A Survey on Haptic Technologies for Mobile Augmented Reality

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Augmented reality (AR) applications have gained much research and industry attention. Moreover, the mobile counterpart—mobile augmented reality (MAR) is one of the most explosive growth areas for AR applications in the mobile environment (e.g., smartphones). The technical improvements in the hardware of smartphones, tablets, and smart-glasses provide an advantage for the wide use of mobile AR in the real world and experience these AR applications anywhere. However, the mobile nature of MAR applications can limit users' interaction capabilities, such as input and haptic feedback. In this survey, we analyze current research issues in the area of human-computer interaction for haptic technologies in MAR scenarios. The survey first presents human sensing capabilities and their applicability in AR applications. We classify haptic devices into two groups according to the triggered sense: *cutaneous/tactile*: touch, active surfaces, and mid-air; *kinesthetic*: manipulandum, grasp, and exoskeleton. Due to MAR applications' mobile capabilities, we mainly focus our study on wearable haptic devices for each category and their AR possibilities. To conclude, we discuss the future paths that haptic feedback should follow for MAR applications and their challenges.

CCS Concepts: • **Human-centered computing → Mixed/augmented reality**; *Haptic devices*; Mobile devices

Additional Key Words and Phrases: Mobile augmented reality, haptic devices, haptic feedback, interactions

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1 INTRODUCTION

Mobile augmented reality (MAR) has attracted interest from both industry and academia over the past decade due to the improvements in hardware and the widespread adoption of smartphones and tablets [38]. The mobile nature of MAR applications makes sense for AR applications so people can experience them anywhere, such as museums (information), malls (shops ads), and streets (directions). Mobile devices such as smartphones can provide MAR applications a powerful, less expensive, and rapid adoption platform [38]. MAR applications display virtual and real

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objects in a physical environment, are interactive in real-time, display an augmented view, and are mobile. We can differentiate two types of MAR applications between *mobile* and *portable* [38]. These two types correspond to the wearability and how obvious is the technology to others. For example, some smart-glasses are more intrusive and obvious (Microsoft HoloLens) than others (Google Glass).

MAR applications tend to run on mobile or wearable devices such as smartphones, tablets, and smart-glasses. These devices provide user's mobility, but at the cost of constrained resources such as computing power and energy. These constraints of mobile devices limit the performance and design of AR applications in the mobile environment. Microsoft,[1] Facebook,[2] and Apple[3] have shown their interest in AR applications and they believe in the viability of this technology. The current trend of mobile AR applications has affected the mobile market (e.g., Pokemon GO[4]).

Another main constraint of mobile devices for MAR applications is the limited interaction space they provide. The input methods used range from wearable controllers (e.g., Myo armband[5]) to mid-air interactions such as hand gesture recognition or gaze control (e.g., Microsoft HoloLens). For example, smart-glasses can offer a small, lightweight package to render the augmented view, but the input interactions of users can be restricted to gestures or swipes in the glasses frame (as Google Glass does). Moreover, the haptic feedback of these mobile devices is even more restricted and motivates us to write this survey about current haptic technologies for MAR applications.

Although input interactions have improved during the past few years due to advances in computer vision, tracking, and image capturing devices such as cameras and infrared devices, the feedback provided by such environments is still primitive [162]. Feedback appears, for example, like images (visual feedback), sounds (sound feedback), or vibrations (vibrotactile feedback). They are aimed to provide a better UX and give the user a sense of agency (SA) [91]. The latter, SA, is related to initiating, executing, and controlling users' actions. Haptic technology allows users to experience touch and kinesthetic sensations in virtual environments. As an example, users can move virtual objects with their bare hands or use a controller and "feel" (e.g., surface, weight) the virtual object while they do it. However, the physical characteristics of these virtual objects, such as texture, size, and weight, cannot be perceived without increasing the complexity of the ecosystem. In the field of **human-computer interaction (HCI)**, we can find different fields of haptics [40]. *Machine haptics* involves the design and development of mechanical devices that can render haptic sensations in the human body. *Computer haptics* focuses on developing algorithms and software to render the stimuli for haptic sensations. *Multimedia haptics* brings the sense of "touch" in augmented reality applications. The haptic devices are mainly characterized by the degree of freedom (number of independent axes to exert force or torque) and the refresh rate. For example, the vibration motor of smartphones creates smooth haptic interactions while typing by producing nondirectional forces with refresh rates of at least 1 kHz.

The increasing computing and sensing capabilities of mobile devices, such as smartphones and wearables, and affordable Internet enable mobile augmented reality possibilities in real scenarios. Following Reference [26], we can define MAR as "an augmented reality technology that combines real and virtual objects in a physical environment and is interactive in real-time, and it displays the augmented view on a mobile device [11]." In this survey, we define users' interactions as:

[1] https://web.archive.org/web/20210116055500/https://www.microsoft.com/en-us/hololens/.
[2] https://web.archive.org/web/20180511105443/https://developers.facebook.com/products/ar-studio.
[3] https://web.archive.org/web/20201106145326/https://www.apple.com/hk/en/augmented-reality/.
[4] https://web.archive.org/web/20200426175341/http://www.pokemongo.com/.
[5] https://web.archive.org/web/20181015145422/https://www.myo.com/.

- *Input interactions* correspond to interactions with virtual objects that appear in the MAR environment, for example, using hand gestures to move a virtual object (e.g., hand controller and wearables).
- *Output interactions* display the application's output (augmented current users' view) on a mobile screen (e.g., smartphone, smart-glass) and other feedback devices (e.g., vibroactuators, LEDs). These stimuli usually display sound, vibration, or visual feedback.

Haptic feedback is a multidisciplinary field that includes several areas such as machine, multimedia, and computer haptics [40]. Despite recent developments and progress in the commercialization of haptic devices, incorporating this feedback in virtual environments is still far from perfect. Haptic feedback can have different mobile applications in the real world, for example: *data visualization*, where haptic can guide visually impaired in the real world (augmented maps); *rehabilitation*, application of forces to injured organs to regain strength; *e-commerce*, allowing the feeling of products (e.g., touch, temperature); *education*, the use of haptics combined with MAR applications improve the learning experience [145]; *entertainment*, mobile gaming already is using haptic feedback such as vibration to render physical touch with the virtual environment (e.g., car crash).

One of the major shortcomings of several (e.g., commercial) haptic devices, even wearables, is their large size and weight [40]. MAR scenarios limit the size of haptic devices. The mobile characteristics of these environments are the focus of our related work on wearable devices. However, there exist myriad developments regarding AR without size/weight limitations, such as active surfaces (Section 5) or manipulandum devices (Section 6). The motivation of this survey is to provide an in-depth literature on haptic devices feasible for MAR applications. Several surveys analyze the current state of haptics and applications in AR environments [41, 67, 90, 115, 130, 162]. We believe that haptic technology has shown the potential to provide tangibility to HCI and, more specifically, MAR applications. Our survey can help HCI and designers improve MAR applications' experiences providing more realistic experiences when users interact with the augmented physical world.

The rest of the article is organized as follows: In Section 2, we present the concepts of our systematic research method. Then, we include a description of input 3 and output 4 interactions in MAR environments. Next, we present several representative haptic devices regarding the involved senses, tactile 5 (cutaneous, active surfaces, mid-air) and kinesthetic 6 (manipulandum, grasping, exoskeleton). In Section 7, we describe several representative works that study the effects of haptic feedback and how to develop it for MAR applications. In Section 8, we mention the current commercial haptic feedback devices on the market. Finally, we present the challenges and future directions for MAR haptic devices (Section 9) before we conclude the survey (Section 10).

2 RESEARCH METHOD

This article focuses on haptic feedback devices and techniques that can be portable enough for users to carry them without much cumbersome. We also describe several input interactions for mobile AR applications to give readers a notion of the current limitations with input interactions, as these interactions are usually related to haptic feedback. For example, when a user points to an augmented object using smart-glasses, subtle haptic feedback can be rendered to confirm the input interaction (sense of agency). The academic research databases were defined following the previously obtained from a conducted exploratory analysis. The following keywords were considered: "haptic feedback," "mobile haptic device," "mobile haptic interface," "mobile augmented reality," "haptic interfaces." We use these keywords to search in the databases ACM Digital Library, IEEE Xplore, Springer, and Science Direct. These keywords were used for searching in the title, abstract,

Table 1. Inclusion and Exclusion Criteria

Criterion	Description
I_1	Studies that address the design, develop, or partial prototype of a haptic interface that is portable for MAR applications
I_2	Studies that describe system or evaluation methods to improve the haptic feedback in MAR applications
I_3	Studies that describe multimodal feedback that is suitable for mobile AR applications
I_4	Studies that include the network and rendering challenges of haptic feedback in mobile environments
E_1	Studies that address the design of haptic feedback not suitable for MAR applications (e.g., too heavy)
E_2	Duplicate studies will be disregarded

and authors' keywords at the beginning of the document. We present in Table 1 the inclusion and exclusion criteria for selection of the related work of interest. We analyze articles with one or more inclusion criteria and remove them from the analysis if presented in at least one of the exclusion criteria.

2.1 Global Analysis of Articles Included

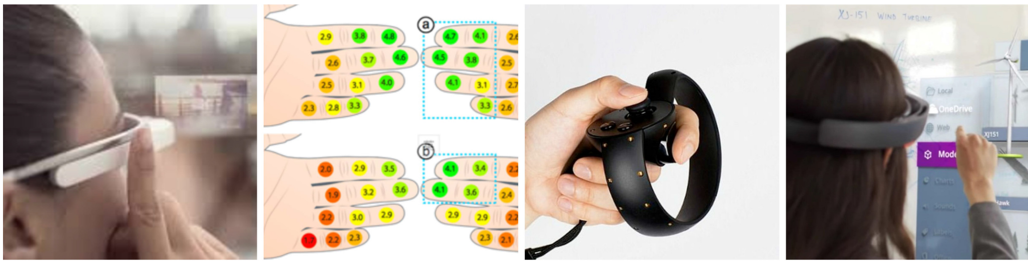
All the included studies in this survey article discuss or present innovative haptic feedback techniques or devices that can be used in MAR applications. We also included some papers related to input interactions in mobile AR applications to provide a brief overview of the interaction (input/output) challenges that designers, researchers, and haptic devices have to overcome in MAR applications. For example, some of the presented haptic feedback works with input interactions, such as text input. Most of the studies are related to cutaneous haptic feedback related to the tactile sensation on the users' skin. The devices that render such tactile stimuli (e.g., vibration) are usually more portable than the kinesthetic counterparts (display forces on the natural degrees of freedom of the body). The presented survey also includes some related work with visual and audio feedback as it is one of the most used non-haptic feedback and can be used to provide pseudo-haptic feedback or multimodal (e.g., visual + haptic) feedback in MAR applications. We also include in this survey novel approaches to render haptic feedback (e.g., thermal stimuli, passive tactile feedback) due to the portability of the proposed devices.

3 INPUT INTERACTIONS

In this section, we describe the main approaches for input interactions with wearable devices. The chosen input technique will also affect [61], in many cases, the options to provide feedback to users. For example, if users interact with a companion device to introduce inputs, then the feedback can be rendered on the companion device. In MAR applications, user input interactions depend on the physical device. Figure 1 depicts different input interfaces for MAR applications. We can observe how the input interaction method can limit the possibilities for haptic feedback. For example, the Oculus controller input method in Figure 1 can provide haptic feedback using vibration stimuli.

3.1 On-device Touch Interfaces

On-device touch interaction means that users can input on a touch-sensitive surface embedded in the device. For example, Google Glass has a touchpad integrated into the spectacle frame, where users' swipe gestures select different menu items displayed on the glasses (Figure 1(a)).



(a) Google Glass. (b) Thumb-to-finger. (c) Oculus controller. (d) HoloLens.

Fig. 1. Wearable input device examples. In (b), proposed device by Reference [57].

3.2 External Touch Devices

Many MAR systems require an external device (e.g., controller) as an input interface. We can see examples in commercial devices such as Oculus Rift controller[6] or on-body wearable devices [77] (see Figure 1(c). The on-body wearable devices utilize human skin as interaction surfaces. The use of external devices as input interfaces open more possibilities for feedback approaches. Current MAR controllers use vibration as the primary haptic feedback.[7]

3.3 Touchless Inputs

Touchless interactions provide great capabilities not only for finger/hand tracking approaches to move a cursor but for gesture recognition to invoke actions. In touchless interfaces, users make gestural mid-air inputs to interact with the MAR system. We can group these interfaces as follows:

- *(i) hands-free interactions*, where the movement of the head or gaze (e.g., HoloLens) and voice recognition (Google Glass) are the interface approaches.
- *(ii) freehand interactions*, where users interact with the system using hand gestures or fingers in mid-air (e.g., Leap Motion). We can further include two sub-groups in this category: *(a)*, worn-based, where the user wears a device to tracks their hand/finger movements (e.g., glove); *(b)*, camera-based, the most common approach to track users hand/finger movements.

For these systems, the feedback that can be provided depends on the input interface technique followed. The primary device's audio and visual feedback will still be provided, which melds the physical and virtual world together (e.g., smartphone, smart-glasses, head-mounted displays).

4 OUTPUT INTERACTIONS

Feedback is an important source of communication when users interface with machines. This flow of information allows interfaces to communicate to users the changes made by users or the gap between actual and intended performance. In this section, we describe the three channels to provide feedback according to the stimuli render on users: *(i)* visual and audio, and (*ii*) haptic feedback. In this section, we first provide a general view of visual and audio feedback approaches in output interactions.

[6] https://web.archive.org/web/20210101175607/https://www.oculus.com/rift/.
[7] https://web.archive.org/web/20200921200207/https://www.vive.com/eu/accessory/controller/.

4.1 Visual and Audio Feedback

Visual feedback and user actions have been strongly related since the first GUI computer system. The visual feedback design, which allows interfaces or devices to react to the user's interactions, is elemental to enable them to give an appropriate response to those actions. We perceive actions that produce sound in our daily lives. For example, beeps resulting from a keypress or clang while dropping an object on the floor. In Reference [107], the authors study the egocentric nature of the action-sound associations (i.e., *gesture*-sound association). This question is critical in AR environments. The egocentric action-sound nature shows that users can learn that certain gestures create different types of sounds. Besides, audio feedback can modify a user's perception of kinesthetic force in AR environments (i.e., change the virtual arm length or movement) [24]. The use of these non-haptics to enhance the UX is demonstrated in several papers [69, 117], and they form the baseline case for feedback communication in several systems.

In MAR applications the pseudo-haptic is commonly used to simulate haptic properties such as stiffness [123], virtual spring [74], object weighting [139], and redirected tool-mediated manipulation [154] by offering supplementary visual cues. Jang and Lee [65] explore the feedback possibilities of pseudo-haptic feedback. Through experimental analysis, the authors [65] demonstrate that pseudo-haptics can render virtual stiffness by modulating visual cues. Moreover, in AR applications, the addition of haptic feedback does not mean suppressing other audio-visual feedback channels; on the contrary, the best approach is to combine the three sense channels. However, due to the different nature of sensory receptors (i.e., audio, visual, touch, and proprioception), the combination of this feedback complicates the design, feasibility, and implementation of these types of feedback. Due to our firm reliance on our visual and auditory senses, there can be situations when haptic feedback does not provide any improvement [3].

