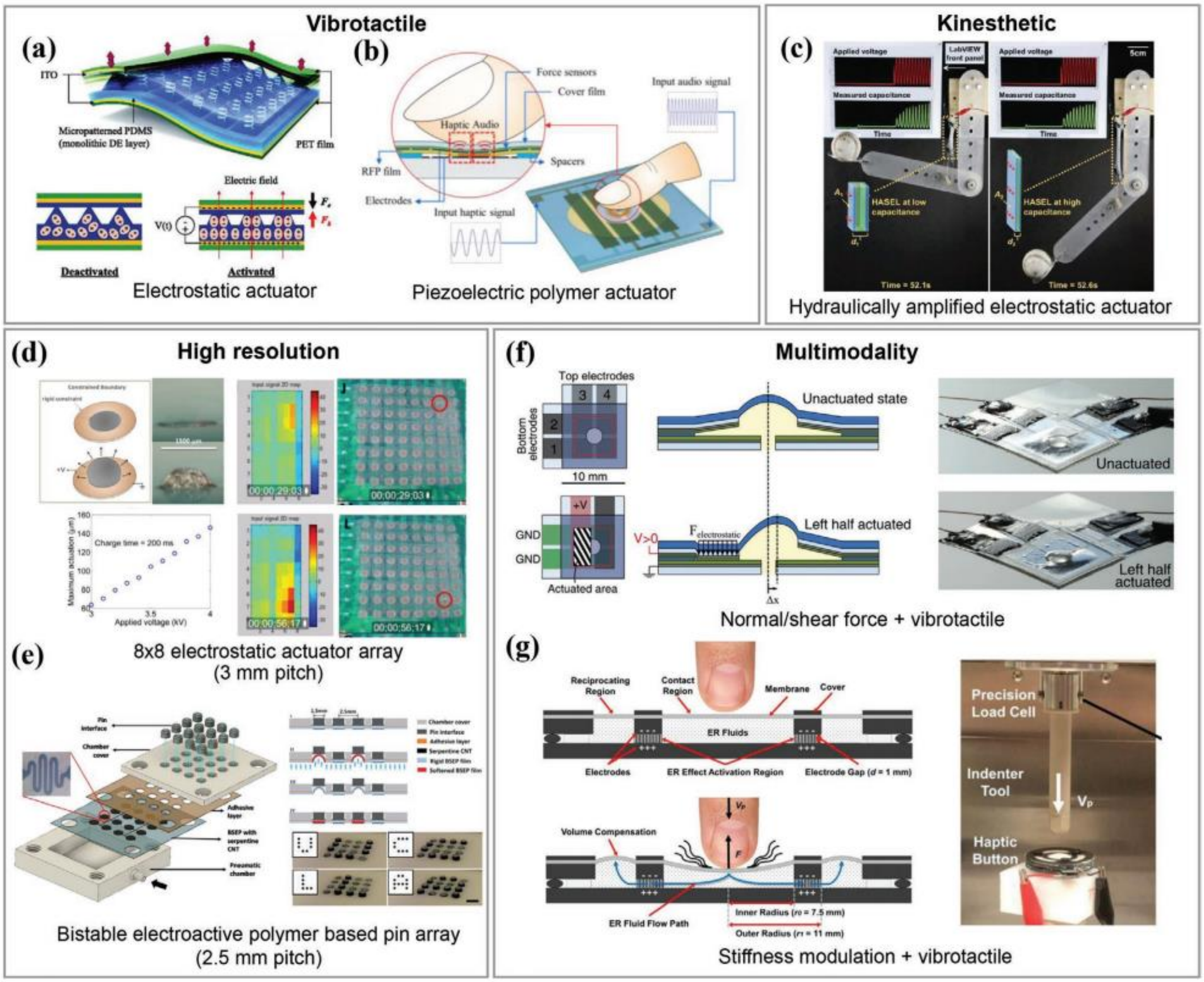


Figure 3. Soft active material-based tactile feedback.

