Wearable Soft Technologies for Haptic Sensing and Feedback

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Virtual reality (VR) and augmented reality (AR) systems have garnered recent widespread attention due to increased accessibility, functionality, and affordability. These systems sense user inputs and typically provide haptic, audio, and visual feedback to blend interactive virtual environments with the real world for an enhanced or simulated reality experience. With applications ranging from immersive entertainment, to teleoperation, to physical therapy, further development of this technology has the potential for impact across multiple disciplines. However, VR/AR devices still face critical challenges that hinder integration into everyday life and additional applications; namely, the rigid and cumbersome form factor of current technology that is incompatible with the dynamic movements and pliable limbs of the human body. Recent advancements in the field of soft materials are uniquely suited to provide solutions to this challenge. Devices fabricated from flexible and elastic bio-compatible materials have significantly greater compatibility with the human body and could lead to a more natural VR/AR experience. This review reports state-of-the-art experimental studies in soft materials for wearable sensing and haptic feedback in VR/AR applications, explores emerging soft technologies for on-body devices, and identifies current challenges and future opportunities toward seamless integration of the virtual and physical world.

1. Introduction

Virtual environments can serve to greatly expand the realms of sensations and experiences previously unattainable due to physical limitations, costs, or technological constraints.[1] For example, computer-generated simulations have provided low-cost and effective solutions to complex and repetitive tasks such as surgical training[2–5] and physical therapy.[6–10] Approaches to integrating virtual worlds with reality can be broadly divided into two categories: virtual reality (VR) and augmented reality (AR). VR aims to completely immerse the user in a simulated world by providing physical feedback and sensations that correspond with interactions within the virtual environment. VR systems most commonly include a headset with stereo display screens that enclose the eyes, handheld controllers for motion tracking and haptic feedback, and a processing unit such as a personal computing device. AR infuses interactive virtual elements into the physical environment, supplementing rather than replacing the real world. AR systems are diverse and can be less specialized—for example, the most prevalent AR system is a smartphone, which includes camera sensors, audio speakers, and a screen display, touchscreen, and haptic motor but offers functionalities beyond generating AR.

In order for VR/AR to be compelling, the fusion of the virtual and physical environments must deliver an intuitive interface and user feedback sufficiently consistent with expectations of reality. However, the capability to merge real-time interactive virtual environments with physical reality in a convincingly authentic manner has been a longstanding challenge. It requires an inherently multidisciplinary approach, drawing from fields such as human-computer interaction,[17,18] kinesiology,[19] animation and graphics,[20–22] audio engineering,[23,24] materials science,[11,25] and robotics.[26,27]

One of the many elements to consider when striving to increase realism in VR/AR systems is device integration with the human body and physical environment to maximize natural interactions with the virtual interface. Of the various components that comprise VR/AR systems, the haptic feedback and sensing input devices are commonly placed on the body. Currently, most body-worn VR/AR devices are bulky and made of rigid materials, impeding upon the natural mechanics of the human body and disrupting the cognitive connection between virtual and physical interactions. Recent progress in soft materials provides potential solutions, particularly the development of soft and human-compatible actuation mechanisms and sensors. Beyond increasing wearability, soft matter devices enable novel approaches to generating haptic feedback with variable stiffness materials and flexible, lightweight actuators, as well as sensing modalities more closely linked with human physiology (**Figure 1**).

In this review, we will: 1) report on the state of the field in wearable haptics, sensing, and commercial VR/AR, 2) present an overview of recent experimental studies on soft body-worn sensing and haptic devices for VR/AR, 3) discuss requirements for the next generation of haptics and wearable sensing, 4) highlight emerging soft wearable technologies, and 5) conclude with challenges and future opportunities for the application of materials science in VR/AR systems. To the best of our knowledge, this work represents the first paper

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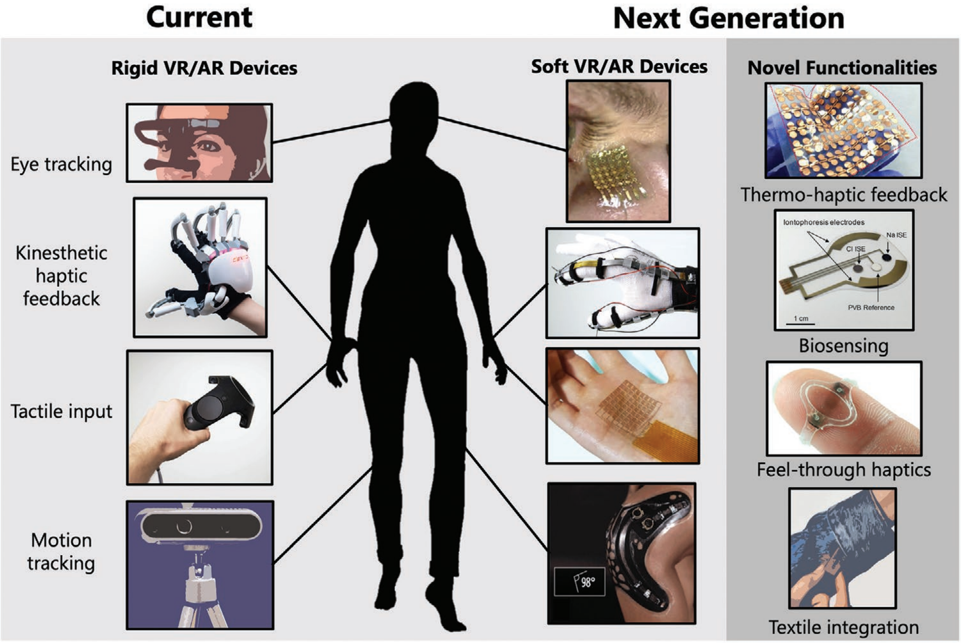

Figure 1. Current rigid VR/AR devices and the next generation of soft VR/AR devices, with novel functionalities enabled by soft matter integration. Left column, from top: Illustration of eye-tracking headset. Photo of kinesthetic haptic feedback glove. Reproduced with permission.[148] Copyright 2020, Dexta Robotics. Photo of handheld VR controller. Reproduced with permission under Unsplash License. Copyright Jesper Aggergaard Illustration of motion-tracking camera. Middle column, from top: Photo of wearable eye-tracking sensor. Reproduced with permission.[14] Copyright 2020, AAAS. Photo of haptic glove with electrostatic clutches. Reproduced with permission.[11] Copyright 2018, ACM. Photo of tactile sensing skin. Reproduced with permission.[204] Copyright 2019, American Chemical Society. Photo of wearable sensor measuring knee angle. Reproduced with permission.[12] Copyright 2018, ACM. Right column, from top: Photo of thermo-haptic feedback electronic skin. Reproduced with permission.[15] Copyright 2020, Wiley-VCH. Photo of wearable biosensor. Reproduced with permission.[16] Copyright 2017, National Academy of Sciences. Illustration of representative eye-tracking device. Photo of feel-through haptic sensor on fingertip. Reproduced with permission.[87] Copyright 2020, Wiley-VCH. Illustration of electronic device in jacket sleeve.

to review the utilization of wearable soft material technologies for haptic sensing and feedback. Such research is still in its nascent stages and the work covered in this review paper is primarily from the last few years. As the field continues to mature, there will eventually be a sufficient number of technological iterations to allow for a more historical perspective and development timeline.

2. State of the Field

2.1. Sensing Overview

Although VR and AR have distinctly different objectives, the relevant sensing functionalities are similar. For fluid integration of virtual and physical worlds, sensors should provide an accurate and comprehensive virtual profile of the physical state of the user in order for the simulated reality to react in a realistic manner, in conjunction with a comparable variety of the user inputs available in the real world.[30] The sensing capabilities of the VR/AR system can significantly influence the realism of the virtual world to the user; limited sensing modalities would force the user into unnatural avenues of interacting with the virtual environment.[31] For instance, the user could be restricted to typing one letter at a time on a virtual keyboard with a motion-controlled cursor rather than using their voice to communicate a specific word or phrase.

2.1.1. Pose & Tactile Sensing

The two standard sensing functionalities for VR/AR are pose estimation and tactile input (**Figure 2**), although the resolution and methodology to accomplish these vary greatly among systems. Pose estimation of the user[1,32] is typically the most highly prioritized for implementation because it offers various capabilities critical for user interaction: gesture and motion-based interfaces, simultaneous virtual and physical exploration, a changing field of view corresponding with head rotation, and so on. For positional tracking, a key performance metric is the degrees-of-freedom (DOF), defined as the ability track translation or rotation along an axis. There are a maximum of 6 DOF within the virtual environment: translation and rotation along the X (pitch), Y (yaw), and Z (roll) axes. As the DOF of the tracking system increases, the spatial consistency for the user in the virtual and physical environment increases. Another component of pose estimation is which parts of the user are tracked; most systems focus on one or a combination of the head, hands, and body. The DOF is not only determined by the type and quantity of sensors, but also the algorithms used to process the sensor data, the quality of the virtual environment rendering, and the system's computational power. Pose estimation in VR/AR is typically implemented via optical tracking with a camera system or triangulation with external base stations.[1]

Most VR/AR systems also include a method for tactile input. In tandem with pose estimation of the hands, if available,

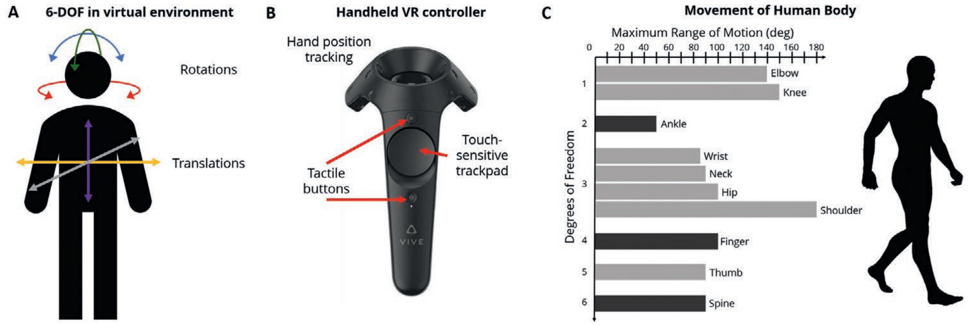

Figure 2. A) Degrees of freedom (DOF) within a virtual environment. B) Sensing inputs included in a typical handheld VR controller. Adapted with permission.[247] Copyright 2020, Springer. C) Range of motion and DOF of body parts where wearable devices could be placed.[29]

tactile sensing is used primarily for the user interface of the virtual environment, such as in navigating menus or selecting objects for interaction.[1,33] The tactile sensors most frequently used are touchscreens, physical buttons, or trackpads. Tactile input offers a reliable and familiar interface to users unaccustomed to a motion tracking system, as it is generally more commonplace in everyday use. These sensors are typically placed on handheld controllers or devices.

2.1.2. Wearable Soft Sensors

While pose estimation and tactile input offer considerable functionality, immersive VR/AR requires a more complete virtual profile of the user's physical and emotional state. Sensing devices fabricated from soft materials offer an expanded range of comfortable placement locations and modalities for biosensing. On-body sensing devices that monitor the user's physiological attributes such as pulse, temperature, perspiration rate, and the qualities of biomarkers carried in bodily fluids could allow for more complex and implicit user inputs, such as emotional reactions[34–36] and physical exertion.[37] The capability to sense these attributes without a conscious initiative from the user in addition to the unobtrusive form factor could substantially increase the realism and potential applications of VR/AR.

Soft wearable sensors address the need for unobtrusive on-body monitoring, but they face another set of challenges related to integration in VR/AR.[38] For commercial viability, the sensors should use low-cost components, have a scalable manufacturing process, and be easy to integrate into existing VR/AR ecosystems. The wearable sensors should accommodate a wide range of body dimensions and be resilient to the various mechanical and thermal stresses associated with regular use. For epidermal electronic systems, the devices must be nontoxic and biocompatible, with particular attention paid to material interactions with the skin.[39,40] Skin-mounted sensors should also be able to adapt to numerous characteristics that vary greatly among individuals, which include oil/sweat/hair gland density and production, elasticity, curvature, and wrinkles. The skin adhesive layer should be tested extensively for functionality and comfort in long wear times, repeated application and removal, and potential residue. To maximize natural motion of the human body, the elasticity and flexibility of the device should accommodate the DOF and range of motion of the placement location (Figure 2).

2.2. Haptics Overview

Feedback is a key feature of modern user interfaces (UI), enabling faster, more accurate and more intuitive interaction with machines. Most human machine interface (HMI) technologies use vision and sound-based feedback for notification, for instance making a clicking sound when touching an on-screen button, or changing the color of a toggle switch when the user swipes the liquid crystal display (LCD) or organic light emitting diodes (OLED) screen. Our other senses (**Figure 3**A) have been far less explored. In particular, the sense of touch is highly developed in humans and essential for nearly all daily activities, but is underused in HMI. This section reviews haptic feedback, which enables the use of the sense of touch in HMI.

With the rise of smartphones, simple short vibrations have become popular for notifications or to confirm a virtual key has been pressed. This vibrotactile feedback is very limited, and cannot provide the sensation of touching a real object. This limitation becomes more problematic with the rapid development of VR (Figure 3B) and AR headsets, that provide bright high-resolution immersive stereoscopic view of virtual worlds or virtual objects.

For immersive and realistic interaction with the 3D virtual world, virtual objects must feel real, meaning that grasping a virtual object allows the human to perceive the object's stiffness (is it hard or squishy?), surface texture (rough, smooth), weight, thermal conductivity and temperature, as well as surface adhesion. Fortunately for designers of haptic hardware, given that sight is the dominant sense for most humans, haptic feedback can be very effective even when only conveying a subset of the aforementioned sensations. Given the importance of the hand for interactions and its great sensitivity, many haptic devices have focused on the hand or forearm.

