IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 4 August 2022, accepted 24 August 2022, date of publication 29 August 2022, date of current version 7 September 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3202986

SURVEY

Haptic Devices: Wearability-Based Taxonomy and Literature Review

ADILZHAN ADILKHANOV, (Member, IEEE), MATTEO RUBAGOTTI, (Senior Member, IEEE), AND ZHANAT KAPPASSOV, (Member, IEEE)
Department of Robotics and Mechatronics, Nazarbayev University, Nur-Sultan 010000, Kazakhstan

Corresponding author: Zhanat Kappassov (zhkappassov@nu.edu.kz)

This work was supported in part by the Ministry of Education and Science of the Republic of Kazakhstan under Research Grant AP09058050, in part by Nazarbayev University through the Collaborative Research Project under Grant 091019CRP2118, and in part by the Faculty Development Competitive Research under Grant 11022021FD2923.

ABSTRACT In the last decade, several new haptic devices have been developed, contributing to the definition of more realistic virtual environments. An overview of this topic requires a description of the various technologies employed in building such devices, and of their application domains. This survey describes the current technology underlying haptic devices, based on the concept of “wearability level”. It reviews more than 90 devices newly developed and described in scientific papers published in the period 2010-2021. The reviewed devices provide either haptic illusions or novel haptic feedback for teleoperation, entertainment, training, education, guidance and notification. They are categorized into grounded, hand-held and wearable devices; the latter are further split into exoskeletons and gloves, finger-worn devices, and arm-worn devices. For the systems in each of these categories, descriptions and tables are provided that analyze their structure, including device mass and employed actuators, their applications, and other characteristics such as type of haptic feedback and tactile illusions. The survey also provides an overview of devices worn in parts of the human body other than arms and hands, and precisely haptic vests, jackets and belts, and haptic devices for head, legs and feet. Finally, the paper discusses research gaps and challenges, and potential future directions.

INDEX TERMS Haptic devices, virtual reality interfaces, kinesthetic feedback, tactile feedback, haptic illusions.

I. INTRODUCTION

The word *haptics* refers to the capability to sense a natural or synthetic mechanical environment through touch [1]. The last decade has seen a dramatic increase of haptic devices, driven by application domains such as haptic robot teleoperation, virtual reality (VR) and augmented reality (AR). However, there is still much work to be done before people can fully interact with objects in a virtual environment (VE). For example, realistic object manipulation, including the perception of textures, shape, weight, softness and temperature, is necessary for better immersion into the virtual world. Thus, advancements in haptic devices are needed to engage our sense of touch in addition to vision [2], which is typically provided by head-mounted displays (HMDs).

Human haptic perception consists of both *kinesthetic* and *cutaneous (tactile)* haptic feedback. Kinesthetic feedback refers to the sense of position and motion of one’s body state mediated by a variety of receptors located in the skin, joints, skeletal muscles and tendons [1]. Cutaneous feedback is instead related to the stimuli detected by low threshold mechanoreceptors under the skin within the contact area [3]. Haptic devices are used to engage these types of feedback and give users the feeling of touch, in some cases providing haptic illusions. They receive information from a VE and act on the user through tactile feedback; at the same time, they send the sensed position and force data of the user to the VE.

Devices used to stimulate kinesthesia are typically grounded, bulky, mechanically complex, expensive and have

The associate editor coordinating the review of this manuscript and approving it for publication was Xiaogang Jin.

a limited workspace. Traditionally, kinesthetic devices are able to provide clear forces or torques to move the user's hand or resist motion [4]. They are widely used in industry and medicine for teleoperation tasks and other tool-based applications, e.g., using manipulator hands and dental drills [5]. These devices typically provide the best approach for high-quality interactions but suffer from limitations in terms of cost and portability.

To avoid the drawbacks of grounded kinesthetic devices, the haptic feedback can be delivered through cutaneous devices. Although cutaneous feedback can be in principle provided for the whole body, it is mostly given through fingertips, as these are usually employed for grasping and manipulation, and are rich in mechanoreceptors [6]. It has been shown that, to some extent, it is possible to compensate for lack of kinesthesia with the modulated cutaneous force technique, without significant performance degradation [7]. Cutaneous feedback can be displayed by mobile, lightweight, compact devices that can be wearable and mounted on the user's body on wrist, palm and fingers.

Despite their complexity, not all kinesthetic devices are grounded. Depending on their purpose, kinesthetic haptic devices can be in the form of exoskeletons (grounded on some part of the body).

A. EXISTING REVIEW PAPERS

Previous reviews in this field focused on haptic devices [1], [4], [8], wearable haptic interfaces [9] including exoskeletons and gloves [8], [10], [11], touch surfaces [12], and applications of haptic devices [5], [8], [13], [14], with nearly all examined devices targeting parts of human arms and hands. Some of these reviews [1], [4], [9], [12], provide a background in the physiology of human sensory-motor control.

The first survey on haptic interfaces and devices, and on their applications was written by Laycock and Day [8], who also examined how haptic feedback was combined with visual display devices (e.g., virtual reality walls and workbenches), so as to improve the immersive experience.

The review paper by Hayward and coauthors [1] provided a classification of haptics in human-computer interfaces. The paper described examples of applications followed by descriptions of human kinesthetic and tactile sensing, and components of haptic interfaces, listing several devices in use at that time.

Culbertson *et al.* [4] reviewed the technology behind creating artificial touch sensations focusing on design, control and application of noninvasive haptic devices. Firstly, they introduced a taxonomy of haptic systems, considering three major categories: graspable, wearable and touchable. Further, they discussed a variety of haptic feedback mechanisms present in each device of the three categories.

The review by Pacchierotti *et al.* [9] analyzed a fraction of haptic systems, considering only wearable haptics for fingertip and hand, which provide cutaneous feedback. The paper presented a taxonomy of haptic wearables, focused on technological and design challenges, and reported future perspectives on the field. Wearable haptic systems were categorized based on the type of tactile stimuli, mechanical properties and interested body part.

Unlike [9], Wang *et al.* [10] considered only glove-type whole-hand wearables with kinesthetic feedback. The main focus was on hardware technology and design challenges at the levels of sensing, actuation, control, transmission and structure. Firstly, the authors discussed anatomical aspects that must be considered for the design of glove-type wearables. Then, the existing research prototypes and commercially available kinesthetic gloves were summarized. Force-feedback gloves were categorized by actuation location into digit-based, palm-based, dorsal-based and ground-based.

Perret and Vander Poorten [11] wrote another literature review on haptic gloves. They briefly discussed the main technical constraints appearing during the design process, with a special focus on actuation technology. The classification of haptic gloves differs from the one introduced in [10], as they are divided into traditional gloves (made of flexible fabric), thimbles, and exoskeletons. Finally, [11] analyzed characteristics and performance of existing commercial devices.

Bastogan *et al.* [12] reviewed another type of haptic devices - surface haptics. The categorization in the paper focused on the three most popular actuation methods: vibrotactile, electrostatic, and ultrasonic. The current technologies for surface haptics displays were classified based on stimulation direction and method. The modern state of the art technologies in surface haptics were reviewed from three perspectives: methods of generating tactile stimuli and the physics behind them, human tactile perception, and tactile rendering algorithms.

Other reviews on haptic devices focused on their applications. Rodriguez *et al.* [5] reviewed the applications of haptic systems in VEs. The applications were divided into three main categories: training, assistance, and entertainment. Both kinesthetic and cutaneous feedback devices are considered for the review, in application fields such as education, medicine and industry.

Shull *et al.* [14] wrote a review on haptic wearables for clinical applications involving sensory impairments. The devices were categorized into three groups depending on the degree of disability - total impairment, partial impairment, or rehabilitation. The review concluded that wearable haptic devices facilitated the rehabilitation rate and improved functionality of medical devices, including prostheses, in a variety of clinical applications such as vestibular loss, osteoarthritis, vision loss and hearing loss.

Talvas *et al.* [13] reviewed the state of the art on bimanual haptics - the field that studies haptic interaction with either remote or virtual environments using both hands of the same person. Currently available bimanual haptic devices, software solutions and existing interaction techniques were discussed with regard to specifications of the human bimanual systems, such as the dominance of the hands, their differences in perception and their interactions at a cognitive level.

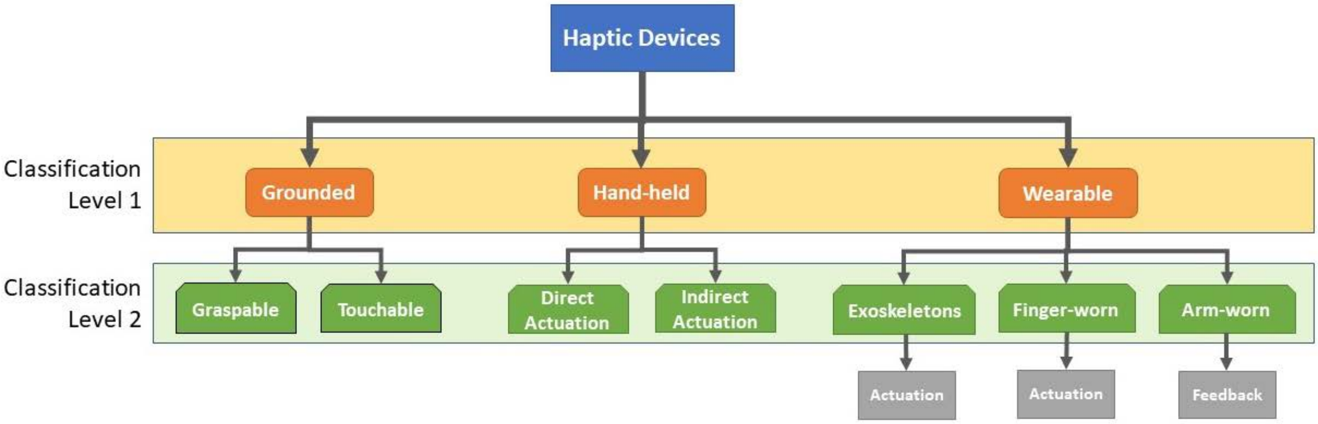

FIGURE 1. Two-level taxonomy of haptic devices based on wearability level (taxonomy level 1) and classification based on further characteristics (taxonomy level 2).

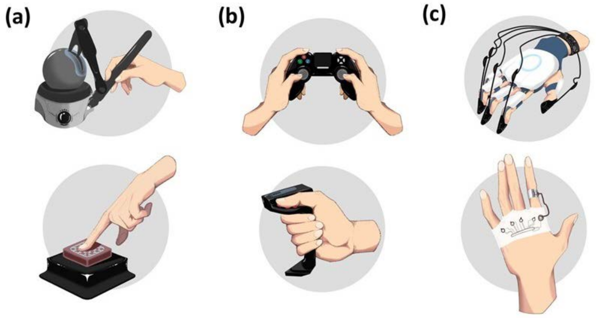

FIGURE 2. Graphical examples of different types of haptic devices classified by wearability level: (a) grounded haptic device; (b) hand-held haptic device; (c) wearable haptic device.

B. MOTIVATION AND CONTRIBUTION

The main motivation for writing this survey paper is the need to provide a taxonomy for the considerable number of recently developed haptic devices, which can allow readers to capture the main trends that will determine the development and design of haptic devices in the coming years. Therefore, unlike [4], which classified haptic devices by design into three major categories (graspable, wearable and touchable), in this review we propose to classify them based on the concept of *wearability level*. Indeed, the current trend in the development of haptic devices consists in moving their base closer to the place of stimulation, shifting from grounded devices (which cannot be worn on parts of the user's body) to hand-held devices, and further towards fully wearable devices. In other words, "only recently, more sophisticated haptic systems have started to be designed with wearability in mind.", which "enables novel forms of communication, cooperation, and integration between humans and machines" [9]. As observed in the recent past for audio and video electronics, the development of haptics is moving towards devices with a higher wearability level to make them suitable in everyday life, the key design aspect being effective integration with the human body without motion constraint. Examples of commercially-available wearables that support haptic feedback are smart watches such as Apple Watch (Apple, USA) and Gear (Samsung, South Korea).

To represent this trend in our taxonomy, in this review we classify haptic systems by wearability level into three categories (see Figs. 1 and 2):

- Grounded devices (not wearable), which are divided into graspable and touchable systems.
- Hand-held devices ("partially" wearable), distinguished based on type of actuation (direct or indirect) with respect to the user's limb.
- Wearable devices, further classified into exoskeletons and gloves, finger-worn devices, and arm-worn devices.

This specific taxonomy based on wearability level is, to the extent of our knowledge, a novel contribution. Furthermore, for all categories, we describe the applications of the devices, the types of employed actuators, and other characteristics such as type of haptic feedback, haptic illusions, degrees of freedom (DoFs), and physical properties such as mass. For each category, we provide a table that summarizes the most important features of more than 90 analyzed devices. For key features regarding different types of illusions related to object manipulation and perception (illusions of weight, shape, size, stiffness, texture), we summarize the applicable approaches. This review paper will mainly focus on devices worn on human hands and arms, as these are by far the most common. Indeed, hands constitute the main part of the body with which humans physically interact with their surroundings, also due to a large number of mechanoreceptors present in them. Nonetheless, there exist devices that target different parts of the human body other than arms and hands, in order to expand the range of applicability of haptics to new scenarios. A brief overview of these devices will also be provided in our paper.

C. SURVEY STRUCTURE

The remainder of the paper is organized as follows. The method used to search and select the papers that describe the analyzed haptic devices is provided in Section II. Section III contains the descriptions of all the surveyed devices. In particular, grounded and hand-held devices are reviewed in Sections III-A and III-B, respectively. Wearable devices are analyzed in separate subsections: exoskeletons in Section III-C, finger-worn devices in Section III-D, and arm-worn devices in Section III-E. A brief overview of devices for parts of the human body other than arms and hands is provided in Section III-F. Finally, Section IV provides a discussion on the applicability of the reviewed devices in various contexts, on the different types of tactile illusions, on existing gaps and challenges, and on potential future directions.

II. METHOD

A. SEARCH AND SELECTION METHODOLOGY

The procedure followed for selecting the papers suitable for this review was the following:

1) Suitable references were searched for by using relevant keywords such as "haptic devices", "haptic technology", "tactile feedback", "haptic interfaces" and "wearable devices" in Google Scholar, ACM Digital Library, IEEEXplore, SpringerLink and Web of Science.
2) The papers that contained one or more of the given keywords in the title and/or in the body of the paper were extracted.
3) The papers that did not satisfy all of the following requisites were removed:
    - the approach described in the paper is original;
    - the authors present a newly built device, or an original modification of an existing device;
    - the described haptic interface provides either haptic illusions or novel haptic feedback for various tasks such as teleoperation and navigation;
    - the paper is written in English and published either in an international journal or in an international conference from 2010 onward.
4) For the selected papers we analyzed (to find additional devices) the references cited in them, together with the papers that were citing them (via Google Scholar). For the newly-found papers, the same selection procedure detailed in steps 2) and 3) was followed.

As a result, more than 90 papers were found that satisfy the above-mentioned requirements.

B. TAXONOMY DEFINITION

After determining the list of relevant papers, the following step consisted of organizing them within the above-mentioned taxonomy based on wearability level. More precisely, each paper was clustered into one of the following categories and sub-categories:

- Grounded device, either
    - graspable, or
    - touchable.
- Hand-held device, either
    - with direct actuation, or
    - with indirect actuation.
- Exoskeleton, based on either
    - resistive force, or
    - locking mechanisms, or
    - pneumatic actuation.
- Finger-worn device, relying on either
    - a moving platform,
    - other solutions.
- Arm-worn device, based on either
    - vibrotactile feedback, or
    - skin stretch and compression feedback, or
    - thermal feedback.

The categories (e.g., grounded devices) were determined a-priori based on our preliminary knowledge of the field; on the other hand, the subcategories (e.g., graspable grounded devices) were dynamically redefined as more papers were classified. The haptic devices that were not designed to be worn on arms or hands were instead classified into the following three subcategories:

- vests, jackets and belts;
- devices for legs and feet;
- devices for head.

At the end of the search and categorization processes, we proceeded generating the description of each paper, which is reported in the following, in Section III. This review work focuses on describing devices introduced in other scientific papers (which are typically laboratory prototypes), for which detailed descriptions and comparisons through tables are provided. Nonetheless, several commercial devices are also mentioned in the suitable subsections for the reader's convenience.