4.2 Haptic Feedback

Haptic devices enable human-computer interaction through touch and external forces. Unlike traditional interfaces such as displays and sound devices, haptic devices render mechanical signals (i.e., external force), stimulating human touch and kinesthetic channels. This field includes robotics, experimental psychology, biology, computer science, system and control, and others. Due to the recent popularity of AR systems, haptic devices have received considerable attention within the research community and entertainment industry (i.e., film and gaming). Visual and auditory channels are not enough to provide a perfect UX in AR ecosystems. There are needs to feel (i.e., touch and move) objects in the virtual world analogously to the physical world. Haptic devices appear in multiple MAR application scenarios:

- *Feedback reinforcement of GUIs*, such as buttons menus confirmation (of action) feedback
- *Games*, to simulate collisions, or movement in games
- *Science and data analysis*, to display confirmation and weights of virtual objects
- *Arts and creation*, to generate innovative simulations in audio/visual communication channels
- *Telerobotics and Teleoperation*, to provide high quality feedback for manual controllers
- *Education and training*, to simulate training, and innovative passive learning methods
- *Rehabilitation*, to improve the living conditions for visually impaired people

Tactile and kinesthetic sensations are the mode operations of haptic feedback. **Tactile/cutaneous**, skin-related sensations; **Kinesthesia/proprioception/force** is related to the sensory organs located in muscles and joints (Table 2). The tactile receptors vary tremendously with the parts of the body they cover. "Proprioceptive, or kinesthetic perception refers to the awareness

Table 2. Haptic Device Classification

Group	Type	Characteristics
Cutaneous/ Tactile	Vibration	Haptic feedback using vibroactuators on the user's skin (i.e., fingertip)
	Skin deformation	Haptic feedback using skin displacement haptic devices
	Active surfaces	Communication of large-scale forces, shapes, and tactile information
	Mid-air	Tactile feedback without contact (i.e., air, ultrasound devices)
Kinesthetic	Manipulandum	Grounded devices with 3 to 6 Degrees of Freedom (DoF)
	Grasp	Simulates grasping interactions of the user's hand or fingers
	Exoskeleton	Grounded on the body, provide forces on the natural DoF of the body

Table 3. Most Representative Cutaneous Haptic Devices: Where PoA Corresponds to the Point of Application

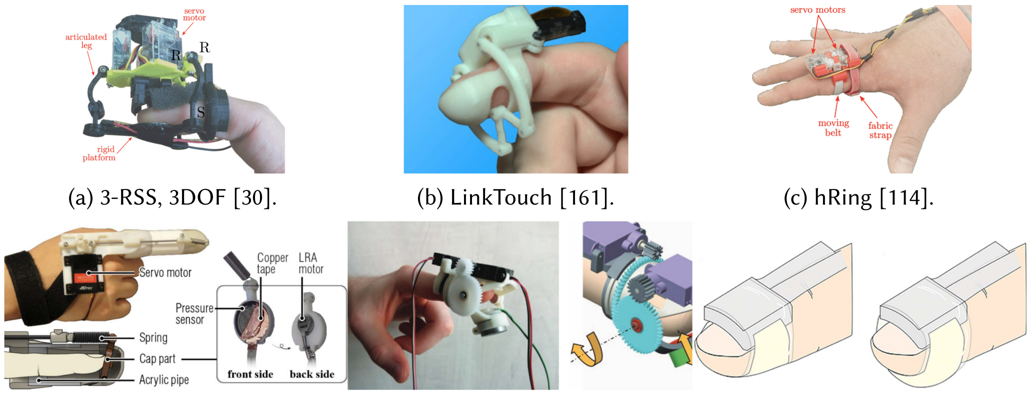
Type	Device	Type of Stimuli	PoA	Characteristics
Wearable	Vibration band [22]	Vibration	Arm wrist	Three vibration motors on a wristband device
	3 RRS [28]	Skin pressure	Fingertip	3DoFs fingertip surface render device
	HapThimble [70]	Pressure and vibration	Fingertip	Fingertip haptic thimble device for pushing virtual buttons
	Haptic Thimble [45]	Contact and vibration in different fingertip locations	Fingertip	Fingertip voicecoil actuator
	Skin displacement [39]	Skin displacement	Fingertips	Skin displacement device to render pull sensations
	Skin wristband [30]	Skin displacement	Arm wrist	Wristband skin stretch device
	Fingersight [56]	Vibration	Finger	Finger camera-haptic vibration device
	BrushTouch [155]	Skin friction	Arm wrist	Wristband skin brushing device
External Devices	Smartphone vibration device [55]	Vibration	Smartphone	Vibroactuator on the smartphone

of one's body state and includes the position, velocity, and force supplied by the muscles" [5]. Together, kinesthetic and cutaneous sensations are "fundamental to manipulation and locomotion" [7] of virtual objects in AR applications.

A haptic interface can include one or several actuators such as vibroactuators, manipulandum, and sensors to measure and react to user interactions. Furthermore, the combination of haptic feedback can improve the overall experience, as it achieves the most realistic scenario. In the following sections, we describe the different approaches and devices in more detail to render haptic feedback in MAR applications.

5 TACTILE, CUTANEOUS FEEDBACK DEVICES

This section enumerates the most novel and important mobile haptic devices that use the cutaneous sensory system to provide haptic feedback in MAR applications. We group the devices by user contact interaction (Table 2), as we think it makes it more natural for the MAR haptic feedback designer to find the most appropriate wearable device according to the feedback they want to provide. For example, when the MAR application renders a texture, the use of active surfaces (section 5.2.3) is preferred due to their high resolution and precise feedback. However, the designs can hinder the portability of some proposed systems. The cutaneous/tactile approach is currently one of the most used haptic feedback devices. We classify the cutaneous devices in categories (see representative examples in Table 3): *vibration devices*, *skin deformation*, and *mid-air devices*.



(a) 3-RSS, 3DOF [30]. (b) LinkTouch [161]. (c) hRing [114].

(d) HapThimble [70]. (e) Haptic Thimble [45]. (f) HydroRing [52].

Fig. 2. Wearable fingertip haptic devices.

5.1 Vibration Devices

The miniaturization and simple design of vibration motors make them a cost-effective and feasible haptic technique to implement. However, vibration patterns are difficult to distinguish in many situations, such as walking, and offer limited information (i.e., duration, strength, and vibration pattern) [22].

5.1.1 Finger-based Wearable Devices. Finger-based devices have been relatively well studied in several works, as they provide a small device design and use the user's fingertip to transmit the haptic data accurately. In MAR applications, fingers are usually the standard interface to interact with AR interfaces. These wearable devices include vibroactuators and other mechanisms to provide sensations akin to pressing buttons in users' fingertips.

Haptic Thimble [45] offers tactile fingertip cues in a 3DoF wearable finger device. The fingertip voice-coil actuator can rotate around a user's finger to provide a more accurate surface rendering. HapThimble [70] is a wearable device that provides vibrotactile, "pseudo-force finger sensing to mimic the physical buttons based on force-penetration for virtual screens." HapThimble can display haptic feedback for mid-air interaction with virtual touchscreen devices.

Authors in Reference [119] propose a vibrotactile ring worn on the proximal phalanx of the index finger. The design of the device is similar to hRing [114], but with different tactile stimuli. The proposed device provides a less intrusive wearable design for AR interaction tasks than other fingertip-based wearables that limit grabbing physical objects. The vibrotactile ring consists of a vibroactuator and a Bluetooth module to communicate with a smartphone or HoloLens.

FingerSight [56] is a novel fingertip device for acquiring visual information through haptic channels. The visual environment information is translated into haptic stimuli. The authors' device aims to provide assistive technologies for the visually impaired. The device consists of a camera capturing device, and two speaker-based vibrators (Figure 4(d)). The authors develop software to detect changes in the background image color (color boundaries) for the experimental testing, so the system generates vibrations. Similarly, the authors in Reference [141] propose a device that allows users to scan the environment using a finger to locate specific targets (i.e., vibrates when the targeted object is found).

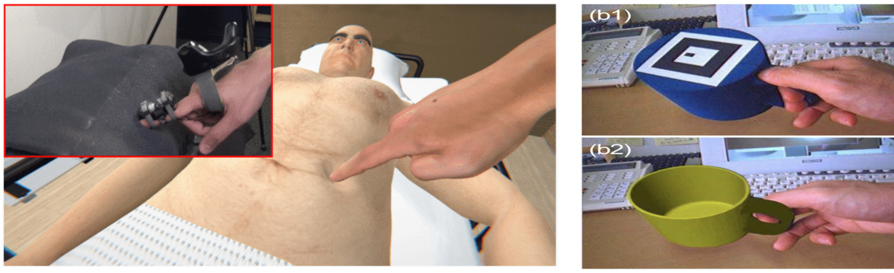
These finger-wearable devices can be used together with other haptic modalities (e.g., skin deformation). Authors in Reference [29] present a combination of a cutaneous fingertip (3DoF) and a kinesthetic finger (1DoF) wearable haptic device. The device consists of a fingertip cutaneous module (servomotors) that uses a mobile platform for stimuli and a grounded exoskeleton on the proximal phalanx to provide kinesthetic force. The addition of kinesthetic feedback improves performance and UX in different tasks (e.g., assisted palpation, interaction with virtual objects such as a hammer). The authors in Reference [136] propose using a multi-finger vibroactuator device to render the intersection of virtual surfaces such as walls and users' avatar hands (e.g., physical boundaries).

Contrary to the current limitations of previous fingertip devices regarding the ability to touch physical objects, the authors in Reference [158] engineered a foldable haptic device. The proposed foldable device is worn on the users' fingernail and renders touch sensations (i.e., pressure and vibrations) when a user presses a virtual object. When not in use, the device keeps the fingerpad (including a vibroactuator) on the fingernail, freeing the users' fingertips to interact with real-world objects. The proposed foldable device can motivate future device designs towards similar approaches. For example, new types of finger-based wearable devices optimize their form-factor and make them more suitable for MAR scenarios (e.g., freeing users to touch/interact with real-world objects).

5.1.2 Other Body-based Wearable Devices. Small wearable devices such as wrist bands provide an alternative for sensations in the hands. These wearable devices offer several advantages: *(i)* reasonable design space; *(ii)* allow hands-free so users can manipulate the physical world, and *(iii)* socially acceptable [123]. In Reference [123], the authors propose a multisensory squeeze and vibrotactile wrist haptics for augmented reality. The proposed device renders evenly squeeze forces around the wrist and includes six radially spaced vibroactuators. The authors present a proof-of-concept application using a combination of squeezes, vibration, and pseudo-haptic effects (e.g., when touching a virtual button). In Reference [22], the authors present an assistive multi-vibrotactile wristband that provides color information using vibration encoding for color-blind users. The authors study different vibration motor displacements and the best configuration based on the user's perception accuracy. Besides, they analyze the best encoding vibration pattern to be easily and quickly recognizable. The vibration pattern dimensionality can enable better and higher bandwidth of information transmission.

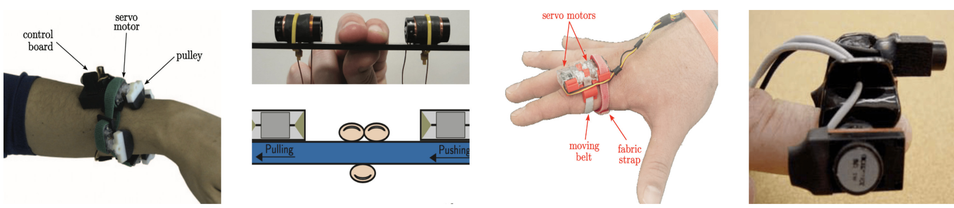
The authors in Reference [99] propose an affordable smart glove that monitors users' finger movements using IMU and vibroactuators placed on finger joints for human-robot interactions and AR applications. In Reference [142], the authors present a haptic collar prototype that consists of a neck-worn device with vibrotactile actuators. The authors evaluate the system for guidance applications, where the actuators encode eight directions for guidance. This wearable device shows the possibilities of wearables in MAR applications such as AR maps.

5.1.3 Tangible External Device. Tangible objects can be used in MAR applications to enhance haptic information of virtual objects. However, these tangible objects render passive haptic feedback, which limits the rendering of richer mechanical properties. The combination of timely active haptic feedback (e.g., vibration) together with the tangible objects can improve the display of varying friction, stiffness, and shape sensations of virtual objects [138]. In Salazar et al. [138], the authors propose using a finger-based haptic device and a tangible object to render different bumps and holes in the tangible object. The device timely renders the haptic sensations to simulate the different shape sensations. The combination of haptic and passive interactions in virtual environments opens a new way of providing simple, unobtrusive, and inexpensive haptic feedback. Lee and Park [78] propose a graspable and touchable interface based on 3D foam for AR scenarios. They use a 3D foam as a passive object that is tangible, traceable, and rendered in an AR application (Figure 3(b)). The idea of passive and tangible objects can enable grasping/touching sensations and the possibility of moving a virtual-complex object on the real one in MAR applications.



(a) Tangible stiffness [138]. (b) Tactile foam [78].

Fig. 3. Tangible shape changing devices.



(a) Stretch [30]. (b) Asymmetric [39]. (c) hRing [114]. (d) FingerSight [56].

Fig. 4. Wearable skin displacement haptic devices. In (b), the two voicecoil actuators simulate the asymmetric vibration on user's fingers.

5.2 Skin Deformation Devices

These wearable devices display displacement (e.g., stretching, asymmetric skin displacement) on the user's skin. These devices are another important source of cutaneous haptic feedback. Furthermore, the location of these devices, sometimes on the user's wrist, unlocks the fingertip mobility limitations of the finger-wearable devices. Therefore, depending on the stimuli to be rendered and the MAR application scenario, these approaches can offer a better design. The wearability of cutaneous haptic devices has focused mainly on vibration stimuli due to the reduced size and portability of their actuators [128]. However, finger-based devices such as the presented in Reference [128] where a platform-based fingertip actuator deforms the skin of the users' finger show the possibilities of other stimuli in users' skin while being wearable.

5.2.1 Finger-based Wearable Devices. In Reference [39], the authors design an asymmetric ungrounded vibration device to simulate pulling sensations through asymmetric skin displacement, (Figure 4(b)). *eShiver* [102] is a haptic force feedback device that renders sheer force on the fingertip. *eShiver* operation is very similar to *ShiverPAD* [34]—both devices eShiver [102] and ShiverPAD [34] use a type of electroadhesion as a friction switch. However, the wearability of the proposed device is lacking. The haptic feedback needs to focus on the stimuli and the correct measure of force for different actions and provide accurate estimations and haptic responses.

Pacchierotti et al. [114] claim the lack of wearable haptic feedback devices besides the vibroactuator approaches. In their paper [114], the authors present an innovative wearable haptic device that consists of a fabric belt attached to the users' finger skin and two servo motors to control the tightness of the belt (Figure 4(c)). The presented 2DoF cutaneous device provides normal and sheer stimuli to the user's proximal phalanx finger. Besides, the placement of the device helps to free the user's fingertips and be able to interact with other hand-tracking devices such as Leap Motion.[8] Bianchi et al. [18] presents a similar fabric-based wearable tactile display stretching the state of a fabric that covers the user's finger. Following the same stretching skin stimuli as the previous two devices, HydroRing [52] uses fluids to provide the tactile stimuli on the users' fingertips. The systems use the fluid flow on the fingertips to render pressure (finger squeeze) and vibration (different pumping frequency of the fluid). The current prototype has room for more portable versions than can be used with MAR applications.

Other haptic devices use platforms under users' fingertips to render different forces according to the platform's position and pressure on the fingertip. In Reference [161], the authors design a 2DoF force feedback fingertip device, (Figure 2(b)). The device can represent contact conditions with a realistic directional force vector feedback. This device displays forces on the user's fingertip pressing the skin. Chinello et al. [28] present a 3DoF wearable cutaneous device for the fingertip (Figure 2(a)). Compared to other devices, the device proposed in the paper enables 3DoF due to its three-legged articulated design. This design will be followed in other papers and studies, as it offers good surface rendering performance in a small package. Spagnoletti et al. [149] propose a combined platform and vibroactuator under the fingertip to render accurate textures of virtual objects. The device can display different object materials rendering different pressure and vibrations on the user's fingertip.

In Reference [90], the authors evaluate two wearable cutaneous devices, "3-RRS fingertip" [113] (see Figure 2) and hRing [114], for the fingers in three different AR tasks such as writing, picking, and moving a virtual object, such as a ball and cardboard (i.e., balancing a virtual ball on a piece of cardboard). The first wearable device, "3-RRS fingertip," presented by Reference [30], uses servo motors to move a rigid platform positioned under the fingertip. While in the writing and grabbing task there was no significant difference, the 3-RSS outperformed the hRing [114] in the balancing task. However, the hRing, due to its construction, is preferred by the users, as it leaves the fingerprints free for touch interactions in the physical world.