Applications that can benefit from rich haptic feedback appear in many VR scenarios[42] (Figure 3C). Haptic feedback can range from providing reinforcement to graphical user interface (GUI) operations (buttons, pull-down menus) to enabling remote surgery. Immersive simulations for training, education, or gaming would gain in realism and effectiveness with better haptic feedback. Telerobotic and teleoperation are the real-world counterparts. Data analysis (e.g., data manipulation and multi-dimensional maps) are another application area. Haptic feedback is a key desired feature for VR/AR applications[43] and tactile internet (teleoperation).[44]

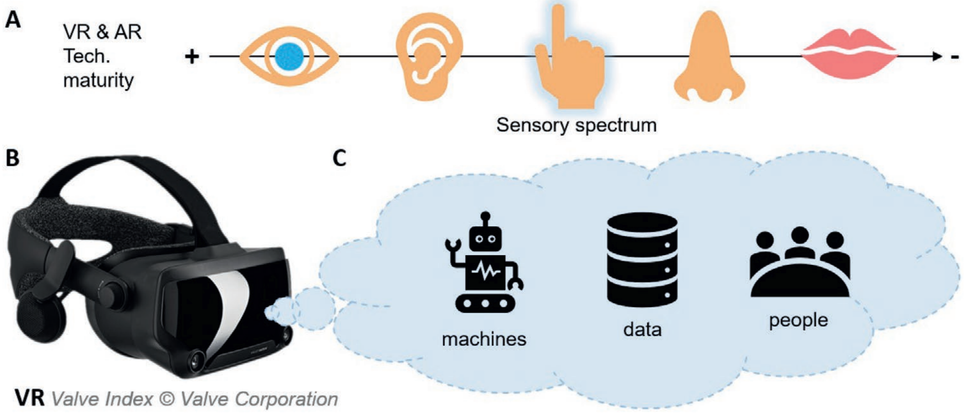

Figure 3. A) Maturity of the VR and AR technologies using each of the human senses. Reproduced with permission.[41] Copyright 2019, The Authors, published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong. B) Oculus Rift Virtual Reality (VR) headset. Reproduced with permission. Valve Index Copyright Valve Corporation. C) Virtual interactions that can benefit from haptic feedback.

We are able to feel shape, texture, and object properties thanks to a rich set of mechanical receptors distributed on our skin. Haptic feedback consists of mechanical stimulus applied on the human body to activate mechanical sensors. One can electrically stimulate mechanoreceptors using electrostimulation,[45–47] leading for now to a sensation akin to buzzing. In this article, we focus on mechanical actuators that stimulate the skin's mechanical sensors to provide haptic feedback.

2.2.1. Cutaneous Haptics

Cutaneous haptics stimulates tactile feeling (i.e., sense of touch we usually get from our fingertips) and is distinct from kinesthetic feedback.[48] Stimuli on the order of 10–100 mN and 10–100 µm are the typical threshold for perception,[49] with strong dependence on actuation frequency, shape and material of the indenter, and with large person to person differences. Cutaneous feeling originates from receptors located in the skin (**Figure 4**A). It comprises of multiple types of sensors[50–52]: Slow-adapting (SA) sensors are sensitive to low frequency mechanical stimulus down to 1 Hz and with a high spatial resolution, below 1 mm on fingertip, depending on a person's age and gender (Figure 4B)[53] and the location on the body (Figure 4C).[50] Fast-adapting (FA) sensors are sensitive to higher frequency stimulus from tens of Hz up to 800 Hz[49] depending on the amplitude and the location, but with a much lower spatial resolution compared to SA sensors. In addition, natural skin contains non-mechanical sensors like thermal sensors that participate in more complex feelings like the recognition of materials. The sensitivity and density of the skin's sensors varies depending on the part of the body that they cover,[53,54] with important implications for the design of haptic devices intended to be mounted on different parts of the body (e.g., fingertip or forehead).

Numerous actuator technologies can provide cutaneous haptic feedback.[55–59] The desired motion can be normal to the skin (e.g., poking) or in a shear direction (e.g., stretching the skin) at frequencies from quasistatic to vibrations up to several kHz. Key actuator characteristics include their force (stress), stroke (strain), speed (frequency), performance to size or weight ratio (energy density and specific power), controllability, and energy efficiency. The actuator is typically the heaviest and bulkiest part of haptic devices, and drives power consumption and wearability. The choice of the actuator is central for soft and wearable haptic devices.

We distinguish between two families of actuators: rotary actuators (e.g., electric motors) and linear actuators. Rotary actuators

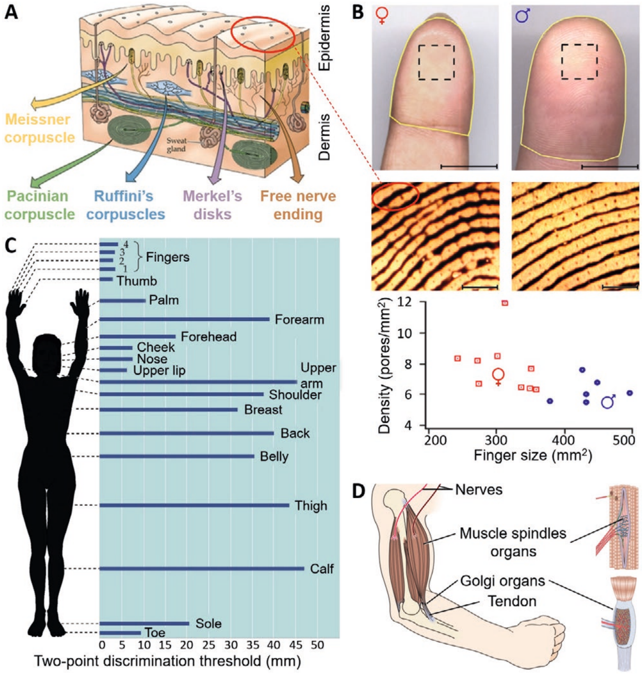

Figure 4. A) Skin's mechanical receptors are responsible for cutaneous haptic perception.[50] B) The density of skin pores on the fingertip varies with finger size and gender.[53] C) Two points discrimination threshold for normal indentation of skin depends on body location.[50] D) Muscles have mechanical receptors responsible for the kinesthetic haptic perception.[50] (A), (C), and (D) reproduced with permission.[50] Copyright 2005, Oxford Publishing Limited; (B) reproduced with permission.[53] Copyright 2009, Society for Neuroscience.

Table 1. Actuator technologies of interest for haptic feedback applications. Blue, yellow, and green colors indicate suitability for cutaneous, kinesthetic and combined haptics.

Principle		Advantages	Drawbacks
Twisted string actuators	Thermally actuated TSA and supercoiled polymer (SCP)	High strain and adequate force	Low efficiency and slow
Electromagnetic motors	Direct drive, using cables or twisted strings	High force, high displacement and robust	Bulky, heavy, and rigid
Pneumatic and hydraulic actuators	McKibben, Pneu-Nets, single cavity and vacuum jamming	High force, flexible and easy to fabricate	Typically require compressor or pump for pressurized fluid. Controllability when in contact
Hydraulically amplified electro Static actuators	Peano-HASEL and HAXEL actuators	High strain, high frequency and flexible	High voltage
Electro magnetic	Voice coils	High frequency and adequate force	High power consumption and rigid
Piezoelectric	Hard ceramics and soft relaxor ferroelectric polymers (RFP)	Compact, high force, high frequency and good efficiency	Low strain, high voltage, and rigid
Dielectric elastomer actuators	Single and multiple stacked membranes	High frequency, high strain and soft	High voltage and low forces
Ionic electro active polymers	Ionic Polymer-Metal Composite (IPMC) and Conducting Polymers (CP)	Low voltage, flexible	Slow and liquid electrolyte
Shape memory polymer	Thermally actuated SMP. Can be coupled with fluidic actuation	High strain and shape memory	Slow, hysteresis
Shape memory alloy	Thermally (TSMA) and magnetic Field actuated (FSMA)	High force and high frequency	Small strain, low efficiency and hysteresis
Liquid crystal elastomer actuators	Thermally or electrically actuated	High strain and soft	High electrical power input or large temperature differences needed and low efficiency

tend to be rigid, although a few examples of soft rotary actuators exist.[60] A cable linkage is often used to transmit force to the human body, but rods or rigid links can also be used. A major advantage of rotatory actuators is that it has no limitation on stroke since they can keep on turning. At the scale of a finger, electromagnetic (EM) motors are too heavy and bulky for cutaneous feedback but work well on the hand, limbs, or joints. For simple vibrotactile feedback, small eccentric mass motors are very popular.

Linear actuators used in haptics or artificial muscles are usually flexible and have a finite stroke. They can be directly mounted on body parts or connected to cables that transmit force. Soft artificial muscles have been the subjects of several recent reviews.[55–59] **Table 1** lists the main relevant technologies.

2.2.2. Kinesthetic Haptics

Kinesthetic or proprioception sensation haptics are related to the awareness of the position and of the movement of body parts, and the forces and torques exerted on them. The mechanoreceptors are located in muscles and tendons (Figure 4D).[52,61,62] **Figure 5** summarizes the requirements for different types of haptics.

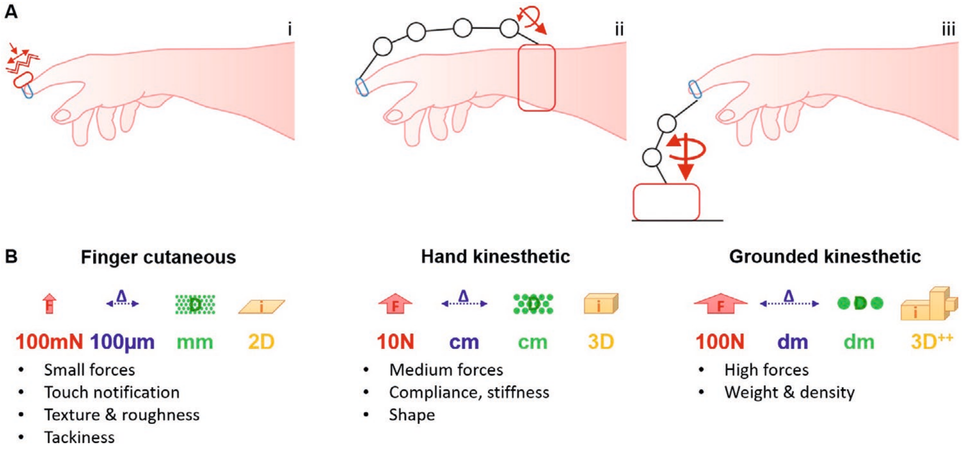

Figure 5. A) Schematic of the connection points of haptic devices and the haptic stimulation provided on the finger for i) cutaneous, ii) hand kinesthetic and iii) grounded kinesthetic haptic feedback.[62] B) Force, displacement, density, and integration actuator requirements for providing cutaneous, hand kinesthetic, and grounded kinesthetic haptic feedback. Reproduced with permission.[48] Copyright 2018, Annual Reviews.

Due to lower force requirements and relatively simpler control for cutaneous haptics, more technologies have been developed for cutaneous haptics than for kinesthetic haptics, especially grounded kinesthetic haptics. Integration of actuators on the body is a major challenge that becomes more complex as the targeted body part (on which haptic feedback must be provided) moves from the slightly curved and soft 2D surface of skin (Figure 5B) to the 3D structure of the hand with multiple joints. Integration of haptic feedback is essential, as explained by ref. [52]: "The effectiveness of any haptic feedback system relies on its ability to integrate with existing human neurosensory pathways". There are two main areas of study for kinesthetic haptics: a) the hand, and b) the entire body.

Hand-Based Kinesthetic Haptics: Kinesthetic haptics on the hand and the fingers allow for manipulation and interaction with virtual objects and machines. Actuators are used to exert forces and displacements on the order of a few Newtons and centimeters, respectively.[63] Such technologies usually take the form of a glove combining both kinesthetic and cutaneous feedback.[62] Kinesthetic haptics differ in their grounding, i.e., whether the actuators that pull a finger are connected to the wrist, shoulder, or to the table, or floor. Grounded kinesthetic feedback requires actuator forces and displacements on the order of 100 N and 10 s of centimeters, using arms,[64] grippers,[65] or cables[66] to stop the hand when touching a table or a wall for example.

Full-Body Kinesthetic Haptics: Whole body haptics aims at controlling body movements or enhancing their force and speed through the use of exoskeletons. They typically provide kinesthetic feedback and assistance with little or no tactile output. The forces required can be well over 100 N, raising issues of bulk and power consumption.

Grounded kinesthetic full-body feedback requires actuators that must be fast enough to follow limb movements without hindering natural motion. This must be accomplished while keeping weight, bulk, and power consumption low enough for the user to carry the suit, or for the suit to carry itself. Moreover, at these levels of performance, the risk of harming the user is significant. Therefore, great care must be paid to the tracking and control, as well as to the stability.