III. RESULTS

A. GROUNDED DEVICES

Grounded (also known as "tabletop") haptic devices are those that cannot be worn on a part of the user's body, due to their size and/or functional features, such as the presence of air reservoirs or compressors. Therefore, the workspace of such devices is limited. Grounded haptic systems can be categorized into graspable and touchable devices (Figure 2a). Since grounded devices are not as limited in terms of size and weight as compared to hand-held and wearable devices, their type of actuation can employ pneumatic actuation with its bulky reservoirs and pumps, or magnetic actuation with its platforms and large electric coils. A summary of the devices described in the remainder of this section is provided in Table 1.

1) GRASPABLE DEVICES

Graspable haptic systems (Fig. 2a, left) are traditionally kinesthetic devices, but some may provide cutaneous feedback (e.g., vibrations) through a held tool. Well-known

TABLE 1. Grounded haptic devices.

Device	Type	Purpose/Haptic Illusion	Kinesthetic Feedback	Cutaneous Feedback	Actuators	Max Force
[15]	graspable	teleoperation	Force Dimension Omega.3	normal/tangential skin deformation	(x3) servomotors (Futaba S3154 RC)	10 N
[16]	graspable	stiffness perception	Phantom Premium 1.5	skin stretch	(x1) DC motor (Portescap 16G88214E)	2 N
[17]	graspable	teleoperation	N/A	skin stretch	(x6) layers of EAP (3M VHB 4910 acrylic film)	1.6 N
[18]	graspable	3D shapes	force due to EMF	N/A	(x9) electromagnetic coils	2 N
[19]	graspable	3D surface exploration	force due to EMF	N/A	(x3) electromagnetic coils	0.959 N
[20]	touchable	textured surfaces	N/A	electrovibration	(x1) capacitive-based touch sensing panel (3M Microtouch)	-
[21]	touchable	directional cues, friction	N/A	skin stretch	(x2) Flexinol SMA wires	3 N
[22]	touchable	teleoperation	N/A	temperature feedback	(x4) Peltier Elements	**14.4°C/sec **18.7°C/sec
[23]	touchable	surface relief	N/A	normal skin deformation	(x16) DC motors (Namiki SLC07-17)	-
[24] [25]	touchable	softness	N/A	normal/tangential skin deformation	(x2) DC motors (Remax 2561:1 3W, Maxon Motors)	20 N
[26]	touchable	softness	N/A	vibrotactile	(x1) VCA (Haptuator Mark 2)	-
[27]	touchable	material roughness	N/A	vibrotactile	(x1) VCA (X-1740, Aoyama Special Steel Co., Japan)	-
[28]	touchable	object slippage	N/A	skin stretch	-	-
[29]	*wearable	stroking, pulsing	N/A	compression and temperature feedback	(x4) nylon-coated ripstop fabric pouches + (x2) water pumps (Bayite BYT-7A006)	***2.3 sec ***2.2 sec

* - considered grounded due to water tanks; ** - speed of heating/cooling; *** - time for filling/emptying.

commercial examples of tabletop graspable devices are Touch (3D Systems, USA - formerly Phantom from Sensable Technologies) and Omega (Force Dimension, Switzerland). These types of haptic devices are very accurate and able to provide a wide range of forces. The design of these devices is focused on having several DoFs with small backlash in the joints, and on using motors with high force and low friction and cogging.

Quek *et al.* [15] developed a haptic device that could be attached to the end-effector of the above-mentioned Omega device (Force Dimension). The novel device provides normal and tangential skin deformation feedback through the movement of rubber tactors whose displacement is generated by a delta parallel kinematic mechanism actuated by three servomotors. Afterwards, Quek *et al.* [16] presented another skin stretch feedback device that used tactor movement - *Skin Stretch Stylus*. The device consists of a vertical bar (with attached skin stretch tactors) actuated by a DC motor through a cable capstan mechanism, which slides on a linear guide carriage. The Stylus is attached to a Phantom Premium device. While the Phantom Premium provides force feedback, the Stylus exerts skin stretch feedback during the interaction with a virtual surface. This sensory augmentation causes a shift in perceived stiffness proportional to the tactor-displacement gain.

A similar device, presented by Han *et al.* in [17], was aimed at assisting a surgeon during magnetic-resonance-guided biopsy procedures - translating the forces sensed by a robotized biopsy needle. The device provides localized skin stretch to both the thumb and index fingertips of the operator. The feedback is delivered through tactors driven by electroactive polymer (EAP) actuators.

Adel *et al.* [18] presented a grounded electromagnetic-based haptic interface. The device aims to render virtual objects of different shapes with the use of an electromagnetic field (EMF) generated by nine individually-controlled coils. The EMF exerts magnetic forces on a permanent magnet attached to the user's fingertip. The fingertip position is tracked by a Leap Motion optical hand-tracking module.

Another approach of providing contact-free, volumetric haptic feedback via EMF was introduced in [19]. Unlike [18], the device presented in [19] uses only three electromagnetic coils placed orthogonally at the center of the base. The magnetic field that exerts attractive and repulsive forces onto a permanent magnet embedded into a hand-held stylus is created by controlling the current flow. The device can be effective in applications such as virtual terrain exploration and rendering the sensation of stirring a viscous liquid. The method of delivering haptic feedback through magnetism (used in both [18] and [19]) also has limitations such as high power consumption, strong cooling system requirement, and a consequent limited continuous interaction.

2) TOUCHABLE DEVICES

Touchable haptic devices (Fig. 2a, right) are interactive displays that allow the user to tactilely interact with objects displayed on the screen. These devices typically provide pure cutaneous feedback through vibrotactile, electrostatic or ultrasonic actuation methods. The idea is to use haptic surfaces for those actions and applications that do not require active movements or high-precision control, such as user interface of different applications, online shopping, entertainment, education and arts [12].

TeslaTouch [20] is a touch screen device that provides cutaneous feedback through electrovibration. The device does not have any moving parts, but only provides the feedback when the user's finger is moved across the surface. The electrovibration principle is based on the control of "electrostatic friction between an instrumented touch surface and the user's finger". The actuation is performed by exciting a transparent electrode with a periodic electrical signal. The haptic illusion of sliding over textured surfaces is rendered by modulating the amplitude and frequency of the signal.

A skin-stretch device for fingertip was developed by Solazzi *et al.* [21]. The device conveys tangential forces in 2DoF when the user's finger is inserted into the thimble-like device. The feedback is delivered by a system of shape memory alloy (SMA) actuators and bias springs. The force displayed on the fingertip is translated from SMA actuators through a textured rubber end-effector (tactor). Based on its characteristics, this device can be used for communicating directional cues and rendering friction with virtual surfaces and objects.

Gallo *et al.* [22] designed a thermal feedback display for teleoperation purposes. The device uses four individually controlled Peltier elements and provides thermal feedback to the user's fingertip by heating up or cooling down the contact surfaces. Due to its superior performance, water cooling was preferred to air cooling despite the complexity of the water pumping system.

Another tactile feedback display was presented by Sarakoglou *et al.* [23]. The device is a 4 × 4 array of pins (tactors) moving perpendicularly to the fingerpad with an amplitude of 2 mm. Each tactor (with a bandwidth of 7-19 Hz) is actuated individually by a DC motor through a flexible tendon transmission system. The device is integrated into a teleoperation system, being attached at the master site to the above-mentioned Omega kinesthetic feedback device.

The Fabric Yielding Display (FYD-2) [24], [25] is a tactile feedback device for rendering softness characteristics of real and artificial specimens. The actuation principle is based on the regulation of the stretching state of the fabric. The ends of the fabric belt are connected to rollers, each powered by a DC motor. The belt stretching principle of FYD-2 is similar to the one used for finger-worn devices: when the two motors rotate towards the outside, the fabric relaxes; when the two motors rotate towards the inside, the fabric's stiffness increases. Also, the device is able to deliver a shearing force to the user's finger when the motors rotate in the same direction. FYD-2 has proven its efficiency in simulating different stiffness values of various materials.

VibeRo [26] introduced another approach of rendering virtual objects softness. The device combines vibrotactile feedback and a pseudo-haptic effect delivered through an HMD for recreating the sensation of squeezing a soft granular object. The vibration stimulus is created by modulating the frequency proportionally to the rate of change of the applied force at the fingertips. In turn, the pseudo-haptic feedback is rendered by adjusting the rate of change of the shape of a soft object seen in an HMD.

Asano *et al.* [27] developed a texture display with vibrotactile feedback. The researchers placed materials with different textures on the top of the end-effector (acrylic plate) connected to a voice coil actuator (VCA). The finger position is captured by a camera. The idea is to modify the perceived fine and macro roughness of material surfaces by stimulating the user's finger with vibrations.

Van Anh Ho *et al.* [28] created a grounded haptic display for generating a pre-slide (incipient slippage) sensation on the user's fingertip for enhancement of grip forces control during teleoperation tasks. The actuation principle of this device is inspired by previous research on localized displacement phenomena during the pre-slide phase of soft objects [30]. The device employs a bundle of stiff pins arranged in two circles. Due to the specific placement, the pins at the outer circles displace before and with higher velocity as compared to those in the inner circles. The display provides effective localized skin displacement that enhances slippage perception.

The device presented in [29], PATCH (Pump-Actuated Thermal Compression Haptics), uses water for providing compression feedback. It comprises of two water tanks, hot and cold, used for pump actuation to provide thermal feedback. The device has four actuators placed under the forearm fabric sleeve. The desired temperature is set by mixing the water from the two tanks in a single tube in specific proportions. PATCH has a similar efficiency in displaying pulsing and stroking patterns as a voice-coil-actuated sleeve.

B. HAND-HELD DEVICES

The devices that can be picked up and held within hands without attaching straps are classified as hand-held devices (see Table 2). Compared to grounded devices, they are lighter, impose fewer constraints on movements and provide a larger workspace. However, they cannot be worn and thus do not give complete freedom of movement. Hand-held devices can render kinesthetic or tactile feedback, or both at the same time.

Well-known commercial examples of hand-held haptic devices are game controllers for Sony PlayStation, Microsoft Xbox video-game consoles, and tracking controllers for Oculus Rift and HTC Vive VR systems. These controllers enhance the user experience while holding them in hand when playing video games. Traditional controllers provide vibrotactile feedback to highlight certain events appearing on the screen: for example, collisions in car racing and battles, and recoil when shooting. While the vibration stimulation became a de-facto standard in such controllers, the articles reviewed in this section consider a variety of different approaches for delivering haptic feedback. We divide hand-held devices into two categories, based on the type of actuation. More precisely, direct actuation devices act on the user's hand directly through the handle and the end-effector, whereas indirect actuation devices change the center of gravity to deliver different haptic cues.

FIGURE 3. Examples of direct and indirect actuation type hand-held devices.

1) DIRECT ACTUATION

Benko *et al.* [31] presented two hand-held controllers (*NormalTouch* and *TextureTouch*) that enable users to feel 3D surfaces, textures and forces during interactions in VR applications. NormalTouch uses a 3D tiltable and extrudable Stewart platform (actuated by three servomotors and equipped with a force sensor) for delivering surface curvature cues to the user's finger resting on it. TextureTouch's end-effector is a 4 × 4 pin-array placed under the user's fingerpad for rendering shapes of virtual objects and textures of virtual surfaces.

Despite the experimentally-proven effectiveness of these two approaches compared to conventional vibrotactile feedback and visual-only feedback, some limitations are in place. These include insufficient rendering of angles, forces and heights by NormalTouch, while TextureTouch suffers from its bulkiness and low pin resolution.

Another device for VR applications was shown in [32]. Researchers upgraded a commercial hand-held controller (HTC Vive's controller) by augmenting its basic functionality (i.e., buttons, 6DoF movement control, thumb joysticks, trigger) with kinesthetic and cutaneous feedback. The novel device, named *CLAW*, can render haptic sensations such as grasping a virtual object and touching a virtual surface through a rotating arm for the index finger equipped with a VCA for cutaneous rendering (i.e., variable stiffness of a grasped virtual object, surface texture).

CapstanCrunch [33] is a device similar to CLAW in terms of form-factor and purpose. It is a hand-grounded device with a rotating arm for the index finger designed to render the softness of a virtual object during touch and grasp. Unlike CLAW, which integrates active actuation through a strong servomotor, CapstanCrunch uses a variable-resistance brake mechanism controlled by a small DC motor. As a consequence, the user experiences a modulated resistance depending on the applied force during finger closure, and very low resistance as the finger opens. In [33], it was shown that CapstanCrunch is better in rendering soft objects with low stiffness values, whereas CLAW is more realistic in rendering rigid objects.

Whitmire *et al.* [34] presented a *Haptic Revolver* - hand-held controller for virtual reality. The device was designed to deliver the tactile sensation of touching a virtual surface. The structure of Haptic Revolver contains an actuated wheel that moves perpendicularly to the fingertip direction to render haptic cues of contact/non-contact with a surface, and rotates to render the sensation of sliding across a virtual surface by providing shear forces when the wheel is in contact with the skin.

TORC [35] is a hand-held device for VR that can render a wide range of haptic cues, including softness of virtual objects and texture of virtual surfaces, and for the precise manipulation of a grasped object by rendering fingers motions. The device was designed relying on a precision grasp. The user's index and middle fingers are placed and captured with a Velcro strap on the finger rest part of the device. The thumb is placed on the opposite side and can be freely moved across a capacitance-based 2D trackpad for the user input. A VCA is placed underneath each of the two rest parts (one for the thumb, and the other for the index and middle finger) to provide vibrotactile sensations.

A device with a similar form-factor was presented by Walker *et al.* [36]. This device, with a cylindrical handle and kinesthetic end-effector extending from the top, was designed to convey sensations for motion guidance in 4DoF. The end-effector is a pair of 2DoF pantograph mechanisms for the thumb and index finger. The device provokes the users to move and rotate their hands in various directions (up/down and forward/backward, twist and tilt). Each joint of the 5-bar linkages pantographs is powered by DC motors.

HaptiVec [37] is another hand-held controller, designed for providing orientation (cardinal directions) in VE. It is made of two devices, one for each hand, which utilize 3 × 5 tactile pin arrays embedded into the handles so as to render directional haptic pressure vectors. HapticVec is a cylindrical shape controller with 15 solenoids with small cylindrical pin contacts arranged in each handle and with one analog 2-axis thumb joystick attached to the top for user control.

PaCaPa (Prop that Alters Contact Angle on PAlm) [38] is a compact box-shaped hand-held device for indirect (tool-based) interaction in VR. It can render shape, size and softness of a virtual object by opening and closing the two sides (wings) of its body. The two wings, opened/closed at the same angle by two servomotors, can open in the range $0° - 90°$. The actuation provides a dynamically changed pressure to palm and fingers, and imitates the angle between the virtual stick and the hand.