Despite the mentioned haptic devices for skin deformation, there are still limited proposed devices that focus on the wearability of these haptic devices [96]. The results provided in Reference [96] show that providing haptic feedback through wearable devices increases the comfort and performance of MAR applications significantly.

All the aforementioned devices can be commonly used to confirm users' actions, such as pointing, selecting, or clicking virtual or augmented objects in MAR interfaces. The nature of the finger-based feedback makes these devices feasible for mobile environments due to their portability.

5.2.2 Other Body-based Wearable Devices. Chinello et al. [30] present a novel cutaneous device capable of rendering skin stretch stimuli, shown in Figure 4(a). The device consists of four cylindrical rotating end-effectors that enable four movements on the user's wrist/arm: clockwise rotation, counter-clockwise rotation, vertical motion, and horizontal motion. The experiment demonstrates that providing skin stretch feedback benefits task completion times and errors. Furthermore, the participants find the device very useful for navigation cues. This proposed device features different skin sensations without reducing user mobility, as in fingertip devices. Pezent et al. [123] propose a wrist-worn haptic device that renders squeeze and vibrotactile feedback (six radial spaced around the wrist). The combination of skin deformation and vibrotactile feedback allows the device to display evenly distributed squeeze forces. The proposed system is used in Reference [123] to render realistic virtual buttons employing squeeze, vibration, and pseudo-haptics.

[8] https://www.leapmotion.com/.

Table 4. Most Distinctive Active Surfaces Haptic Devices

Type	Device	Type of Stimuli	Point of Application	Characteristics
Pin Array	Smartphone pin array [66]	Touch pressure	Finger	Pin array to deploy on smartphone sides
	Portable tactile display [163]	Touch pressure	Finger	Pin array using shape memory alloy materials
Finger-based	Normal-/TextureTouch [17]	Pressure	Fingertip	Fingertip device to render surfaces and textures

(a) SMA [163]. (b) NormalTouch. (c) TextureTouch.

Fig. 5. Wearable fingertip active surface devices [17].

In Reference [155], the authors propose an innovative wearable tactile stimulation feedback device through brushing. The device consists of multiple wrist-worn haptic interfaces that brush the user's skin instead of conventional vibrotactile wristband devices. The proposed device requires a greater degree of calibration in comparison to vibrotactile devices. Their experimental study shows that certain cues using brushing are better recognized than a vibration.

5.2.3 Active Surfaces. Active surfaces feature the best performance for rendering surfaces with great resolution and accuracy, see Table 4 for representative devices. However, many of these devices lack portability due to the haptic actuators' design (i.e., vacuum air-based, big-sized pin array actuators). In this survey, we focus on appropriate devices for MAR applications in terms of size and portability.

Pin array stiff: Velazquez et al. [163] present a low-cost, compact, and lightweight portable tactile display that can render surface and texture information. The device consists of an array of 8×8 pins based on **shape memory alloy (SMA)** following approaches proposed in References [64, 80] with non-portable pin array actuators. The shape memory alloy materials are capable of recovering a predetermined shape upon heating. The device uses this property on a spring to create a linear actuator (see Figure 5(a)). However, owing to its nature, this material does not offer accurate control, and the frequency response is affected.

In Reference [68], the authors propose PinPad, a pin array device capable of fast and high-resolution output using a 40×25 array of actuated pins. PinPad offers a better spatial and temporal resolution in comparison to the state-of-the-art pin array devices. The experiment results show that the tactile feedback provided by PinPad enables high-resolution stimuli on the fingers. Besides, their portability, resolution, and accuracy can be included as texture/surface render devices for MAR applications.

Pin array flexible: Following a similar pin-based technique, authors in Reference [122] propose a novel flexible haptic interface using magnetic actuators for each pin. The array of pins can be placed in soft materials (due to its flexibility between pins) and allows for localized haptic and tactile feedback. In Reference [81], authors propose a thin mm-scale transducer surface to generate dynamic mechanical stimulus on the users' skin. When a voltage is applied, the actuator changes its shape (e.g., bump). The square-based actuator can display several different stimuli in the fingertip (e.g., clockwise, front/back, left/right, up/down) according to the shear force applied (e.g., left, right, fully, and no actuated). The flexibility of the material used and the small size allow these devices to be worn on different body parts, such as the forearm, with minimum additional weight.

Pin array embedded in other devices: Active surfaces can be embedded in other devices such as controllers where the pin-arrays display force on the user's skin. Benko et al. [17] propose two devices for texture rendering. The first device (*NormalTouch*) consists of a hand-held controller and an active tiltable and extrudable platform similar to the cutaneous devices. The other proposed device (*TextureTouch*) is a hand-held controller that renders 3D surfaces using a 4×4 array of actuated pins (see Figure 5). *NormalTouch* renders the surface of the virtual object, moving the platform according to the virtual object surface and the user's movement. *TextureTouch* works similarly to the previous device. However, it can display fine-grained surface structures. Both devices are tracked, and the hand is rendered in the virtual environment. The experiment results show that both devices provide good accuracy and low error in the tracing paths and fidelity assessment tasks. The proposed devices are finger-based, which implies wearability and makes them useful surfaces/textures of virtual objects rendering haptic devices for the MAR ecosystem. Jang et al. [66] propose a novel haptic-edged display based on a linear touch pin array around a smartphone screen. The device provides an innovative haptic interaction and can also be used as a haptic notification method (i.e., changing the pin array placement). This approach can be used as a feasible haptic feedback implementation for MAR applications on smartphones.

5.3 Mid-air Devices

The main limitation of the aforementioned devices corresponds to the user's free movement that some devices apply. Mid-air devices appear as a good solution for touchless interactions, but the size and weight of many current devices do not make them a good wearable solution for MAR applications (Table 5). Mid-air haptic feedback such as ultrasound devices can statistically improve the performance of the interactions of users [72].

5.3.1 *Ultrasonic/ultrasound Haptic Devices.*

These are the most distinguishable mid-air devices, and they have been studied in many related works. Moreover, due to the actuators' size, it is possible to wear some of these mid-air devices on the body. Therefore, they are a good candidate if we want to provide touchless interactions for MAR applications. UltraHaptics [23] is a well-known and innovative mid-air ultrasonic haptic feedback. It provides multi-point haptic feedback on a user's skin. During the specific phase, known as amplitude and frequency configuration, the device can render different focal points and generates surfaces on the user's skin through ultrasound waves. This device will push forward many other related works on mid-air surfaces and stand up as one of the main mid-air haptic devices.

SkinHaptics [150] is a wearable ultrasound hand-focused device. The device consists of an ultrasound array that attaches to the user's hand and provides tactile feedback in and through the hand. The experiment setup comprises a three-by-four ultrasound array matrix to simulate a numeric keypad. One of the limitations of this feedback technique is the sensations perceived by participants on the skin and deeper inside the hand spread from the focus points.

5.3.2 *Air-based Mid-air Interfaces.*

Push air to the user's hand to render the haptic feedback sensation. Usually, these interfaces render virtual surfaces roughly, as they lack good resolution and accuracy. Sodhi et al. [148] present an innovative device for mid-air tactile interactions based on air-jet approaches. Their device uses compressed air pressure to stimulate the user's skin and

Table 5. Representative Mid-air Haptic Devices

Type	Device	Type of Stimuli	Point of Application	Characteristics
Ultrasound	SkinHaptics [150]	Mid-air skin pressure	Hand	Ultrasound haptic device
	UltraHaptics [23]	Mid-air skin pressure	Hand	Ultrasound haptic device
Air-jet	Aireal [148]	Mid-air skin pressure	Hand	Vortex-based
Laser-based	LaserStroke [76]	Thermal	Hand	Laser device to render surface on user's palm
	Laser and acoustic [110]	Thermal + mid-air skin pressure	Hand	Laser+Ultrasound device for better accuracy and haptic perception
Other	Electric [151]	Electrostatic	Fingertip	Electric arcs for the haptic feedback

(a) Ultrahaptics [23]. (b) Aireal vortex [148]. (c) Electric arc [151].

Fig. 6. Wearable mid-air haptic devices.

stimulate the touch sensation (Figure 6(b)). The device can track the user's hand (3D depth-camera) and actuate accurately on the user's skin. The device provides a long-distance range and easy implementation and deployment. However, due to the vortex nature of the feedback, it cannot provide high-resolution tactile sensations. VacuumTouch [48] consists of a touch screen surface that sucks the air between its surface and the area where users can touch with their fingers. The authors propose several designs such as "suction button," "suction slider," and "suction dial" that can be implemented. This paper introduces a haptic interface based on an attractive force sensation using previously sucked air on the user's finger. In Reference [6], the authors discuss the current work on mid-air haptic feedback. Two tactile feedback methods are described in the paper: air-jet and acoustic radiation pressure. The former uses either direct compressed air methods and vortex-based methods [148] to simulate the tactile sensation. The latter uses ultrasound to produce tactile sensations [23]. The advantages of air-jet against ultrasound are its easy implementation and coverage. However, air-jet implementations have several disadvantages, such as size, low spatial resolution (i.e., big focal point), and slower transfer. Both methods offer advantages but not a complete solution to interact freely with AR applications. Authors in Reference [140] propose a novel placement on the user's forehead for a phased ultrasonic array for unobtrusive and portability of ultrasound feedback. Although the proposed system in Reference [140] targets VR applications, the location of the array can open new research and developments in the MAR ecosystem when the users wear smart-glasses to visualize the AR interfaces.

Laser approaches are noted owing to the accuracy and precision of their deployed systems. They are usually combined with other mid-air solutions such as ultrasound to provide the best mid-air approach. However, due to the nature of laser devices, they can be dangerous to use in mobile environments, and the presented work illustrates the combination of several mid-air devices. LaserStroke [76] stimulates the user's tactile senses using a laser that irradiates the user's palm, which is covered with an elastic material (latex glove). The authors demonstrate the capabilities and usefulness of the laser as a tactile stimulator. The thermal changes on the user's palm provide a sequence of tactile stimuli. LaserStroke is an interactive mid-air system that tracks the user's hand with Leap Motion and irradiates laser beams on the user's palm to provide tactile stimuli. Ochiai et al. [110] present a new approach to render "haptic images" combining femtosecond-laser light fields and ultrasonic acoustic actuators. The former provides an accurate tactile perception. The latter produces continuous and less fine-grained contact between the laser tactile perceptions. The novel combination of both mid-air fields offers the advantages of both approaches and hence, a better performance than ultrasonic or laser stimulation separately.

Finally, the addition of other feedback cues such as visual and audio can improve mid-air interactions. The authors in Reference [44] propose the addition of peripheral visual cues in an ultrasound haptic device to improve hand gesture recognition (the visual cues guide the user's hand to the correct position). In Reference [112] the authors include auditory feedback together with an ultrasound device to provide multi-sensory feedback and increase the perceived pleasantness of the interactions.

5.3.3 Electrostatic-based Mid-air. In Reference [16], the authors control the electrostatic friction between a touch surface and the user's finger using electrovibration to control. The proposed system can render different textures on the full touch display; the stimulations cannot be local to a particular point. Spelmezan et al. [151] demonstrate a novel mid-air method using touchable electric arcs on the finger while hovering (Figure 6(c)). The device uses high-voltage arcs (safe to touch) that discharge when the finger is near the device's surface to stimulate finger sensing. The authors also consider the dangers and the security measures that the prototype should satisfy. The proposed device can be extended to multiple keys in the future.

5.4 Magnetic-based Mid-air

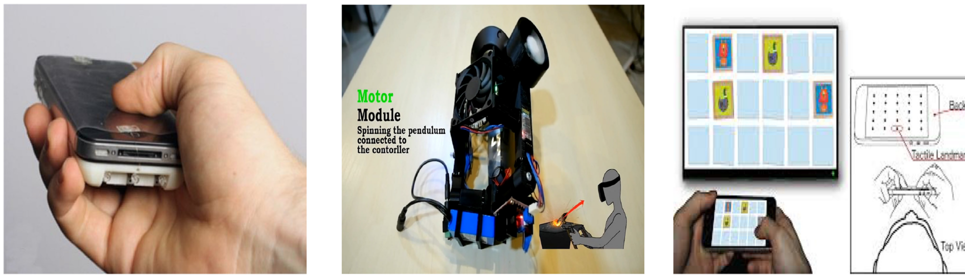
Magnetic tracking, sensing, and feedback allow wearable devices such as smartwatches to provide fingertip haptic feedback (vibrations) when the user interacts with the screen [8, 94]. Ashbrook et al. [8] design an input device in the shape of a finger-ring, which allows users input gestures such as click and selection by simply touching or twisting the ring. The ring device is a metal ring (passive) that works in conjunction with a wrist-worn bracelet to track the users' interactions with the ring magnetically. In Reference [94] the authors propose the use of a magnetometer array to track the magnet installed on the user's fingernail and coil (installed in the smartwatch), so the user can interact with the device without touching (or occluding) the objects on the screen.

Mid-air haptic stimuli can also open new interaction methods for the visually impaired, such as presenting Braille characters by using ultrasounds [118]. The addition of a mid-air haptic improves the attractiveness and pleasure of MAR applications [137]. Moreover, mid-air haptic devices feature the main advantages of not covering the user's skin. Therefore, they enable many possibilities for mobility, free movement, and touch experiences in the real world.

5.5 Other Tactile Approaches

In this section, we describe different haptic feedback approaches that require an external device such as smartphones to display the stimuli.

5.5.1 Tactile Feedback. Roudaut et al. [135] propose a foil overlaid touchscreen to enable spatial gesture outputs. The transparent foil device can provide up to a 1 cm motion range on a smartphone (Figure 7(a)). The gesture output is non-visual and non-auditory, only tactile as it moves (motors for X-Y coordinates) the transparent foil along with the user's finger. Results demonstrate that these 2-D gesture outputs are easy to learn by transfer. The novel approach of moving the touch (i.e., touchscreen) surface on the user's fingertips enables surface rendering capabilities on a portable device. We can think of different speed movements to render virtual objects moving in a MAR application.



(a) [135]. (b) [27]. (c) [37].

Fig. 7. External tactile feedback devices.

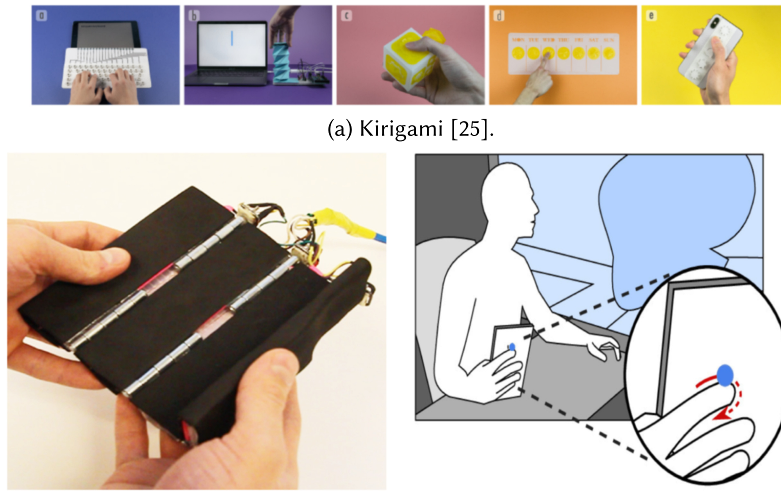
Sword of Elements (SoEs) [27] is an attachable augmented reality vibrotactile feedback device (Figure 7(b)). It is an attachable solution to enhance player experience in VR environments. The device is attached to the HTC VIVE controller[9] and features a motor module, an electronic fan (i.e., VR wind) and a thermal module. In Reference [144], the authors extend the dimension of the vibroactuator on smartphones using four actuators to provide two-dimensional vibrotactile capabilities. The smartphone displays the vibrotactile flows to enable dynamic phantom sensations. The 2D vibrotactile flows can display sensations in both 2D and circles in both directions.