Exoskeletons and grounded kinesthetic feedback devices share many actuator requirements. However, their integration can differ. Most commonly, grounded kinesthetic feedback devices take the form of a workstation that controls hand and arm motion and in which the user is seated[67] (**Figure 6**A). The hand can, for example, be attached to an articulated robotic arm for hand position in space. Moreover, cable transmissions can be further used to control hand pose[68] (Figure 6B). Alternatively, the user can hold an external object like a pen[69] (Figure 6C) providing up to 6 axis force and torque feedback. Holding the pen directly allows for grounded kinesthetic feedback but can make it harder to simultaneously provide the user with cutaneous haptic feedback. This approach is the easiest to implement for the user, and is widely used in surgical robots.[70]

Hydraulic actuators were initially widely used to provide grounded kinesthetic feedback. A decade ago, pneumatic actuators became more popular[71] because they are much lighter, and can intrinsically offer some damping and shock absorption, and thus allow for softer, more comfortable and safer exosuits.[72] Pneumatic actuators require a connection to a source of pressurized fluid, either in a tank or using a compressor. Such hardware requirements can add significantly to the weight of the haptic device.

2.2.3. Wearable Haptics

Wearablility is essential for mobile applications such as in VR, where users should be free to move at least around a room, or for AR where the user must roam freely around a city. As described by Pacchierotti et al.,[62] wearability is a broad topic that includes the haptic device's form factor, its weight, the impairment it causes, and comfort.

A small form factor is obviously preferred, but is much more important for devices in contact with the finger than on a thigh. Conformable and smooth designs that follow the natural curves of the limb are preferred to protruding shapes that can impede natural movements. Haptic devices must fit body limbs without impairing user movements, which can be challenging when the actuators are large and rigid. Cutaneous actuators are placed on the skin and must be as small as possible to avoid collisions with other parts of the body. For instance, they must not interfere with other fingers or the palm when grasping. To minimize obstruction, the drive mechanism for cutaneous devices can be moved away from the skin, for example on top of fingers or on the back of the hand, and cables or other linkages can be used to transmit force to the skin. This is more challenging for AR as the user interacts with real and virtual objects, and must be able to grasp physical objects unimpeded. Soft actuators are required in such cases.[47,73]

Impairment is a bigger issue for kinesthetic devices because they must cover and control joints to control movements, and the higher forces required lead to larger actuators. Kinesthetic devices should not hinder motion when kinesthetic feedback

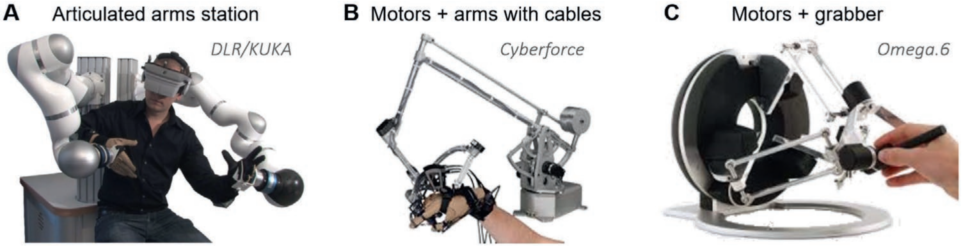

Figure 6. Grounded kinesthetic feedback stations based on electromagnetic motors integrated on A) an exoskeleton,[67] B) a free arm with cable transmission,[68] and C) an external grabber.[69] (A) reproduced with permission.[67] Copyright 2011, IEEE; (B) reproduced with permission.[68] CyberGlove Systems; (C) reproduced with courtesy of Force Dimension.[69] Copyright Force Dimension.

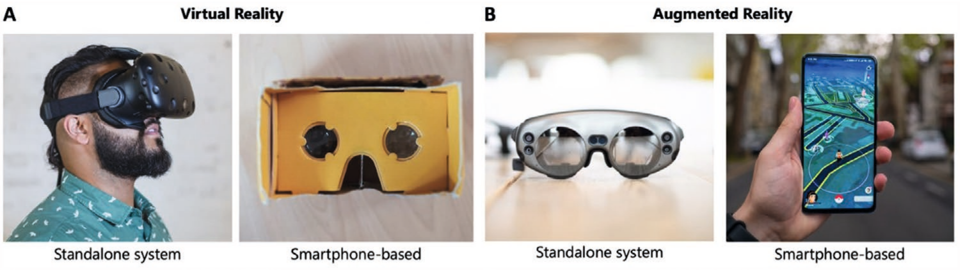

Figure 7. A) Commercial VR systems. Photograph of standalone commercial VR system 118546176 © Creativecommonsstockphotos. Reproduced under Creative Commons 0 License. Photograph of smartphone-based VR system. Reproduced under Unsplash License. Copyright by Sigmund. B) Commercial augmented reality systems. Photograph of standalone augmented reality system. Reproduced under Unsplash License. Copyright Bram Van Oost. Photograph of augmented reality smartphone-based system. Reproduced with permission under Unsplash License. Copyright Mika Baumeister.

is not provided. As with cutaneous devices, impairment can be decreased by using flexible cables to transmit force instead of directly mounting actuators on the body joints. Using cables is also an easy way to adapt to the size and shape of the limb. Last, comfort is an important determinant for user acceptance of wearable haptic devices.

In many cases, it is preferable to use soft materials that are breathable and do not require tight contact with the skin. In general, softness is key for developing a conformable device that improves comfort and freedom of movement. This can be achieved in three different ways: i) by using directly soft actuators, ii) by using small hard actuators incorporated into a soft matrix or carrier substrate, or iii) by using flexible cables connected to rigid actuators such as motors worn on the belt or compressors worn in a backpack. Electrical wiring and fluidic tubing must be small and flexible enough to not interfere with the user's natural motion.

2.3. Commercial Systems Overview

Commercially available VR systems such as the Oculus Quest and HTC VIVE Cosmos offer 6-DOF tracking of the head and body by placing multiple outward-facing cameras on the wearable headset (**Figure 7**A). Handheld position-tracking controllers with tactile buttons remain the most common method of user input, although more recent models include the capability for controller-free hand tracking. Externally placed sensor base stations provide hand, body, and head localization via triangulation and determine the physical boundaries of the VR workspace.[28,74] If controllers are included in the system, haptic feedback is typically conveyed through embedded vibro-tactile motors in the controller.[28] Lower-cost VR headsets such as the Google Cardboard and Samsung Gear VR rely on a smartphone to provide the sensing, computation, and display. These products primarily equip the user with an ergonomic accessory to strap the smartphone to the head and a downloadable smartphone app to generate the VR (Figure 7A). Smartphone-dependent headsets typically do not include the hand and body position-tracking functionality, which severely limits the user's interactions with the VR. Additionally, because the smartphone is used as the head-mounted display and there are no additional devices, haptic feedback is limited or nonexistent. These systems are generally marketed toward immersive entertainment applications.

The devices and capabilities of commercially available AR are much more diverse, but can still be broadly divided into specialized standalone and smartphone-based systems (Figure 7B). Recent standalone AR systems include Google Glass, Magic Leap 1, and Microsoft Hololens 2.[75,76] These systems include headsets with eye-tracking, orientation sensing, microphones, outward facing cameras, and handheld controllers with a trackpad and tactile buttons. The handheld controllers provide haptic feedback via vibro-tactile motors. Specialized standalone AR systems are primarily marketed toward enterprise for telepresence or enhanced productivity purposes. However, the most common AR system by far is the smartphone, as AR functionalities become increasingly standard in these devices. AR is typically generated with a downloadable app and uses the camera system, which may include multiple cameras and a laser rangefinder, as well as orientation sensors and the touchscreen. The capability to generate AR has also been included in tablet computers, such as the Apple iPad, in a similar fashion. The apps that offer AR in smartphones and tablet computers have a wide range of functions. These include providing an overlay of virtual to-scale furniture in a live video stream of a room to assist with purchasing decisions and enhancing gaming experiences by having interactive characters appear in a real-time video stream of the player's environment.[77]

Despite rapid progress in commercial VR/AR in the past decade, specialized standalone systems are still uncommon for the general public. This is likely due to relatively expensive initial costs, which in addition to the device hardware, may also require the purchase of a sufficiently powerful computer with a high-end graphics card. Because most devices are marketed for immersive entertainment purposes, commercial VR/AR systems are a luxury rather than a necessity. Furthermore, current VR/AR technology is still very young and provides limited functionality. Widespread assimilation of VR/AR into daily life requires compelling functionality without sacrificing comfort, free movement, and intuitive interactions with both the real and virtual world.

3. Integrated Soft Matter Systems for VR/AR

Although soft materials have considerable potential to advance the capabilities of VR/AR, there are relatively few examples of soft device integration within these ecosystems and it remains an application area rich with opportunity. In this section, case studies of soft technology implementations in VR/AR are examined.

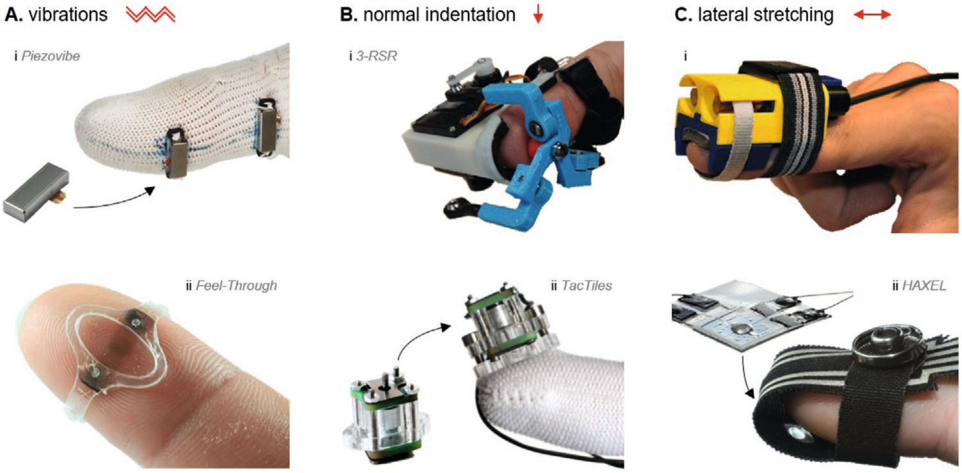

Figure 8. Cutaneous haptic feedback devices. A) Vibrations on skin using (i) Piezovibe[83] based on resonating piezoelectric beams, and (ii) Feel-Through[73] based on ultrathin DEA. B) Normal indentation of skin using (i) 3-RSR[84] based on servo motors and (ii) TacTiles[85] based on voice coils. C) Lateral stretching of skin using (i) rotary motors[86] and (ii) HAXEL[87] based on hydraulically amplified electrostatic actuators. (A-i) Reproduced with permission.[83] Copyright 2018, ACM; (A-ii) Reproduced with permission.[73] Copyright 2020, Wiley-VCH; (B-i) reproduced with permission.[84] Copyright 2015, IEEE; (B-ii) Reproduced with permission.[85] Copyright 2019, IEEE; (C-i) reproduced with permission.[86] Copyright 2010, IEEE. (C-ii) Reproduced with permission.[87] Copyright 2020, Wiley-VCH.

3.1. Handheld Devices

One challenge with using handheld controllers is producing a physically accurate portrayal of a virtual object in the grasp of the user. Handheld controllers are most commonly manufactured from hard plastics and cannot alter their form factor to produce the variety of textures, shapes, and material compliance the user encounters in the virtual world. Variable shape and stiffness material architectures to provide real-time haptic feedback for VR have been demonstrated as potential solutions.

Barreiros et al.[78] introduced a 12 DOF fluidic elastomer actuator sleeve for a responsive handheld VR controller. The device provides persistent tactile and kinesthetic feedback with 12 individually addressable chambers fabricated from thermoplastic films sandwiched between elastomer layers. The chambers are controlled via miniature solenoid pneumatic valves and is capable of exerting forces from 5 to 45 N, exceeding the detection threshold of 32.8 mN for a human finger.[79] The sleeve partially enveloped an HTC Vive controller and was used to convey feedback for shooting a gun in VR carnival games.

Murray et al.[25] created a compliant handle that used elastomeric polyurethene lattice structures for an inflatable and variable stiffness handheld VR controller with an operating range of 0–150 kPa. The deformation of the device served both as user input via squeezing and bending and haptic feedback via inflation and deflation. The compliance change was used to simulate the sensations of holding either a foam or metal sword.

3.2. Cutaneous Feedback Devices

Three approaches exist for providing cutaneous haptic feedback: First and most obvious is the direct application on skin of a mechanical stimuli. As described by Pacchierotti et al.,[62] one distinguishes three types of stimulus on skin, discussed below: 1) vibration, 2) normal indentation, and 3) lateral stretch (**Figure 8**). Second is indirect force application using ultrasound[80,81] or air flow.[82] These systems are rather bulky and require some fixed infrastructure, with no wearable mid-air systems existing today. Third is the electrostimulation of the skin.[45–47] Electrostimulation devices are light, soft, low-power and wearable, but require electrodes on the fingertips and provide a limited range of cutaneous sensations.

3.2.1. Vibrotactile Stimulation

Vibrotactile stimulation on fingers requires forces on the order of 10 mN and a displacement of only 10 µm. Vibrations propagate in all directions and human localization accuracy is low, making vibrotactile actuators easier to integrate because, unlike for indentation, accurate actuator positioning is not needed. One device close to the fingertip is sufficient. A vibrotactile actuator should be capable of frequencies higher than 50 Hz, which rules out slower actuation technologies such as shape memory polymer (SMP) or ionic electroactive polymer (i-EAP). Most commercial vibrotactile actuators are based on eccentric mass-based EM motors,[88] piezoelectric oscillating masses (Figure 8 Ai),[83] or membranes.[89] They are small, light, and low power. However, the resonant frequency of piezoelectric beams is fixed, and motors have slow spin-up time and cannot change the frequency independently of the amplitude. Voice coil-based vibrators[85] offer more freedom to configure vibrations. However, actuators that are not soft can disturb the sense of touch when grabbing real objects in AR. This has motivated the development of softer technologies such as dielectric elastomer actuators (DEA)[73] (Figure 8 Aii), which are extremely thin (18 µm) and soft. Shape memory alloy (SMA)[90] are also very small and discrete, although not capable of rapid 50 Hz motion. Finally, hydraulically amplified electrostatic actuators (HAES)[87] are stronger but thin and flexible while being able to provide vibrotactile as well as other types of stimuli.