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.

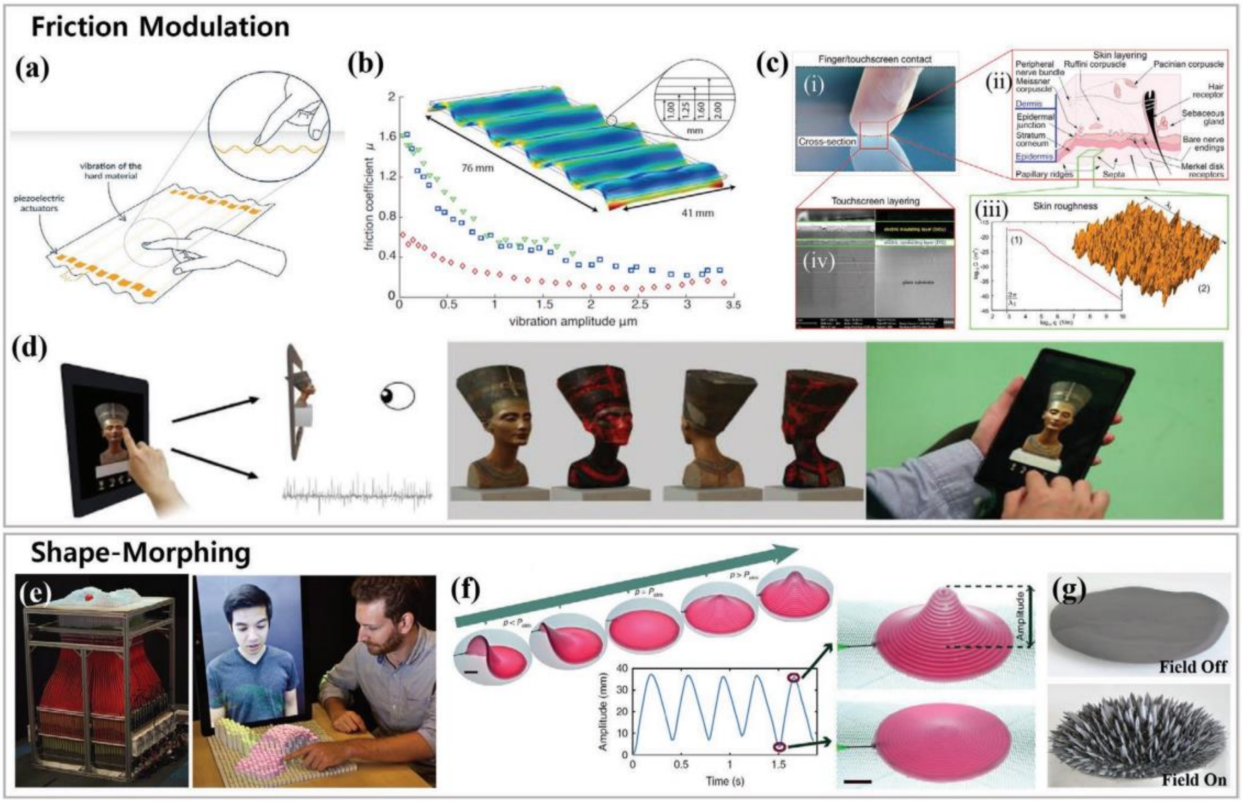


Figure 4. Touch-based haptic interfaces.

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.