5.5.2 Finger-based Feedback. In Reference [37] the authors introduce a passive back-of-device tactile landmark to estimate finger location without seeing the screen's device (Figure 7(c)). The authors propose several landmark designs and study the performance with the base case (no landmarks). The experiment results show that the back-of-device tactile landmarks outperform the base case. Hudin et al. [58] present a system that renders independent tactile stimuli to multiple fingers without tracking their positions on a transparent surface. The tactile rendering approach is based on wave time-reversal focusing, which "enables the spatial and temporal mechanical waves rendering using multiple transducers to create an impulse response." The system can provide multiple foci simultaneously and, therefore, multitouch tactile simulation.

5.5.3 Shape Changing Devices. Another less-traditional approach to enable cutaneous haptic feedback is the use of kirigami and origami-based structure [25]. The different types of geometric structures (see Figure 8(a)) can render a different set of haptic feedback such as bouncing, bistable, and rotational. These structures can be tuned through different geometric parameters to provide different force feedback properties. The hand-foldable material of the proposed kirigami and origami structures make them suitable for mobile environments, as they can be folded when necessary. HaptoBend is a shape-changing input device that provides passive feedback [93]. The proposed device (Figure 8(b)) can provide realistic feedback of 2D plane-like shapes (e.g., book, smartphone) and 3D shapes (e.g., torch) of virtual objects. The results of the gesture elicitation study show the effectiveness of this shape-changing device to render passive feedback of virtual objects.

The use of configurable tactile elements has been proposed in several works [47, 156]. These elements can emerge from a hidden reservoir when needed to provide haptic feedback in different spaces and with different stimuli (e.g., poking, vibration). Figure 8(c) depicts a reconfigurable ferromagnetic marble that is embedded in the back of a handheld device such as a smartphone [47]. This reconfigurable haptic can be shaped in different diameters and provide two types of feedback poking and vibration in different locations of the periphery of the distal phalanx. Results

[9] https://web.archive.org/web/20201108125748/https://www.vive.com/us/accessory/controller/.



(a) Kirigami [25].

(b) HaptoBend [93]. (c) Pulp [47].

Fig. 8. External tactile feedback devices.

show that participants can perceive up to five peripheral zones on the finger pulp for poking and vibration feedback and five different locomotive patterns around their finger (e.g., the clockwise motion of the marble). Koo et al. [71] develop a flexible tactile display that stimulates human skin and features softness and flexibility. They demonstrate the tactile, haptic display as a fingertip haptic device. The device's flexibility is one of the key features and enables adaptable wearables for cutaneous feedback in other parts of the body. The tactile display uses a dielectric elastomer actuator, which changes its thickness based on the applied voltage. However, the device requires a high voltage to work, and its low bandwidth can hinder the applicability of this device.

5.6 Other Tactile Approaches

5.6.1 Thermal Feedback. Although most of the haptic devices presented here are based on vibrotactile and pressure sensations, thermal feedback can provide novel immersive experiences in MAR applications [88]. Authors in Reference [88] propose a wearable and modular thermal feedback system that can provide warm and cold stimuli in users' bodies. The system consists of an armband with several Peltier modules that users can wear on their body, such as forearm, waist, or legs (see Figure 9). The thermal feedback can display navigation information or provide enhanced notifications (e.g., thermal feedback and system notification).

6 KINESTHETIC FEEDBACK DEVICES

In this section, we describe the different kinesthetic haptic approaches we can consider during MAR applications' design and development. Kinesthetic devices display forces or motions usually through a grounded tool, while *manipulandum* devices are not usually portable enough to consider in these scenarios. However, *grasping* haptic devices and *exoskeletons* (e.g., haptic gloves) include some wearable devices that can be used in the MAR ecosystem.

6.1 Manipulandum

A manipulandum is a haptic device that renders the virtual forces using grounded systems with different DOFs, depending on the device's characteristics and feedback, see Table 6 for representa-

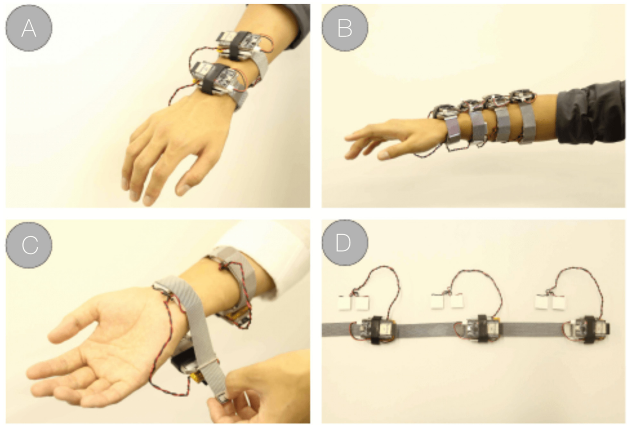


Fig. 9. Thermal feedback [88].

Table 6. Representative Manipulandum Haptic Devices

Type	Device	Type of Stimuli	Point of Application	Characteristics
Grounded	Haplet [46]	Force	Finger/Hand	Portable manipulandum

tive devices. The nature of manipulandum (i.e., grounded device) makes the wearability of these devices difficult and less feasible than other MAR devices.

Haplet [46] is a portable haptic device that features different feedback approaches such as visual, force, and tactile. The device has a transparent robotic arm with a vibroactuator at the tip (Figure 10(a)). The device can be attached to any laptop and smartphone display. The device is also limited in its DoF but is an affordable device that provides useful feedback for rendering textures. Authors in Reference [92] continue the *Haplet* idea with 3D-printed open-source hardware. The system design follows the manipulandum portable idea, but the authors include different designs that can be attached to the main *Haplet-like* device.

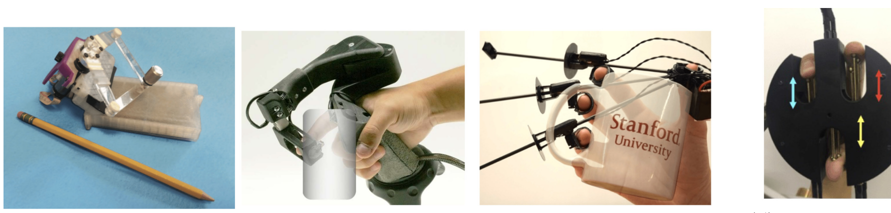
6.2 Grasp Devices

A grasp action in the virtual world enables users interactions between virtual objects and the user's hands. Users can then push, pull, and move virtual objects as they would in the physical world, see Table 7. For example, holding a glass requires a haptic device to render force or vibration on the fingertips. Furthermore, the gravity forces while holding an object can be displayed using these grasping haptic devices. Ungrounded devices present several advantages regarding wearability and feasibility to use them in MAR applications. The devices presented in Reference [31] show the possibilities of ungrounded haptic devices designed to stimulated kinesthetic pad oppositions grip forces for grasping virtual objects. Although the presented devices are focused on VR applications, the device's portability makes it suitable for MAR scenarios.

Minamizawa et al. [98] propose a device to present a virtual object's weight. The device consists of two servos that move a belt surrounding the user's fingertip. When the two motors spin in the same direction, the belt applies a tangential force over the user's fingertip, depicted in Figure 2(c). According to the motors' spin, users can perceive the weight of virtual objects (i.e., two devices for each index and thumb fingers) while grasping. *Wolverine* [32] is a portable wearable haptic device designed to allow users to grasp rigid virtual objects. The authors created a light and low-cost device, which renders force between the user's thumb and the three other fingers (Figure 10(c)). Handa et al. [53] create a haptic display that renders virtual objects' shapes, hardness,

Table 7. Representative Grasp Haptic Devices

Type	Device	Type of Stimuli	Point of Application	Characteristics
Grounded	Grasp + PHANToM [104]	Force-opposition	Hand	Grounded grasping device
Finger-based	Wolverine [32]	Force-opposition	Finger	Finger object grasping device
	3D Grasping	Force-opposition [53]	Fingertips	3D grasping device for 3 fingertips
	Tangential force [98]	Sking stretch	Finger	Finger belt, skin stretch
	CLAW [33]	Force and vibration	Hand and finger	Controller for grasping virtual object, touching virtual surfaces, and triggering



(a) Haplet device [46]. (b) Grasp [33]. (c) Wolverine [32]. (d) 3D grasping device [53].

Fig. 10. Manipulandum and grasping devices.

and textures. The proposed multi-fingered haptic 3D shape display simulates grasping actions using three fingers (Figure 10(d)). The device uses external linear actuators to activate the nine spheres within the device. This article provides an innovative device to render surfaces and simulate the user's grasping actions. CLAW [33] (Figure 10(b)) is a handheld controller that renders force in the hand and vibration in the fingertip (e.g., grasping and touching virtual devices).

6.3 Exoskeleton Devices

Exoskeleton devices are worn by a user (attached to the body). Hence, designers must decide on the importance of the user's mobility while using the device and the nature of the feedback to be rendered (Table 8). These haptic devices provide a force on the natural DoF of the body. Depending on the device's feedback, the size, weight, and complexity could vary.

Haptic gloves are seen as a feasible and lightweight approach among exoskeleton-wearable devices. These gloves allow users to pick up, grab, and feel virtual objects. In the past decade companies have developed haptic glove devices such as *Cybergrasp*[10] and Rutgers Master II [21]. One of the issues with these devices is related to the stability of haptic feedback and safety, as many of them use pneumatic/hydraulic actuators. The slow reaction time of this mechanical/fluid feedback can also hinder the overall UX.

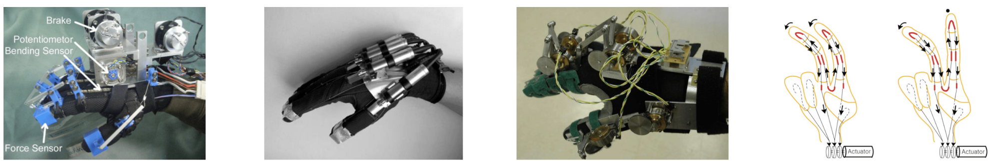
Due to the high DoF number of a human hand, haptic glove devices can focus on particular interaction approaches such as grasping, touching, pulling. To simplify the device design and provide better haptic feedback, designers need to consider the haptic feedback scenarios. The actuator placement can also restrict the user's hand movements, and the device design should be considered for mobile environments such as streets and shops. Furthermore, the haptic interface complexity can make the design and implementation of the actuators and their size and weight.

In Reference [73], the authors present a virtual glove to recreate the **"Simple Test for Evaluation Hand Function" (STEF)**. Compared with other grounded devices such as *manipulandums*,

[10] http://www.cyberglovesystems.com/cybergrasp/.

Table 8. Representative Exoskeleton Haptic Devices

Type	Device	Type of Stimuli	Point of Application	Author/Reference	Characteristics
Gloves	Rutgers Master II	Force	Hand	[21]	Glove mechanical haptic device
	Smart glove	Force	Hand	[106]	Fluid-based actuators
	Jointless glove	Force	Hand	[62]	Wire-based glove



(a) VR-STEF [73]. (b) MR-Fluid [106]. (c) MR-Mechanic [19]. (d) Jointless [62].

Fig. 11. Exoskeleton devices.

this prototype is cheaper and simpler to set up. Electromagnetic brakes generate the rendered force, and the force is transmitted to the fingers by the wire-pulley system (see Figure 11(a)). This passive force display glove system aims to help during the rehabilitation of stroke patients. *Smart glove* [106] is a glove that renders haptic feedback on the user's fingertips. The device uses fluid-based (magneto-rheological) actuators and flexible link mechanisms to transmit force to the user's fingertips (see Figure 11(b)). The MR fluid actuator mechanism activates when a magnetic field, by an external current, is applied. The device provides a better reaction time for the haptic feedback than other pneumatic/hydraulic actuators due to the use of MR fluids. In Reference [19], the authors continue the MR fluid actuator approach to develop a compact haptic glove device (Figure 11(c)). In Reference [62], the authors propose a miniature jointless structure in a hand exoskeleton. With a jointless design, the device avoids conventional pin joint structure issues and enables the actuator's compactness. The device uses two wires as tendons to simulate extension and flexion; each pair of wires are embedded inside a glove (Figure 11(d)). The device aims to help stroke patients with their rehabilitation.

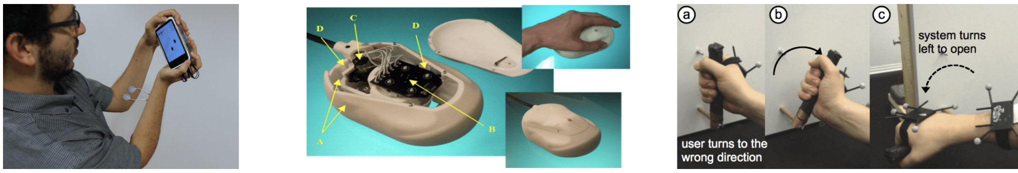
Fang et al. [42] propose an innovative worn and self-contained system that renders forces on users' hands via individual joints and retractable wires that can be programmatically locked. The proposed system is lightweight, low-cost, and suitable due to its wearability in MAR scenarios.

6.4 Other Kinesthetic Approaches

In this section, we describe several systems that do not fit in the mentioned groups but still offer potential approaches for MAR applications.

6.4.1 Electro Muscle Stimulation (EMS). EMS has been considered in several works [83, 84] to display force feedback. The portability and autonomy [83] of these electronic devices make them a strong candidate for MAR applications. However, the rendered force on users' muscles lacks continuity and can be violent in some scenarios [83]. For example, *Affordance++* [85] allows the users to actuate with physical objects and show how the movement should be. The authors propose *affordance++*, an EMS device to enable object-user dynamic communication (Figure 12(c)). Although EMS can be sharp and strong for mobile scenarios, the concept of object-behavior dynamic communication can be instrumental in MAR environments.

6.4.2 External Device. In Reference [129], the authors present a touchscreen-based haptic system that features kinesthetic force feedback (Figure 12(b)). The device provides static friction to simulate virtual constraints such as boundaries, area-of-effect fields, and paths. The experiments



(a) EMS. (b) Mouse haptic [129]. (c) Affordance++.

Fig. 12. Grasping devices.

demonstrate these haptic functions in a virtual maze and walls. The device aims to provide rehabilitation for upper limb stroke patients as it engages patients with haptic feedback. Haptic simulation of contours, boundaries, and textures of virtual objects is an important topic that AR/MAR applications need to integrate to provide a full interaction and better UX.

6.5 Pseudo-haptic and Muscle Tension

As mentioned in the previous section, pseudo-haptics use simulates illusory haptic feedback without providing actual haptic stimuli. Authors in Reference [134] propose a novel system combining pseudo-haptic feedback with the additional input modality of muscle tension (provided by an EMG wearable device, Myo armband). The addition of muscle tension as input allows users to feel different sensations such as different objects weight by using pseudo-haptic feedback. This approach allows simple wearable EMG to measure muscle contractions and can be implemented easily in MAR applications. Moreover, the concept of enhancing pseudo-haptic feedback with the additional input of muscle tension opens possibilities for future MAR applications to provide haptic feedback in terms of muscle tension (e.g., lifting a heavy object).

7 STIMULI AND PERCEPTION STUDIES

In this section, we describe several representative works that study the effects of haptic feedback on users' perceptions. According to the scenario, we enumerate different modes, systems, evaluations, and guidelines to develop similar haptic feedback (e.g., forces to use or appropriate feedback channels according to the scenario) in the MAR ecosystem.

7.1 User Experience with Haptic Feedback

Haptic feedback improves the user experience of MAR applications using tactile and kinesthetic sensations on users. As within visual [108] and audio feedback [87], tactile sensations produce different emotional responses. In Reference [165], the authors study the emotional responses of tactile icons. They evaluate the different responses according to four physical parameters of tactile feedback: amplitude, frequency, duration, and envelope. The authors use the **valence-arousal (V-A)** space to quantify the emotions [127]. The paper presents the response to tactile feedback using a vibrotactile actuator attached to the back of a smartphone. The results show that amplitude (i.e., perceived intensity) and duration have similar emotional responses. Therefore, tactile feedback needs to consider the emotional responses that can arise [109].