3.2.2. Normal Indentation

Normal indentation of skin requires force and displacement on the order of 100 mN and 100 µm, respectively. Compared to vibrotactile actuators, the speed can be lower, as only a few Hz is sufficient for indentation actuators. Integration is more challenging, however, because placement and orientation are important to convey the desired feeling. Cutaneous actuators can be adhered to skin, attached around the finger, or mounted on a glove (Figure 8). Flat, convex, and slightly concave skin surfaces are most suitable. Finger joints and the palm usually receive little interest[91] for placement of haptic actuators.

Fluidic actuators in the form of an inflated cavity[92–94] work well for pushing on the skin at low speed. Fluidic actuation requires tubes or microfluidic channels. Electric motors are effective but bulky (Figure 8B-i).[95–98] A broad range of electrically-driven actuators have been demonstrated for normal indentation of finger skin, using EM means (Figure 8B-ii),[85,99] piezo-electric,[100,101] dielectric elastomer actuators,[102,103] i-EAP,[104,105] SMP,[106,107] SMA,[108,109] or electrostatic zipping.[87] However, few technologies are soft and wearable with small form factor.

3.2.3. Skin Stretch

Skin stretching is relatively challenging to induce compared with normal indentation. Common ways to stretch skin on the finger are to roll a belt (Figure 8C-i)[110,111] using motors, or to use a mobile platform[112] articulated with rods[84,113] or wires[114] connected to motors. The motors are installed on the back of the finger. Most of these devices are also capable of wide normal indentation by compressing the finger.

3.2.4. Multimode Cutaneous Feedback

Only a few haptic devices combine all type of cutaneous stimuli. Most of them take the form of a cube containing several actuators to be able to move in all directions at different speeds. They are rather bulky and complex. We identified EM voice coils[99] and SMA[115,116] actuators. In contrast, the recent HAXEL actuator (Figure 8C-ii)[87] is the only one until now which is able to provide all type of stimulus using only one actuator. In addition, it is soft, thin, and lightweight. For AR applications, softness and thinness are key to interact naturally with both virtual and real objects. Ribbon-based actuators[110,111] are promising due to their low thickness and compliance matching with the fingertip. DEA actuators are also well suited because they can be engineered to be thin and soft[73] (Figure 8 Aii).

3.3. Grounded Hand-Based Kinesthetic Haptics

Hand kinesthetic feedback requires actuators capable of exerting an order of magnitude times higher force and displacement than for cutaneous feedback. Kinesthetic feedback on the hand is particularly challenging because fingers have a very high force to mass ratio, as they are driven mostly by large forearm muscles, not muscles in the hand (except for the thumb). Haptic actuators for the hand thus need to be small enough to fit on fingers yet powerful enough to compete with muscles of volume several times that of the finger.

3.3.1. Cables and Motors

Motors that can easily provide the required forces are too bulky and heavy to wear on fingers. Most commercial kinesthetic haptic feedback systems are powered by electromagnetic motors. The motors have been placed on the back of the hand[117] or forearm.[118] A common way to circumvent this issue is to place the actuators on the forearm and connect them to fingers using flexible cables. The development of small ratchets and pulleys helped to better transmit force to the fingers and to block unwanted motion. The use of flexible cables[117,118] (**Figure 9**A) or twisted string actuators (TSA)[119] (Figure 9B) makes these systems feel soft and wearable.

3.3.2. Artificial Muscles

It is challenging to scale up artificial muscles to meet kinesthetic feedback force and displacement requirements while keeping acceptable limits on size and energy consumption. For example, it is possible to use DEA or piezoelectricity for kinesthetic feedback but DEAs that are large enough to move arms or fingers (Figure 9C) are slow and challenging to fabricate.[120,124,125] EM voice coils and SMA[126] scale poorly due to power consumption. Thermal twisted and coiled polymer muscles[127] and SMP[128] are potential candidates but have low energy efficiency. Fluidic actuators can provide kinesthetic feedback using hard pistons,[129] soft pneu-Nets[121,130] (Figure 9D) and McKibben muscle[122,131–133] (Figure 9E). Finally, we note that peano-HASEL devices[134,135] actuators are promising but remain to be demonstrated for kinesthetic feedback.

3.3.3. Brakes and Clutches

In contrast to cutaneous feedback that requires skin to be pushed or stretched, some kinesthetic feedback can be provided by merely blocking limb motion. This approach of actively blocking motion is suitable when interacting with a virtual environment in which objects are not pushing on the user. One can thus provide kinesthetic feedback using brakes and clutches, mechanisms that can dynamically block or couple motion. This enables variable stiffness systems that can stop limb motion when the limb is about to make contact with a virtual object, or resist movement when compressing a soft virtual object. Clutches are especially interesting as they can be simpler, smaller, and require far less power than actuators. However, clutch mechanisms are more sensitive to any slack in the system, and must be attached firmly because they exert a force to deal with slack. Several clutch technologies exist[136] including EM motors,[137] fluidic vacuum jamming,[138–140] magneto-rheologic,[141] and electrostatic[136,142] clutches. Fluidic clutches need a pump or a pressure tank. Electrostatic clutches[136,142] are

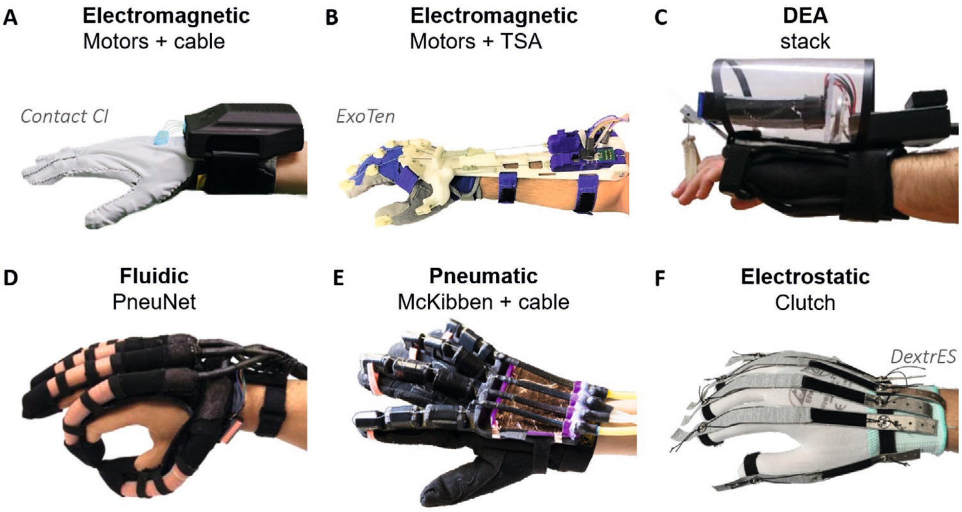

Figure 9. Kinesthetic haptic feedback glove using A) electromagnetic motors with cables,[118] B) electromagnetic motors with TSA,[119] C) stacked DEAs[120] D) fluidic pneu-Net actuators,[121] E) pneumatic McKibben actuators with cables,[122] and F) using electrostatic clutches.[11] (A) reproduced with permission.[118] Copyright Contact Control Interface; (B) reproduced with permission.[119] Copyright 2018, IEEE; (C) reproduced with permission.[120] Copyright 2008, SPIE; (D) reproduced with permission.[121] Copyright 2015, Elsevier; (E) reproduced with permission.[122] Copyright 2017, UC San Diego Jacobs School of Engineering; (F) Reproduced with permission.[11] Copyright 2018, ACM.

especially interesting as they can be soft and wearable for providing kinesthetic feedback within an ultra-thin and light glove format[83,123] (Figure 9F). These clutches deliver a high blocking high force (20 N cm^{-2}) over large travel while being very lightweight and flexible. Power consumption is low (mW cm^{-2}) but they require several hundred volts for operation.

3.4. On-Hand Kinesthetic Haptics

For on-hand use, there are three main ways to integrate the mechanical systems that provide kinesthetic haptics.[124,143] First, finger digit-based devices can be integrated between fingers to control their spacing. Such devices[124,137] (**Figure 10**A) usually block the movement of the fingers by taking support on the thumb. Second, devices can be applied on the palm[144–146] and be used to control finger movements (Figure 10B). Third, the majority of kinesthetic feedback devices use a hand dorsal based approach where the device is placed on the top of the hand (Figure 10C). The main advantage of the hand dorsal based integration compared to others is that the palm and the fingers are not obstructed, which enables the user to completely close the hand and grasp real objects. In addition, the skin on the finger remains easily accessible to provide cutaneous feedback using tactile actuators. These advantages are likely why existing commercial devices use a dorsal based approach with a glove form factor.[143]

Electrostimulation can provide kinesthetic feedback[149–151] but is not popular, possibly due to lack of user acceptance. Visual illusions can enhance kinesthetic feedback.[152,153]

Multiple hand dorsal based kinesthetic haptic feedback gloves have been developed.[154,155] They can be divided into two main types. First, jointless gloves[117–119] use cables integrated within a textile glove to block or move fingers. They are small, light, and flexible, but require additional rigid structures to attach and actuate the cables (Figure 9D). Second, jointed gloves use an exoskeleton over the top of the hand to control the fingers (Figure 10C). These exoskeletons can be directly powered by motors[156] or pistons,[129] or indirectly using cables.[117,157,158] They are simple and easy to control, but they are bulky, occupying a large volume above the hand in order to adapt to hand size and shape variability.[154] Electrostatic clutches[83,123] offer a good middle ground between these approaches by placing the brakes directly on fingers, which are simple, thin, and flexible.

Progress on the performance, size, softness, and integration is making untethered hand kinesthetic feedback usable in VR

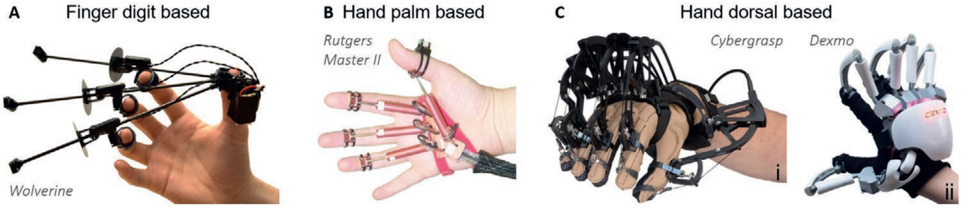

Figure 10. Different integration of hand kinesthetic haptic feedback devices A) between fingertips and thumb,[137] B). on hand palm[144] and C. on the back of the hand.[147,148] (A) reproduced with permission.[137] Copyright 2016, IEEE; B) reproduced with permission.[144] Copyright 2002, IEEE; (C-i) reproduced with permission.[147] Copyright CyberGlove Systems; (C-ii) reproduced with permission.[148] Copyright 2020, Dexta Robotics.

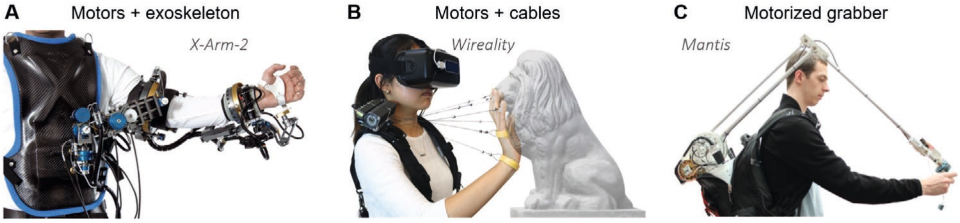

Figure 11. Wearable grounded kinesthetic feedback devices based on A) motors on an exoskeleton,[166] B) motors with cable attached to fingertips,[66] and C) motors on a grabber.[171] (A) reproduced with permission.[166] Copyright 2011, IEEE; (B) reproduced with permission.[66] Copyright 2020, The Authors; (C) reproduced with permission.[171] Copyright 2019, ACM.

applications. AR applications remain more challenging, due to the bulk of commercially available solutions.

3.5. Grounded Kinesthetic Full-Body Feedback and Exoskeletons

Most exoskeletons and grounded kinesthetic feedback devices today rely on EM motors. Very high efficiency and high torque motors are available, designed for the rapidly expanding market of electric mobility (electric scooters, bicycles and cars).[159–161] Clutches are widely used in robotics and on exoskeletons to lock joints in position and reduce energy consumption. Lightweight and soft ES clutches have been demonstrated on the ankle[142] and the elbow.[162] They are good candidates to provide grounded kinesthetic feedback.

High-force grounded kinesthetic feedback systems are generally fixed, as the weight and the bulk of most of these systems is beyond what a human can carry without the assistance of a lower limb exoskeleton.[163,164] Making the haptic system soft adds an additional level of challenge as soft systems do no directly support compressive loads.[163]

Recently, several wearable grounded kinesthetic feedback systems have been developed. They provide kinesthetic feedback by creating a reaction force at the trunk which serves as the grounded reference.[48] These wearable systems use three integration approaches. First, a wearable rigid articulated arm exoskeleton[165–168] (**Figure 11**A) controls the movement of the arm and the hand with precision, but the whole device remains relatively bulky and requires multiple cables. A soft exoskeleton jacket has been developed using single inflated cavities around the arm.[169] It is less precise but much softer and more comfortable. This is a good example of the dilemma that arises between the rigidity and tight fit required for precision and the use of softer and looser wearable materials needed for comfort. Second are devices that use free moving cables attached to motors mounted on the shoulder, which control hand and finger motion[66] (Figure 11B). This approach is interesting as it uses minimal hardware, making the device small and light, maximizing its wearability. However, some movements are restricted, such as closing the fist, turning the hand, crossing the hands, or moving the hand behind. Third is an external grabber anchored to the user's back[170,171] (Figure 11C). This system is wearable but cumbersome and not very precise because of the leverage of the thin and long arm plus the slack of the anchor in the backpack.