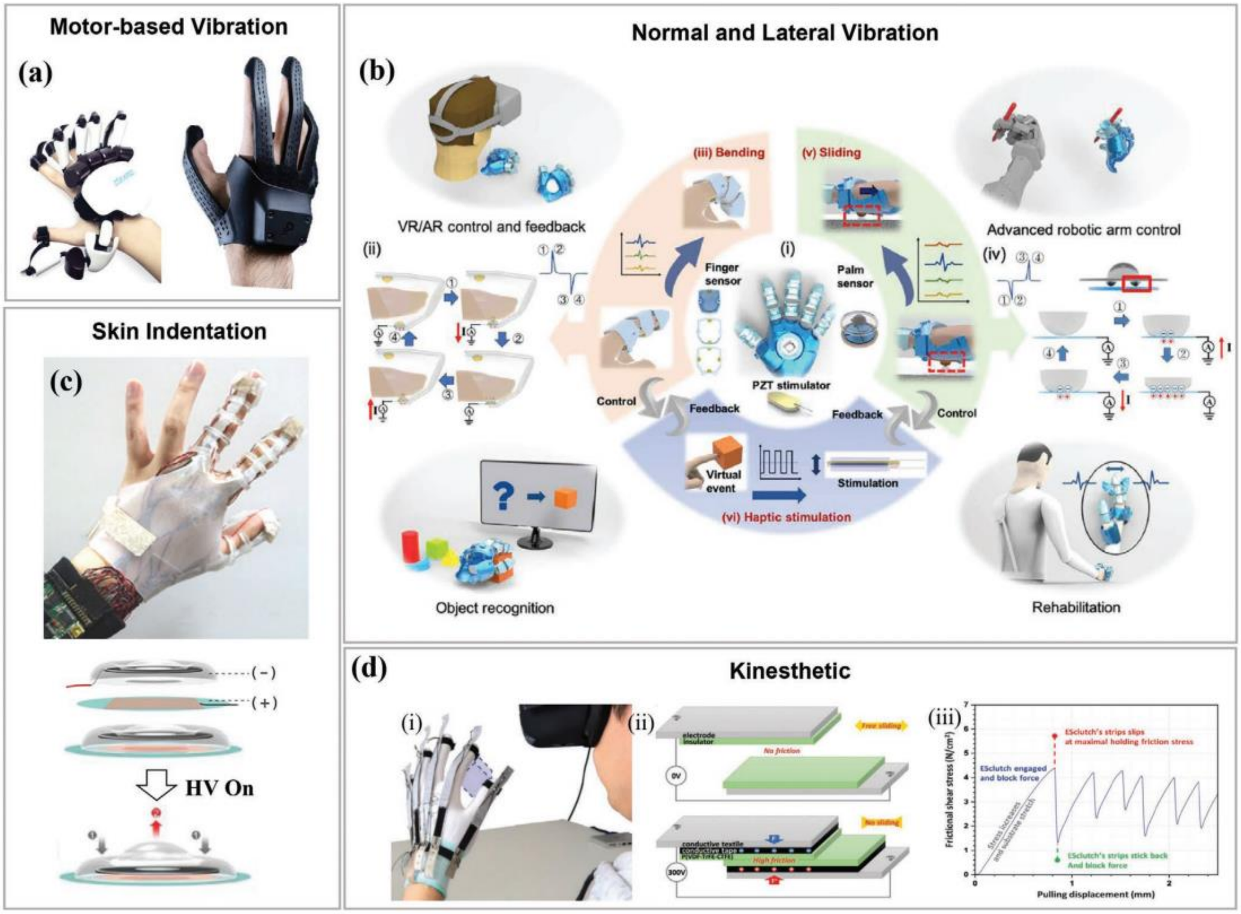


Figure 5. Hand-worn haptic devices.

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.