Papetti et al. [120] study the effect of vibrations when the fingertip is pressing a button. Many works have focused on vibrotactile thresholds without considering the effects of applied forces in the tactile sensation. One key insight from the experiment results is that vibrotactile sensitivity depends on applying pressure with the fingertips. Therefore, the active forces should be taken into consideration when designing vibrotactile feedback approaches. In Reference [9], the authors illustrate with several experiments on how the dynamics of vibrotactile actuators change as a function of the body attachment. As with many wearable tactile displays, the tactors attached to the skin can vary the user's perception (i.e., attenuation), depending on their location.

7.2 Cutaneous Feedback

Pacchierotti et al. [113] present an innovative approach to remote cutaneous interaction methods. This approach works with any haptic fingertip device. The proposed algorithm maps the remotely sensed data to the motor or actuators inside the haptic device. The model can sense and remotely render the haptic sensations in 3DoF scenarios. However, the algorithm has some limitations, such as the vibration perception against the user's applied forces, as it only renders the remotely sensed data, not the current situation on the user's side.

7.3 Vibration Stimuli

Vibration sensations can be even more challenging in mobile environments, as the users' movements (e.g., walking) can reduce the effectiveness of haptic stimuli. One-dimensional vibration transmission has been studied since the phantom sensations in Reference [4]. The authors study the information transmission on the skin along through the location of vibration sensors. The results of the experiments show that the phantom sensation can display information with a low learning curve. Hoggan et al. [55] report their experimental insights into the relationship and benefits of audio and tactile icons to optimize information transmission. This study demonstrates that the dimensions of the vibration patterns [55] (i.e., tempo/rate, duration, strength) enable more resolution for haptic information transmission. Although, as the previous study [159], it depends on the scenario and the user's environment. The resolution of these solutions should adapt to the conditions of the scenario, as MAR applications are usually run in the wild, such as streets. Previous studies have focused on vibration intensity and duration along with perceived stimulus. Blum et al. [20] propose the addition of accelerometer data to improve haptic feedback of vibration actuators. For example, if the user is running, then the vibration will be more intense than when the user is still. The addition of other surrounding information to provide better haptics according to the situation will improve the haptic feedback perception.

7.3.1 Estimation of Stimuli Forces. In Reference [101], the authors propose a method to estimate fingertip tactile force in actions involving grasping objects. They use a custom sensing glove to estimate the contact force on the fingertip. HACHIStack [49] is an innovative system that can estimate the contact time in the touchscreen of objects approaching a touchscreen. This sensing method provides the estimation of the approaching velocity and reduces touch latency experienced with current touch screens.

Textures rendering using haptic devices open several challenges regarding the forces to display, the accuracy of the stimuli, and fidelity of the rendered forces (e.g., friction) [97, 132]. In Reference [97], authors present a technique to render textures on a tactile display. The authors measure a series of fingertip swipe movements across different textures and store the data as spatial friction maps. The proposed method parametrizes the stochastic friction patterns in a 202-parameter model. Rekik et al. [132] study the importance of surface haptic techniques to render real textures. They focus on two major approaches: **Surface Haptic Object (SHO)**, based on the finger position, and **Surface Haptic Texture (SHT)**, based on finger velocity. Then, they propose a new rendering technique called **Localized Haptic Texture (LHT)**, based on the elementary tactile information that is rendered on display, *taxel*. The device to render the texture's friction is a tactile tablet that uses ultrasonic vibration to regulate the friction between the user's finger and the touchscreen. Extensive experiments demonstrate that LHT improves the tactile rendering quality over SHO and SHT.

7.3.2 Mid-air Stimuli. Israr et al. [63] propose *Stereohaptics*: "a haptic interaction toolkit for tangible virtual experiences." They aim to provide a framework and ultrasonic haptic devices to create, edit, and render rich dynamic haptic using audio-based devices. Nakamura and Yamamoto [2016] propose a contact pad that can emulate the sensation of softness. The haptic display provides lateral force feedback and softness rendering with electroadhesion using contact pads on the screens. The device also improves UX on displays, but it is limited to pushing and lateral force feedback. In Reference [10], the authors introduce passive haptic *retargeting* feedback, using dynamically aligning physical and virtual objects using our vision system (hacking human perception). The paper demonstrates three approaches that use dynamic remapping and body alignment to reuse passive haptics of the same physical objects across multiple virtual objects. The paper focuses on VR, passive haptics, and dynamic remapping, which could be useful in future AR/MAR applications.

7.4 Kinesthetic

An important aspect of these grasping actions is the fidelity between the rendering of virtual objects and the user's hand pose. Suppose the system aims to achieve great UX, the haptic feedback has to be displayed accordingly to the hand's position. *Hand Ons* [60] is a real-time adaptive animation interface for animating contact and precision manipulations of virtual objects with haptic feedback. The system provides contact and force information of virtual objects. Therefore, the haptic feedback can enhance control and interaction with virtual objects.

Meli et al. [95] present a technique called *sensory subtraction* to substitute the haptic force with cutaneous stimuli. Therefore, the device can emulate haptic force on the user's skin with kinesthetic and cutaneous devices. The proposed device aims to outperform other sensory approaches such as substitution techniques (i.e., substituting kinesthetic forces for other haptic feedback). This paper demonstrates the benefits of hybrid haptic feedback approaches such as kinesthetic plus cutaneous (i.e., subtraction of haptic feedback instead of feedback replacement).

Pfeiffer et al. [124] compare vibration haptic and EMS feedback devices in free-hand interaction scenarios. They conducted several experiments to investigate the intensity of the user's perception of both approaches and the haptic feedback design (i.e., vibration, EMS) to reflect the hand gesture best. The overall results indicate that participants feel better with EMS, but it provides a more realistic feeling than vibration feedback. Besides that, the authors mention privacy considerations with vibration devices, as they can be detected by others around (i.e., noise and movement) in opposition to EMS. In Reference [157], the authors describe the properties of proprioceptive sensations induced by non-grounded haptic devices. They use a vibration speaker that pulls or pushes users' arms in a particular direction by using a force. This haptic asymmetric vibration design induces the sensory illusion of pulling and pushing the user's hand. The experiment results show that changes in the vibroactuator input signal can alternate direction and magnitude force on users.

7.5 Distal Feedback

Many wearable devices provide direct tactile feedback on users' fingertips or skin surfaces that directly interact with the virtual/augmented object. For example, a button interaction renders its haptic feedback on the users' fingertips while pressing the button. However, in skin displacement and other non-fingertip-based wearables, the haptic feedback stimuli are rather distal from the interaction point [54]. In Reference [54], the authors study the efficiency of distal feedback through a Fitts' Law task. They compare the task using haptic feedback on a smartphone and in a wearable device placed on users' wrists in button tasks on the smartphone display. The results show that distal feedback provides statistically comparable performance. It is a suitable alternative when interaction location feedback is limited (e.g., MAR applications where users' fingertips should be free from haptic devices).

7.6 Challenges of Tactile Feedback

There are several issues with tactile feedback in scenarios that require high accuracy and precision. In such scenarios, high rate refresh requirements are necessary to avoid possibly unstable behaviors in kinesthetic robotic teleoperations. If we compare it with video (60 Hz or more), then the difficulties during the design and development of cutaneous haptic devices are clear. However, the adaptability of humans also includes the tactile sense, and even in situations with low haptic rendering. The user ignores **small** imperfections and gaps in the stimulation. Further, other feedback channels, such as visual or audio, improve the overall haptic feedback experience. In situations where the imperfections are too visible, the realism breaks down similarly to videos with a lower frame rate. Wearable finger-based cutaneous haptic devices are increasing in popularity as the most suitable approach for MAR applications. However, there is still the need to study the detection thresholds of these devices. The insights of these studies can improve the resolution of the haptic feedback and reduce the network transmission of unnecessary feedback information (i.e., levels not perceived by users). Furthermore, the developments in wearable haptic devices open new challenges and innovative ideas for MAR and the forthcoming *tactile Internet* [43]. The high requirements regarding latency create new topics and research paths in the networking and sensor (i.e., electronics) fields (see more in Section 9).

7.7 Multimodal Feedback

The dominance of the visual sense can sometimes restrain our perception of the relationship between haptic and other non-haptic feedback, such as in many studies and commercial applications such as video games. The visual feedback and vibrotactile feedback are so strongly related that the haptic device vibrates if a user touches a wall. However, we can link together other non-haptic feedback such as sound to enhance the experience in non-visual MAR applications. In Reference [75], the authors propose a real-time audio-level algorithm for vibrotactile sensory translation. The authors' implementation improves auditory-tactile feedback, and hence, enhances users' immersion. The algorithm extracts loudness and roughness from audio signals and translates them to vibrotactile perceptual metrics: intensity and roughness. The designers of haptic feedback for MAR applications have to consider the limitations of simple vibration designs and their capabilities. The information transmission limitations of vibrotactile actuators have been studied extensively. The nature of these cutaneous haptic devices makes the transmission of high-dimensional data complex, as they are limited to patterns such as intensity, duration, and frequency.

8 AR ECOSYSTEMS

In this survey, we analyze the current state-of-the-art devices and approaches to provide haptic feedback in MAR applications. In this section, we enumerate the different commercial devices that can be used to display MAR applications, including devices whose first purpose was not AR scenarios (e.g., HTC Vive). AR ecosystems have been gaining more importance in recent years with the commercialization of several MAR/VR devices such as Oculus Rift and HTC Vive for gaming and Google Glass and Microsoft Hololens for AR applications. Furthermore, commercial software and device companies are opening their frameworks to developers for AR and MAR applications (i.e., Apple ARKit[11]).

[11]https://web.archive.org/web/20200922092644/https://developer.apple.com/augmented-reality/.

Although many devices and technologies focus their attention on the VR ecosystem, most of these solutions can be extrapolated to MAR scenarios. In the case of MAR applications, compactness and weight design are important due to the scenarios' mobile nature. Some devices such as HTC Vive and Oculus Rift provide controllers with haptic feedback (i.e., vibration) to interact and feel virtual environments. These devices were designed for VR scenarios, but their features make them feasible for AR and MAR applications due to the compactness and lightweight.

9 CHALLENGES AND FUTURE DIRECTIONS

Despite the recent advances and interest in wearable haptics, it is still challenging to provide rich haptic feedback in MAR environments. However, wearable haptic devices significantly improve the performance, UX, and comfort in different AR tasks [119], such as guidance and gaming.

9.1 Design Challenges

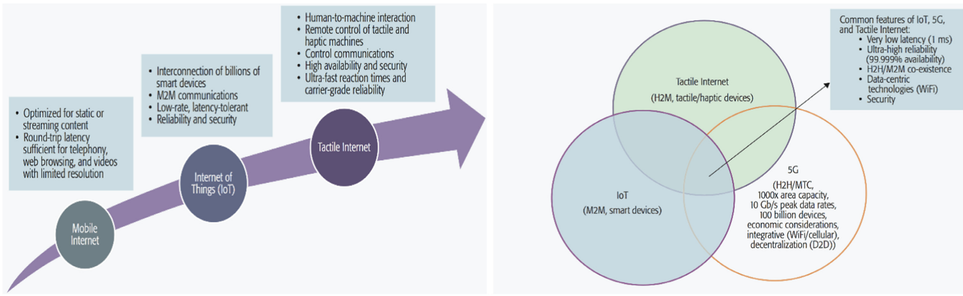
Many MAR applications rely on smartphones or handheld devices to render virtual objects on a display. These devices usually are held by users with one or both hands, constraining users' movements to grab or interact with physical objects. In Reference [119], the authors propose a novel proof-of-concept that includes a display wrist-worn device in combination with an IMU and a fingertip haptic (i.e., vibroactuator) thimble. The wrist-mounted display allows users to locate their avatar hand in the 3D space while the haptic thimble provides feedback during the interactions with the virtual environment.

To design haptic feedback and their mechanical interfaces, there is an approach that assumes passivity for the haptic device and stable human interaction with the device [59]. The passivity condition formulated by Reference [36] utilizes this fact. For example, mid-air interfaces do not analyze the speed and distance covered by users' hands/fingers and configure the feedback stimuli accordingly.

Pacchierotti et al. [116] present a taxonomy of current wearable haptic devices for hands and fingerprints. They also discuss the future paths and challenges of wearable haptic interfaces. The authors estimate that gaming and VR are the paths to follow, as the current and future gaming market will significantly benefit from haptic advances [116]. To conclude, the authors mention the possibilities for assistive and privacy-aware applications. In the latter, wearable devices will enable new notification interfaces that only the receiver will notice.

9.2 Network Requirements

The network requirements for future MAR application feasibility need to be tackled. Network requirements such as latency and transmission errors are important topics to study. Fettweis and Alamouti [43] coin the ecosystem of the *Tactile Internet*. The *Tactile Internet* presents several challenges for mobile networks and also the Internet's backbone, such as latency and ultra-high reliability [1, 89, 146] (Figure 13). The *Tactile Internet* requires *1 ms* delay to achieve a real-time haptic performance in scenarios such MAR. Pilz et al. [125] demonstrate the implementation of the wireless network towards 5G with *1 ms* delay requirements. Only the delay from glass-to-glass (i.e., the time between video recorded by smartphone camera until the frame is rendered in the smartphone screen) is considerable bigger (19.18 ms) than the expected *1ms* for the round-trip delay of the *Tactile Internet* [14]. Therefore, the accumulated delay from the mobile network will not satisfy the latency that the *Tactile Internet* demands. Popovski [126] analyzes the current mechanisms to provide **Ultra-Reliable Communication (URC)** in 5G wireless systems. URC will bring highly reliable connectivity for the next generation of applications, such as vehicular-to-vehicular communications, the *Tactile Internet*, and sensor networks over 5G cellular networks. However, the high-reliability capabilities can affect the stringent latency requirements of the aforementioned



(a) Revolutions. (b) Network challenges.

Fig. 13. Tactile Internet the next revolution, figures by Reference [89]

services. Besides, the number of users contributes to this tradeoff between latency and high reliability.

Furthermore, the demanding requirement of *1 ms* latency is not only limited by mobile and backbone networks but from sensing devices. The authors in References [153, 164] analyze multimodal techniques to aggregate different haptic human sensing information to the network to achieve the latency requirements and not affect the reliability of the ecosystem. Reference [153] studies how human perceptions work and how the human brain combines sensory information. The authors aim to integrate different sensory information without decreasing the perceptive effectiveness and accuracy.

Although current 4G technologies can deliver the expected requirements for most of the MAR applications, the demanding requirements of haptic rendering are not satisfied by current mobile networks. 5G networks' low-latency and high throughput can solve the demanding requirements (e.g., the immediacy of haptic rendering) of haptic devices and provide the so-called *tactile* experience [147]. 5G can also leverage new wearable designs, as the energy requirements can be reduced in scenarios where haptic devices require sophisticated algorithms (e.g., machine learning) to render the feedback. These required computational capabilities can be offloaded in edge or cloud systems [147].

9.2.1 Weber-Fechner Law. "It is a measure of the minimum difference between two stimuli which are necessary in order for the difference to be distinguishable." The **Just Noticeable Difference (JND)** measure is widely used in the haptic feedback ecosystem. The cutaneous and force (kinesthetic) perceptions can differ between users, and it is not easy to quantify the differences. Lee et al. [79] aim to quantitatively answer the JND in finger-tracking systems and the visual and proprioceptive conflicts that can arise in these scenarios. The experiment result shows that participants rely on haptic cues in proprioceptive and visual situations. In situations where the visual, proprioceptive error is high, the haptic cues lose their role in the tracking system, as the users will not rely on them. This paper demonstrates the improvements in finger-tracking systems using cutaneous haptic feedback with visual, proprioceptive low error.

9.2.2 Deadband. Deadband compression techniques transmit new haptic data only when the user perceives stimuli (JND). In Reference [160], the authors extend their work on *deadband* approaches for cutaneous haptic data. The compression technique for cutaneous haptic feedback uses the JND as the perceptual threshold for the compression algorithm. The result shows an average reduction of around 60%. The benefits of *deadband* compression algorithms are plausible, and the implementation of the JND threshold algorithm feasible. Difficulties can appear in the perception measures, as it is a personal characteristic that can vary between users.