The field of grounded kinesthetic feedback is progressing rapidly with the development of truly wearable systems. Following the advances made on haptic gloves, new wearable grounded kinesthetic feedback systems are expected to come in the next few years.

3.6. Electronic Skins

Working toward improving compatibility with the human body, electronic skins (e-skins) offer exceptional freedom of motion by being lightweight, thin, flexible, and stretchable.[172] E-skins are typically adhered directly to the user's skin and eliminate the need for additional straps, clothing, or tapes. Furthermore, e-skins can offer a superior customized fit by virtue of its ability to conform to the unique skin surface characteristics of the user. In addition to increasing wearability, e-skins enable novel techniques in sensing and haptics for VR/AR.

3.6.1. VR Applications

Mishra et al.[14] introduced skin conformal eye-tracking sensors placed directly on the user's face for VR eye therapy exercises (**Figure 12**A). The sensors use the electrooculography (EOG) technique, which noninvasively measures the voltage difference between the cornea and retina via skin-mounted electrodes placed on opposing sides of the eye to detect eyeball movement.[174] This is in contrast with the standard videooculography approach, typically implemented with cameras mounted on a headset to visually track eye movements via computer vision algorithms. By patterning stretchable mesh patterns with Ag nanoparticles on a polyimide (PI) substrate encased in an adhesive elastomer membrane, the EOG sensors achieved 100% biaxial strain and 180° flexibility with a 1.5 mm radius. With its low-profile form factor, these sensors were placed on the user's face underneath a VR headset for integration with the existing ecosystem and tracked 1° to 3° eye movements with 91% accuracy for virtual objects at three different perceived distances.

Chossat et al.[173] developed an e-skin using microfluidic channels of ionic liquid and liquid metal with a conductive thread interface embedded in an elastomer substrate for motion detection (Figure 12B). By placing the e-skin only on the back of a hand rather than taking the form of a glove, the palm of the hand is left bare and the dexterity of the hand is almost completely preserved. The e-skin features 11 resistive strain sensors for 1 DOF tracking of finger joints and enables real-time joint angle detection from 0° to 130° for 3D graphical reconstruction.

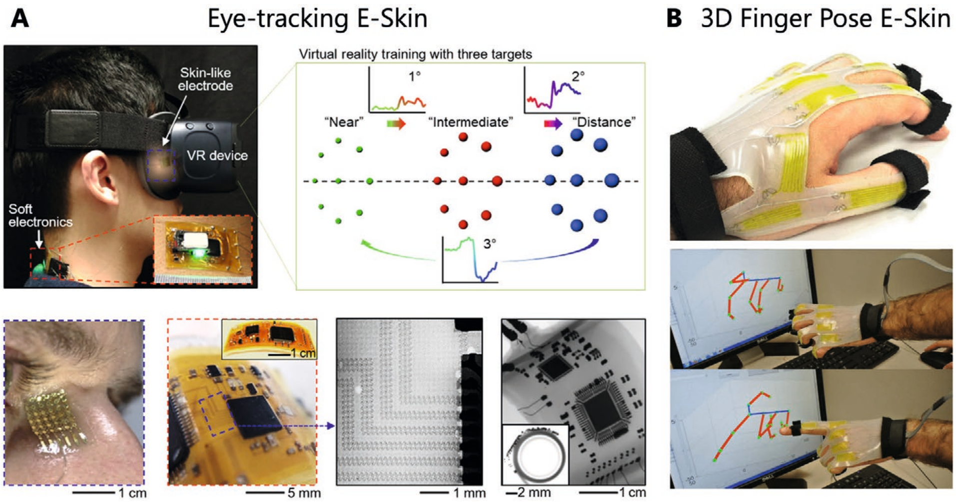

Figure 12. A) Skin-mounted flexible electronics for eye tracking with electrooculography. Reproduced with permission from.[14] Copyright 2020, AAAS. B) Wearable strain sensor glove for 3D finger pose recognition integrated with a VR system. Adapted with permission.[173] Copyright 2015, IEEE.

3.6.2. E-skins for AR

While design goals of sensing e-skins for AR and VR are largely the same, there are significant differences in designing haptic e-skins for AR and VR. Because AR only intends to supplement the real world with virtual elements, the e-skin should not interfere with the perception of natural tactile stimulation from interactions with physical objects. In contrast, with the objective of complete immersion in the virtual world for VR, it is acceptable and may even be desirable to inhibit real world tactile stimuli in favor of providing the appropriate haptic feedback for virtual interactions.

Withana et al.[13] constructed a ”feel-through” tactile feedback e-skin for AR interactions. The device is fabricated from screen printed Ag/AgCl nanoparticle and poly(3,4-ethylenedioxythio phene):polystyrene sulfonate (PEDOT:PSS) inks with a resin binder for insulation and integrated into a temporary tattoo for a total thickness of 35 µm. It provides electro-tactile stimulation by injecting electrical current (≈1–2 mA) into the skin via direct contact with electrodes, achieving tactile sensations comparable to mechanical actuators.[175] Depending on the placement location of the e-skin, the spatial density of the individually addressable tactile pixels (taxels) and output area can be varied accordingly, e.g. higher taxel resolution and smaller surface area for a fingertip compared to a forearm. The taxel resolutions demonstrated had 2 or 5 mm electrode diameters with 4 mm or 9 mm center-to-center spacing in actuating areas of 10 mm × 10 mm or 23 mm × 41 mm, respectively.

3.6.3. E-skins with Haptic Feedback

In addition to sensing, e-skins can also be engineered to provide various modalities of haptic feedback. Yu et al.[176] introduced a wireless, battery-free haptic e-skin with an array of mm-scale vibratory actuators (**Figure 13**A). The e-skin features magnetic disk actuators and integrated circuit (IC) chips with serpentine Cu traces on a polyimide (PI) substrate embedded in layers of polydimethylsiloxane (PDMS) and fabric. The Cu traces are used as interconnects between the microelectronics as well as near field communication (NFC) coils for power delivery and data communication, which have a working range of 80 cm. The e-skin can bend about 145° (≈5.1 cm radius), fold 150° (≈5 cm radius), twist 50°, and has an elastic limit of 0.3%. The e-skin can support up to 32 individually addressable actuators in a variety of different shapes.

Lee et al.[15] report an e-skin capable of heating and cooling human skin for thermal feedback in VR (Figure 13B). The skin-like thermo-haptic device can stretch up to 230% and was integrated into a motion tracking glove. The e-skin was fabricated from layers of thermally conductive elastomer that encapsulated serpentine Cu electrodes on a PI substrate that connected alternating p- and n- type bismuth telluride thermoelectric pellets. Using the Peltier effect, the thermoelectric pellets enable a rapid thermal response when voltage is applied. The thermo-haptic e-skin was used to simulate a cold beer bottle (15° C), chilly soft drink bottle (18° C), warm tea mug (35° C), and hot coffee mug (40° C) in VR.

4. Emerging Sensor Technologies

To realize the full potential of VR/AR, device form factors must prioritize compatibility with the human body. In addition to being soft, elastic, and flexible, intimate contact with the skin and body demands greater material performance requirements such as breathability, biocompatibility, and adaptability to the physical characteristics that vary greatly among individuals. Soft sensors must also offer comparable functionality to current rigid devices in the two essential sensing capabilities for VR/AR: pose estimation and tactile contact. Herein, state-of-the-art strategies and advancements in the three key areas of soft tissue compatibility, pose estimation, and tactile contact for next generation VR/AR are discussed (**Figure 14**).

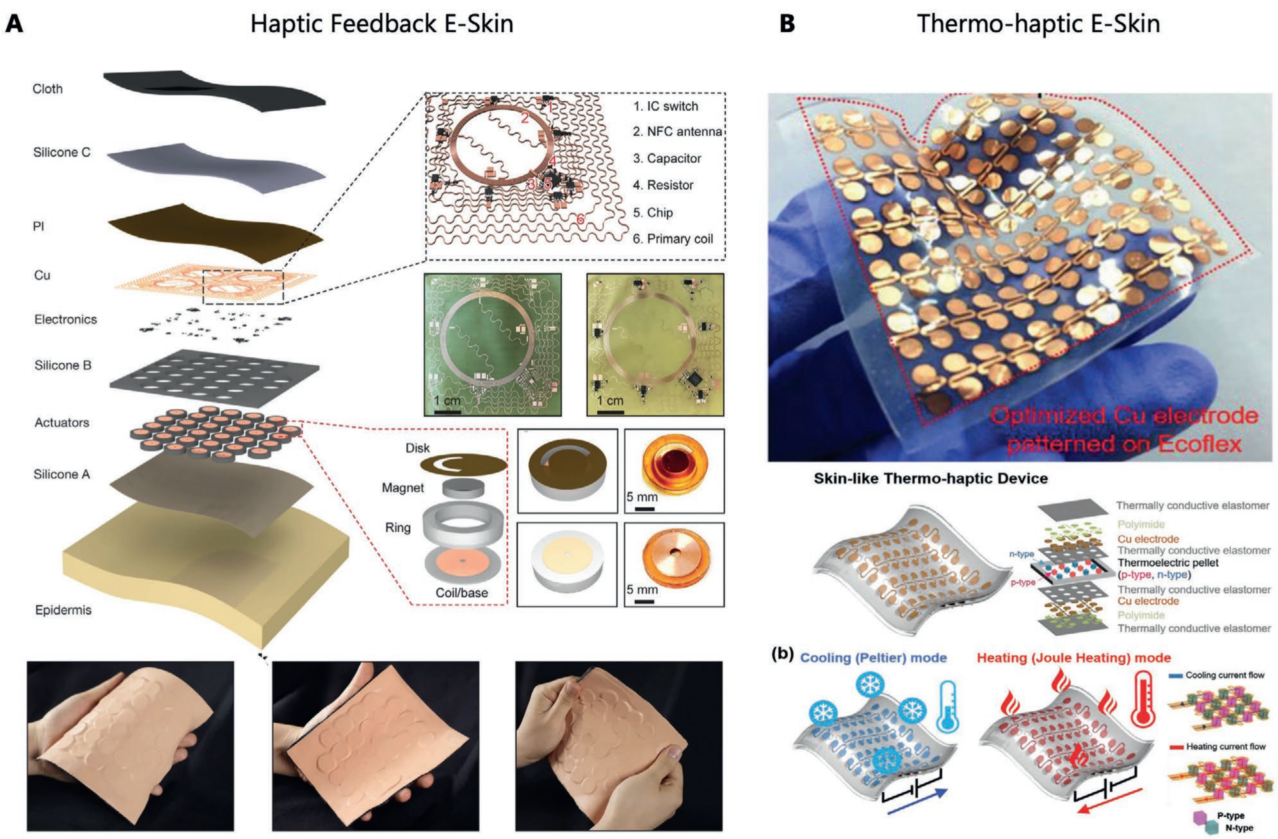

Figure 13. A) E-skin for haptic feedback in AR and VR. Reproduced with permission.[176] Copyright 2019, Nature Publishing Group. B) E-skin for thermo-haptic feedback. Adapted with permission.[15] Copyright 2020, Wiley-VCH.

4.1. Soft Material Architectures

Beyond increasing wear comfort, the shift toward soft materials integration is motivated by increased sensor accuracy enabled by the close mechanical coupling of the sensing device and human body. In contrast to soft e-skins, rigid sensing devices are restricted by limited body placement locations and a lack of conformal contact that results in motion artifacts. To address this, several promising soft material architectures have been developed that address the requirements of VR/AR sensing. However, not all of these technologies have been fully implemented in VR/AR systems. Hybrid circuits, epidermal electronics, and textile-based electronics can enable comparable sensing functionality to current rigid devices. In addition, soft materials integration allows for physiological monitoring via biochemical sensing for novel inputs to VR/AR. In this section, we review these emerging soft materials architectures and discuss requirements for creating soft, flexible, and stretchable e-skins for VR/AR sensing applications (**Figure 15**).

4.1.1. Soft Tissue Compatibility

For the layer-by-layer architectures common in soft wearable sensors, the substrate layer typically exerts the most influence on the mechanical and biocompatible properties of the device

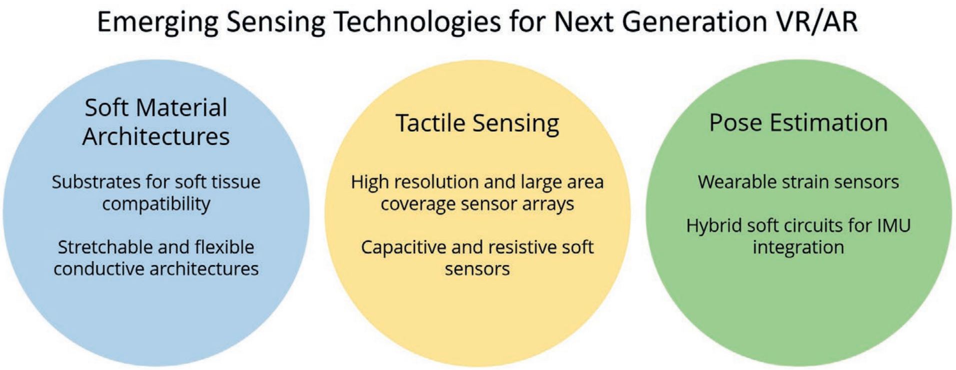

Figure 14. Overview of innovation areas leading to next generation VR/AR sensing technologies.