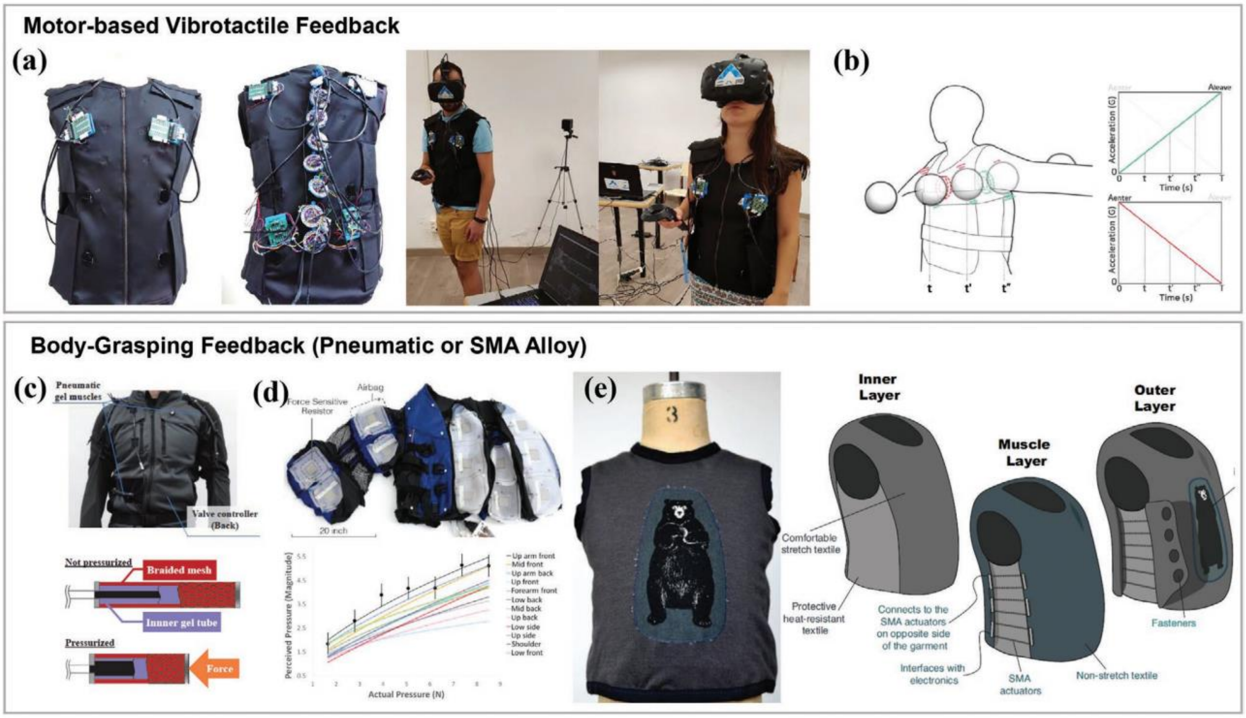


Figure 6. Vest-worn haptic devices.

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.