While most hand-held haptic devices for VR are designed for interaction with virtual objects without any reference to real samples, Choi *et al.* [39] presented a mobile haptic tool that combines active transient vibrations with pseudo-haptic illusions to augment the perceived softness of haptic proxy objects (i.e., real objects whose perception is modified in VR interactions). The device was designed to be held with one hand using a pointed grasp, with the index finger resting on

TABLE 2. **Hand-held haptic devices.**

Device	Purpose	Kinesthetic Feedback	Cutaneous Feedback	Actuators	Mass
[31]	surface shape rendering	extrusion of the platform	tilt of the platform	(x3) servomotors (Hitec HS-5035HD)	150
[31]	rendering shape of virtual objects and surface structure	N/A	4x4 pin-array	(x16) servomotors (Hitec HS-5035HD)	600 g
[32]	grasping object, touching surfaces, triggering	force feedback on index finger	vibrotactile on the index fingerpad	(x1) VCA + (x1) LRA + (x1) servomotor (Hitec HSB-9370TH)	420 g
[33]	softness of touched and grasped objects	resistance force	N/A	(x1) coreless motor (E-flite EFL9052)	-
[34]	touch, shear, texture, and shape rendering	N/A	shear force by rotating wheel	(x1) servomotor (Hitec HS-5070MH) + (x1) DC motor (Faulhaber 1524-SR)	237 g
[35]	in-hand interaction - texture, compliance	N/A	vibrotactile	(x2) VCA (Dayton Audio DAEX9-4SM)	-
[36]	guidance in medical training, teleoperation and VE	tangential forces	N/A	(x4) DC motors (Faulhaber 64:1) + (x1) DC motor (Pololu 50:1)	76 g
[37]	orientation in VE	N/A	pressure vectors using pin array	(x15) solenoids in each hand (DC0410, Yong Ci Neng Co.)	-
[38]	size, shape and stiffness of a virtual object	opening/closing wings to change the angle	N/A	(x2) servomotors (TowerPro SG92R)	65 g
[39]	softness of haptic proxy objects	N/A	vibrotactile	(x1) VCA (Tectonic Elements TEAX19C01-9)	-
[40]	tele-micromanipulation, microassembly	force feedback on fingertips	N/A	(x1) coreless motor (DCX10L, Maxon Motor)	40 g
[41]	rendering weight/shape of virtual hand-tools	DPHF - weight shifting	N/A	(x1) stepper motor (NEMA-14 type)	440 g
[42]	rendering shape of virtual hand-tools	DPHF - weight shifting in 2D planar area	N/A	(x2) servomotors (Pololu 150:1 HPCB) + (x2) servomotors (Pololu 50:1 HPCB)	400 g
[43]	objects with different scale/ material/fill state	DPHF - weight shifting + air resistance	N/A	(x2) servomotor (MG996R)	598 g
[44]	rendering forces of various directions and magnitudes	DPHF - propeller-induced propulsive force	N/A	(x6) brushless motors (2600KV T-Motor F40 III)	692 g
[45]	dynamic weight motion illusion	DPHF - propeller-induced propulsive force	N/A	(x2) brushless motor (KV3900)	1069 g
[46]	stiffness rendering	extension/retraction of the connecting cable	vibrotactile (Vive controller)	(x2) servomotors (Actuonix L12-R Micro Linear Servo)	*673 g
[46]	stiffness rendering	lock/unlock of ball joints and hinge	vibrotactile (Vive controller)	(x3) servomotors (FEETECH FS5115M)	*793 g
[46]	rendering midair impassable surface	lock/unlock of ball joints and ratchet mechanism	vibrotactile (Vive controller)	(x2) servomotors (FEETECH FS5115M) + (x2) servomotors (Hitec HS-35HD)	*651 g
[47]	rendering virtual objects in hand on demand	force feedback by pivoting handle	vibrotactile feedback from inside the handle	(x1) servomotor(Hitec HS-7115TH) + (x1) VCA	*188 g

* - weight without controllers or trackers.

a finger rest platform. When a user makes the first contact with a proxy object, a VCA placed under the platform generates a transient vibration. The contact with the object and further pressure applied by the user is captured by a capacitive sensor. Then, the captured pressure is applied for rendering a visuo-haptic illusion.

Sakr *et al.* [40], [48] proposed hand-held robotized tweezers for microassembly, as hand-held haptic devices can find their application not only in VR. The active tweezers can be used as either an upgraded version of classical tweezers providing a force feedback, or as a master device in a micromanipulation system to provide the motion control of a slave robot. The master tool is an ordinary tweezer equipped with a DC motor that provides force feedback and controls the opening of branches, and multiple sensors like strain gauges, force sensor under a user's fingertip and markers for its motion capture system. This interface aims to help the operator to feel micro-sized objects by scaling up the robotic gripper work area to a human scale.

2) INDIRECT ACTUATION

Rendering multiple virtual hand tools (e.g. a sword, a crank, a baseball bat) with various shapes is a rather difficult task that cannot be solved with conventional VR controllers. An obvious way of solving this problem is to use a different proxy object for each virtual tool, which might not be an efficient solution in many cases.

An alternative approach to avoid this issue is *Dynamic Passive Haptic Feedback* (DPHF), introduced by Zenner and Krüger [41]. DPHF is a mix of active haptic systems (which directly actuate the human limb) and haptic proxy objects. *Shifty*, presented in [41] is an example of a device using DPHF. The rod-shaped device shifts the position of its center of mass ("weight shifting") using one stepper motor placed on the grip end of the device. This in turn modifies the moment of inertia exerted on the user's hand, to enhance the perception of virtual objects that are changing in shape (length and thickness) and weight. Indeed, psychological studies of the human shape perception mechanism have shown that weight shifting mechanisms can alter the perception of an object's shape without even seeing it [49], [50], [51], [52], [53].

Transcalibur [42] is another weight-shifting device for imitation of various virtual hand-tools (e.g., swords, guns, crossbows), able to dynamically present 2D shapes by changing its mass properties on a planar area. The authors called this kind of illusion *Haptic Shape Illusion*. Transcalibur resembles a handle with two rotatable arms with a maximum rotation angle of 90°. A weighting module is attached to each arm and can slide along it.

Another hand-held haptic device that can give a sensation of operating virtual objects with various shapes and sizes is *Drag:on* [43]. Drag:on uses its pair of wings to dynamically change its surface. Two servomotors can independently open and close the fans to shift the weight and increase/decrease the air resistance that occurs at the controller during hand motions. The device can be used to enhance the realism of VR sport experiences, and of other physical interactions such as rowing, swimming or driving. Its main limitation is the need to keep it in motion for perceiving the haptic feedback.

Drag:on was not the first device to use air resistance for ungrounded force feedback. Researchers have investigated the implementation of propeller propulsion to create thrust via air flow [44], [45]. The idea is to equip a handle held by a user with propellers, so that the user's wrist becomes a pivot point experiencing torque applied by the propeller propulsion. The modulation of the propeller speed and rotational direction causes a dynamic force feedback, giving a perception of change in the center of mass. The main difference with the above-mentioned indirect actuation devices is that propeller-based devices are capable of delivering continuous force feedback creating a dynamic *weight motion illusion* [45] rather than a shape illusion [42].

Heo *et al.* [44] introduced a hand-held VR controller that can deliver a large physical force in 3D. The device, named *Thor's Hammer*, has six brushless motors and accompanying tri-blade propellers that generate bi-directional thrust (up to 4 N) in three axes. Motors and propellers are mounted on the sides of a carbon fiber pipe cubic cage. Thor's Hammer demonstrated enhanced realism of VR experience such as holding a virtual stick in flowing water, herding a sheep and simulating different weights. Despite its high rendering accuracy (RMSE of less than 0.11 N and 3.degree), compared to other devices the device has high actuation latency (309.4 ms), a large weight and size, high power consumption, and noise.

Aero-plane [45] uses only two jet-propellers, and provides an even greater thrust (up to 14 N). The device resembles a cylindrical handle with the jet propellers at one end, and a counterbalancing weight at the other end. Despite the parallel direction of propeller thrust, the independent control of the propeller provides the user with a torque around the handle axis. Therefore, Aero-plane is able to provide the haptic illusions of a shifting weight on a 2D plane. The device showed an increased immersion level in VR applications such as rolling a ball on a 2D plane, operating virtual food with different virtual cooking utensils, and fishing. Aero-plane shares the same practical disadvantages as Thor's Hammer.

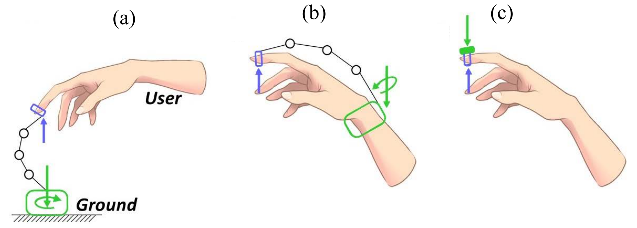

FIGURE 4. Schematics of different groundings of haptic devices: (a) world-grounded (i.e. tabletop) haptic device, (b) body-grounded kinesthetic device (i.e. exoskeleton), (c) finger-worn cutaneous device. The reaction forces are shown in green, actuation force in violet. Adapted from [9].

Thus far we have reviewed hand-held devices designed to be used with one hand or with two independent hands. Instead, Strasnick *et al.* [46] focused on rendering haptic feedback *between* two hands for bimanual interactions. Examples provided by the authors are driving with a virtual steering wheel and operations with two-handed tools or weapons. The system with two controllers physically linked through an electro-mechanically actuated connector is named *Haptic Links*. There are three prototypes of Haptic Links - *Chain*, *Layer-Hinge* and *Ratchet-Hinge* - which are different in terms of linkage design.

Another haptic device for VR that utilizes a proxy object is *PIVOT* [47]. Although the device is wrist-worn, it also comprises a pivoting handle to be placed in the user's hand, and is thus a hybrid between wrist-worn and hand-held devices. In synchronization with VE, the motorized hinge is able to quickly bring/move out the generic haptic handle to/from the user's hand, thus simulating the grasping or throwing of a virtual object. Also, PIVOT can to exert forces in both directions along the axis normal to the palm surface, imitating gravity, inertia or drag.

C. EXOSKELETONS

The most typical forms of wearable haptic devices are haptic gloves and exoskeleton systems (or, in short, exoskeletons). The main difference between them is that not necessarily all haptic gloves have an exoskeletal structure, and not necessarily all exoskeletal systems are in the form of a glove. These devices are aimed at rendering kinesthetic haptic feedback while being grounded on the user's body [9]. Please notice that gloves and exoskeletons that are used as prosthetic devices or for the enhancement of lost capabilities of disabled people are out of the scope of this review paper, also due to space limitation.

The main drawback of body-grounded haptics is that the wearers feel two types of forces applied to their bodies: the force applied to the desired point of haptic stimulation, and an undesired reaction force at the point of attachment to the body, which counterbalances the first one (Fig. 4b). In order

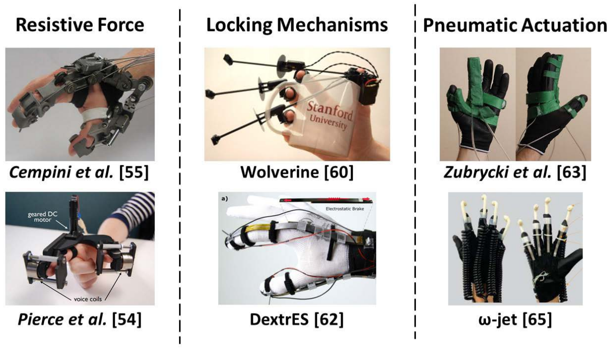

FIGURE 5. Examples of resistive force (left column), Locking mechanism (central column) and pneumatic actuation (right column) type haptic gloves and exoskeleton devices.

to make the reaction force less perceivable, one typically designs the device to distribute it onto a large contact surface. Also, moving the body-grounded base as close as possible to the point of application of the haptic stimulus improves wearability (Fig. 4c). However, as mentioned in [10], a very close location of the base and the end-effector to each other makes the device only provide tactile feedback, and all kinesthetic properties disappear.

Present commercially available glove-based haptic exoskeletons are Dexmo (Dextra Robotics, China) and CyberGrasp (CyberGlove Systems LLC, USA). These devices provide a realistic grasping sensation by means of resistive forces. The factors that prevent widespread use of these devices are practical limitations such as careful putting on/off, low versatility to different user sizes, and expensiveness due to the number and complexity of mechanisms.

The previous review papers on haptic gloves and exoskeletons were considering a classification by haptic stimuli [9], actuation technology of haptic gloves for VR [11], pros and cons of existing force feedback gloves, and the design guidelines [10] and requirements of hand exoskeletons [54].

Pacchierotti *et al.* [9] defined exoskeletons as "a type of haptic interface which is grounded to the body". Their review paper focused on two groups of exoskeleton devices, based on kinesthetic and vibrotactile feedback.

In a review on haptic gloves for VR by Perret *et al.* [11], the authors categorized the devices into three groups - traditional gloves, thimbles and exoskeletons. This review is focused on commercially available prototypes and discusses the design challenges facing this technology.

The most recent and detailed review on exoskeletons and gloves was published in 2019 by Wang *et al.* [10]. The paper presents a classification of both research prototypes and commercially available haptic gloves, and design guidelines for the hardware components of force feedback gloves (actuation, sensing, transmission, control and mechanical structure), referring to anatomical features of the human hand. Wang *et al.* classified the kinesthetic gloves by the location of the actuation - ground-based, dorsal-based, palm-based, and digit-based gloves. This approach is intuitive and reasonable due to the strong effect of the location of the actuation on force feedback performance and device characteristics (weight and size).

As an alternative approach to [10], in this review we propose to classify exoskeleton systems and haptic gloves by means of delivering haptic cues - through resistive force, locking mechanisms or pneumatic actuation. All the reviewed devices, summarized in Table 3, explored different approaches of delivering the sensation of grasping or gripping virtual objects.

1) RESISTIVE FORCE

This type of haptic gloves and exoskeletons provide a force feedback by actuating motors that generate resistive force, whose key feature is to be bidirectional and non-discrete. Therefore, these devices can provide the haptic illusion of various size, shape and stiffness levels of graspable virtual objects.

Pierce *et al.* [55] developed a two-finger-wearable haptic device with both kinesthetic and tactile feedback designed for teleoperation over a robotic gripper. The device represents a gripper-style rigid structure which covers the user's index finger and thumb from the dorsal side. The angle between the thumb and index finger is controlled via a 1-DoF revolute joint actuated by a geared DC motor. There are movable rigid platforms at both fingertips, which provide pressure force and vibrotactile feedback via voice coil actuators.

Another finger-thumb style wearable exoskeleton device was proposed by Cempini *et al.* [56]. However, this device has more DoF and more complex kinematics compared to the device proposed in [55], due to its modular structure. There are sixteen DoF in total - seven for the index finger (three passive, four active) and nine for the thumb (six passive, three active). The force is applied to carpal, metacarpal, and phalangeal joints (all being of revolute type) through a cable-driven actuation system.

Dexmo [57] is a hand exoskeleton system with force feedback for rendering the sensation of grasping a virtual object. The device has a simple and lightweight design and consists of the following main parts: controller, force feedback units, rigid connectors and finger caps. Dexmo is worn on the dorsal side of the hand, being attached to the fingertips with finger caps and to the palm with a strap. The main controller is in the central unit, placed on the back of the palm. Each of the five finger caps is connected to the central unit through rigid connectors and the force feedback unit. The force feedback unit consists of two rotational sensors, which track the angle of upper and lower connectors, and a micro servomotor that locks the joints (rotation of both connectors) in response to a scene in the VE. Thus, Dexmo can only provide a binary force feedback not being able to render the stiffness of virtual objects.

Jo *et al.* [58] developed a three-finger exoskeleton system for VR to render the stiffness of various virtual objects. The system is similar to Dexmo in terms of form-factor - palm-based central unit and rigid linkages (5 DoF) for fingertips.

TABLE 3. Exoskeletons and gloves.

Device	Type	Purpose/Haptic Illusion	Kinesthetic Feedback	Cutaneous Feedback	Max Force[N]	Mass[g]
[55]	resistive force	teleoperation	(x1) DC motor	vibrotactile & normal force	6.7	-
[56]	resistive force	HRI	(x2) DC motor + cables	N/A	-	438*
[57]	resistive force	object grasping	(x5) micro servomotors	N/A	-	270
[58]	resistive force	object grasping	(x3) DC motors	N/A	2	488
[59]	resistive force	object grasping	(x2) DC motors + TSA system	N/A	80	360
[60]	resistive force	teleoperation	(x1) active Delta robot structure	N/A	5	2,224
[61]	locking mechanism	object grasping	(x3) DC motors	N/A	106	55
[62]	locking mechanism	weight & stiffness of grasped object	(x2) DC motors	vibrotactile	-	65
[63]	locking mechanism	object grasping	(x2) ES brakes	vibrotactile	20	8
[64]	pneumatic actuation	stiffness of grasped object	(x2) jamming pads/tubes	vibrotactile	7	70
[65]	pneumatic actuation	object grasping	(x2) soft elastomer actuators	N/A	2.1	30.8
[66]	pneumatic actuation	stiffness of grasped object	(x4) air-jet nozzles	N/A	0.7	175

* - weight without actuating block placed on the forearm.

However, this device is designed only for three fingers - thumb, index and middle fingers. The device is connected only to the fingertips through a ring with a click buckle for ease of wearability. Each fingertip is powered by a DC motor located on the dorsum of the hand.

ExoTen-Glove [59] is a haptic glove for VR applications based on *twisted string actuation* (TSA), for rendering the sensation of grasping virtual objects with various stiffness. Generally, a TSA system is an actuating module consisting of a high speed and low torque DC motor and a twisted string, which connects the motor with the load (tendon). The rotation of the DC motors is transformed into a linear motion at the load side by the contraction of the spring. Such an actuation approach allows for a lighter and less bulky exoskeleton structure as compared to [55], [56], and [58]. ExoTen-Glove has two TSA modules - one for the thumb and one for the other fingers - placed on the forearm. The tendons are attached to a commercial soft glove.