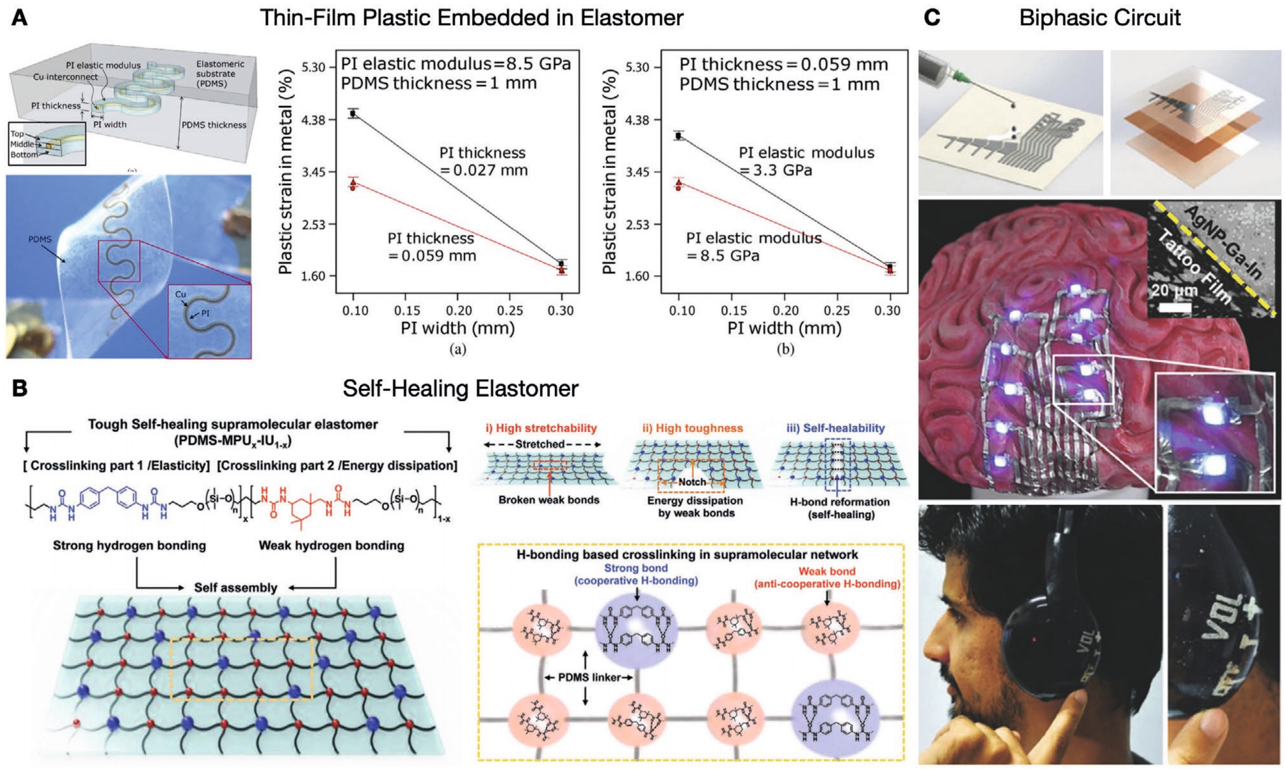

Figure 15. A) Serpentine Cu and PI interconnects embedded in PDMS for a stretchable circuit. Adapted with permission.[177] Copyright 2011, IEEE. B) Self-healing elastomer molecular structure. Reproduced with permission.[178] Copyright 2018, Wiley-VCH. C) Hybrid circuit manufactured with a room-temperature inkjet manufacturing technique. Reproduced with permission.[179] Copyright 2018, Wiley-VCH.

(**Table 2**). The substrate can be defined as a uniform material that provides foundational structural support for embedded or superficial components, and generally interfaces directly with the skin or the electrode.[38,40] The two classes of substrate materials that have been demonstrated in sensing systems for VR/AR applications are elastomers and thin polymer films (Figure 15A).

The material properties of elastomers are chiefly dictated by how the polymer chains are crosslinked.[180] Chemically cross-linked elastomers, notably silicones such as PDMS and Ecoflex, offer excellent mechanical, thermal, and chemical stability due to the strong covalent bonds that bind the polymer chains together. Physically cross-linked elastomers, e.g. poly(styrene-butadiene-styrene) (SBS), are formed through comparatively weaker connections such as hydrogen bonding. This results in a softer, albeit less stable elastomer that is more responsive to applied pressure, heat, and solvents. Elastomer networks with

Table 2. Summary of substrate materials relevant to the typical layer-by-layer architecture of emerging wearable sensing technologies.

Substrates	Examples	Advantages	Challenges
Elastomers	PDMS, Ecoflex, PU	Intrinsic elasticity comparable to human skin; non-toxic; chemically inert; bio-compatible	Limited permeability to gas blocks sweat evaporation; limited wear time to prevent skin irritation
Self-healing elastomers	Cu-DOU-CPU, PDMS	Extend device lifetime; reduce user maintenance needs	Limited mechanical properties; relatively unknown bio-compatibility; resilience of material typically decreases after self-healing
Textiles	Nylon, PTFE	Ease of integration into everyday use; intuitive don and doff; washability	Potential degradation from washing; resilience to everyday stresses
Thin-film plastics	PI, PEN, PET	Low-cost; existing mass manufacturing infrastructure; compatible with IC chips and thin metal film interconnects; accessible fabrication techniques	Not inherently stretchable; anisotropic compliance
Hydrogels	PVA, PAAM, PAA	Porosity is compatible with biochemical sensing mechanisms; intrinsically soft; bio-compatible	Typically requires submersion in aqueous medium leading to limited wear time; high responsiveness to external stimuli results in low robustness
Tattoo-film	Acrylates/Va/Vinyl Neodecanoate Copolymer	Low-cost; existing mass manufacturing infrastructure; long wear times; widely accepted by users	Limited durability; susceptible to wear and degradation; devices may require recalibration after body placement

both chemical and physical bonds, such as polyurethane-based (PU) elastomers, offer a compromise between stability and reactivity. The most widely used elastomers for on-body sensors are either chemically cross-linked or chemically and physically cross-linked due to the desire for robustness to environmental and wear-induced stresses.

PDMS, in particular, is a very common substrate material because of its compatibility with a variety of conductive fillers, elasticity[181] comparable to that of human skin (55%),[182] non-toxic and bio-compatible properties, ease of manufacturing, and chemical inertness. In addition to acting as a substrate material, PDMS has been used to encapsulate components that are too fragile or unsuitable for close contact with skin. However, like most silicone elastomers that are cast in thin-films for e-skins, PDMS has an inherently limited permeability to gas and blocks sweat evaporation, which causes irritation in long-term epidermal wear. Yang et al.[183] sought to address this by introducing breathable woven mesh structures fabricated with PDMS.

4.1.2. Self-Healing Elastomers

More recently, rapid advancements in self-healing elastomers has sparked an interest in its applications for wearable devices[184] (Figure 15B). The ability for the substrate to self-heal can greatly extend the lifetime of the device and reduce the need for maintenance and repair. Approaches to the self-healing mechanism varies greatly; some recent methods include incorporating multi-strength hydrogen bonds[178] and disulfide metahesis in PDMS polymers,[185] building a covalently cross-linked polyurethane elastomer with triple dynamic bonds (Cu-DOU-CPU),[186] and using Diels–Alder reactions to form thermoreversible cross-links in the polymer network.[187] Although self-healing elastomers are a promising path forward for wearable substrates, there are still several challenges that require progress before this technology can be integrated into soft VR/AR devices: demanding requirements for external energy inputs that enable the self-healing processes, a lack of extensive testing for biocompatibility, and typically a reduction in resilience of the material after the self-healing process.

4.1.3. Thin-Film Plastics

Rigid polymers such as PI, polyethylene naphthalate (PEN), and polyethylene terephthalate (PET) can achieve flexibility through a thin (sub-mm) film form factor. These thin plastic films are particularly attractive for wearable electronics because of their low cost, existing mass manufacturing (e.g. roll-to-roll and gravure printing) infrastructure, and compatibility with conventional IC chips and thin metal film interconnects. In addition, thin polymer films are very well-suited for rapid prototyping due to widespread commercial availability and accessible fabrication techniques, which include laser cutting, laser patterning, chemical etching, screen printing, and electroplating.

Although the polymer films are not inherently stretchable, they can be patterned into wavy and serpentine structures to dissipate strain via in-plane and out-of-plane bending. A common approach is to use PI to reinforce wavy Cu interconnects embedded in PDMS, which has been demonstrated to achieve elongations up to 250%.[188] For IC chip integration, the stiff-island technique is commonly used, where IC chips are bonded to a thin metal and polymer substrate of nominal surface area and connected to other parts of the device via serpentine conductive interconnects.[12] This method minimizes the areas of necessary rigidity and preserves most of the overall flexibility and elasticity of the device, while enabling the use of IC chip capabilities. To mitigate the persistent compliance mismatch from the presence of rigid IC chips, the flexible VR/AR devices avoid placement in body locations that exceed the limitations of their conformability.

4.1.4. Hybrid Circuits

Hybrid circuits are composed of soft substrates, stretchable wiring, and rigid microelectronic components. This soft material architecture enables the use of rigid IC chips in a stretchable format, critical to VR/AR because IC chip capabilities are required for orientation sensing, signal processing, and computation (Figure 15C). These hybrid circuits are often described as using the stiff-island technique, which aims to shield the rigid IC chips from tensile strain by dissipating the strain energy through the stretchable conductive interconnects and substrate.

Promising stretchable conductive architectures that possess metallic conductivity for IC chip interfacing include liquid metal microfluidics, serpentine wiring, and bi-phasic traces of liquid metal coated on printed conductive ink (**Table 3**). Liquid metal interconnects consist of microfluidic channels containing metals that are in liquid phase at room temperature, such as eutectic gallium indium (EGaIn) or Galinstan, embedded within a soft substrate.[189] As the substrate is stretched or bent, the liquid metal flows within the channels to adapt to the deformation while retaining conductivity. In contrast, a rigid conductor might fracture, delaminate, or break, and the circuit would fail. Serpentine wiring uses flexible thin metal films or narrow wires in pre-stretched or geometric patterns to dissipate strain along the prescribed axes.[190] Fused solid thin film and liquid metals combined with printed conductive ink facilitates the high conductivity required for interfacing with IC chips in tandem with a very consistent and automated manufacturing process.[179,191]

To mitigate the stress concentrations at the interface between the rigid components and soft materials, functionally-graded interfaces should be implemented. Stiffness gradients in the substrate material in the areas surrounding the rigid microelectronics will aid in distributing stress and improving the stretchability of the overall device.[192] However, introducing these functionally-graded interfaces remains an open challenge and such structures may never reach comparable elasticity to that devices using intrinsically stretchable sensing mechanisms. Despite this, hybrid circuits are still a critically important material architecture and the stretchability of these circuits is generally adequate to can accommodate unrestricted human motion and skin stretch.

Table 3. Summary of stretchable and flexible conductive architectures relevant to emerging wearable sensing technologies.

Conductive architectures	Principle	Advantages	Challenges
Serpentine interconnects	Rigid thin metal films or narrow wires in pre-stretched or geometric patterns to dissipate strain	Direct interfacing with IC chips; well-explored and consistent manufacturing processes	Not intrinsically stretchable; limited to prescribed directions of stretchability
Conductive elastomers	Conductive particles or polymers embedded within a soft elastomeric matrix	Compatible with 3D printing, screen printing, molding, and other scalable manufacturing methods	Limitations on microelectronic interfacing; loss of conductivity when stretched
Liquid-metal interconnects	Microfluidic channels with liquid-phase metals adapt to applied deformation	Intrinsically stretchable; metallic conductivity allows direct interfacing with IC chips	Durability of channels; change in conductivity as channels deform
Conductive inks	Conductive nanoparticles suspended in composite of printable viscosity	Consistent and scalable manufacturing processes	Typically, conductivity decreases significantly when stretched; limitations on choice of substrate
Textile-based	Thin metal wires woven into fabric fibers; thin film coating of metal on fabric; thin film coating of conductive polymers on fabric	Ease of integration into everyday use; intuitive don and doff; washability	Microelectronics interfacing; resilience to environmental stresses

4.1.5. Epidermal Electronics

Epidermal electronics are skin-mounted systems in which the device substrate makes direct conformal contact with the skin, typically attached with an adhesive.[193] The devices incorporate thin film serpentine wiring, patterned liquid metal interconnects, or directly printed traces embedded in an ultrathin tattoo film. This material architecture is useful for VR/AR applications by virtue of its outstanding freedom of motion while still providing a large surface area for various sensors and haptic feedback mechanisms.