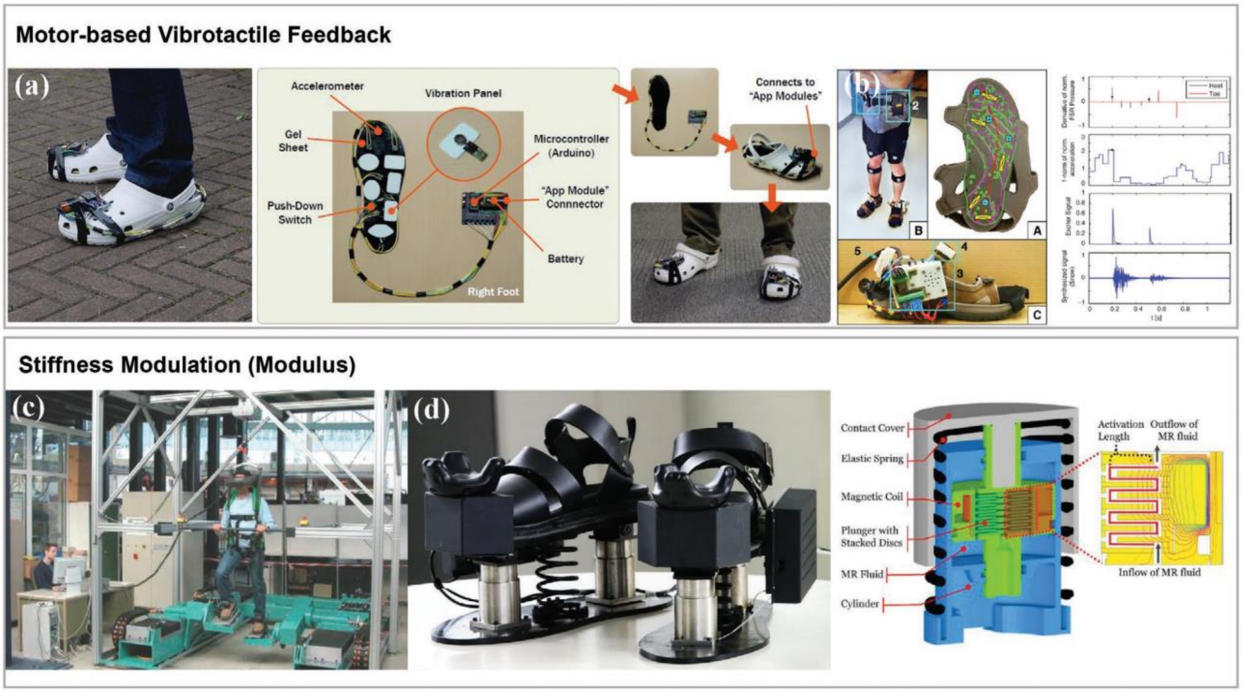


Figure 7. Foot-worn haptic devices.

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.