9.3 Designing for the Elderly and Visually Impaired

The design and development of AR/MAR applications need to consider other populations such as the elderly or visually impaired to not leave them behind in the forthcoming AR/MAR era. Liang et al. [82] present eight elements that need to be considered in an AR architecture: "user, interaction, device, virtual content, real content, transmission, server, and physical world." The author also describes five preliminary design principles of AR systems: changeability, synchronization, partial one-to-one, antecedent, and hidden reality. The authors identify an AR pillbox as an example of AR for the aging population. Reference [12] presents one of the first works to substitute vision by tactile sensing. Reference [121] describes the relevant issues on designing haptic assistive technologies for the visually impaired. The first issue using tactile mechanical feedback as a substitution for vision is the low spatial resolution of the tactile sensing. Besides, the field of view is considerably smaller for touch. Another approach uses electrotactile displays [151] to simulate a mechanical interaction. However, it suffers from similar limitations. One well-known example of vision substitution using electrotactile feedback is the tongue-based feedback device proposed by References [13] and [86]. Another body of work focuses on haptic feedback devices for navigation MAR applications for the visually impaired [2]. The use of only audio information for guiding can be challenging for users to understand the given acoustic information (e.g., recognize persons and obstacles). Therefore, it is crucial to design systems that provide multimodal feedback [2]. For example, Ramadhan et al. propose a wearable smart system to guide visually impaired persons using a vibroactuator on users' wrist to alert of obstacles in front of them [131]. Furthermore, the performance of assistive technologies differs significantly between testing environments and the real world. The authors also mention the effect of affective touch experiences and their importance in visual substitution approaches. There are several areas of haptic assistive technology, such as Braille devices and mobility devices. One of the main differences in the way we understand information is that it is not possible to map a visual scene into the tactile sensory skin. The visually impaired population should be considered not only for assistive technologies but for the AR/MAR ecosystem (i.e., not only for visual feedback).

9.4 Haptic Feedback as Guidance System

Haptic devices can also be used to provide hand guidance to users [15]. To guide the users' hands towards the desired orientation, the proposed system in Reference [15] vibrates the users' fingertips tracking users' hands in the process. The system utilizes the illusion of grasping a virtual object to guide the hand. Different haptic feedback (e.g., pressure, skin stretch) can be used in future MAR applications for more immersive systems providing new cues (besides avatar displayed in users' devices) to guide users in the virtual environment.

Spiers and Dollar [152] propose a shape-changing haptic interface for navigation systems. The authors compare their device with the more common vibrotactile devices used in navigation systems. The device consists of a cube-shaped object with an upper half that can rotate and slide over its other half to display navigation cues such as forward, turn left, turn right, and go backward. Wearable shape-changing devices in the AR/MAR ecosystem (i.e., textiles) can enable other stimuli that can be useful in no display vision situations.

9.5 Haptic Feedback and Learning Process

Several works analyze the addition of haptic feedback on the learning process. In Reference [51], the authors include kinesthetic feedback in physics simulations to help students understand the force behavior involved in gears mechanical system. Reference [111] follows a similar approach using a force feedback joystick to teaching dynamic systems. Reference [100] analyzes the understanding of improvements using touch roles in the cognitive-learning process and efficacy in haptic augmentation. Another important field that can be enhanced by haptic feedback is medical training [35, 50]. In Reference [133], the authors realize a survey about olfactory feedback, haptic feedback, and immersive applications applied in teaching and learning; for example, to teach the abstract concept of the Bohr atomic model.

In Reference [143], the authors propose **passive haptic learning (PHL)** stimulation method to teach piano pieces. The authors use a pair of wearable gloves with vibroactuators on the back of each finger for learning and retention. Reference [103] proposes a collaborative mixed reality interface. The immersive exploration can help to explore and understand health-related data. Collaborative techniques can enhance the current AR/MAR applications' usability and learning process.

10 CONCLUSION

In this survey, we depict the state-of-the-art of several wearable haptic devices and their capabilities in the MAR ecosystem. Furthermore, we classify the haptic feedback devices by their sensory nature and their design characteristics, such as mid-air or exoskeleton. We start with a brief description of haptic devices' main features and the importance of audio and visual as non-haptic devices in enhancing the UX and improving overall interaction performance. Then, we analyze the main characteristics of the proposed devices and their applicability as wearables for MAR applications. Although many works and commercial products regard haptic devices, we still miss an affordable, portable, and straightforward approach for wearable haptic devices in MAR applications. Moreover, these devices' fidelity is limited to one scenario, such as surface/texture rendering, grasping, or pushing. However, the size or difficulty of implementation hinders their deployment in mobile environments, where the user's scenarios and circumstances can change. With this work, we aim to understand better mechanisms, challenges, and future possibilities of haptic feedback in the MAR field.

REFERENCES

[1] Adnan Aijaz, Mischa Dohler, A. Hamid Aghvami, Vasilis Friderikos, and Magnus Frodigh. 2016. Realizing the tactile internet: Haptic communications over next generation 5G cellular networks. *IEEE Wirel. Commun.* (2016), 1–8. DOI:https://doi.org/10.1109/MWC.2016.1500157RP

[2] Raluca Maria Aileni, George Suciu, Victor Suciu, Sever Pasca, and Jean Ciurea. 2020. Smart systems to improve the mobility of people with visual impairment through IoM and IoMT. In *Technological Trends in Improved Mobility of the Visually Impaired.* Springer, 65–84.

[3] Motoyuki Akamatsu, I. Scott MacKenzie, and Thierry Hasbroucq. 1995. A comparison of tactile, auditory, and visual feedback in a pointing task using a mouse-type device. *Ergonomics* 38, 4 (1995), 816–827.

[4] David S. Alles. 1970. Information transmission by phantom sensations. *IEEE Trans. Man-mach. Syst.* 11, 1 (1970), 85–91.

[5] Margherita Antona and Constantine Stephanidis. 2015. *Universal Access in Human-Computer Interaction. Access to the Human Environment and Culture: 9th International Conference, UAHCI 2015, Held as Part of HCI International 2015, Los Angeles, CA, USA, August 2–7, 2015, Proceedings.* Vol. 9178. Springer.

[6] Faisal Arafsha, Longyu Zhang, Haiwei Dong, and Abdulmotaleb El Saddik. 2015. Contactless haptic feedback: State of the art. *2015 IEEE International Symposium on Haptic, Audio and Visual Environments and Games, HAVE 2015 - Proceedings.* DOI:https://doi.org/10.1109/HAVE.2015.7359447

[7] E. Arai, T. Arai, and M. Takano. 2001. Haptics: A key to fast paced interactivity. In *Human Friendly Mechatronics: Selected Papers of the International Conference on Machine Automation: ICMA 2000: September 27-29, 2000, Osaka, Japan.* Elsevier Science, 11.

[8] Daniel Ashbrook, Patrick Baudisch, and Sean White. 2011. Nenya: Subtle and eyes-free mobile input with a magnetically-tracked finger ring. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* 2043–2046.

[9] Mojtaba Azadi and Lynette A. Jones. 2014. Vibrotactile actuators: Effect of load and body site on performance. In *Proceedings of the IEEE Haptics Symposium (HAPTICS'14).* IEEE, 351–356.

[10] Mahdi Azmandian, Mark Hancock, Hrvoje Benko, Eyal Ofek, and Andrew D. Wilson. 2016. Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, 1968–1979.
[11] Ronald T. Azuma. 1997. A survey of augmented reality. *Presence: Teleop. Virt. Environ.* 6, 4 (1997), 355–385.
[12] Paul Bach-y Rita, Carter C. Collins, Frank A. Saunders, Benjamin White, and Lawrence Scadden. 1969. Vision substitution by tactile image projection. *Nature* 221, 5184 (1969), 963–964.
[13] Paul Bach-y Rita, Kurt A. Kaczmarek, Mitchell E. Tyler, and Jorge Garcia-Lara. 1998. Form perception with a 49-point electrotactile stimulus array on the tongue: a technical note. *J. Rehab. Res. Devel.* 35, 4 (1998), 427.
[14] Christoph Bachhuber and Eckehard Steinbach. 2017. Are today's video communication solutions ready for the tactile internet? In *Proceedings of the IEEE Wireless Communications and Networking Conference Workshops (WCNCW'17)*. IEEE, 1–6.
[15] Tommaso Lisini Baldi, Nicole D'Aurizio, and Domenico Prattichizzo. 2020. Hand guidance using grasping metaphor and wearable haptics. In *Proceedings of the IEEE Haptics Symposium (HAPTICS'20)*. IEEE, 961–967.
[16] Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison. 2010. TeslaTouch: Electrovibration for touch surfaces. In *Proceedings of the 23rd ACM Symposium on User Interface Software and Technology*. ACM, 283–292.
[17] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. Normaltouch and texturetouch: High-fidelity 3D haptic shape rendering on handheld virtual reality controllers. In *Proceedings of the 29th Symposium on User Interface Software and Technology*. ACM, 717–728.
[18] Matteo Bianchi, Edoardo Battaglia, Mattia Poggiani, Simone Ciotti, and Antonio Bicchi. 2016. A wearable fabric-based display for haptic multi-cue delivery. In *Proceedings of the IEEE Haptics Symposium*. 277–283. DOI: https://doi.org/10.1109/HAPTICS.2016.7463190
[19] Jonathan Blake and Hakan B. Gurocak. 2009. Haptic glove with MR brakes for virtual reality. *IEEE/ASME Trans. Mechatron.* 14, 5 (2009), 606–615.
[20] Jeffrey R. Blum, Ilja Frissen, and Jeremy R. Cooperstock. 2015. Improving haptic feedback on wearable devices through accelerometer measurements. In*Proceedings of the 28th ACM Symposium on User Interface Software & Technology*. 31–36. DOI: https://doi.org/10.1145/2807442.2807474
[21] Mourad Bouzit, Grigore Burdea, George Popescu, and Rares Boian. 2002. The Rutgers Master II-New design force-feedback glove. *IEEE/ASME Trans. Mechatron.* 7, 2 (2002), 256–263.
[22] Marta G. Carcedo, Soon Hau Chua, Simon Perrault, Raj Wozniak Pawełand Joshi, Mohammad Obaid, Morten Fjeld, and Shengdong Zhao. 2016. HaptiColor: Interpolating color information as haptic feedback to assist the colorblind. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 3572–3583. DOI: https://doi.org/10.1145/2858036.2858220
[23] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: Multi-point mid-air haptic feedback for touch surfaces. In *Proceedings of the 26th ACM Symposium on User Interface Software and Technology*. ACM, 505–514.
[24] Angela Chang and Conor O'Sullivan. 2005. Audio-haptic feedback in mobile phones. In *CHI'05 Extended Abstracts on Human Factors in Computing Systems*. ACM, 1264–1267.
[25] Zekun Chang, Tung D. Ta, Koya Narumi, Heeju Kim, Fuminori Okuya, Dongchi Li, Kunihiro Kato, Jie Qi, Yoshinobu Miyamoto, Kazuya Saito et al. 2020. Kirigami haptic swatches: Design methods for cut-and-fold haptic feedback mechanisms. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–12.
[26] Dimitris Chatzopoulos, Carlos Bermejo, Zhanpeng Huang, and Pan Hui. 2017. Mobile augmented reality survey: From where we are to where we go. *IEEE Access* 5 (2017), 6917–6950.
[27] Yang-sheng Chen, Kong-chang Lee, Chien-hsing Chou, and Kuan-yin Lu. 2016. SoEs : Attachable augmented haptic on gaming controller for immersive interaction. (2016), 71–72. DOI: https://doi.org/10.1145/2984751.2985707
[28] Francesco Chinello, Monica Malvezzi, Claudio Pacchierotti, and Domenico Prattichizzo. 2015. Design and development of a 3RRS wearable fingertip cutaneous device. In *Proceedings of the IEEE International Conference on Advanced Intelligent Mechatronics (AIM'15)*. IEEE, 293–298.
[29] Francesco Chinello, Monica Malvezzi, Domenico Prattichizzo, and Claudio Pacchierotti. 2019. A modular wearable finger interface for cutaneous and kinesthetic interaction: control and evaluation. *IEEE Trans. Industr. Electron.* 67, 1 (2019), 706–716.
[30] Francesco Chinello, Claudio Pacchierotti, Nikos G. Tsagarakis, and Domenico Prattichizzo. 2016. Design of a wearable skin stretch cutaneous device for the upper limb. In *Proceedings of the IEEE Haptics Symposium*. 14–20. DOI: https://doi.org/10.1109/HAPTICS.2016.7463149
[31] Inrak Choi, Heather Culbertson, Mark R. Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *Proceedings of the 30th ACM Symposium on User Interface Software and Technology*. 119–130.

[32] Inrak Choi, Elliot W. Hawkes, David L. Christensen, Christopher J. Ploch, and Sean Follmer. 2016. Wolverine: A wearable haptic interface for grasping in virtual reality. In *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*. 986–993. DOI: https://doi.org/10.1109/IROS.2016.7759169

[33] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. Demonstration of CLAW: A multi-functional handheld VR haptic controller. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, D205.

[34] Erik C. Chubb, J Edward Colgate, and Michael A. Peshkin. 2010. ShiverPad: A glass haptic surface that produces shear force on a bare finger. *IEEE Trans. Haptics* 3, 3 (2010), 189–198.

[35] Timothy R. Coles, Dwight Meglan, and Nigel W. John. 2011. The role of haptics in medical training simulators: A survey of the state of the art. *IEEE Trans. Haptics* 4, 1 (2011), 51–66.

[36] J. Edward Colgate and Gerd Schenkel. 1994. Passivity of a class of sampled-data systems: Application to haptic interfaces. In *Proceedings of the American Control Conference*. IEEE, 3236–3240.

[37] Christian Corsten, Christian Cherek, Thorsten Karrer, and Jan Borchers. 2015. HaptiCase: Back-of-device tactile landmarks for eyes-free absolute indirect touch. In *Proceedings of the 33rd ACM Conference on Human Factors in Computing Systems*. ACM, 2171–2180.

[38] Alan B. Craig. 2013. *Understanding Augmented Reality: Concepts and Applications*. Newnes.

[39] Heather Culbertson, Julie M. Walker, and Allison M. Okamura. 2016. Modeling and design of asymmetric vibrations to induce ungrounded pulling sensation through asymmetric skin displacement. In *Proceedings of the IEEE Haptics Symposium*. 27–33. DOI: https://doi.org/10.1109/HAPTICS.2016.7463151

[40] Abdulmotaleb El Saddik. 2007. The potential of haptics technologies. *IEEE Instrum. Measur. Mag.* 10, 1 (2007), 10–17.

[41] Nima Enayati, Elena De Momi, and Giancarlo Ferrigno. 2016. Haptics in robot-assisted surgery: Challenges and benefits. *IEEE Rev. Biomed. Eng.* 9 (2016), 49–65.

[42] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. 2020. Wireality: Enabling complex tangible geometries in virtual reality with worn multi-string haptics. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–10.

[43] Gerhard Fettweis and Siavash Alamouti. 2014. 5G: Personal mobile internet beyond what cellular did to telephony. *IEEE Commun. Mag.* 52, 2 (2014), 140–145. DOI: https://doi.org/10.1109/MCOM.2014.6736754

[44] Euan Freeman, Dong-Bach Vo, and Stephen Brewster. 2019. HaptiGlow: Helping users position their hands for better mid-air gestures and ultrasound haptic feedback. In *Proceedings of the IEEE World Haptics Conference (WHC'19)*. IEEE, 289–294.