Much progress has been made in passive, low-power consumption, and untethered epidermal electronics, primarily driven by the integration of NFC antennas[194–196] (**Figure 16**A). The NFC antennas can be used for both power and data transmission to the epidermal device, with the router and power

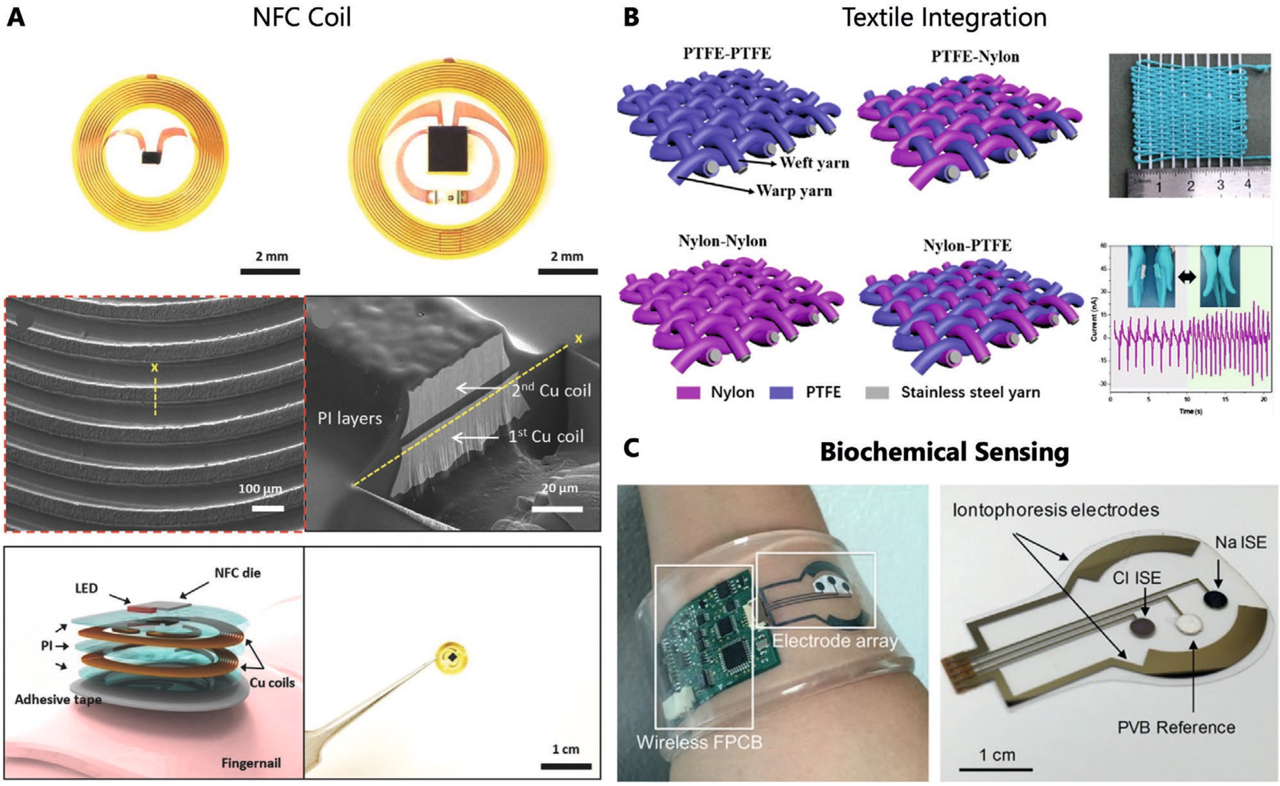

Figure 16. A) Wearable and flexible near field communication (NFC) coil. Reproduced with permission.[194] Copyright 2015, Wiley-VCH. B) Conductive fabric and yarn for a wearable sensing textile for human motion and pulse monitoring. Reproduced with permission.[197] Copyright 2020, American Chemical Society. C) Fully integrated wearable sweat extraction and analysis. Reproduced with permission.[16] Copyright 2017, Proceedings of the National Academy of the Sciences.

source not mounted to the body. This allows for unrestrained movement of the limbs, but requires proximity to an externally located router. In addition, NFC might not support the data transfer rates required for VR/AR applications, where high fidelity and perhaps a high sampling rate is crucial to a realistic experience in the virtual world. One potential solution is to exploit the availability of surface area and design the tattoo to cover large surfaces of the body to transmit data from the sensors to a centralized wireless router.

4.1.6. Textile-based Electronics

Textile-based electronics leverage wires incorporated directly into fabrics and clothing[197] (Figure 16B). Conductive textiles has been fabricated using three different approaches: thin metal wires are woven into the fibers of the fabric, the fabric has a thin-film coating of metal, or the fabric has a thin-film coating of conductive polymers. Textile-based electronics are particularly compelling for VR/AR applications because of the seamless and unobtrusive integration into everyday clothing. This concept is being pursued in industry, such as in Google's Project Jacquard. Project Jacquard has demonstrated a denim jacket with a small computational unit that lets the user interact via contact and motions when wearing the specific denim garment. In addition, fabric-based devices are typically easy and intuitive to don and doff. Textiles have been used as substrates as well as electrodes for capacitive sensing.

While not conventional textiles in material composition, such as that of nylon, polyester, or cotton, recent work has begun to explore the utility of the woven mesh structure with new materials, such as PDMS and Ag nanowires in search of high breathability and conductivity. However, textile-based electronics face the significant challenge of washability and resilience to environmental stresses. If embedded into clothing, the electronic components must be either easily removable before washed or able to withstand water exposure and mechanical stresses applied in common laundry machines. The longevity of the conductive fabric remains an open challenge, as washing the fabric will generally degrade the conductive coatings and thin conductive fibers.[198]

4.1.7. Biochemical Sensing

Wearable physiological monitoring devices have been an area of keen interest for personalized and mobile health applications, which has resulted in the development of noninvasive skin-mounted biochemical sensors[16,199–201] (Figure 16C). Biochemical sensors measure biomarkers such as glucose, lactic acid, cationic ions, and pH found in samples of bodily fluids such as sweat, tears, and saliva. Measuring the presence and quantity of these biomarkers can provide insight into various health and physical conditions, such as stress and diabetes.

Although biochemical sensors have not yet been utilized in VR/AR applications, these novel sensing inputs could revolutionize VR/AR through an unprecedented level of responsiveness to the user's physiological state. For example, with the ability to measure sweat production and composition, sophisticated user attributes such as physical exertion, emotional state, and stress level could be accomplished without the need for explicit input and interpretation from the user. The VR/AR environment can then be adjusted accordingly to stimulate the desired reaction from the user.

Biochemical sensors require an intrinsically soft substrate for intimate and conformal contact with the skin, which is especially critical for noninvasive sensing that measures skin secretions. Because the biomarkers are typically carried in a fluid, the substrate must also be porous to allow transport through to the active sensing mechanism. The active sensing layer typically consists of a bioreceptor that will react selectively with the desired biomarker and a physico-chemical transducer that generates the reaction into a useful signal (i.e., electrical, optical, etc.).[199] Common substrate materials include tattoo-film and hydrogels. Hydrogels are particularly attractive due to the compatibility with biochemical sensing mechanisms and high porosity.

However, a remaining challenge for biochemical sensors is accurate and real-time monitoring. For VR/AR integration, substantial collaboration across multiple disciplines to ensure accurate interpretation of the data, a framework for the simulated virtual world to respond appropriately, and further development of rapid, reliable, and continuous biochemical sensing mechanisms.

4.2. Pose Estimation

Pose estimation (6-DOF) is jointly accomplished with positional tracking (3-DOF) and orientation tracking (3-DOF). Positional tracking has been implemented with intrinsically soft strain sensing mechanisms.[205] In contrast, orientation tracking still requires rigid microelectromechanical systems (MEMS) components (e.g., inertial measurement units (IMU), accelerometers, gyroscopes, and magnetometers) and thus relies on the seamless integration of these microelectronics into a soft and stretchable circuit.

Much of the research efforts in soft sensing has focused on strain sensors due to the exceptionally compelling case for soft materials integration.[206] Strain sensors transduce mechanical deformation to electrical signals, and thus the inherent deformability of a soft material is very well-suited to this application. Although strain may not necessarily be the modality directly used for positional tracking, soft curvature, stretch, and bend sensors generally use the same fundamental sensing mechanisms and differ only in algorithmic interpretation. Therefore, soft curvature, stretch, and bend sensors will be considered synonymous with strain henceforth. Soft strain sensors typically have 1 DOF and are placed on the fingers, arms, and legs to track joint angles in order to infer position. Multiple strain sensors placed on the same appendage can be used to increase the DOF of the sensing system.

4.2.1. Soft Strain Sensors

A variety of soft strain sensing mechanisms have been developed, but the two types that are the best suited to wearable sensing applications are resistive sensors and capacitive sensors. These two sensing mechanisms enable the high flexibility and stretchability required for wearable applications, while having a relatively simple electrical interface. Key performance metrics for strain sensors include stretchability, linearity, and sensitivity (gauge factor = GF).

Resistive Sensing: Resistive sensors are commonly composed of an electrically conductive material embedded in a stretchable substrate. As strain is applied, the conductor undergoes microstructural deformations that results in a change in electrical resistance. Both the piezoresistivity of the material itself and modification to the geometric structure determine the magnitude of change in the electrical resistance as a function of strain. Frequently used conductive materials include carbon black,[207] Ag nanowires,[208] carbon nanotubes (CNT),[209] Au nanowires,[210] and graphene.[211] The stretchable substrates are typically silicone elastomers,[212] such as PDMS, Ecoflex, and Dragonskin. Liao et al.[213] introduced an ultrasensitive strain sensor fabricated from PDMS and Ag nanowires with a stretchability of 60% and an extraordinary GF of 150,000. Ha et al.[214] demonstrated a multidimensional resistive strain sensor that distinguishes strain along the *x*- and *y*- axes with a GF over 20 and stretchability of ≈60%. The sensor was fabricated from Ag nanowires on a stiffness variable substrate made of a stiff elastomer and a stretchable elastomer.

Capacitive Sensing: Capacitive sensors are made of a deformable dielectric layer placed between two compliant electrodes. As strain is applied, the distance between the electrodes decreases and the capacitance increases. Common dielectric materials include silicone elastomers, rubbers, and hydrogels, while common electrode materials include CNTs, graphene, and metallic nanowires.

Xu et al.[215] recently reported a capacitive strain sensor fabricated from a combination of ionic hydrogels and Ag nanofibers with stretchability up to 1000% and remarkable sensitivity (GF = 165). The strain sensor was mounted to the skin and was able to detect real-time arm and finger movements, breathing, speaking, blinking, smiling, and pulse. Kim et al.[216] introduced a capacitive strain sensor fabricated from Ag nanowires embedded in a PDMS substrate in an interdigitated pattern. The sensor achieved a GF of −2.0, no hysteresis behavior up to a strain of 15% and was used to detect finger and wrist motions. Bartlett

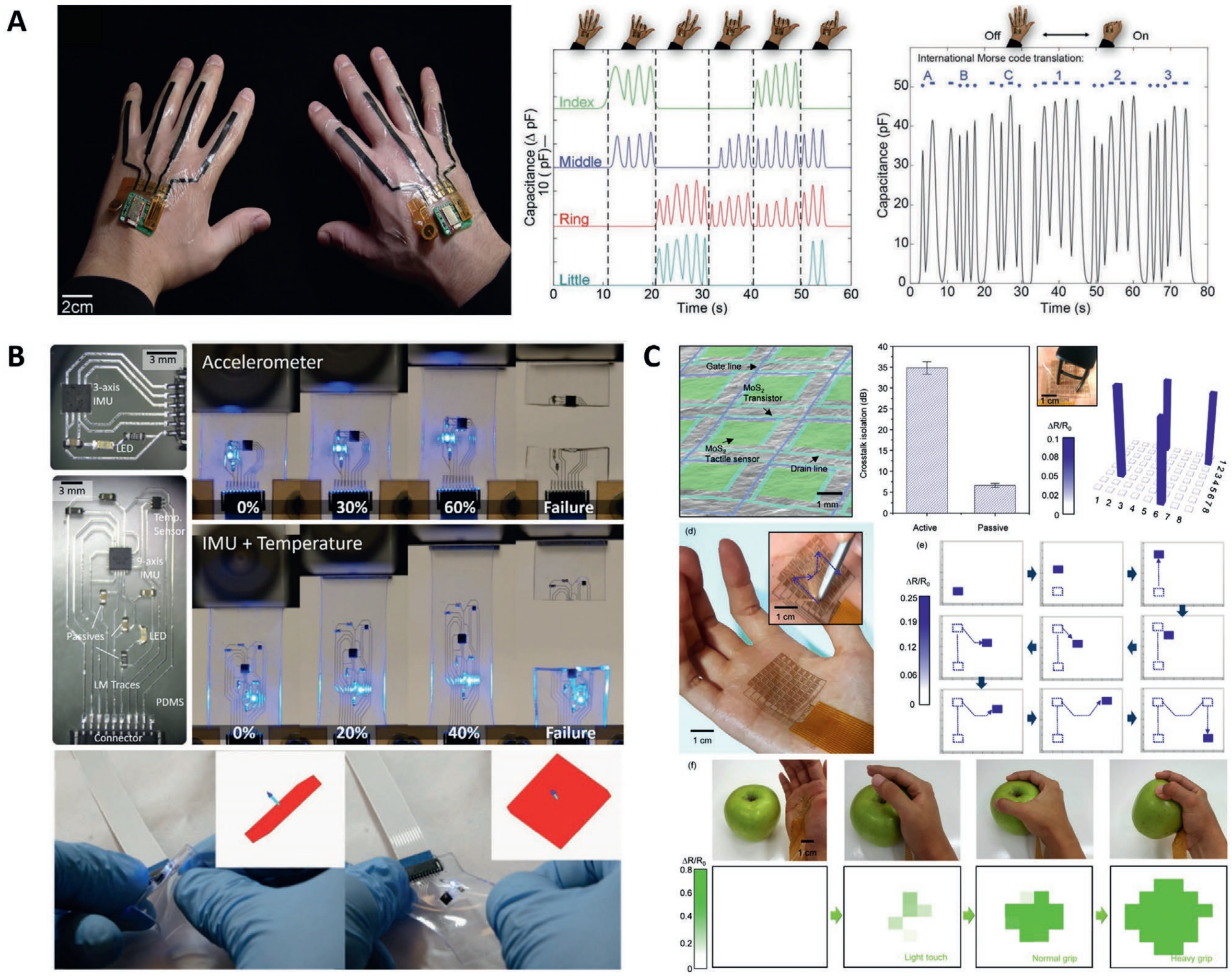

Figure 17. A) Finger pose recognition with soft capacitive strain sensors. Reproduced with permission.[202] Copyright 2016, Wiley-VCH. B) IMU and accelerometer integration with a liquid metal hybrid circuit. Adapted with permission.[203] Copyright 2018, Wiley-VCH. C) High resolution tactile sensing skin with transistor array. Reprinted with permission.[204] Copyright 2019, American Chemical Society.

et al.[202] (**Figure 17**A) demonstrated a rapid fabrication technique for capacitive strain sensors that uses off-the-shelf acrylic tapes (VHB 4905 as the insulator, eCAP 7850 as the conductor). Using a CO_2 laser cutter, the fabrication process produced 108 cm scale strain sensors in under 45 minutes with 100% yield and a variance of less than 2% across the batch of sensors.