While the above-mentioned exoskeleton devices focus on providing force feedback to the user's fingers, *W*Δ [60] is designed for providing force feedback to the user's hand back (wrist). The exoskeletal system is worn on the user's forearm and provides the actuation through a hybrid serial-parallel kinematic structure and passive gimbals. WΔ has shown its efficiency in teleoperation by rendering contact forces sensed by a controlled robot end-effector.

2) LOCKING MECHANISMS

The working principle of this type of haptic gloves and exoskeletons is that a locking mechanism actuated by a motor makes the system rigid, restricting the movement of the user's proximities. This type of actuation is unidirectional and can only convey the sensation of rigid virtual objects.

Wolverine is an exoskeleton force-feedback device presented in [61], designed to deliver kinesthetic feedback in a specific configuration - between the fingers (index, middle and ring) and thumb - to simulate grasping of rigid objects in VR. The base of the device (microcontroller, motor driver, inertial measurement unit (IMU) and battery) is mounted on the thumb, whereas each of the three other fingertips is attached to a sliding mount. The thumb and the other fingers are interconnected through an exoskeleton structure consisting of carbon fiber rods with sliding mounts moving along them. The rods are linked to the base with ball joints (3DoF). Each sliding mount is equipped with a braking mechanism actuated by a DC motor at the moment when it is required to simulate a grasp. Since Wolverine uses the same passive actuation principle as Dexmo, stiffness rendering is also impossible with Wolverine.

Grabity [62] represents another approach for rendering virtual object grasping with a haptic exoskeleton. The device with a gripper-like form-factor [55], [56] combines a unidirectional brake mechanism [61] with vibrotactile feedback. The base of the device is mounted on the thumb, whereas the sliding part is mounted on the index finger. Both the base and the sliding part have a pad for fingers with a linear VCA attached to the fingertips. The addition of a pair of vibromotors allows rendering touch and gravity (pulling force) sensations via symmetric and asymmetric vibrational stimuli, respectively.

Another device with a locking mechanism was designed in the form of standard exoskeletons for the hand. The key unit of *DextrES* [63] consists of electrostatic (ES) brakes, which can generate a resistive force on the wearer's index finger and thumb. Each ES brake is made of metal strips that slide freely on each other and do not constrain limb movement when no voltage is applied. Being mounted to a textile glove and attached to the back of the thumb and index finger, the ES clutches block the human joints' movement when the control voltage is applied, thus simulating the object grasping sensation. In addition to the kinesthetic feedback, DextrES utilizes vibromotors attached to the fingertips for enhancing the haptic illusion of grasping.

3) PNEUMATIC ACTUATION

This type of device uses pneumatic actuation (using either a pump or a compressor) for delivering force feedback, via soft actuators and tubes attached to a fabric glove.

Zubrycki and Granosik [64] presented a haptic glove that uses the *jamming principle* for providing force feedback. The key feature of this device is a combination of jamming tubes (or jamming pads) and vibration motors. The jamming elements are elastic actuators made of latex rubber. These elements are placed on the inner side of the hand joints and, being controlled by the vacuum pressure, can resist or block movement of the user's joint. The combination of jamming mechanisms and vibrotactile stimuli provides the user with the sensation of grasping virtual objects with various stiffness levels. The disadvantages of this approach are the need for a bulky pneumatic system (which leads to a limited workspace), and considerable actuation time (0.5 s).

In contrast, Zhang *et al.* [65] demonstrated an approach with pneumatic actuation using high pressure instead of vacuum as in [64]. Silicone elastomer actuators, placed inside a textile glove, are attached to the dorsal side of the thumb and index finger. During high air-pressure supply, the actuators bend creating a resistive force on the fingertips.

Besides pneumatic (low/high pressure) soft actuation, air flow is also used for providing air-jet force-feedback: this is the case of *ω-jet* [66], a glove without exoskeletal structure able to convey stiffness and elasticity sensations while interacting with virtual balls of different size and stiffness. The device is equipped with four nozzles (for index, middle, ring and little fingers) for air jetting and four bend sensors for finger angle detection. The nozzles are attached to the dorsal side of the fingers such that they slightly protrude beyond the fingertip. The bend sensors are positioned along the ventral side of the fingers.

While the haptic sensations delivered by haptic gloves and exoskeletons can be of high fidelity, they have some practical limitations. The weight of such devices is comparatively high, which causes fatigue over periods of more than one hour [47]. Typically haptic gloves and exoskeletons are cumbersome and thus often limit the full range of the wearer's motion. In addition, it requires a long time to put them on and to take them off [32].

D. FINGER-WORN DEVICES

Finger-worn haptic devices (also known as *thimbles*, and listed in Table 4) mostly focus on the tactile stimulation of the fingerpads. Indeed, the latter show one of the highest density of tactile receptors within the human body [6], and most dexterous manipulation activities involve our fingertips [67]. This is especially true for the index finger, which is involved in most actions and gestures.

During fingerpad-object interaction, mechanoreceptors are stimulated by different physical cues due to changes in contact surface, local surface orientation and skin stretch. Thus, most haptic thimbles are designed relying on these principles, and based on two main approaches: moving platform mechanisms [3], [7], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], and shearing belt mechanisms [79], [80], [81], [82]. Other less common approaches are moving tactors [83], and systems with electrical [84], thermal [76], vibration [85], [86] and pneumatic [87] stimulation.

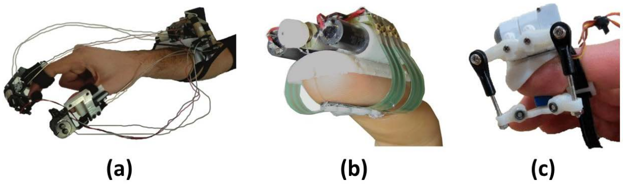
(a) (b) (c)

FIGURE 6. Finger-worn haptic devices of a moving plate type: (a) a heavy and bulky device with sheathed tendon actuation [68], (b) lighter and more compact devices with actuation through DC motors and gears/cables [69], (c) light and compact devices actuation through servomotors and rigid links [74].

1) MOVING PLATFORM

Typically, moving-platform type devices possess a parallel mechanical structure (Fig. 6). The whole system can be separated into two parts - base and end effector (moving platform). The base is placed on the nail side on the last phalanx of a finger, and supports joints and actuators. It is fastened with a strap on the intermediate (middle) phalanx. On the volar side of the finger, an end-effector acts on the fingerpad providing cutaneous feedback through mechanical skin deformation. The end-effector usually moves with 3 DoF - via a combination of rotational and prismatic joints - covering most of the fingerpad.

The overall trend in the development of moving plate type finger-worn haptic devices is shown in Fig. 6. The development of haptic thimbles of this type started from creating portable versions of the previously-available bulky grounded haptic thimbles (see, e.g, [92]). For example, Solazzi *et al.* [68] created *Active Thimble* for virtual shape exploration making it wearable and mobile, but still cumbersome due to the use of a heavy motor pack with sheathed tendon actuation of the end-effector. Later, a decrease in size and weight of devices was achieved through the use of cables [7], [88] or gears [73] controlled by light DC motors. The end-effector of *Haptic Thimble* presented in [73] is equipped with a VCA for surface edges and texture rendering.

The authors of [7] and [88] showed similar fingertip haptic devices. Their approach consists of controlling position and orientation of the end-effector through wires whose lengths and strains are tuned by three DC motors. Later on, these DC motors were replaced by servomotors [3], [77], [93]. In [3], [73], and [77], a vibromotor is mounted on the mobile platform for providing rendering surface features such as edges, texture and stiffness.

The authors of [71] and [70] presented two haptic thimbles in which the cable links between the base and mobile platforms are substituted with rigid 3D-printed limbs. These new prototypes have a 3-DoF kinematic chain which allows compact dimensions with minimum encumbrance within the hand workspace and mechanical interference with other fingers. The devices show increased performance compared to

TABLE 4. Finger-worn haptic devices. Type: MP - moving platform, SB - shearing belt, OT - other types.

Device	Type	Haptic Feedback	Haptic Illusion	VE	Actuators	Mass
[68]	MP	skin stretch	surface shape	-	(x4) DC motors (Faulhaber 1524) + (x1) VCA (BEI Kimco LA08-10)	256 g
[73]	MP	skin stretch + vibrotactile	surface shape & texture	VR	(x1) VCA + (x2) servomotors	30 g
[88]	MP	skin stretch	surface curvature	-	(x3) DC motors (Faulhaber 0615S)	30 g
[7]	MP	skin stretch	stiffness	-	(x3) DC motors (Faulhaber 0615S)	35 g
[3]	MP	skin stretch + vibrotactile	palpation (robotic surgery)	VR	(x3) servomotors (Pololu SubMicro) + (x1) vibromotor (Force Reactor, Alps Electric)	-
[77]	MP	skin stretch + vibrotactile	object manipulation	VR	(x1) ERM vibromotor (VPM2, Solarbotics)	10 g
[71]	MP	skin stretch	surface exploration	VR	(x3) servomotors (Turnigy TS531A)	-
[70]	MP	skin stretch	surface orientation	-	(x3) servomotors (Turnigy TGY-1370A)	-
[89]	MP	skin stretch + vibrotactile	surface exploration, softness	VR	(x3) servomotors (HiTech HS-5035HD)	25 g
[74]	MP	skin stretch	object manipulation	VR	(x3) servomotors (HK-282A RC)	16 g
[75]	MP	skin stretch	weight, stiffness, friction	VR	(x2) DC motors (Faulhaber 0615S)	32 g
[78]	MP	skin stretch + force feedback	teleoperation	VR	-	42 g
[83]	MP	skin stretch	surface exploration & weight	VR	(x2) DC motors (Maxon RE8)	22 g
[79]	SB	skin stretch	gravity & grip force	-	(x2) DC motors (Maxon RE10)	35 g
[80]	SB	skin stretch	stiffness	VR/AR	(x2) servomotors (HiTech HS-40)	15 g
[85]	OT	vibrotactile	stiffness	VR	(x1) ERM vibromotor (Precision Microdrives 310-113)	-
[86]	OT	vibrotactile	surface texture	VR/AR	(x1) VCA (Bone Conductor Transducer, Adafruit)	9.6 g
[84]	OT	vibrotactile + electrical	hardness, friction, fine & macro roughness	-	(x1) DC motor (Maxon 118386) + (x1) 4×5 electrode array	15 g
[90]	OT	force feedback	contact & softness	-	HC-DEAs (VHB 4910, 3M)	-
[91]	OT	skin stretch	contact/non-contact	-	TCP actuators	14 g

cable-driven moving platform devices in terms of the maximum normal force exerted on user's fingertip (up to 4.7 N).

Later, the device of [70] was improved by adding vibrotactile feedback under the moving plate, which gives the perception of surface softness [89]. A further improvement of the device described in [89] was proposed in [78], by adding a 1-DoF kinesthetic finger module for better virtual manipulation performance. The fingertip module is grounded on the distal phalanx, whereas the kinesthetic module with an additional servomotor is fixed on the proximal phalanx. The two modules are connected through a rigid rod that provides force stimuli to the proximal and distal interphalangeal joints.

A rubber tactor is mounted on a moving platform in [74], [83], and [75] for better shear force provision. In [75] the tactor is placed on a delta parallel mechanism actuated with a motor-linkage tether driven by two DC motors, able to exert the normal force up to 7.5 N. On the other hand, in *HapTip* [83], a tactor is mounted on a static platform under the fingertip and can only provide shear force (up to 3 N). Wearing such skin-stretch devices on multiple fingers gives the ability to render the feelings of weight of a virtual object and of roughness of virtual surfaces.

Lim *et al.* [94] presented a haptic device with a moving actuator. The tactor is set into motion by SMA actuators through two transmission mechanisms: a 3-DoF tip-tilt and 2-DoF planar 3D-printed springs. The choice of SMA-type actuators was due to their mechanical simplicity, shear deformation of the fingertip skin, lightweight and silent operation with smooth motion. The designed 5-DoF fingerpad device can provide a reliable weight sensation for virtual objects.

2) SHEARING BELT

Another popular approach of providing haptic cues to user's fingerpad is based on the use of a fabric belt. The first device of this type was introduced by Minamizawa *et al.* [79]. Due to the fingerpads deformation caused by the shearing belt, the device can reproduce a realistic gravity sensation even in the absence of proprioceptive stimuli on wrist or arm.

Devices of this type consist of a pair of DC motors placed on the platform fixed to the nail side of the user's finger, and a belt that is in contact with the fingerpad (Fig. 7). The ends of the belt are attached to two pulleys actuated by the DC motors. When the motors rotate in the same direction, the belt generates shearing stress on the fingertip, while, when the motors rotate in opposite directions, the belt exerts a normal force on the fingertip.

In *hRing*, Pacchierotti *et al.* [80] replaced the DC motors used in [79] with servomotors, which allows controlling the amount of skin deformation, proportional to the motor position. hRing provides cutaneous stimuli to the proximal phalanx of the finger instead of the fingertip, which makes the user's fingertips free to interact with the real environment (e.g., in AR applications). In [95] and [82], it was shown that such haptic stimulation can considerably alter the perceived stiffness of real objects, even when the tactile stimuli are not delivered at the contact point.

Bianchi *et al.* [81], [96] went further and presented the *Wearable Fabric Yielding Display (W-FYD)*, a fabric-based finger-worn display for multi-cue delivery. The device aims to enable both active and passive softness exploration. From the mechanical perspective, it differs from previous rolling

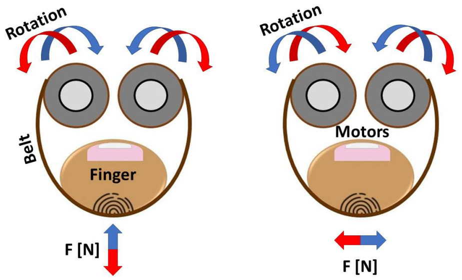

FIGURE 7. **Working principle of shearing belt type haptic devices.**

fabric-belt fingertip devices by the addition of a lifting mechanism that independently regulates the pressure exerted by the belt on the fingerpad. However, its mechanical complexity leads to larger normal forces applied to the fingerpad (8.5 N) as well as an increase in weight and dimensions.

Aoki *et al.* [97] presented a device with form-factor similar to shearing-belt type devices. However, a thin wire was used instead of a belt to decrease weight. The wire is moved only perpendicularly to the fingerpad, exerting a force up to 40 mN.

Overall, thimbles of this type are very simple, compact and light. They can be used in multi-finger combination and can provide the sensation of weight, inertia and stiffness while grasping a virtual object. Their main disadvantage - impairing hand mobility - comes from the need for well tightening in order to avoid instability during shear force display, and this blocks the phalanges articulation.

3) OTHER TYPES

Vibrotactile stimulus is one of the most popular types of cutaneous feedback due to the small and lightweight form factor of vibrotactile actuators that allows to develop highly-wearable interfaces [9].

Maereg *et al.* [85] proposed to use vibrotactile feedback directly on fingertips without using moving platforms. The haptic setup consists of five eccentric rotating mass (ERM) vibrotactile actuators, one actuator per finger, fixed on fingerpads via straps. The frequency of vibrations is modulated proportionally to the interaction force. In combination with visual feedback provided through an HMD, the tactile device can give the sensation of tapping a stiff object in the VE. The controller is placed on the wrist, which makes the overall structure highly wearable and wireless.

A finger-worn device utilizing vibration feedback in combination with normal and shear force feedback was presented in [98]. The haptic feedback is delivered through the use of magnetic field actuation. The device structure consists of a plastic cuboid casing with its top side being soft (nitrile rubber). The casing is filled with ferro-fluid and attached to the distal phalanx. The ferro-fluid is used for magnetic field enhancement, and lubrication of a neodymium magnet (NMEF) placed inside the casing. The feedback is delivered to the fingertip with the movement of the NMEF. In turn, the NMEF movement (normal to the fingertip and rotational) is caused by the control of the voltage of a solenoid winded around the casing and the orientation of an external neodymium magnet (ENM). The orientation of ENM is regulated by a DC motor attached to the bottom side of the casing.

Most of the previously described finger-worn haptic devices focus on providing tactile stimuli to the most sensitive part of the skin - the fingerpad. Gaudeni *et al.* [86] presented a haptic ring that provides a vibrotactile feedback, and can be worn on three different locations: fingertip, dorsal side of proximal phalanx, and wrist. The device is composed of a VCA enclosed in a 3D-printed housing that can be fixed to a limb. In [86], it was concluded that the vibrotactile cues provided by the haptic ring on the proximal phalanx are sufficient for a user to distinguish between different surface textures. Thus, this type of design can help free the fingertips for other tasks.