[45] Massimiliano Gabardi, Massimiliano Solazzi, Daniele Leonardis, and Antonio Frisoli. 2016. A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features. In *Proceedings of the IEEE Haptics Symposium*. 140–146. DOI: https://doi.org/10.1109/HAPTICS.2016.7463168

[46] Colin Gallacher, Arash Mohtat, Steve Ding, and József Kövecses. 2016. Toward open-source portable haptic displays with visual-force-tactile feedback colocation. In *Proceedings of the IEEE Haptics Symposium*. 65–71. DOI: https://doi.org/10.1109/HAPTICS.2016.7463157

[47] Alix Goguey, Deepak Ranjan Sahoo, Simon Robinson, Jennifer Pearson, and Matt Jones. 2019. Pulp friction: Exploring the finger pad periphery for subtle haptic feedback. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–13.

[48] Taku Hachisu and Masaaki Fukumoto. 2014. VacuumTouch: Attractive force feedback interface for haptic interactive surface using air suction. In *Proceedings of the 32nd ACM Conference on Human Factors in Computing Systems*. 411–420. DOI: https://doi.org/10.1145/2556288.2557252

[49] Taku Hachisu and Hiroyuki Kajimoto. 2013. HACHIStack: Dual-layer photo touch sensing for haptic and auditory tapping interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 1411. DOI: https://doi.org/10.1145/2470654.2466187

[50] Zainab Haji, Aysha Arif, Shizrah Jamal, and Rabia Ghafoor. 2021. Augmented reality in clinical dental training and education. *J. Pakist. Med. Assoc.* 71, 1 (Suppl 1) (2021), S42.

[51] Insook Han and John B. Black. 2011. Incorporating haptic feedback in simulation for learning physics. *Comput. Educ.* 57, 4 (2011), 2281–2290.

[52] Teng Han, Fraser Anderson, Pourang Irani, and Tovi Grossman. 2018. HydroRing: Supporting mixed reality haptics using liquid flow. In *Proceedings of the 31st ACM Symposium on User Interface Software and Technology*. ACM, 913–925.

[53] Takuya Handa, Kenji Murase, Makiko Azuma, Toshihiro Shimizu, Satoru Kondo, and Hiroyuki Shinoda. 2017. A haptic three-dimensional shape display with three fingers grasping. In *Proceedings of the IEEE Virtual Reality Conference (VR'17)*. IEEE, 325–326.

[54] Jay Henderson, Jeff Avery, Laurent Grisoni, and Edward Lank. 2019. Leveraging Distal vibrotactile feedback for target acquisition. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–11.

[55] Eve Hoggan, Andrew Crossan, Stephen A. Brewster, and Topi Kaaresoja. 2009. Audio or tactile feedback. In *Proceedings of the 27th International Conference on Human Factors in Computing Systems*. DOI: https://doi.org/10.1145/1518701.1519045

[56] Samantha Horvath, John Galeotti, Bing Wu, Roberta Klatzky, Mel Siegel, and George Stetten. 2014. FingerSight: Fingertip haptic sensing of the visual environment. *IEEE J. Translat. Eng. Health Med.* 2, 1 (2014). DOI: https://doi.org/10.1109/JTEHM.2014.2309343

[57] Da-Yuan Huang, Liwei Chan, Shuo Yang, Fan Wang, Rong-Hao Liang, De-Nian Yang, Yi-Ping Hung, and Bing-Yu Chen. 2016. DigitSpace: Designing thumb-to-fingers touch interfaces for one-handed and eyes-free interactions. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, 1526–1537.

[58] Charles Hudin, Jos Lozada, and Vincent Hayward. 2015. Localized tactile feedback on a transparent surface through time-reversal wave focusing. *IEEE Trans. Haptics* 8, 2 (2015), 188–198. DOI: https://doi.org/10.1109/TOH.2015.2411267

[59] Thomas Hulin, Alin Albu-Schaffer, and Gerd Hirzinger. 2014. Passivity and stability boundaries for haptic systems with time delay. *IEEE Trans. Contr. Syst. Technol.* 22, 4 (2014), 1297–1309.

[60] Ben Humberston and Dinesh K. Pai. 2015. Hands on: Interactive animation of precision manipulation and contact. In *Proceedings of the 14th ACM SIGGRAPH/Eurographics Symposium on Computer Animation*. ACM, 63–72.

[61] Wolfgang Hürst and Casper Van Wezel. 2011. Multimodal interaction concepts for mobile augmented reality applications. In *Proceedings of the International Conference on Multimedia Modeling*. Springer, 157–167.

[62] HyunKi In, Kyu-Jin Cho, KyuRi Kim, and BumSuk Lee. 2011. Jointless structure and under-actuation mechanism for compact hand exoskeleton. In *Proceedings of the IEEE International Conference on Rehabilitation Robotics (ICORR'11)*. IEEE, 1–6.

[63] Ali Israr, Siyan Zhao, Kyna Mcintosh, Zachary Schwemler, Adam Fritz, John Mars, Job Bedford, Christian Frisson, Ivan Huerta, Maggie Kosek et al. 2016. Stereohaptics: A haptic interaction toolkit for tangible virtual experiences. In *ACM SIGGRAPH 2016 Studio.*.

[64] Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: Adding haptic surface to graphics. In *Proceedings of the 28th Conference on Computer Graphics and Interactive Techniques*. ACM, 469–476.

[65] Inyoung Jang and Dongjun Lee. 2014. On utilizing pseudo-haptics for cutaneous fingertip haptic device. In *Proceedings of the IEEE Haptics Symposium*. 635–639. DOI: https://doi.org/10.1109/HAPTICS.2014.6775529

[66] Sungjune Jang, Lawrence H. Kim, Kesler Tanner, Hiroshi Ishii, and Sean Follmer. 2016. Haptic edge display for mobile tactile interaction. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 3706–3716. DOI: https://doi.org/10.1145/2858036.2858264

[67] Seokhee Jeon and Seungmoon Choi. 2009. Haptic augmented reality: Taxonomy and an example of stiffness modulation. *Pres.: Teleop. Virt. Environ.* 18, 5 (2009), 387–408.

[68] Jingun Jung, Eunhye Youn, and Geehyuk Lee. 2017. PinPad: Touchpad interaction with fast and high-resolution tactile output. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, 2416–2425.

[69] Steven W. Keele and Michael I. Posner. 1968. Processing of visual feedback in rapid movements. *J. Experim. Psychol.* 77, 1 (1968), 155.

[70] Hwan Kim, Minhwan Kim, and Woohun Lee. 2016. HapThimble : A wearable haptic device towards usable virtual touch screen. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 3694–3705. DOI: https://doi.org/10.1145/2858036.2858196

[71] Ig Mo Koo, Kwangmok Jung, Ja Choon Koo, Jae-Do Nam, Young Kwan Lee, and Hyouk Ryeol Choi. 2008. Development of soft-actuator-based wearable tactile display. *IEEE Trans. Robot.* 24, 3 (2008), 549–558.

[72] Georgios Korres, Said Chehabeddine, and Mohamad Eid. 2020. Mid-air tactile feedback co-located with virtual touchscreen improves dual-task performance. *IEEE Trans. Haptics* 13, 4 (2020), 825–830.

[73] Ken'ichi Koyanagi, Yuki Fujii, and Junji Furusho. 2005. Development of VR-STEF system with force display glove system. In *Proceedings of the International Conference on Augmented Tele-existence*. ACM, 91–97.

[74] Anatole Lécuyer, J.-M. Burkhardt, Sabine Coquillart, and Philippe Coiffet. 2001. "Boundary of illusion": An experiment of sensory integration with a pseudo-haptic system. In *Proceedings of the IEEE Virtual Reality Conference*. IEEE, 115–122.

[75] Dongjun Lee, Antonio Franchi, Hyoung Il Son, Changsu Ha, Heinrich H. Bulthoff, and Paolo Robuffo Giordano. 2013. Semiautonomous haptic teleoperation control architecture of multiple unmanned aerial vehicles. *IEEE/ASME Trans. Mechatron.* 18, 4 (2013), 1334–1345. DOI: https://doi.org/10.1109/TMECH.2013.2263963

[76] Hojin Lee, Hojun Cha, Junsuk Park, Seungmoon Choi, Hyung-Sik Kim, and Soon-Cheol Chung. 2016. LaserStroke. In *Proceedings of the 29th Symposium on User Interface Software and Technology*. 73–74. DOI: https://doi.org/10.1145/2984751.2985708

[77] Lik-Hang Lee and Pan Hui. 2018. Interaction methods for smart glasses: A survey. *IEEE Access* 6 (2018), 28712–28732.

[78] Woohun Lee and Jun Park. 2005. Augmented foam: A tangible augmented reality for product design. In *Proceedings of the 4th IEEE and ACM International Symposium on Mixed and Augmented Reality*. 106–109. DOI: https://doi.org/10.1109/ISMAR.2005.16

[79] Yongseok Lee, Inyoung Jang, and Dongjun Lee. 2015. Enlarging just noticeable differences of visual-proprioceptive conflict in VR using haptic feedback. In *Proceedings of the IEEE World Haptics Conference*. 19–24. DOI: https://doi.org/10.1109/WHC.2015.7177685

[80] Daniel Leithinger and Hiroshi Ishii. 2010. Relief: A scalable actuated shape display. In *Proceedings of the 4th International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 221–222.

[81] Edouard Leroy, Ronan Hinchet, and Herbert Shea. 2020. Multimode hydraulically amplified electrostatic actuators for wearable haptics. *Adv. Mater.* 32, 36 (2020), 2002564.

[82] Sha Liang. 2016. Design principles of augmented reality focusing on the ageing population. In *Proceedings of the 30th International BCS Human Computer Interaction Conference: Fusion!* BCS Learning & Development Ltd.

[83] P. Lopes and P. Baudisch. 2013. Muscle-propelled force feedback: Bringing force feedback to mobile devices. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 2577–2580. DOI: https://doi.org/10.1145/2459236.2459276

[84] Pedro Lopes, Alexandra Ion, and Patrick Baudisch. 2015. Impacto: Simulating physical impact by combining tactile stimulation with electrical muscle stimulation. In *Proceedings of the 28th ACM Symposium on User Interface Software & Technology*. ACM, 11–19.

[85] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. 2015. Affordance++. In *Proceedings of the 33rd ACM Conference on Human Factors in Computing Systems*. 2515–2524. DOI: https://doi.org/10.1145/2702123.2702128

[86] Cecil A. Lozano, Kurt A. Kaczmarek, and Marco Santello. 2009. Electrotactile stimulation on the tongue: Intensity perception, discrimination, and cross-modality estimation. *Somatosens. Motor Res.* 26, 2–3 (2009), 50–63.

[87] Clifford K. Madsen. 1997. Emotional response to music. *Psychomusicol.: J. Res. Music Cog.* 16, 1–2 (1997), 59.

[88] Tomosuke Maeda and Tetsuo Kurahashi. 2019. Thermodule: Wearable and modular thermal feedback system based on a wireless platform. In *Proceedings of the 10th Augmented Human International Conference*. 1–8.

[89] Martin Maier, Mahfuzulhoq Chowdhury, Bhaskar Prasad Rimal, and Dung Pham Van. 2016. The tactile internet: vision, recent progress, and open challenges. *IEEE Commun. Mag.* 54, 5 (2016), 138–145. DOI: https://doi.org/10.1109/MCOM.2016.7470948

[90] Maurizio Maisto, Claudio Pacchierotti, Francesco Chinello, Gionata Salvietti, Alessandro De Luca, and Domenico Prattichizzo. 2017. Evaluation of wearable haptic systems for the fingers in augmented reality applications. *IEEE Trans. Haptics* 10, 4 (2017), 511–522.

[91] Anthony J. Marcel. 2003. The sense of agency: Awareness and ownership of action. In *Agency and Self-Awareness: Issues in Philosophy and Psychology*, Johannes Roessler and Naomi Eilan (Eds.). Clarendon Press, 48–93.

[92] M. O. Martinez, J. Campion, T. Gholami, M. K. Rittikaidachar, A. C. Barron, and A. M. Okamura. 2017. Open source, modular, customizable, 3-D printed kinesthetic haptic devices. In *Proceedings of the IEEE World Haptics Conference (WHC'17)*. 142–147. DOI: https://doi.org/10.1109/WHC.2017.7989891

[93] John C. McClelland, Robert J. Teather, and Audrey Girouard. 2017. HaptoBend: Shape-changing passive haptic feedback in virtual reality. In *Proceedings of the 5th Symposium on Spatial User Interaction*. 82–90.

[94] Jess McIntosh, Paul Strohmeier, Jarrod Knibbe, Sebastian Boring, and Kasper Hornbæk. 2019. Magnetips: Combining fingertip tracking and haptic feedback for around-device interaction. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–12.

[95] Leonardo Meli, Claudio Pacchierotti, and Domenico Prattichizzo. 2014. Sensory subtraction in robot-assisted surgery: Fingertip skin deformation feedback to ensure safety and improve transparency in bimanual haptic interaction. *IEEE Trans. Biomed. Eng.* 61, 4 (2014), 1318–1327.

[96] Leonardo Meli, Claudio Pacchierotti, Gionata Salvietti, Francesco Chinello, Maurizio Maisto, Alessandro De Luca, and Domenico Prattichizzo. 2018. Combining wearable finger haptics and Augmented Reality: User evaluation using an external camera and the Microsoft HoloLens. *IEEE Robot. Autom. Lett.* 3, 4 (2018), 4297–4304.

[97] David J. Meyer, Michael A. Peshkin, and J. Edward Colgate. 2016. Tactile paintbrush: A procedural method for generating spatial haptic texture. In *Proceedings of the IEEE Haptics Symposium*. 259–264. DOI: https://doi.org/10.1109/HAPTICS.2016.7463187

[98] Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. 2007. Gravity grabber: Wearable haptic display to present virtual mass sensation. In *ACM SIGGRAPH 2007 Emerging Technologies*. ACM.

[99] Vu Trieu Minh, Nikita Katushin, Reza Moezzi, Klodian Dhoska, and John Pumwa. 2021. Smart glove for augmented and virtual reality. *Int. J. Inno. Technol. Interdisc. Sci.* 4, 2 (2021), 663–671.

[100] James Minogue and M. Gail Jones. 2006. Haptics in education: Exploring an untapped sensory modality. *Rev. Educ. Res.* 76, 3 (2006), 317–348.

[101] Mostafa Mohammadi, Tommaso Lisini Baldi, Stefano Scheggi, and Domenico Prattichizzo. 2016. Fingertip force estimation via inertial and magnetic sensors in deformable object manipulation. In *Proceedings of the IEEE Haptics Symposium*. 284–289. DOI: https://doi.org/10.1109/HAPTICS.2016.7463191

[102] Joseph Mullenbach, Michael Peshkin, and J. Edward Colgate. 2016. eShiver: Force feedback on fingertips through oscillatory motion of an electroadhesive surface. In *Proceedings of the IEEE Haptics Symposium*. 271–276. DOI: https://doi.org/10.1109/HAPTICS.2016.7463189

[103] Jens Müller, Simon Butscher, and Harald Reiterer. 2016. Immersive analysis of health-related data with mixed reality interfaces: Potentials and open question. In *Proceedings of the ACM Companion on Interactive Surfaces and Spaces*. ACM, 71–76.

[104] Zoran Najdovski, Saeid Nahavandi, and Toshio Fukuda. 2014. Design, development, and evaluation of a pinch–grasp haptic interface. *IEEE/ASME Trans. Mechatron.* 19, 1 (2014), 45–54.

[105] Taku Nakamura and Akio Yamamoto. 2016. Extension of an electrostatic visuo-haptic display to provide softness sensation. In *Proceedings of the IEEE Haptics Symposium*. 78–83. DOI: https://doi.org/10.1109/HAPTICS.2016.7463159

[106] Y. Nam, M. Park, and R. Yamane. 2007. Smart glove: Hand master using magnetorheological fluid actuators. In *Proc. SPIE*, Vol. 6794. 679434–1.

[107] Nicole Navolio, Guillaume Lemaitre, Alain Forget, and Laurie M. Heller. 2016. The egocentric nature of action-sound associations. *Front. Psychol.* 7 (2016).

[108] N. Kaya and Helena Epps. 2004. Relationship between color and emotion: A study of college students. *Coll. Stud. J.* 38, 3 (2004), 396.