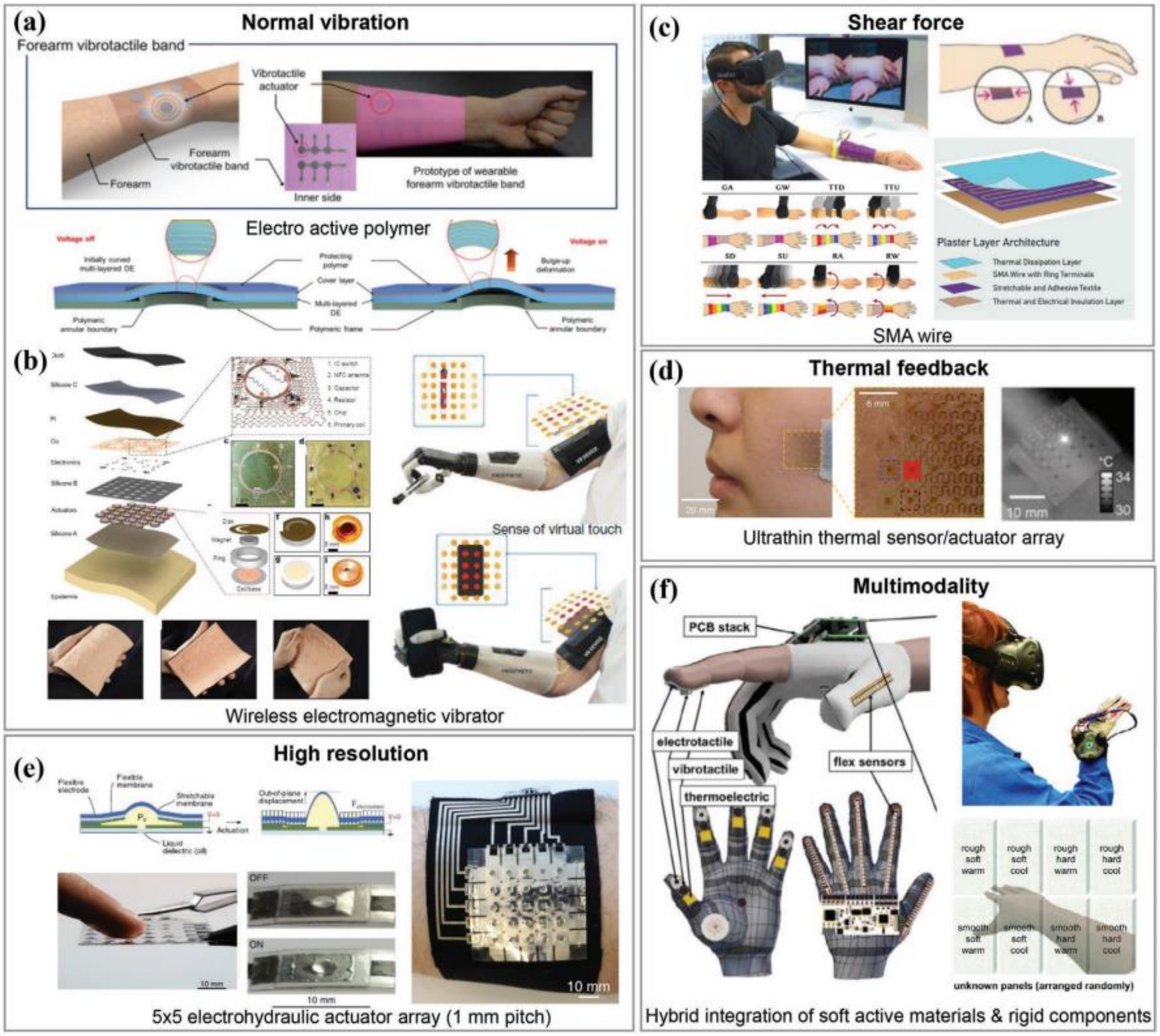


Figure 8. Skin-attachable haptic interfaces.

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

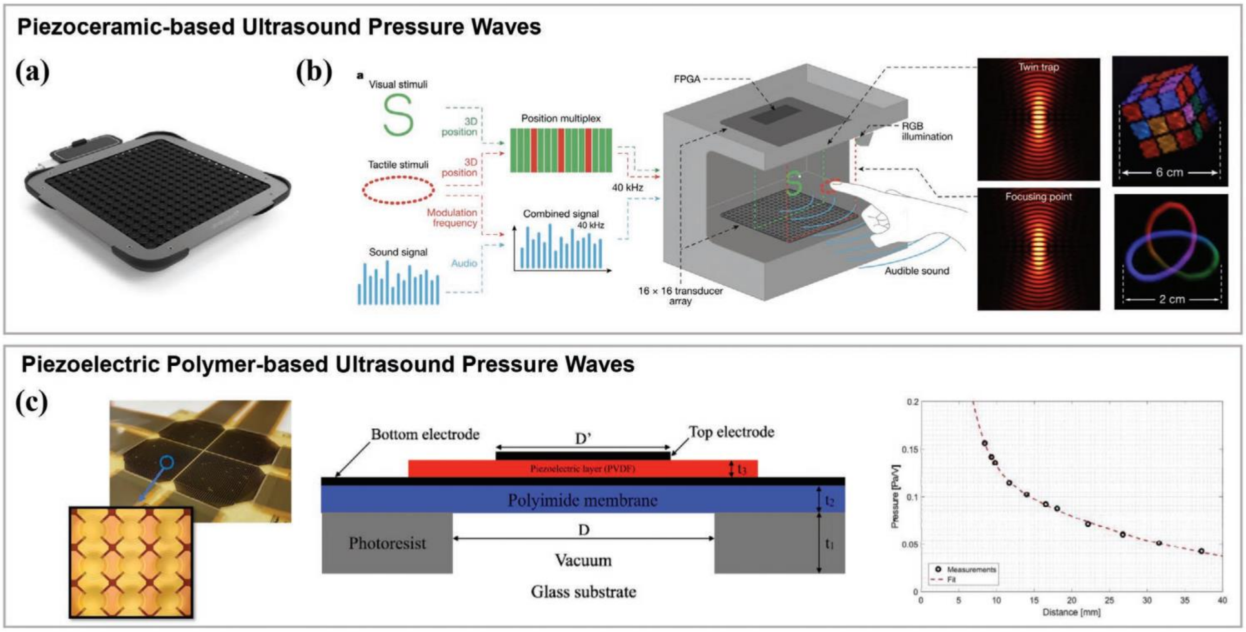


Figure 9.
a) Ultrasound haptic system having high resolution and large spatial region for non-contact, sophisticated in-air haptic stimulation. Ultraleap device delivers mid-air tactile sensations around 300 mm above from the haptic display by generating focal points using the multiple ultrasound waves. 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.