Several studies have proposed the use of direct electrical stimulation of the nerves to achieve high responsiveness of skin and small device size of a device. However, it is still challenging to reproduce realistic tactile cues using this method. Thus, in 2017, Yem and Kajimoto [84] developed a finger-worn tactile device called *FinGAR* (Finger Glove for Augmented Reality). The device uses a combination of electrical and mechanical (vibrational) actuation that gives four different stimulation modes: skin deformation, high-frequency vibration, anodic and cathodic stimulation. Thus, the sensation of four tactile dimensions - macro roughness and hardness (affected by low-frequency vibration and cathodic stimulation), friction and fine roughness (affected by high-frequency vibration and anodic stimulation) - can be reproduced by a combination of these modes. The ‘‘glove’’ consists of three FinGAR devices to be worn on the thumb, index and middle fingers. Every single thimble is made of three main parts - a 3D-printed base that grips both sides of the distal phalanx, a DC motor and a 4 × 5 electrode array film.

All the haptic devices described above employed a variety of different actuators that provide different tactile sensations (such as contact with objects and surfaces, and properties like roughness, shape and softness) through rigid end-effectors. Stiff surface end-effectors, suitable for shape rendering, cannot effectively render softness perception, which is a major goal for modern haptic interfaces. According to Srinivasan and LaMotte [99], Moscatelli *et al.* [100] and Dhong *et al.* [101], both contact area and indentation depth must be controlled to render the stiffness of virtual deformable objects. Since the feedback applied by stiff surfaces controls only the indentation of the skin, the most effective strategy is to use soft interfaces such as dielectric elastomer actuators (DEAs), electrostatic actuators and pneumatic actuators.

Frediani *et al.* [90] introduced a wearable tactile display for the fingertip which is able to simulate contact with soft bodies in the VE using a soft actuator. The new

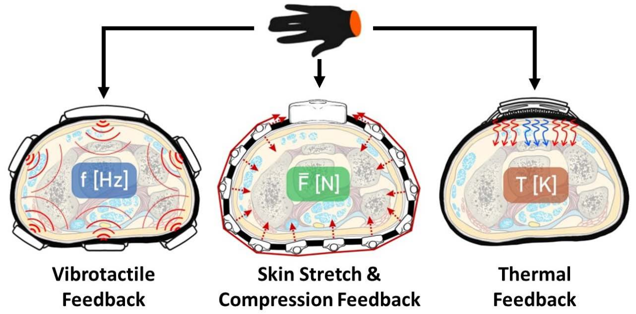

FIGURE 8. Schematics of three actuation types of arm-worn haptic devices put on the cross-section of the forearm: (a) vibrotactile feedback, (b) skin stretch and compression feedback, (c) thermal feedback.

approach is based on DEAs, which are intrinsically soft, compact, lightweight, and silent during operation. The device is mounted on the user's fingertip with the actuator being integrated within a plastic case and placed under the user's fingerpad. The main drawback of using DEAs is the need for high driving voltages (4.5 kV).

Chossat *et al.* [91] proposed a finger-worn skin-stretch device based on a soft elastomeric adhesive skin and twisted and coiled polyethylene (TCP) actuators, which had not been considered for wearable devices before. The haptic skin is worn on the back side of the index finger. The skin can be pulled via nine retainers. When heated, the TCP actuators contract and pull the retainers; the TCP is released when cooled down. The bandwidth of such a system is rather low and thus TCP-based stimuli are less effective in interactions with a virtual wall than VCA-based stimuli.

E. ARM-WORN DEVICES

Arms as a possible location for haptic feedback have been used less than hands, possibly due to the lower density of mechanoreceptors [102]. Indeed, since the human tactile acuity varies across the skin surface, relocating haptic cues away from the actual location where they are typically experienced (mainly, fingertips) may degrade the sense of realism. This is probably the reason why wrist-worn bracelet-type devices have been investigated more recently than other types of wearable haptic systems. Bracelets, however, have the advantage of freeing the fingers for other tasks, which makes it possible for users to easily switch between the VE and the real world, or to change the tactile feeling of real objects by augmenting them with virtual textures [86].

The application of these haptic devices can be split into two categories: guiding (e.g. navigation, telemanipulation) [103], [104], [105], [106], [107], [108] and enhancement of tactile perception [109], [110], [111], [112]. In order to properly use devices of the first category, the user has to complete a training phase. Instead, devices of the second category do not require such phase, but have to provide a strong haptic stimulus that can be easily perceived.

In terms of the type of stimuli, wrist-worn bracelet-type devices can be divided into vibrotactile, skin stretch and compression, and thermal, as detailed in the following.

1) VIBROTACTILE FEEDBACK

As observed for previous tactile devices discussed in this survey, vibrotactile stimulation has been preferred by many haptic wristband developers due to the compact size and the light weight of the vibration actuators. Thus, wrist-worn haptic devices of this type are mostly used for applications within physical activities. For example, the authors of [103] used haptic bands called *Hapi Bands* for guidance in Yoga postures.

Panëels *et al.* [104] introduced a tactile bracelet for navigation tasks. The device has the form of a wristwatch and is equipped with six electromagnetic actuators arranged in a circle that provide vibrotactile feedback. The navigational information is delivered via a combination of vibration patterns including duration, pauses, frequency, amplitude, position and number of tactors.

Another haptic wristband for navigation was described in [105], where vibrotactile feedback is provided to navigate a user during human-robot guidance. The actuation is performed by three cylindrical vibromotors, which provide a haptic signal when the human deviates from the planned trajectory.

The arm-worn device presented in [115] uses vibrotactile feedback for haptic communication. The device consists of a sleeve with six VCAs placed in the Braille layout. Language messages are encoded through vibrotactile patterns. The results of the presented experiments show that it is possible to use haptic devices as an alternative to visual and auditory communication channels. Prior to the usage of the device, a training phase is required to learn haptic cues representing nine phonemes.

Haptic wristbands have shown effectiveness in performing teleoperation tasks. Bimbo *et al.* [113] presented a haptic system for operation in cluttered environments. The wearable (master) part of the system consists of two vibrotactile bracelets, worn on the user's forearm and upper arm. Four vibration motors, evenly positioned around the arm, provide directional information about the collisions sensed by the slave system (IIT/Pisa SoftHand and Universal Robot arm). The amplitude of the vibration stimuli is proportional to the force of the collision.

Zhao *et al.* [114] have introduced an approach of providing vibration-like feedback using dielectric elastomer actuation. A 2×2 array of dielectric elastomer actuators is placed inside a textile sleeve. Each actuator is controlled independently and provides normal force to the wearer's skin on the forearm when a voltage is applied. The soft actuators have moderate bandwidth (up to over 200 Hz) and an actuation force of 1 N.

In the field of AR/VR hand interactions, Pezent *et al.* [111], [112] presented a haptic wristband called *Tasbi*. The bracelet's hardware consists of six linear resonant actuators (LRAs) evenly distributed around the circumference of the

TABLE 5. Arm-worn haptic devices.

Device	Haptic Feedback	Actuation Place	Haptic Stimulation	Actuators	Mass
[103]	vibrotactile	wrist + arm + waist	patterns for static posture	(x4) ERM motors (Precision Microdrives 310-101)	-
[104]	vibrotactile	wrist	direction cues	(x6) electromagnetic actuators	-
[105]	vibrotactile	wrist	direction cues	(x3) vibromotors (Precision Microdrives 303-100)	-
[113]	vibrotactile	forearm + arm	stiffness of collided objects	(x4) vibromotors (Precision Microdrives 307-100)	-
[114]	vibrotactile	wrist	patterns for notifications	(x4) DEAs	-
[115]	vibrotactile	forearm	patterns for communication	(x6) VCAs (TEAX13C02, Tectonic Elements)	-
[116]	vibrotactile	arms	patterns for notifications	(x4) ERMs	-
[112]	vibrotactile + compression	wrist	stiffness of virtual button	(x6) LRA + (x1) tensioning mechanism	200 g
[117]	skin stretch	wrist	direction cues	(x2) servomotors (Futaba S3114)	160 g
[118]	skin stretch	wrist	2D geometric shapes and characters	(x1) gear motor (Precision Microdrives 206-110) + (x1) linear microservo (Spektrum AS2000L)	-
[107]	skin stretch	wrist	direction cues	(x4) servomotors (Hitec HS-40)	95 g
[119]	compression	wrist	patterns for notifications	(x1) blood pressure cuff (AEG BMG 5610)	-
[120]	compression	wrist	spatial patterns	(x1) shape memory alloy spring (30-coil, Flexinol)	-
[121]	skin stretch	forearm	touch sensations	(x15) shape memory alloy plasters (BMF150 SMA)	-
[109]	skin stretch	wrist	grasping a virtual object	(x2) RC servomotors (Tower Pro SG90, Umemoto LLC)	100 g
[110]	skin stretch + compression	wrist + forearm	forces on teleoperated gripper	(x1) micro linear actuator (L12-P, Actronix) + (x4) servomotors (Dynamixel XL-320, Robotis)	306 g
[122]	skin stretch + compression + vibrotactile	forearm	directional cues	(x2) servomotors (HS-625MG, Hitec) + (x4) vibromotors (Precision Microdrives 307-100)	220 g
[123]	skin stretch + compression + vibrotactile	arm	phonemes for communication	(x4) vibrotactors (C2 Tactors, Engineering Acoustics) + (x1) servomotor (HS-485HB, Hitec RCD USA) + (x1) servomotor (HS5070MH, Hitec RCD USA)	-
[106]	compression	wrist	direction cues	(x4) thick low-density polyethylene thermoplastic	-
[124]	skin stretch	wrist	direction cues	(x4) silicone rubber actuators	-
[108]	positional	forearm	patterns for abstract info	(x4) continuous rotation servomotors	403 g
[125]	thermal	forearm	direction cues	(x3) thermal electric coolers (MCPE1-01708NCS, Multicomp) + (x3) thermistors (MC65F103A, Amphenol Sensors)	-
[126]	thermal	wrist	patterns for abstract info	(x1) thermoelectric module (TE-127-1.0-2.5, TE Technology)	-
[127]	thermal	wrist	patterns for guidance and notifications	(x6) thermoelectric modules	-
[128]	thermal	wrist + forearm + ankle + neck	enhancement of movie experience	(x2) thermoelectric modules in series	91 g

wrist for vibration stimuli, and a sophisticated tensioning mechanism for producing pure, uniform squeezing (normal to the skin) force. Tasbi uses squeeze and vibration to create ‘‘a highly believable’’ tactile illusion of pressing on a variable-stiffness virtual button with a finger.

Another example of the utilization of haptic bracelets in entertainment is live music performances. Turchet *et al.* [116] presented an arm-worn device for generating music-related haptic stimuli. The device delivers vibrotactile feedback to the audience in response to the actions of the performers on their instruments. In their previous work [129], the same authors proposed this system for music performers’ communication. The vibrotactile system can be also worn to other body parts such as chest and legs.

2) SKIN STRETCH AND COMPRESSION FEEDBACK

The high sensitivity of human skin to tangential stretches motivated the development of haptic bands with skin stretch feedback [107], [108], [109], [110], [118], [124]. In comparison, compression feedback provides less attention-demanding, and more prolonged background feedback [119], [120].

Caswell *et al.* [117] evaluated that the minimum skin displacement required to be applied on the forearm to be perceived by a user is 2 mm. Based on this requirement, a forearm-mounted directional skin stretch device was designed. The skin stretch feedback is provided by a rubber coated tactor attached to a planar-sliding plate that is position-controlled by two servomotors through steel wires.

Ion *et al.* [118] have developed a novel forearm-worn haptic device, namely the *skin drag* display. The device produces skin-stretch feedback by dragging a physical tactor along the user’s skin within the circular 2D working space of the display. It was shown that the skin drag display delivers geometric shapes and characters to a wearer with a lower error rate (around 19%) comparing with vibrotactile feedback.

Chinello *et al.* [107] presented a wristband for haptic guidance. The device provides skin stretch feedback for human guidance and robotic telemanipulation. The stimulus is generated through four cylindrical servomotors, each of which is connected to two plastic end-effectors covered with rubber. Depending on the combination of actuated motors and the direction of rotation, the bracelet is able to provide either rotation (about the forearm) or translation (along dorsal, palmar, radial and ulnar sides) cues.

Squeezeback, presented in ([119]), is a haptic bracelet that provides a compression feedback. The device uses inflatable straps which apply a uniform pressure around the wearer's wrist to deliver notifications. It was found that users employ more time to react to compression stimuli (due to inflation time) compared to vibrations.

Another approach of delivering a compression feedback was demonstrated by *HapticClench* in [120]. The haptic wristband generates squeezing pressure feedback using SMA springs wound around the wrist. The device is able to provide four different levels of load. Also, the authors have built a miniaturized copy of HapticClench for a finger. It was revealed that a higher load is required to distinguish the squeeze on a finger than on a wrist. However, the use of SMA wires for delivering tactile sensations still has a number of limitations such as high power consumption near peak values, high temperature during actuation and long cooling time.

Touch me Gently [121] is also using SMA wires for delivering haptics to the user's forearm. However, unlike the previous, this device generates cutaneous feedback through skin-stretch. Studies investigated that this system of SMA-based matrix on forearm is able to give touch sensations such as the feeling of one's wrist being grabbed, or one's arm being stroked. Moreover, these sensations were clearly distinguished even without a visual augmentation.

Moriyama *et al.* [109] presented a wrist-worn haptic device for VR interfaces able to give, on the wrist, the sensation of grasping an object with fingertips (index finger and thumb). Two five-bar mechanism devices convey a 2-DoF (normal and lateral) force to the dorsal (corresponding to thumb) and volar (corresponding to index finger) sides of the wrist.

A novel wearable skin stretch device for the upper limb called *hBracelet* was developed to improve telepresence during remote control of a robot-manipulator [110]. The system consists of two parts (front and rear), each equipped with a pair of servomotors and a shearing belt (similar to devices from Section III-D2), coupled with a linear actuator, that controls the distance between them. As a result of the combination of normal, shear and longitudinal forces, hBracelet can provide four types of haptic feedback, informing the user about the forces recorded by the sensors on the robot gripper.

Aggravi *et al.* [122] have combined the shearing-belt approach with vibrotactile feedback by attaching four equidistant vibration motors to an elastic fabric belt. Thus, the forearm-worn haptic device can provide three types of cutaneous feedback - skin-stretch, compression and vibrotactile.

Dunkelberger *et al.* [123], [130] presented a device called *MISSIVE*. This upper-arm-worn device is designed for haptic communication by encoding English language phonemes as multi-sensory cues. MISSIVE consists of two bands - distal (which houses four vibrotactors) and proximal (which houses two servomotors for radial squeezing and lateral skin stretching).

Raitor *et al.* [106] introduced a haptic wristband, *WRAP*, which utilizes pneumatic actuation for guidance applications. Four actuators made of low-density polyethylene (LDPE) thermoplastic are evenly spaced around the band (dorsal, palmar, radial and ulnar sides). The airflow goes from the air supply through solenoid valves. The impulse from the raised actuator is comparable to vibrotactile feedback. However, WRAP generates a medium-frequency pulsing (5 Hz), simultaneously stimulating several different mechanoreceptors compared with high-frequency vibration stimuli (above 100 Hz).

Pneumatic actuation can be applied for delivering not only compression feedback but skin-stretch feedback as well. Kanjanapas *et al.* [124] have developed a wrist-worn haptic device that delivers a 2-DoF shear force to the wearer's skin via pneumatic soft linear tactor. The actuation is performed by pressurizing/depressurizing four silicone rubber actuators arranged in a cross shape. At the center of the cross, there is a dome-shaped tactor head that can stretch the skin in eight directions. The accuracy of recognition of directional cues by users of this device (86%) is lower than that of WRAP (99.4%). Thus, it can be noted that skin stretch at a single contact point on the forearm is less preferred for identifying directional cues than the normal force at different contact points.

Wu and Culbertson [131] developed a haptic forearm-worn sleeve with pneumatic actuation, which provides a haptic illusion of lateral motion along the arm. The feedback is rendered by a linear array of six thermoplastic pneumatic actuators inflated/deflated by air pressure. Each of the actuators overlaps with its neighboring actuator, allowing for smooth travel of a point of pressure.