[109] Marianna Obrist, Sriram Subramanian, Elia Gatti, Benjamin Long, and Thomas Carter. 2015. Emotions mediated through mid-air haptics. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. Association for Computing Machinery, 2053–2062. https://doi.org/10.1145/2702123.2702361

[110] Yoichi Ochiai, Kota Kumagai, Takayuki Hoshi, Satoshi Hasegawa, and Yoshio Hayasaki. 2016. Cross-field aerial haptics : Rendering haptic feedback in air with light and acoustic fields. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 3238–3247. DOI: https://doi.org/10.1145/2858036.2858489

[111] Allison M. Okamura, Christopher Richard, Mark Cutkosky et al. 2002. Feeling is believing: Using a force-feedback joystick to teach dynamic systems. *J. Eng. Educ.* 91, 3 (2002), 345–349.

[112] Cisem Ozkul, David Geerts, and Isa Rutten. 2020. Combining auditory and mid-air haptic feedback for a light switch button. In *Proceedings of the International Conference on Multimodal Interaction*. 60–69.

[113] Claudio Pacchierotti, Domenico Prattichizzo, and Katherine J. Kuchenbecker. 2015. Displaying sensed tactile cues with a fingertip haptic device. *IEEE Trans. Haptics* 8, 4 (2015), 384–396. DOI: https://doi.org/10.1109/TOH.2015.2445770

[114] Claudio Pacchierotti, Gionata Salvietti, Irfan Hussain, Leonardo Meli, and Domenico Prattichizzo. 2016. The hRing: A wearable haptic device to avoid occlusions in hand tracking. In *Proceedings of the Haptics Symposium (HAPTICS'16)*. IEEE, 134–139.

[115] Claudio Pacchierotti, Stephen Sinclair, Massimiliano Solazzi, Antonio Frisoli, Vincent Hayward, and Domenico Prattichizzo. 2017. Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives. *IEEE Trans. Haptics* 10, 4 (2017), 580–600.

[116] Claudio Pacchierotti, Stephen Sinclair, Massimiliano Solazzi, Antonio Frisoli, Vincent Hayward, and Domenico Prattichizzo. 2017. Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives. *IEEE Trans. Haptics* 10, 4 (2017), 580–600.

[117] Claudio Pacchierotti, Asad Tirmizi, and Domenico Prattichizzo. 2014. Improving transparency in teleoperation by means of cutaneous tactile force feedback. *ACM Trans. Appl. Percept.* 11, 1 (2014), 4.

[118] Viktorija Paneva, Sofia Seinfeld, Michael Kraiczi, and Jörg Müller. 2020. HaptiRead: Reading Braille as mid-air haptic information. *arXiv preprint arXiv:2005.06292* (2020).

[119] Gianluca Paolocci, Tommaso Lisini Baldi, Davide Barcelli, and Domenico Prattichizzo. 2020. Combining wristband display and wearable haptics for augmented reality. In *Proceedings of the IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW'20)*. IEEE, 633–634.

[120] Stefano Papetti, Hanna Jarvelainen, and Gian Marco Schmid. 2015. Vibrotactile sensitivity in active finger pressing. In *Proceedings of the IEEE World Haptics Conference*. 457–462. DOI: https://doi.org/10.1109/WHC.2015.7177754

[121] Dianne T. V. Pawluk, Richard J. Adams, Senior Member, and Ryo Kitada. 2015. Designing haptic assistive technology for individuals who are blind or visually impaired. 8, 3 (2015), 258–278.

[122] Fabrizio Pece, Juan Jose Zarate, Velko Vechev, Nadine Besse, Olexandr Gudozhnik, Herbert Shea, and Otmar Hilliges. 2017. Magtics: Flexible and thin form factor magnetic actuators for dynamic and wearable haptic feedback. In *Proceedings of the 30th ACM Symposium on User Interface Software and Technology*. ACM, 143–154.

[123] Evan Pezent, Ali Israr, Majed Samad, Shea Robinson, Priyanshu Agarwal, Hrvoje Benko, and Nick Colonnese. 2019. Tasbi: Multisensory squeeze and vibrotactile wrist haptics for augmented and virtual reality. In *Proceedings of the IEEE World Haptics Conference (WHC'19)*. IEEE, 1–6.

[124] Max Pfeiffer, Stefan Schneegass, Florian Alt, and Michael Rohs. 2014. Let me grab this: A comparison of EMS and vibration for haptic feedback in free-hand interaction. In *Proceedings of the 5th International Conference on Augmented Human*. 1–8. DOI: https://doi.org/10.1145/2582051.2582099

[125] Jens Pilz, Matthias Mehlhose, Thomas Wirth, Dennis Wieruch, Bernd Holfeld, and Thomas Haustein. 2016. A tactile internet demonstration: 1ms ultra low delay for wireless communications towards 5G. In *Proceedings of the IEEE INFOCOM Conference*. 862–863. DOI: https://doi.org/10.1109/INFCOMW.2016.7562198

[126] Petar Popovski. 2014. Ultra-reliable communication in 5G wireless systems. (2014), 146–151. DOI: https://doi.org/10.4108/icst.5gu.2014.258154

[127] Jonathan Posner, James A. Russell, and Bradley S. Peterson. 2005. The circumplex model of affect: An integrative approach to affective neuroscience, cognitive development, and psychopathology. *Devel. Psychopathol.* 17, 3 (2005), 715–734.

[128] Domenico Prattichizzo, Francesco Chinello, Claudio Pacchierotti, and Monica Malvezzi. 2013. Towards wearability in fingertip haptics: a 3-DoF wearable device for cutaneous force feedback. *IEEE Trans. Haptics* 6, 4 (2013), 506–516.

[129] Mark Price and Frank C. Sup. 2016. A robotic touchscreen totem for two-dimensional haptic force display. In *Proceedings of the IEEE Haptics Symposium*. 72–77. DOI: https://doi.org/10.1109/HAPTICS.2016.7463158

[130] Ismo Rakkolainen, Euan Freeman, Antti Sand, Roope Raisamo, and Stephen Brewster. 2020. A survey of mid-air ultrasound haptics and its applications. *IEEE Trans. Haptics* 14, 1 (2020), 2–19.

[131] Ali Jasim Ramadhan. 2018. Wearable smart system for visually impaired people. *Sensors* 18, 3 (2018), 843.

[132] Yosra Rekik, Eric Vezzoli, Laurent Grisoni, and Frédéric Giraud. 2017. Localized haptic texture: A rendering technique based on taxels for high density tactile feedback. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. ACM, 5006–5015.

[133] Emmanuelle Richard, Angèle Tijou, Paul Richard, and J.-L. Ferrier. 2006. Multi-modal virtual environments for education with haptic and olfactory feedback. *Virt. Real.* 10, 3-4 (2006), 207–225.

[134] Michael Rietzler, Gabriel Haas, Thomas Dreja, Florian Geiselhart, and Enrico Rukzio. 2019. Virtual muscle force: Communicating kinesthetic forces through pseudo-haptic feedback and muscle input. In *Proceedings of the 32nd ACM Symposium on User Interface Software and Technology (UIST'19)*. Association for Computing Machinery, New York, NY, 913–922. DOI: https://doi.org/10.1145/3332165.3347871

[135] Anne Roudaut, Andreas Rau, Christoph Sterz, Max Plauth, Pedro Lopes, and Patrick Baudisch. 2013. Gesture output: Eyes-free output using a force feedback touch surface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. DOI: https://doi.org/10.1145/2470654.2481352

[136] Dariusz Rumiński and Gudrun Klinker. 2018. Augmenting mixed reality applications with the vibro motors wearable. In *Proceedings of the IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct'18)*. IEEE, 401–402.

[137] Isa Rutten and David Geerts. 2020. Better because it's new: The impact of perceived novelty on the added value of mid-air haptic feedback. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–13.

[138] Steeven Villa Salazar, Claudio Pacchierotti, Xavier de Tinguy, Anderson Maciel, and Maud Marchal. 2020. Altering the stiffness, friction, and shape perception of tangible objects in virtual reality using wearable haptics. *IEEE Trans. Haptics* 13, 1 (2020), 167–174.

[139] Majed Samad, Elia Gatti, Anne Hermes, Hrvoje Benko, and Cesare Parise. 2019. Pseudo-haptic weight: Changing the perceived weight of virtual objects by manipulating control-display ratio. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI'19)*. Association for Computing Machinery, New York, NY, 1–13. DOI: https://doi.org/10.1145/3290605.3300550

[140] Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori. 2015. Head-mounted display with mid-air tactile feedback. In *Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology*. 51–58.

[141] Antti Sand, Vera Remizova, I. Scott MacKenzie, Oleg Spakov, Katariina Nieminen, Ismo Rakkolainen, Anneli Kylliäinen, Veikko Surakka, and Julia Kuosmanen. 2020. Tactile feedback on mid-air gestural interaction with a large fogscreen. In *Proceedings of the 23rd International Conference on Academic Mindtrek*. 161–164.

[142] Stefanie Schaack, George Chernyshov, Kirill Ragozin, Benjamin Tag, Roshan Peiris, and Kai Kunze. 2019. Haptic collar: Vibrotactile feedback around the neck for guidance applications. In *Proceedings of the 10th Augmented Human International Conference*. 1–4.

[143] Caitlyn Seim, Tanya Estes, and Thad Starner. 2015. Towards passive haptic learning of piano songs. In *Proceedings of the IEEE World Haptics Conference*. 445–450. DOI: https://doi.org/10.1109/WHC.2015.7177752

[144] Jongman Seo and Seungmoon Choi. 2015. Edge flows: Improving information transmission in mobile devices using two-dimensional vibrotactile flows. In *Proceedings of the IEEE World Haptics Conference*. 25–30. DOI: https://doi.org/10.1109/WHC.2015.7177686

[145] Thomas G. Simpson and Karen Rafferty. 2020. Evaluating the effect of reinforcement haptics on motor learning and cognitive workload in driver training. In *Proceedings of the International Conference on Augmented Reality, Virtual Reality and Computer Graphics*. Springer, 203–211.

[146] M. Simsek, A. Aijaz, M. Dohler, J. Sachs, and G. Fettweis. 2016. 5G-Enabled tactile internet. *IEEE J. Select. Areas Commun.* 34, 3 (2016), 460–473. DOI: https://doi.org/10.1109/JSAC.2016.2525398

[147] Yushan Siriwardhana, Pawani Porambage, Madhusanka Liyanage, and Mika Ylinattila. 2021. A survey on mobile augmented reality with 5G mobile edge computing: Architectures, applications and technical aspects. *IEEE Commun. Surv. Tutor.* 23, 2 (2021), 1160–1192.

[148] Rajinder Sodhi, Ivan Poupyrev, Matthew Glisson, and Ali Israr. 2013. AIREAL: interactive tactile experiences in free air. *ACM Trans. Graph.* 32, 4 (2013), 134.

[149] Giovanni Spagnoletti, Leonardo Meli, Tommaso Lisini Baldi, Guido Gioioso, Claudio Pacchierotti, and Domenico Prattichizzo. 2018. Rendering of pressure and textures using wearable haptics in immersive vr environments. In *Proceedings of the IEEE Conference on Virtual Reality and 3D User Interfaces (VR'18)*. IEEE, 691–692.

[150] Daniel Spelmezan, Rafael Morales González, and Sriram Subramanian. 2016. SkinHaptics: Ultrasound focused in the hand creates tactile sensations. In *Proceedings of the IEEE Haptics Symposium.* 98–105. DOI: https://doi.org/10.1109/HAPTICS.2016.7463162

[151] Daniel Spelmezan, Deepak Ranjan Sahoo, and Sriram Subramanian. 2016. Sparkle: Towards haptic hover-feedback with electric arcs. In *Proceedings of the 29th Symposium on User Interface Software and Technology.* ACM, 55–57.

[152] Adam J. Spiers and Aaron M. Dollar. 2016. Outdoor pedestrian navigation assistance with a shape-changing haptic interface and comparison with a vibrotactile device. In *Proceedings of the IEEE Haptics Symposium.* 34–40. DOI: https://doi.org/10.1109/HAPTICS.2016.7463152

[153] Eckehard Steinbach, Sandra Hirche, Marc Ernst, Fernanda Brandi, Rahul Chaudhari, Julius Kammerl, and Iason Vittorias. 2012. Haptic communications. *Proc. IEEE* 100, 4 (2012), 937–956. DOI: https://doi.org/10.1109/JPROC.2011.2182100

[154] Patrick L. Strandholt, Oana A. Dogaru, Niels C. Nilsson, Rolf Nordahl, and Stefania Serafin. 2020. Knock on wood: Combining redirected touching and physical props for tool-based interaction in virtual reality. In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI'20)*. Association for Computing Machinery, New York, NY, 1–13. DOI: https://doi.org/10.1145/3313831.3376303

[155] Evan Strasnick, Jessica R. Cauchard, and James A. Landay. 2017. BrushTouch: Exploring an alternative tactile method for wearable haptics. In *Proceedings of the CHI Conference on Human Factors in Computing Systems.* ACM, 3120–3125.

[156] Evan Strasnick, Jackie Yang, Kesler Tanner, Alex Olwal, and Sean Follmer. 2017. Shiftio: Reconfigurable tactile elements for dynamic affordances and mobile interaction. In *Proceedings of the CHI Conference on Human Factors in Computing Systems.* 5075–5086.

[157] Takeshi Tanabe, Hiroaki Yano, and Hiroo Iwata. 2016. Properties of proprioceptive sensation with a vibration speaker-type non-grounded haptic interface. In *Proceedings of the IEEE Haptics Symposium.* 21–26. DOI: https://doi.org/10.1109/HAPTICS.2016.7463150

[158] Shan-Yuan Teng, Pengyu Li, Romain Nith, Joshua Fonseca, and Pedro Lopes. 2021. Touch&Fold: A foldable haptic actuator for rendering touch in mixed reality. In *Proceedings of the CHI Conference on Human Factors in Computing Systems.* 1–14.

[159] Hussain Tinwala and I. Scott MacKenzie. 2009. Eyes-free text entry on a touchscreen phone. In *Proceedings of the IEEE Toronto International Conference - Science and Technology for Humanity.* 83–88. DOI: https://doi.org/10.1109/TIC-STH.2009.5444381

[160] Asad Tirmizi, Claudio Pacchierotti, Irfan Hussain, Gianluca Alberico, and Domenico Prattichizzo. 2016. A perceptually-motivated deadband compression approach for cutaneous haptic feedback. In *Proceedings of the IEEE Haptics Symposium.* 223–228. DOI: https://doi.org/10.1109/HAPTICS.2016.7463181

[161] Dzmitry Tsetserukou, Shotaro Hosokawa, and Kazuhiko Terashima. 2014. LinkTouch: A wearable haptic device with five-bar linkage mechanism for presentation of two-DoF force feedback at the fingerpad. In *Proceedings of the Haptics Symposium.* IEEE, 307–312.

[162] James Vallino and Christopher Brown. 1999. Haptics in augmented reality. In *Proceedings of the IEEE International Conference on Multimedia Computing and Systems.* IEEE, 195–200.

[163] Ramiro Velazquez, Edwige Pissaloux, Moustapha Hafez, and Jérôme Szewczyk. 2005. A low-cost highly-portable tactile display based on shape memory alloy micro-actuators. In *Proceedings of theIEEE International Conference on Virtual Environments, Human-computer Interfaces and Measurement Systems*

[164] Jeroen G. W. Wildenbeest, David A. Abbink, Cock J. M. Heemskerk, Frans C. T. Van Der Helm, and Henri Boessenkool. 2013. The impact of haptic feedback quality on the performance of teleoperated assembly tasks. *IEEE Trans. Haptics* 6, 2 (2013), 242–252. DOI: https://doi.org/10.1109/TOH.2012.19

[165] Yongjae Yoo, Taekbeom Yoo, Jihyun Kong, and Seungmoon Choi. 2015. Emotional responses of tactile icons: Effects of amplitude, frequency, duration, and envelope. In *Proceedings of the IEEE World Haptics Conference (WHC'15)*. IEEE, 235–240.

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