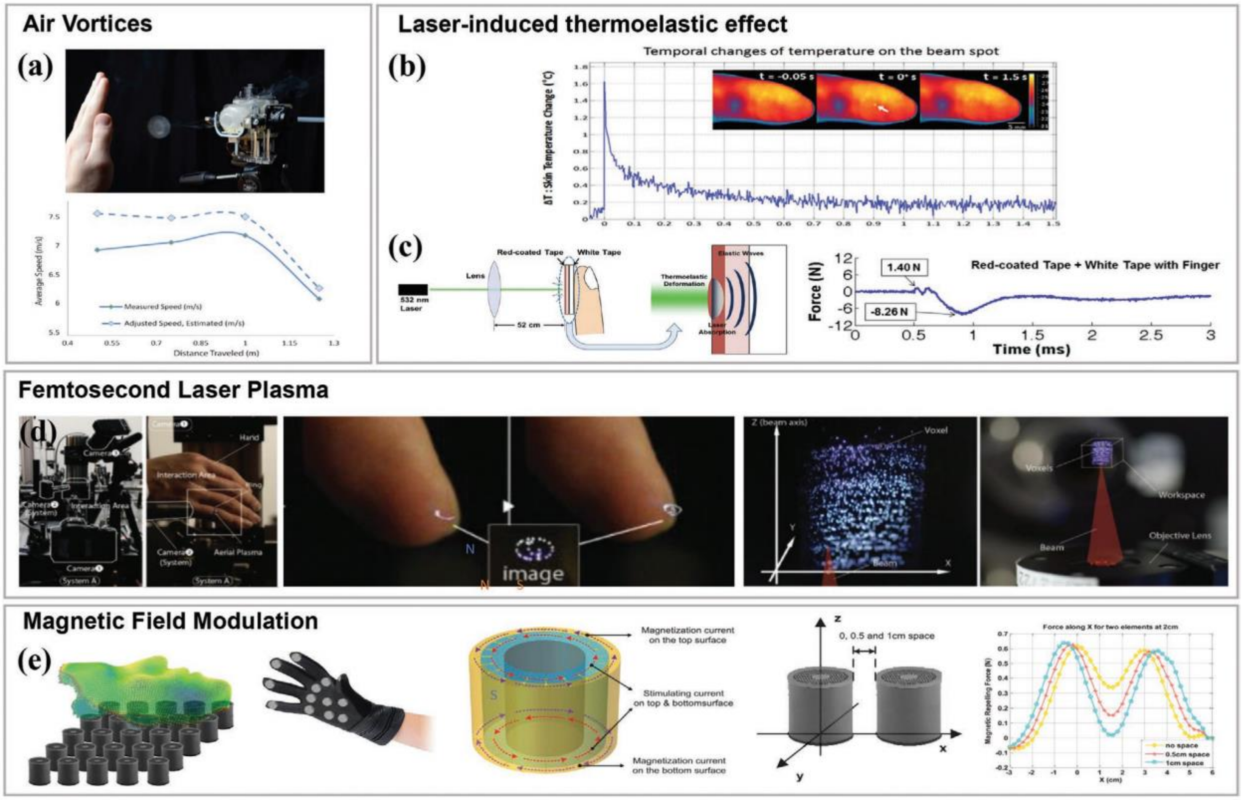


Figure 10. Potential mid-air haptic devices have been explored to enrich the mid-air interaction experience.

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.