Dobbelstein *et al.* [108] presented a forearm-worn haptic device named *Movelet*. Compared to the previously reviewed bracelet-type devices, Movelet can convey both momentary and positional feedback. This can be used to provide a variety of abstract information to the user such as progress of an ongoing process, navigation, time and quantity awareness. The feedback is generated due to the device's self-movement along the user's forearm. The system hardware is made of four interlinked segments, each containing a wheel powered by a servomotor.

3) THERMAL FEEDBACK

Thermal feedback is another cutaneous stimulus that can be used as an additional communication channel or as a method of enhancing virtual experience. From the physiological point of view, the face is the most thermally sensitive region of human body, whereas on the hand, the thenar eminence (located at the base of the thumb) is known to be more sensitive to thermal changes than fingertips [132]. Thermal feedback is based on stimulating two types of mechanoreceptors, sensitive to heat and cold, with the number of cold-sensitive receptors on the body being higher as compared to warmth-sensitive receptors [132], [133]. Also, people react to cold stimuli quicker than to warm stimuli due to the difference in the conduction velocities of their afferent fibers [134].

Tewell *et al.* [125] developed a forearm-worn thermal feedback device for providing navigational cues called *Heat-Nav*, which uses three thermoelectric coolers and three thermistors.

Singhal and Jones [126] proposed a wrist-strap-based thermal display, based on a single Peltier element and three thermistors, to evaluate thermal pattern recognition on the hand and arm. This study offers insight into how thermal icons, created by varying direction (warming or cooling), amplitude, spatial extent and duration of thermal stimulation, may be used in the context of cutaneous communication systems.

Peiris *et al.* [127] designed *ThermalBracelet* - a haptic wristband for guidance and notifications via thermal feedback, which uses Peltier elements as the main thermal actuator. Three different configurations of thermal actuators placement around the wrist - four, six and eight- were studied. The results of user studies showed that the mean perceived accuracy for thermal feedback around the wrist was higher than that of vibrotactile stimulation (89% vs 78%).

TherModule [128] is a mobile, wireless wearable device for providing thermal sensations to enhance movie experience. It can be worn on the wrist in form of a bracelet as well as on forearm, ankle or neck. TherModule employs two Peltier elements connected in series and mounted on a metal band. The actuation time for providing hot and cool stimuli (up to 5.8 s) is relatively low compared with other types of tactile feedback. Unlike *Mood Glove* [135] which renders vibrotactile cues on user's palm to enhance the audio channel (mood music) during watching a movie, TherModule uses thermal feedback along with a visual channel.

F. BEYOND HUMAN ARMS AND HANDS

The vast majority of aforementioned wearable haptic devices are designed to be grasped or worn on hands. However, haptic stimuli can be also applied to other parts of the human body. As a representative subset of the corresponding devices, in this section, we report a brief overview of haptic devices for torso, lower limbs and head.

1) HAPTIC VESTS, JACKETS AND BELTS

Haptic devices for torso are usually designed in the form of vest or jacket. Vests provide more flexibility with respect to body size, whereas jackets cover more space on the wearer's body including shoulders. Both vests and jackets provide haptic feedback to a rather large surface area, but the number of haptic actuators per unit area is lower in comparison with hand-held wearable devices. Also, while vests and jackets target mostly the upper torso, the waist is stimulated via haptic belts. Usually, these devices are designed to be worn over clothes; therefore, their applications are typically not requiring high precision and realism as, for instance, haptic systems for fingers.

The most common use for haptic vests and jackets is navigation in the real environment for pedestrians [136], [137], [138], for cyclists [139] and motorcyclists [140] by complementing visual/audio channel, or being the main source of guidance for visually impaired users [141], [142]. *HARVEST* [143] is a haptic vest designed to project sensations recorded by a glove to the wearer's back for enhancing the performance of dexterous work.

Besides that, haptic vests, jackets and belts serve for entertainment - for deeper immersion into VE during gaming [144], [145], [146] and for enhancing music/story listening experience [147], [148]. Also, there are already two commercially available haptic vests for VR applications - TactSuit (BHaptics, South Korea) and Skinetic (Actronika, France). Both vests utilize vibromotors (ERM for Tactsuit, LRA for Skinetic) for generating tactile stimuli at multiple positions on the user's torso.

All the above-mentioned devices provide either vibrotactile or compression (pneumatic) feedback, which is convenient for their form-factor in terms of actuation efficiency, precision, and sensitivity. However, there is also an example of applying SMA actuators in a haptic vest [149], which has proven its effectiveness in hugging therapy for kids with autism. Another type of haptic feedback rendering is demonstrated by *HapticSerpent* [150], a haptic device worn on the waist that provides tactile cues via a 6-DOF robotic hand attached to a belt from the front side.

2) HAPTIC DEVICES FOR LEGS AND FEET

Most haptic devices for legs and feet aim to enhance the walking experience in a VE - simulation of different terrains [151], [152], [153], [154], [155], [156], [157], imitation of stepping on stairs [158] and imitation of interactive forces [157]. All, except [157], provide haptic feedback to the user's feet.

In terms of form-factor, this type of haptic devices can be divided into two categories - ordinary shoes equipped with actuators [151], [152], [153], [159], [160], [161] and custom-made systems [155], [156], [157], where the devices introduced in [156], [157] are grounded and the devices introduced in [151], [152], [153], [159], [160], [161], and [155] are wearable devices. The first category usually employs vibrotactile actuators for haptic cues rendering, whereas a variety of actuation types is observed in the second category, such as magnetorheological fluid actuators in [155], pneumatic actuators in [154], servomotor-controlled scissor mechanism in [158] and an array of omnidirectional rolling elements with different friction coefficients in [156].

Besides the enhancement of the VE experience, haptic shoes can be also used for navigation by providing directional patterns [161], serve as a controller for menu selection [160] and for helping patients with Parkinson's disease in making steps [159].

3) HAPTIC DEVICES FOR HEAD

The least common type of haptic devices are those for the human head. Most of them are wearable and designed in form of headdress equipped with sensors and actuators, e.g. helmet [162] and hat [163]. In terms of application, haptic devices for head are usually used for navigation in real [162], [163] or virtual environments [164].

The most common type of actuation is vibrations, but the range of applicable frequencies and amplitudes is limited compared with vibrotactile devices for other body parts. A different type of actuation is used in *Proximity-Hat* [163], in which navigational cues are rendered through a servomotor-controlled mechanism that applies normal force on the wearer's head. A more detailed study on head-attached vibrotactile devices is presented in [165].

IV. DISCUSSION AND CONCLUSIONS

Section III has reviewed research trends and applications of haptic devices, categorizing them based on the concept of wearability level. Based on these results, we can identify four main application domains for haptic devices:

- Teleoperation - haptic feedback is embedded into a controller to provide tactile information related to a robot under control. Examples are the generation of (i) preslide sensations on the user's fingertips to improve the control of the robot grip force [28], (ii) force feedback for rendering contact forces sensed by the controlled robot end-effector [60], and (iii) directional information (via vibration) about the collisions sensed by the controlled robot [113].
- Entertainment - haptic feedback is provided along with a visual and/or auditory channel to widen the immersion and realism of movies, video games, web surfing (including VR/AR applications). An example is the use of haptic vests, jackets and belts for deeper VE immersion during gaming [144], [145], [146].
- Training/Education - haptic feedback is used to enhance the realism of particular training/education scenarios by imitating the necessary equipment or the physical interaction with the environment. For instance, haptics-based medical simulators can be used for training doctors to manipulate organs and tissues using special tools [166].
- Guidance/Notifications - haptic feedback is provided independently from auditory/visual channels and represents patterns for particular actions or messages. Many commercial smartwatches, for example, are provided with integrated vibrotactile haptic feedback for providing notifications.

A different categorization can be introduced based on the purpose of the device, defining two groups, aimed at either the enhancement or at the replacement of other perception channels. The first group includes almost all application types listed above, where the haptic feedback is provided along with or in accordance with auditory or visual information (for example, when a game controller provides vibrotactile feedback to highlight some actions shown on the screen). The second group usually includes the last application type - guidance/notifications. Here, the haptic feedback is delivered to decrease the load from other perception channels or when the information from these channels is unavailable (for example, when directional cues for navigation are provided in form of tactile patterns instead of a map shown on a screen).

Using the taxonomy introduced in this survey, Table 6 summarizes the use of different stimuli in the reviewed applications for arms and hands, linking them to different types of haptic illusions or guiding interfaces. Five major haptic illusions - simulation of weight, shape, size, stiffness and texture - aim at haptic dexterous manipulation in a VE. Therefore, these illusions are common in application domains such as entertainment and training/education where the user interacts with a virtual world for different purposes and enables at least one of these perceptions. The other three categories listed in Table 6 represent guiding interfaces that provide haptic feedback during teleoperation and navigation tasks, and for notifications. Therefore, these three categories can be referred to corresponding application domains such as teleoperation and guidance/notifications.

A. EXISTING GAPS AND CHALLENGES

One of the main challenges in the development of haptic devices is the fact that the system designer has to pay attention to multiple and co-existing design objectives and constraints, including (i) differences in the bodies of potential users (e.g., height, arm size, etc.), (ii) level of portability, (iii) battery performance, (iv) level of operating noise, and (v) adaptation to a specific tactile stimulus.

In order to reach a convincing level of realism in rendering haptic dexterous manipulation in a VE, it is essential to emphasize the major haptic illusions that constitute this action, i.e., weight, shape, size, stiffness and texture. The sense of weight is mainly delivered by finger-worn devices with skin stretch feedback via shearing belts, moving tactors, and VCAs. Shape rendering is also mainly provided by finger-worn devices, but with the use of moving platforms. The size of a grasped object can only be perceived using kinesthetic feedback; the devices that use a locking mechanism can only render static size, while those that provide a resistive force to the motion of the fingers can also render size changes. The stiffness of virtual objects can be rendered in most cases by vibrotactile or resistive force feedback. Finally, only cutaneous feedback devices can provide the sensation of surface texture; in most cases, this task is achieved by vibrotactile stimulation. In Table 6 it can be seen that no bracelets were used for shape, size and texture rendering, and no exoskeletons were used for texture rendering.

The majority of the research papers considered in this survey either show a new specific stimulation approach, or demonstrate the use of an existing stimulation approach in a new application. The development of these technologies may remain at the level of laboratory prototypes if it will not reach the average user in conditions of daily use: this, in our opinion, is the main gap to be filled in future research.

TABLE 6. Haptic devices with different feedback types for rendering particular haptic illusions or guiding interfaces, including grounded, hand-held, exoskeleton-type, finger-worn and arm-worn devices.

Guidance / Haptic Illusions	Cutaneous Feedback					Kinesthetic Feedback				
	vibrotactile	skin-stretch	compression	thermal	electrical	resistive force	locking mechanism	weight shifting	magnetic	air propulsion
weight	[62]	[15], [3], [74], [75] [79], [83], [94]	[111]			[47]		[41]–[43]		[44], [45]
shape		[68]–[71], [73] [78], [89]	[23]			[58], [31] [32], [34]			[18], [19]	
size						[32], [33], [38] [55], [56], [59] [58], [64], [65] [78]	[57] [61]–[63]	[41]–[43]		[45]
stiffness	[26], [39], [62] [77], [89] [84], [85]	[16], [17], [75]	[25], [111] [81], [82] [90]			[33], [38], [46] [55], [56], [64] [58], [59], [65]				[66]
texture	[27], [32], [35] [73], [77], [86] [89], [98]	[31], [34]	[23]		[20] [84]					
teleoperation	[110], [113], [122]	[107], [110], [122] [36]	[110], [122] [106]	[22]		[40]				
navigation	[104], [105]	[21], [37] [117], [124]		[125], [127]						
notification	[103]	[118]	[29], [114] [119], [120]	[29] [126]–[128], [131]						

TABLE 7. Devices vs haptic sensations: V - vibration, SS - skinstretch, RF - resistive force, LM - locking mechanism.

device	weight	shape	size	stiffness	texture
[32] CLAW		RF	RF		V
[62] Grabity	V		LM	V	
[58] Jo et al.		RF	RF	RF	
[89] Chinello et al.		SS		V	V

Indeed, in order to attract users in real-life applications, it is our opinion that tactile devices should become more versatile, allowing their use in multiple areas, providing a wide range of haptic stimuli. This constitutes a considerable challenge, as the use of multiple haptic devices in a limited space poses problems related to the overall weight of the device, and to the difficulties of system integration.

B. POTENTIAL FUTURE DIRECTIONS

In this section, we provide some recommendations to overcome the aforementioned research gap, and give an overview of how the role of haptic devices can gain more importance thanks to developments in related technologies.

1) FILLING THE RESEARCH GAP

We focus on dexterous manipulation of a virtual object, which constitutes one of the most relevant applications of haptic devices. Referring to Table 6, we can analyze basic tactile illusions such as perception of weight, shape, size, stiffness and texture. As observable from the table, few devices can convey multiple haptic illusions, and only four of them (summarized in Table 7) can deliver three different sensations.

From our point of view, referring to Table 7, the design specifications of an improved haptic device (as compared to what is currently available) can be proposed by combining different features from these four devices. For example, the first device, CLAW [32], is designed for rendering shape, size and texture. CLAW has the potential to render weight via skin stretch feedback delivered through the asymmetric vibration of its vibromotor, and to render stiffness using either vibrations or resistive force feedback. Grabity [62] could use its vibromotors to render texture, but it would be difficult to simulate shapes with the form-factor of this device since it limits the user finger motion with a precision grip. Despite its wearability and free movement of the user hand, the exoskeleton from [58] would benefit from the presence of additional stimulation methods to simultaneously render weight and texture. The finger-worn moving-platform type device from [89] has the potential to render weight using the shearing force delivered by the platform. The weight sensation can be delivered by asymmetric vibration of its motors. These motors generate mechanical vibrations when current flows in their coils. The coils unavoidably heat up due to Joule-Lenz law, and this is undesirable due to two reasons: 1) heated coils stimulate tactile mechanoreceptors that are not supposed to be stimulated, and 2) the coils may heat up more than 160 degrees Celsius, thus damaging the device. In order to mitigate this problem, a maximum allowable stimulation time interval can be defined at the software level, to guarantee that the motors never reach this maximum temperature.

As already mentioned in Section IV-A, integrating the sensors from these four devices can constitute a considerable challenge, mostly due to limited space availability. However, we foresee that this problem could be solved in the coming years, thanks to the availability of haptic devices which, compared to their earlier versions, have become lighter and smaller in size, meanwhile providing more functionalities with a lower power consumption.

2) INTEGRATION OF DIFFERENT TECHNOLOGIES

VE technologies constitute an important field of future studies for further improvement of haptics. Since VE and haptics are complementary to each other in many applications, it is necessary to conduct investigations on the relationship between these two technologies. More research should be undertaken to understand when the desired effect can be obtained by pseudo-haptics (i.e., "illusional haptic perceptions evoked by human vision" [167]) and when an actual haptic feedback is required for better realism. In addition, researchers should find ways for better synchronization of haptic and audio/video effects.

Finally, a future direction of this technology should also concern the problem of designing haptic effects for VR/AR and other visual streams. For example, current gaming devices with haptic feedback require additional work to be done in order to create and link haptic feedback to video/audio channels. The same procedure is required to add haptic feedback to cinema seats to enhance immersion into a movie, or to a vehicle seats to highlight some messages from the vehicle console. Therefore, the future development and popularization of this technology depend on speeding up and simplifying these processes. One of the solutions may be the implementation of artificial intelligence for key events extraction and linking to corresponding haptic effects.

ACKNOWLEDGMENT

The authors are thankful to Danissa Sandykbaeva, a current graduate student and a Research Assistant with Nazarbayev University, for the illustrations in Figs. 2, 7, and 8.

REFERENCES

[1] V. Hayward, O. R. Astley, M. Cruz-Hernandez, D. Grant, and G. Robles-De-La-Torre, "Haptic interfaces and devices," *Sens. Rev.*, vol. 24, no. 1, pp. 16–29, 2004.

[2] R. Sigrist, G. Rauter, R. Riener, and P. Wolf, "Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review," *Psychon. Bull. Rev.*, vol. 20, no. 1, pp. 21–53, Feb. 2013.

[3] C. Pacchierotti, D. Prattichizzo, and K. J. Kuchenbecker, "Cutaneous feedback of fingertip deformation and vibration for palpation in robotic surgery," *IEEE Trans. Biomed. Eng.*, vol. 63, no. 2, pp. 278–287, Feb. 2016.