Remaining Challenges: The advantages and disadvantages of capacitive strain sensors and resistive strain sensors are complementary to each other. Capacitive sensors tend to have a low gauge factor, but high linearity and low hysteresis. Resistive sensors tend to have a high gauge factor, but high hysteresis and nonlinearity. For further detail on soft strain sensors,[206] and[217] cover this topic in depth.

While research efforts have been intensely focused on the fabrication and characterization of novel soft strain sensors, the challenges for VR/AR integration are in data transmission and algorithm development. To provide sufficient resolution of the body, hands, and head, the numerous strain sensors required will need either wireless transceivers or stretchable and unobtrusive wiring to the main computing unit. In addition, pose estimation algorithm development for VR/AR has primarily focused on optical sensing methods. While basic pose estimation has been demonstrated in VR/AR with the introduction of these soft strain sensors, more extensive collaboration with computer scientists is required for widespread use of this technology.

4.2.2. IMU Integration

Accelerometers, gyroscopes, and magnetometers, or the combination of all three integrated in IMUs, are used for orientation sensing. IMUs used in VR/AR typically combine a 3 DOF gyroscope, 3 DOF accelerometer, and 3 DOF magnetometer for a total of 9 DOF.[218,219] However, a 9 DOF IMU would still only be capable of 3 DOF rotational tracking, and positional tracking would be required for the objective of 6 DOF in a virtual environment. Accelerometers measure linear acceleration, gyroscopes measure angular velocity, and magnetometers measure the strength of Earth's magnetic field. With sensor fusion of these three sensors integrated in an IMU, it is possible to measure the roll, pitch, and yaw of a moving object. Because there are not yet intrinsically soft versions to measure these modalities, orientation sensing requires hybrid sensing devices that combine rigid microelectronics with stretchable substrates and conductive interconnects.

However, the interface of these rigid microelectronics with soft materials presents a persistent challenge. Because of the large disparity in Young's moduli between the MEMS components and the soft substrate and conductive architecture, stress concentrations occur at the edges of where the MEMS component meets the soft material. These stress concentrations fundamentally limit the elasticity of the sensing device and lead to mechanical rupture or tearing in these regions. In addition, conventional MEMS sensors require metallic conductivity for proper functionality, which limit the types of soft conductive architectures that can be used for electrical interfacing.

One promising approach to reliably integrating IMUs in a soft stretchable circuit is to use liquid metal (LM) wiring embedded in a stretchable elastomer[203,220,221] (Figure 17B). The soft circuit fabrication method involves selectively wetting EGaIn to laser patterned Cu traces on PDMS and "soldering" the surface-mount IMU to the LM circuit with HCl vapor. This integration technique for IMUs was shown to be compatible with on-board signal processing and various other sensors in the same LM circuit and provided valid data used for robot decision-making. However, the soft stretchable IMU circuit is susceptible to failure from punctures to the thin encapsulating PDMS layer and the stress concentrations as discussed previously.

4.3. Tactile Sensing

Tactile sensing has become an essential input source in VR/AR because it enables intuitive, reliable, and high-precision interactions with the user interface. Soft tactile sensing has been an area of tremendous interest due to broad applications in robotics, prosthetics, e-skins, and human-computer interaction. Methods for pressure and contact detection use the same principles of resistive and capacitive sensing previously discussed for strain sensing. However, it is much more common to see implementations that involve conductive liquids (e.g. EGaIn) injected into microfluidic channels embedded in stretchable substrates.[222–224] As the microfluidic channels stretch or deform under applied pressure, the length of the liquid conductive trace is increased, which decreases the resistance. Another form of capacitive sensing that is very common in touchscreens capitalizes on the human body's ability to serve as an electrical conductor. This type of capacitive sensing typically consists of an insulator coated with a thin conductive layer. Touching the screen generates a change in the sensor's electrostatic field, which can be measured with capacitance. This form of capacitive sensing is almost ubiquitous in modern smartphone touchscreens, generally with glass as the insulator and iridium tin oxide as the conductive layer, and offers very high-resolution tactile inputs.

Because of the demand for high resolution and large area coverage, tactile sensors are often arranged in matrix form for use with multiplexed sampling to localize the applied force. However, significant challenges with high resolution and large area coverage for tactile sensing includes the large number of wires required for signal transduction, as well as the substantial data processing required for contact localization. Recent research efforts show promising progress with stretchable transistor arrays[204,225] (Figure 17C) and machine learning.[226]

Wearable tactile input devices impose additional challenges such as the potential for frequent accidental contact and the need to support a large range of applied pressures (1–100 kPa), which is standard for tactile interactions. Most high-resolution soft tactile contact sensors have not been developed for the range and magnitude of expected applied forces, and it remains an open challenge to find the best approach to address accidental contact from both an algorithmic and device design perspective. For human touch in particular, the capacitive sensing mechanism that relies on humans as conductors is effective at mitigating unintentional touch input from non-conductive objects but is still susceptible to self-contact.

5. Emerging Soft-Matter Technologies for Haptics

Soft actuation is a growing and dynamic field. Novel device concepts enabled by new high-performance materials lead to improved strain, speed, force and power density, and easier textile integration, while increasingly taking sustainability into account. Progress in haptics requires suitable hardware, an understanding of human perception, and human-machine interfaces. Soft materials intrinsically deliver low forces, so engineering solution need to be found. A link must be maintained between academic research on actuators, generally performed in engineering and physical science departments, and the development of emerging human machine interfaces, often carried out in computer science and social science departments. Integration is a major challenge for haptics, without which the forces cannot be effectively and safely transmitted from the actuator to the user. Integration is often overlooked in academia, yet essential for the user experience, comfort, and plays a preponderant role in user acceptance.

Power density, force density, and cycle life are important metrics for soft actuators: performance on par with, or exceeding, mammalian muscle is desired for compact wearable haptics. The exact force and displacement numbers for any haptic task are difficult to predict without user testing, given the large differences in perception thresholds and comfort levels between different users, but also because we fuse information from our different senses. When we see a red-hot virtual object, we expect to feel heat. When we touch a VR puppy, we expect to feel soft fur. This expectation can be exploited by the HMI designer to deliver immersive and convincing touch sensation while using a limited set of actuators. Creating convincing haptics is much easier when we control what the user sees and hears. We summarize here some promising technologies for wearable haptic feedback.

5.1. Fluidic Actuators

Fluidic actuators offer many advantages, provided the compressor can be removed. Kurumaya et al. reported McKibben inspired muscle fibers[227,228] that allowed for much better integration in exoskeletons than conventional McKibben muscles. These actuators are almost cable-like in form-factor, providing versatility for on-body or textile integration. They can be grouped in bundles to scale force depending on the task. By tuning device size (down to 1 mm inner diameter) and choice of elastomer, operation at pressures of 50 kPa are possible. Recent development in pumps that are soft, thin, and stretchable[229,230] pave a route to using fluidic devices using direct electrical actuation. Such soft pumps could make the complete fluidic haptic system soft and wearable. The pressure and the flow rate delivered by the soft pumps are sufficient for fluidic actuators to provide cutaneous and kinesthetic feedback, but lifetime must be improved. Finally, fluidic systems require tubing that can be fragile and complex when dealing with many wearable actuators. The development of 3D printing and new printing materials allows embedding these tubes inside the framework of the fluidic systems,[231,232] easing their design and integration.

5.2. Electrostatic Actuators

An effective and promising alternative to direct fluidic actuation is hydraulically amplified electrostatic devices, such as the HASEL and peano-HASEL actuators[134,135] for kinesthetic haptics and the HAXEL actuators for cutaneous feedback.[87] Using fluidic coupling enables softness and force transmission. Using electrostatic forces allows for very high energy density[233] and high speed, up to hundreds of hertz. Hydraulically amplified electrostatic devices offer freedom of design and scalability. HASEL actuators can be stacked to generate higher force and displacement.

Electrostatic (ES) clutches are an active area for variable stiffness. Recent progress on high force density ES clutches enables on-body use, blocking tens of newtons.[83,123,136,142] Their simple design eases their integration in soft kinesthetic systems. While they can only block motion, ES clutches could constitute an effective and low-power alternative to more complex actuator technologies.

5.3. Ultrasoft Actuators

Ultra-soft “feel-through” haptic devices are attracting growing interest as they are needed in AR in order to interact simultaneously with both virtual and real objects in the mixed reality world. This includes the Tacttoo electrostimulation device, which was presented several years ago.[47] DEAs, when engineered into 18 µm thick devices, allow mounting on fingertips, enabling, like Tacttoo, to feel real objects while being able to provide rich cutaneous feedback.[73]

5.4. Tactile Texture Actuators

An underexplored yet essential haptic mode of stimulation is skin stretch. This is used to sense slippage and object softness, as well as surface texture. Tactile texture was not discussed in this paper because it requires advanced cutaneous feedback devices that are not yet soft and wearable. Combining high frequency cutaneous actuators with the lateral movements of the finger on the actuator enables the reproduction of different surface friction.[234–236] The most common technologies for tactile texture are ultrasonic piezoelectric actuators and electro-adhesion actuators.[237–239] It would be interesting to make these technologies soft and wearable to provide texture feedback when holding virtual objects. This could help to differentiate virtual surfaces and enrich the virtual world. One promising path is the recent HAXEL actuators[87] that can generate in-plane motion, allowing lateral forces to be directly applied to fingertip or skin, providing a more realistic wearable haptic feeling than only normal forces or vibrotactile.

5.5. Electrostimulation

In principle, electrostimulation could provide complete haptic feedback by stimulating the desired nerves without stimulating undesired muscle activity. Using electrode patches on skin at multiple locations has been shown to provide cutaneous haptics[45,47,81,151] and kinesthetic haptics.[149,150] Portable electrostimulation devices using (non-implant) surface electrodes have been developed, but they are mainly used for fitness training and are unsuitable for haptics. User acceptance is yet to be determined.

6. Conclusions and Outlook

Despite tremendous progress in soft sensors over the past decades, full system-level implementations of soft wearables for VR/AR remains a challenge. This is likely a direct result of component-level innovations that academic research tends to focus on, making system-level integration an anomaly. Research efforts in soft electronics have yet to deliver devices that not only sense, but also process, fuse, and transmit data without dependency on bulky hardware. The vast majority of soft sensors are still reliant on external rigid components that prevent an entirely compliant and wearable system. Further progress in wireless technology is also required for unrestrained movement, as wireless sensors that rely on NFC still require close proximity to a bulky receiver.

There also needs to be continued progress on stretchable circuits that can interface with a VR/AR system without the need for cumbersome computing hardware or bulky interconnects. This challenge exists for soft circuits based on elastomers, tattoo-films, and textiles. Facile integration of soft technologies into the existing VR/AR ecosystem is a critical factor in widespread adoption of these advances. Further progress in MEMS for powerful yet micro-scale processors in tandem with the stiff-island technique for hybrid stretchable circuits may be a promising path forward.

For VR/AR applications, another challenge is the seamless integration of these soft sensors with haptic technologies for kinesthetic and tactile feedback. Wearable devices ideally have multifunctional capabilities to reduce the physical burden on the user and the process of donning and doffing. Rather than approaching on-body sensing and haptic feedback as independent objectives, it would be beneficial to implement multipurpose mechanisms. Some promising approaches to this include tactile displays that integrate both tactile sensing and feedback, embedded sensing and actuation, and rigidity tuning.

Beyond mechanical stimulation, we rely on temperature of objects to infer their thermal conductivity. This thermal feedback enables us to rapidly identify materials. Heating a haptic device using the Joule effect is easy. However, it is much harder to effectively cool down wearable devices. Most thermal haptics devices use fans, pipes or Peltier devices for cooling,[229,240–242] but the spatial accuracy is low and the response is slow. Combining thermal and mechanical haptics presents serious integration challenges.

Several new types of feedback may, in the future, be used to reinforce VR immersion[243–246] and complement haptic feedback. Such systems could use the sense of taste, for example. However, haptic feedback will remain key for accurate manipulation tasks.

Last, power sources and energy storage will continue to be a challenge for wearable devices. There have been research efforts in on-body sensing and haptic feedback devices toward low power consumption, but there must also be progress in wearable energy storage and harvesting. Future generations of VR/AR will require soft batteries that can cover large surfaces of the body without impairing motion. Alternatively, energy harvesting from body motion, heat, friction, and contact should be developed and incorporated into the VR/AR system.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

augmented reality, haptics, sensing, soft electronics, soft robotics, virtual reality, wearable computing

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