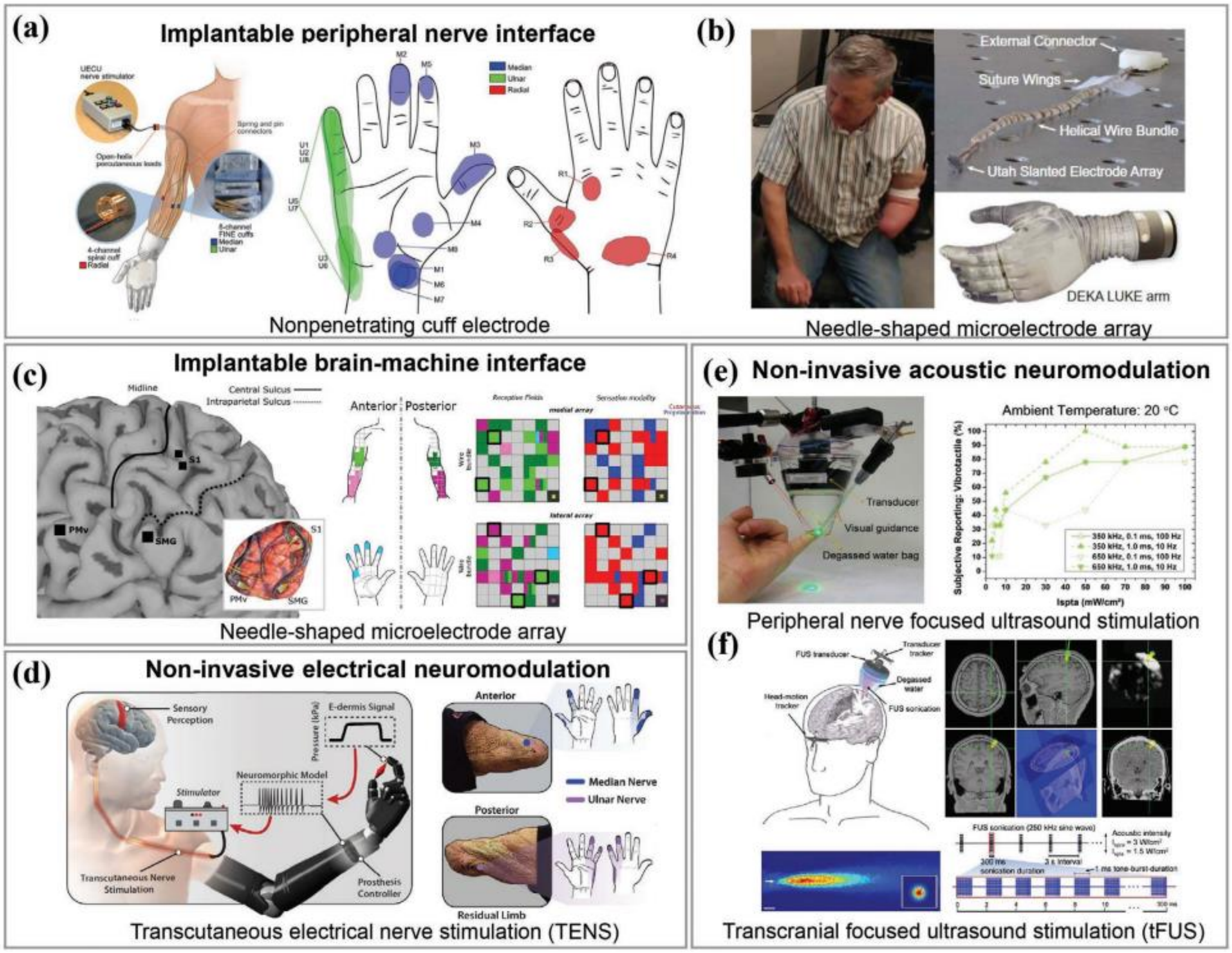


Figure 11. Neuro-haptic interfaces for tactile sensory feedback.

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.

Figure 12. Summary of challenges and Opportunities of haptic interfaces for VR/AR technology.
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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.
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e) Neuro-haptic Interfaces. Reproduced with permission.[201] Copyright 2016, BMC Neuroscience