[4] H. Culbertson, S. B. Schorr, and A. M. Okamura, "Haptics: The present and future of artificial touch sensation," *Annu. Rev. Control, Robot., Auton. Syst.*, vol. 1, pp. 385–409, May 2018.

[5] A. G. R. Ramírez, F. J. G. Luna, O. O. V. Villegas, and M. Nandayapa, "Applications of haptic systems in virtual environments: A brief review," in *Advanced Topics on Computer Vision, Control and Robotics in Mechatronics*. Cham, Switzerland: Springer, 2018, pp. 349–377.

[6] G. Westling and R. S. Johansson, "Responses in glabrous skin mechanoreceptors during precision grip in humans," *Exp. Brain Res.*, vol. 66, no. 1, pp. 40–128, Mar. 1987.

[7] C. Pacchierotti, A. Tirmizi, and D. Prattichizzo, "Improving transparency in teleoperation by means of cutaneous tactile force feedback," *ACM Trans. Appl. Perception*, vol. 11, no. 4, pp. 1–16, Apr. 2014.

[8] S. D. Laycock and A. M. Day, "Recent developments and applications of haptic devices," *Comput. Graph. Forum*, vol. 22, no. 2, pp. 117–132, Jun. 2003.

[9] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 580–600, Oct./Dec. 2017.

[10] D. Wang, M. Song, A. Naqash, Y. Zheng, W. Xu, and Y. Zhang, "Toward whole-hand kinesthetic feedback: A survey of force feedback gloves," *IEEE Trans. Haptics*, vol. 12, no. 2, pp. 189–204, Apr./Jun. 2019.

[11] J. Perret and E. V. Poorten, "Touching virtual reality: A review of haptic gloves," in *Proc. Int. Conf. New Actuat.*, Jun. 2018, pp. 270–274.

[12] C. Basdogan, F. Giraud, V. Levesque, and S. Choi, "A review of surface haptics: Enabling tactile effects on touch surfaces," *IEEE Trans. Haptics*, vol. 13, no. 3, pp. 450–470, Jul. 2020.

[13] A. Talvas, M. Marchal, and A. Lecuyer, "A survey on bimanual haptic interaction," *IEEE Trans. Haptics*, vol. 7, no. 3, pp. 285–300, Jul. 2014.

[14] P. B. Shull and D. D. Damian, "Haptic wearables as sensory replacement, sensory augmentation and trainer—A review," *J. NeuroEng. Rehabil.*, vol. 12, no. 1, pp. 1–13, Dec. 2015.

[15] Z. F. Quek, S. B. Schorr, I. Nisky, W. R. Provancher, and A. M. Okamura, "Sensory substitution using 3-degree-of-freedom tangential and normal skin deformation feedback," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Feb. 2014, pp. 27–33.

[16] Z. F. Quek, S. B. Schorr, I. Nisky, A. M. Okamura, and W. R. Provancher, "Augmentation of stiffness perception with a 1-degree-of-freedom skin stretch device," *IEEE Trans. Human-Mach. Syst.*, vol. 44, no. 6, pp. 731–742, Dec. 2014.

[17] A. K. Han, J. H. Bae, K. C. Gregoriou, C. J. Ploch, R. E. Goldman, G. H. Glover, B. L. Daniel, and M. R. Cutkosky, "MR-compatible haptic display of membrane puncture in robot-assisted needle procedures," *IEEE Trans. Haptics*, vol. 11, no. 3, pp. 443–454, Jul. 2018.

[18] A. Adel, M. M. Micheal, M. A. Self, S. Abdennadher, and I. S. M. Khalil, "Rendering of virtual volumetric shapes using an electromagnetic-based haptic interface," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 8737–8742.

[19] J. J. Zarate, T. Langerak, B. Thomaszewski, and O. Hilliges, "Contact-free nonplanar haptics with a spherical electromagnet," in *Proc. IEEE Haptics Symp.*, Mar. 2020, pp. 698–704.

[20] O. Bau, I. Poupyrev, A. Israr, and C. Harrison, "TeslaTouch: Electrovibration for touch surfaces," in *Proc. 23rd Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2010, pp. 283–292.

[21] M. Solazzi, W. R. Provancher, A. Frisoli, and M. Bergamasco, "Design of a SMA actuated 2-DoF tactile device for displaying tangential skin displacement," in *Proc. IEEE World Haptics Conf.*, Jun. 2011, pp. 31–36.

[22] S. Gallo, L. Santos-Carreras, G. Rognini, M. Hara, A. Yamamoto, and T. Higuchi, "Towards multimodal haptics for teleoperation: Design of a tactile thermal display," in *Proc. 12th IEEE Int. Workshop Adv. Motion Control (AMC)*, Mar. 2012, pp. 1–5.

[23] I. Sarakoglou, N. Garcia-Hernandez, N. G. Tsagarakis, and D. G. Caldwell, "A high performance tactile feedback display and its integration in teleoperation," *IEEE Trans. Haptics*, vol. 5, no. 3, pp. 252–263, 3rd Quart., 2012.

[24] A. Serio, M. Bianchi, and A. Bicchi, "A device for mimicking the contact force/contact area relationship of different materials with applications to softness rendering," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Nov. 2013, pp. 4484–4490.

[25] M. Bianchi and A. Serio, "Design and characterization of a fabric-based softness display," *IEEE Trans. Haptics*, vol. 8, no. 2, pp. 152–163, Apr. 2015.

[26] A. Adilkhanov, A. Yelenov, R. S. Reddy, A. Terekhov, and Z. Kappassov, "VibeRo: Vibrotactile stiffness perception interface for virtual reality," *IEEE Robot. Autom. Lett.*, vol. 5, no. 2, pp. 2785–2792, Apr. 2020.

[27] S. Asano, S. Okamoto, Y. Matsuura, and Y. Yamada, "Toward quality texture display: Vibrotactile stimuli to modify material roughness sensations," *Adv. Robot.*, vol. 28, no. 16, pp. 1079–1089, Aug. 2014.

[28] V. A. Ho, H. Honda, and S. Hirai, "Development of a novel slip haptic display device based on the localized displacement phenomenon," *IEEE Robot. Autom. Lett.*, vol. 1, no. 1, pp. 585–592, Jan. 2016.

[29] D. T. Goetz, D. K. Owusu-Antwi, and H. Culbertson, "PATCH: Pump-actuated thermal compression haptics," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2020, pp. 643–649.

[30] V. A. Ho and S. Hirai, "A novel model for assessing sliding mechanics and tactile sensation of human-like fingertips during slip action," *Robot. Auto. Syst.*, vol. 63, pp. 253–267, Jan. 2015.

[31] H. Benko, C. Holz, M. Sinclair, and E. Ofek, "NormalTouch and TextureTouch: high-fidelity 3D haptic shape rendering on handheld virtual reality controllers," in *Proc. 29th Annu. Symp. User Interface Softw. Technol.*, Oct. 2016, pp. 717–728.

[32] I. Choi, E. Ofek, H. Benko, M. Sinclair, and C. Holz, "CLAW: A multifunctional handheld haptic controller for grasping, touching, and triggering in virtual reality," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2018, pp. 1–13.

[33] M. Sinclair, E. Ofek, M. Gonzalez-Franco, and C. Holz, "CapstanCrunch: A haptic VR controller with user-supplied force feedback," in *Proc. 32nd Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2019, pp. 815–829.

[34] E. Whitmire, H. Benko, C. Holz, E. Ofek, and M. Sinclair, "Haptic revolver: Touch, shear, texture, and shape rendering on a reconfigurable virtual reality controller," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2018, pp. 1–12.

[35] J. Lee, M. Sinclair, M. Gonzalez-Franco, E. Ofek, and C. Holz, "TORC: A virtual reality controller for in-hand high-dexterity finger interaction," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–13.

[36] J. M. Walker, N. Zemiti, P. Poignet, and A. M. Okamura, "Holdable haptic device for 4-DOF motion guidance," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 109–114.

[37] D. K. Y. Chen, J.-B. Chossat, and P. B. Shull, "HaptiVec: Presenting haptic feedback vectors in handheld controllers using embedded tactile pin arrays," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–11.

[38] Y. Sun, S. Yoshida, T. Narumi, and M. Hirose, "PaCaPa: A handheld VR device for rendering size, shape, and stiffness of virtual objects in tool-based interactions," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–12.

[39] I. Choi, Y. Zhao, E. J. Gonzalez, and S. Follmer, "Augmenting perceived softness of haptic proxy objects through transient vibration and visuo-haptic illusion in virtual reality," *IEEE Trans. Vis. Comput. Graphics*, vol. 27, no. 12, pp. 4387–4400, Dec. 2021.

[40] S. Sakr, B. Cagneau, T. Daunizeau, S. Regnier, and S. Haliyo, "Haptic remote control interface for robotic micro-assembly at low frequency," in *Proc. Int. Conf. Manipulation, Autom. Robot. Small Scales (MARSS)*, Jul. 2020, pp. 1–7.

[41] A. Zenner and A. Krüger, "Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality," *IEEE Trans. Vis. Comput. Graphics*, vol. 23, no. 4, pp. 1285–1294, Apr. 2017.

[42] J. Shigeyama, T. Hashimoto, S. Yoshida, T. Narumi, T. Tanikawa, and M. Hirose, "Transcalibur: A weight shifting virtual reality controller for 2D shape rendering based on computational perception model," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–11.

[43] A. Zenner and A. Krüger, "Drag: On: A virtual reality controller providing haptic feedback based on drag and weight shift," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–12.

[44] S. Heo, C. Chung, G. Lee, and D. Wigdor, "Thor's hammer: An ungrounded force feedback device utilizing propeller-induced propulsive force," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2018, pp. 1–11.

[45] S. Je, M. J. Kim, W. Lee, B. Lee, X.-D. Yang, P. Lopes, and A. Bianchi, "Aero-plane: A handheld force-feedback device that renders weight motion illusion on a virtual 2D plane," in *Proc. 32nd Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2019, pp. 763–775.

[46] E. Strasnick, C. Holz, E. Ofek, M. Sinclair, and H. Benko, "Haptic links: Bimanual haptics for virtual reality using variable stiffness actuation," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2018, pp. 1–12.

[47] R. Kovacs, E. Ofek, M. Gonzalez Franco, A. F. Siu, S. Marwecki, C. Holz, and M. Sinclair, "Haptic PIVOT: On-demand handhelds in VR," in *Proc. 33rd Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2020, pp. 1046–1059.

[48] S. Sakr, T. Daunizeau, D. Reversat, S. Regnier, and S. Haliyo, "An ungrounded master device for tele-microassembly," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2018, pp. 5533–5538.

[49] C. C. Pagano, P. Fitzpatrick, and M. T. Turvey, "Tensorial basis to the constancy of perceived object extent over variations of dynamic touch," *Perception Psychophys.*, vol. 54, no. 1, pp. 43–54, Jan. 1993.

[50] M. Turvey, "Dynamic touch," *Amer. Psycholog.*, vol. 51, pp. 1134–1152, Jan. 1996.

[51] M. T. Turvey, G. Burton, E. L. Amazeen, M. Butwill, and C. Carello, "Perceiving the width and height of a hand-held object by dynamic touch," *J. Experim. Psychol., Hum. Perception Perform.*, vol. 24, no. 1, pp. 35–48, 1998.

[52] I. Kingma, R. van de Langenberg, and P. J. Beek, "Which mechanical invariants are associated with the perception of length and heaviness of a nonvisible handheld rod? Testing the inertia tensor hypothesis," *J. Experim. Psychol., Hum. Perception Perform.*, vol. 30, no. 2, pp. 346–354, 2004.

[53] T. Amemiya and T. Maeda, "Asymmetric oscillation distorts the perceived heaviness of handheld objects," *IEEE Trans. Haptics*, vol. 1, no. 1, pp. 9–18, Jan. 2008.

[54] M. Sarac, M. Solazzi, and A. Frisoli, "Design requirements of generic hand exoskeletons and survey of hand exoskeletons for rehabilitation, assistive, or haptic use," *IEEE Trans. Haptics*, vol. 12, no. 4, pp. 400–413, Oct. 2019.

[55] R. M. Pierce, E. A. Fedalei, and K. J. Kuchenbecker, "A wearable device for controlling a robot gripper with fingertip contact, pressure, vibrotactile, and grip force feedback," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Feb. 2014, pp. 19–25.

[56] M. Cempini, M. Cortese, and N. Vitiello, "A powered finger–thumb wearable hand exoskeleton with self-aligning joint axes," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 2, pp. 705–716, Apr. 2015.

[57] X. Gu, Y. Zhang, W. Sun, Y. Bian, D. Zhou, and P. O. Kristensson, "Dexmo: An inexpensive and lightweight mechanical exoskeleton for motion capture and force feedback in VR," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2016, pp. 1991–1995.

[58] I. Jo, Y. Park, H. Kim, and J. Bae, "Evaluation of a wearable hand kinesthetic feedback system for virtual reality: Psychophysical and user experience evaluation," *IEEE Trans. Human-Mach. Syst.*, vol. 49, no. 5, pp. 430–439, Oct. 2019.

[59] M. Hosseini, A. Sengul, Y. Pane, J. D. Schutter, and H. Bruyninck, "ExoTen-Glove: A force-feedback haptic glove based on twisted string actuation system," in *Proc. IEEE Int. Symp. Robot Hum. Interact. Commun.*, Aug. 2018, pp. 320–327.

[60] M. Laghi, M. G. Catalano, G. Grioli, and A. Bicchi, "A wearable wrist haptic display for motion tracking and force feedback in the operational space," *Wearable Technol.*, vol. 2, p. e5, May 2021.

[61] I. Choi, E. W. Hawkes, D. L. Christensen, C. J. Ploch, and S. Follmer, "Wolverine: A wearable haptic interface for grasping in virtual reality," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Oct. 2016, pp. 986–993.

[62] I. Choi, H. Culbertson, M. R. Miller, A. Olwal, and S. Follmer, "Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality," in *Proc. 30th Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2017, pp. 119–130.

[63] R. Hinchet, V. Vechev, H. Shea, and O. Hilliges, "DextrES: Wearable haptic feedback for grasping in VR via a thin form-factor electrostatic brake," in *Proc. 31st Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2018, pp. 901–912.

[64] I. Zubrycki and G. Granosik, "Novel haptic device using jamming principle for providing kinaesthetic feedback in glove-based control interface," *J. Intell. Robotic Syst.*, vol. 85, nos. 3–4, pp. 413–429, Mar. 2017.

[65] Y. Zhang, D. Wang, Z. Wang, Y. Wang, L. Wen, and Y. Zhang, "A two-fingered force feedback glove using soft actuators," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2018, pp. 186–191.

[66] M. Okui, T. Masuda, T. Tamura, Y. Onozuka, and T. Nakamura, "Wearable air-jet force feedback device without exoskeletal structure and its application to elastic ball rendering," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2020, pp. 276–281.

[67] M. R. Cutkosky, "On grasp choice, grasp models, and the design of hands for manufacturing tasks," *IEEE Trans. Robot. Autom.*, vol. 5, no. 3, pp. 269–279, Jun. 1989.

[68] M. Solazzi, A. Frisoli, and M. Bergamasco, "Design of a novel finger haptic interface for contact and orientation display," in *Proc. IEEE Haptics Symp.*, Mar. 2010, pp. 129–132.

[69] D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi, "Towards wearability in fingertip haptics: A 3-DoF wearable device for cutaneous force feedback," *IEEE Trans. Haptics*, vol. 6, no. 4, pp. 506–516, Oct./Dec. 2013.

[70] F. Chinello, M. Malvezzi, C. Pacchierotti, and D. Prattichizzo, "Design and development of a 3RRS wearable fingertip cutaneous device," in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2015, pp. 293–298.

[71] A. G. Perez, D. Lobo, F. Chinello, G. Cirio, M. Malvezzi, J. San Martin, D. Prattichizzo, and M. A. Otaduy, "Soft finger tactile rendering for wearable haptics," in *Proc. IEEE World Haptics Conf. (WHC)*, Jun. 2015, pp. 327–332.

[72] J. D. Brown, M. Ibrahim, E. D. Z. Chase, C. Pacchierotti, and K. J. Kuchenbecker, "Data-driven comparison of four cutaneous displays for pinching palpation in robotic surgery," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Apr. 2016, pp. 147–154.

[73] M. Gabardi, M. Solazzi, D. Leonardis, and A. Frisoli, "A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Apr. 2016, pp. 140–146.

[74] D. Leonardis, M. Solazzi, I. Bortone, and A. Frisoli, "A 3-RSR haptic wearable device for rendering fingertip contact forces," *IEEE Trans. Haptics*, vol. 10, no. 3, pp. 305–316, Jul./Sep. 2017.

[75] S. B. Schorr and A. M. Okamura, "Three-dimensional skin deformation as force substitution: Wearable device design and performance during haptic exploration of virtual environments," *IEEE Trans. Haptics*, vol. 10, no. 3, pp. 418–430, Jul. 2017.

[76] M. Gabardi, D. Leonardis, M. Solazzi, and A. Frisoli, "Development of a miniaturized thermal module designed for integration in a wearable haptic device," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2018, pp. 100–105.

[77] J. Frohner, G. Salvietti, P. Beckerle, and D. Prattichizzo, "Can wearable haptic devices foster the embodiment of virtual limbs?" *IEEE Trans. Haptics*, vol. 12, no. 3, pp. 339–349, Jul. 2019.

[78] F. Chinello, M. Malvezzi, D. Prattichizzo, and C. Pacchierotti, "A modular wearable finger interface for cutaneous and kinesthetic interaction: Control and evaluation," *IEEE Trans. Ind. Electron.*, vol. 67, no. 1, pp. 706–716, Jan. 2020.

[79] K. Minamizawa, S. Fukamachi, H. Kajimoto, N. Kawakami, and S. Tachi, "Gravity Grabber: Wearable haptic display to present virtual mass sensation," in *Proc. ACM Special Interest Group Comput. Graph. Interact. Techn. Conf.*, 2007, p. 43.

[80] C. Pacchierotti, G. Salvietti, I. Hussain, L. Meli, and D. Prattichizzo, "The hRing: A wearable haptic device to avoid occlusions in hand tracking," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Apr. 2016, pp. 134–139.

[81] S. Fani, S. Ciotti, E. Battaglia, A. Moscatelli, and M. Bianchi, "W-FYD: A wearable fabric-based display for haptic multi-cue delivery and tactile augmented reality," *IEEE Trans. Haptics*, vol. 11, no. 2, pp. 304–316, Apr. 2018.

[82] X. de Tinguy, C. Pacchierotti, M. Marchal, and A. Lecuyer, "Enhancing the stiffness perception of tangible objects in mixed reality using wearable haptics," in *Proc. IEEE Conf. Virtual Reality 3D User Interface (VR)*, Mar. 2018, pp. 81–90.

[83] A. Girard, M. Marchal, F. Gosselin, A. Chabrier, F. Louveau, and A. Lécuyer, "HapTip: Displaying haptic shear forces at the fingertips for multi-finger interaction in virtual environments," *Frontiers ICT*, vol. 3, pp. 1–15, Apr. 2016.

[84] V. Yem and H. Kajimoto, "Wearable tactile device using mechanical and electrical stimulation for fingertip interaction with virtual world," in *Proc. IEEE Virtual Reality (VR)*, Mar. 2017, pp. 99–104.

[85] A. T. Maereg, A. Nagar, D. Reid, and E. L. Secco, "Wearable vibrotactile haptic device for stiffness discrimination during virtual interactions," *Frontiers Robot. AI*, vol. 4, pp. 1–9, Sep. 2017.

[86] C. Gaudeni, L. Meli, L. A. Jones, and D. Prattichizzo, "Presenting surface features using a haptic ring: A psychophysical study on relocating vibrotactile feedback," *IEEE Trans. Haptics*, vol. 12, no. 4, pp. 428–437, Oct. 2019.

[87] Y.-L. Feng, C. L. Fernando, J. Rod, and K. Minamizawa, "Submerged haptics: A 3-DOF fingertip haptic display using miniature 3D printed airbags," in *Proc. ACM SIGGRAPH Posters*, Jul. 2017, pp. 1–2.

[88] F. Chinello, M. Malvezzi, C. Pacchierotti, and D. Prattichizzo, "A three DoFs wearable tactile display for exploration and manipulation of virtual objects," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2012, pp. 71–76.

[89] F. Chinello, C. Pacchierotti, M. Malvezzi, and D. Prattichizzo, "A three revolute-revolute-spherical wearable fingertip cutaneous device for stiffness rendering," *IEEE Trans. Haptics*, vol. 11, no. 1, pp. 39–50, Jan./Mar. 2018.

[90] G. Frediani, D. Mazzei, D. E. De Rossi, and F. Carpi, "Wearable wireless tactile display for virtual interactions with soft bodies," *Frontiers Bioeng. Biotechnol.*, vol. 2, pp. 1–7, Sep. 2014.

[91] J.-B. Chossat, D. K. Y. Chen, Y.-L. Park, and P. B. Shull, "Soft wearable skin-stretch device for haptic feedback using twisted and coiled polymer actuators," *IEEE Trans. Haptics*, vol. 12, no. 4, pp. 521–532, Oct. 2019.

[92] A. Frisoli, M. Solazzi, F. Salsedo, and M. Bergamasco, "A fingertip haptic display for improving curvature discrimination," *Presence*, vol. 17, no. 6, pp. 550–561, Dec. 2008.

[93] S. Music, G. Salvietti, P. B. G. Dohmann, F. Chinello, D. Prattichizzo, and S. Hirche, "Human–robot team interaction through wearable haptics for cooperative manipulation," *IEEE Trans. Haptics*, vol. 12, no. 3, pp. 350–362, Jul. 2019.

[94] B. Lim, K. Kim, and D. Hwang, "On the design of the 5-DoF finger-wearable cutaneous haptic device," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2017, pp. 872–878.

[95] M. Maisto, C. Pacchierotti, F. Chinello, G. Salvietti, A. De Luca, and D. Prattichizzo, "Evaluation of wearable haptic systems for the fingers in augmented reality applications," *IEEE Trans. Haptics*, vol. 10, no. 4, pp. 511–522, Oct. 2017.

[96] M. Bianchi, E. Battaglia, M. Poggiani, S. Ciotti, and A. Bicchi, "A wearable fabric-based display for haptic multi-cue delivery," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Apr. 2016, pp. 277–283.

[97] T. Aoki, H. Mitake, D. Keoki, S. Hasegawa, and M. Sato, "Wearable haptic device to present contact sensation based on cutaneous sensation using thin wire," in *Proc. Int. Conf. Adv. Comput. Enterntainment Technol. (ACE)*, 2009, pp. 115–122.

[98] H. Singh, B. Suthar, S. Z. Mehdi, and J.-H. Ryu, "Ferro-fluid based portable fingertip haptic display and its preliminary experimental evaluation," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2018, pp. 14–19.

[99] M. A. Srinivasan and R. H. LaMotte, "Tactual discrimination of softness," *J. Neurophysiol.*, vol. 73, no. 1, pp. 88–101, Jan. 1995.

[100] A. Moscatelli, M. Bianchi, A. Serio, A. Terekhov, V. Hayward, M. O. Ernst, and A. Bicchi, "The change in fingertip contact area as a novel proprioceptive cue," *Current Biol.*, vol. 26, no. 9, pp. 1159–1163, May 2016.

[101] C. Dhong, R. Miller, N. B. Root, S. Gupta, L. V. Kayser, C. W. Carpenter, K. J. Loh, V. S. Ramachandran, and D. J. Lipomi, "Role of indentation depth and contact area on human perception of softness for haptic interfaces," *Sci. Adv.*, vol. 5, no. 8, pp. 1–13, Aug. 2019.

[102] R. S. Johansson and A. B. Vallbo, "Tactile sensibility in the human hand: Relative and absolute densities of four types of mechanoreceptive units in glabrous skin," *J. Physiol.*, vol. 286, no. 1, pp. 283–300, 1979.

[103] M. F. Rotella, K. Guerin, X. He, and A. M. Okamura, "HAPI bands: A haptic augmented posture interface," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2012, pp. 163–170.

[104] S. Paneels, M. Anastassova, S. Strachan, S. P. Van, S. Sivacoumarane, and C. Bolzmacher, "What's around me? Multi-actuator haptic feedback on the wrist," in *Proc. World Haptics Conf. (WHC)*, Apr. 2013, pp. 407–412.

[105] S. Scheggi, M. Aggravi, F. Morbidi, and D. Prattichizzo, "Cooperative human-robot haptic navigation," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2014, pp. 2693–2698.

[106] M. Raitor, J. M. Walker, A. M. Okamura, and H. Culbertson, "WRAP: Wearable, restricted-aperture pneumatics for haptic guidance," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2017, pp. 427–432.

[107] F. Chinello, C. Pacchierotti, J. Bimbo, N. G. Tsagarakis, and D. Prattichizzo, "Design and evaluation of a wearable skin stretch device for haptic guidance," *IEEE Robot. Automat. Lett.*, vol. 3, no. 1, pp. 524–531, Dec. 2018.

[108] D. Dobbelstein, E. Stemasov, D. Besserer, I. Stenske, and E. Rukzio, "Movelet: A self-actuated movable bracelet for positional haptic feedback on the user's forearm," in *Proc. ACM Int. Symp. Wearable Comput.*, Oct. 2018, pp. 33–39.

[109] T. K. Moriyama, A. Nishi, R. Sakuragi, T. Nakamura, and H. Kajimoto, "Development of a wearable haptic device that presents haptics sensation of the finger pad to the forearm," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2018, pp. 180–185.

[110] L. Meli, I. Hussain, M. Aurilio, M. Malvezzi, M. K. O'Malley, and D. Prattichizzo, "The hBracelet: A wearable haptic device for the distributed mechanotactile stimulation of the upper limb," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 2198–2205, Jul. 2018.

[111] E. Pezent, A. Israr, M. Samad, S. Robinson, P. Agarwal, H. Benko, and N. Colonnese, "Tasbi: Multisensory squeeze and vibrotactile wrist haptics for augmented and virtual reality," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 1–6.

[112] E. Pezent, M. K. O'Malley, A. Israr, M. Samad, S. Robinson, P. Agarwal, H. Benko, and N. Colonnese, "Explorations of wrist haptic feedback for AR/VR interactions with tasbi," in *Proc. Extended Abstr. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2020, pp. 1–4.

[113] J. Bimbo, C. Pacchierotti, M. Aggravi, N. Tsagarakis, and D. Prattichizzo, "Teleoperation in cluttered environments using wearable haptic feedback," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2017, pp. 3401–3408.

[114] H. Zhao, A. M. Hussain, A. Israr, D. M. Vogt, M. Duduta, D. R. Clarke, and R. J. Wood, "A wearable soft haptic communicator based on dielectric elastomer actuators," *Soft Robot.*, vol. 7, no. 4, pp. 451–461, Aug. 2020.

[115] S. Zhao, A. Israr, F. Lau, and F. Abnousi, "Coding tactile symbols for phonemic communication," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2018, pp. 1–13.

[116] L. Turchet, T. West, and M. M. Wanderley, "Touching the audience: Musical haptic wearables for augmented and participatory live music performances," *Pers. Ubiquitous Comput.*, vol. 25, no. 4, pp. 749–769, Aug. 2021.

[117] N. A. Caswell, R. T. Yardley, M. N. Montandon, and W. R. Provancher, "Design of a forearm-mounted directional skin stretch device," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2012, pp. 365–370.

[118] A. Ion, E. J. Wang, and P. Baudisch, "Skin drag displays: Dragging a physical tactor across the user's skin produces a stronger tactile stimulus than vibrotactile," in *Proc. 33rd Annu. ACM Conf. Hum. Factors Comput. Syst.*, Apr. 2015, pp. 2501–2504.

[119] H. Pohl, P. Brandes, H. N. Quang, and M. Rohs, "Squeezeback: Pneumatic compression for notifications," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2017, pp. 5318–5330.

[120] A. Gupta, A. A. R. Irudayaraj, and R. Balakrishnan, "HapticClench: Investigating squeeze sensations using memory alloys," in *Proc. 30th Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2017, pp. 109–117.

[121] S. Muthukumarana, D. S. Elvitigala, J. P. Forero Cortes, D. J. Matthies, and S. Nanayakkara, *Touch Me Gently: Recreating Perception Touch Using a Shape-Memory Alloy Matrix*, 2020, pp. 1–12.

[122] M. Aggravi, F. Pause, P. R. Giordano, and C. Pacchierotti, "Design and evaluation of a wearable haptic device for skin stretch, pressure, and vibrotactile stimuli," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 2166–2173, Jul. 2018.

[123] N. Dunkelberger, J. L. Sullivan, J. Bradley, I. Manickam, G. Dasarathy, R. Baraniuk, and M. K. O'Malley, "A multisensory approach to present phonemes as language through a wearable haptic device," *IEEE Trans. Haptics*, vol. 14, no. 1, pp. 188–199, Jan. 2021.

[124] S. Kanjanapas, C. M. Nunez, S. R. Williams, A. M. Okamura, and M. Luo, "Design and analysis of pneumatic 2-DoF soft haptic devices for shear display," *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 1365–1371, Apr. 2019.

[125] J. Tewell, J. Bird, and G. R. Buchanan, "Heat-Nav: Using temperature changes as navigation cues," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2017, pp. 1131–1135.

[126] A. Singhal and L. A. Jones, "Creating thermal icons—A model-based approach," *ACM Trans. Appl. Perception*, vol. 15, no. 2, pp. 1–22, Apr. 2018.

[127] R. L. Peiris, Y.-L. Feng, L. Chan, and K. Minamizawa, "ThermalBracelet: Exploring thermal haptic feedback around the wrist," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2019, pp. 1–11.

[128] T. Maeda and T. Kurahashi, "TherModule: Wearable and modular thermal feedback system based on a wireless platform," in *Proc. 10th Augmented Hum. Int. Conf.*, Mar. 2019, pp. 1–8.

[129] L. Turchet and M. Barthet, "Co-design of musical haptic wearables for electronic music performer's communication," *IEEE Trans. Human-Mach. Syst.*, vol. 49, no. 2, pp. 183–193, Apr. 2019.

[130] N. Dunkelberger *et al.*, "Improving perception accuracy with multi-sensory haptic cue delivery," in *Haptics: Science, Technology, and Applications* (Lecture Notes in Computer Science), vol. 10894, D. Prattichizzo, H. Shinoda, H. Tan, E. Ruffaldi, and A. Frisoli, Eds. Cham, Switzerland: Springer, 2018, doi: 10.1007/978-3-319-93399-3_26.

[131] W. Wu and H. Culbertson, "Wearable haptic pneumatic device for creating the illusion of lateral motion on the arm," in *Proc. IEEE World Haptics Conf. (WHC)*, Jul. 2019, pp. 193–198.

[132] J. C. Stevens and K. K. Choo, "Temperature sensitivity of the body surface over the life span," *Somatosensory Motor Res.*, vol. 15, no. 1, pp. 13–28, Jan. 1998.

[133] L. A. Jones and H.-N. Ho, "Warm or cool, large or small? The challenge of thermal displays," *IEEE Trans. Haptics*, vol. 1, no. 1, pp. 53–70, Jan. 2008.

[134] D. Yarnitsky and J. Ochoa, "Warm and cold specific somatosensory systems. psychophysical thresholds, reaction times and peripheral conduction velocities," *Brain*, vol. 114, no. 4, pp. 26–1819, 1991.

[135] A. Mazzoni and N. Bryan-Kinns, "Mood glove: A haptic wearable prototype system to enhance mood music in film," *Entertainment Comput.*, vol. 17, pp. 9–17, Nov. 2016.

[136] A. A. G. Dharma, E. Ariwa, and K. Tomimatsu, "Green technology and wearable haptic feedback display with 5×12 arrays of vibrotactile actuators," in *Proc. IEEE 3rd Int. Conf. Consum. Electron. Berlin (ICCE-Berlin)*, Sep. 2013, pp. 272–274.

[137] A. A. G. Dharma, T. Oami, Y. Obata, L. Yan, and K. Tomimatsu, "Design of a wearable haptic vest as a supportive tool for navigation," in *Proc. Int. Conf. Hum.-Comput. Interact.*, Jul. 2013, pp. 568–577.

[138] Y. Li, Y. Obata, M. Kumagai, M. Ishikawa, M. Owaki, N. Fukami, and K. Tomimatsu, "A design study for the haptic vest as a navigation system," *Int. J. Asia Digital Art Design Association*, vol. 17, no. 1, pp. 10–17, 2013.

[139] H. Steltenpohl and A. Bouwer, "Vibrobelt: Tactile navigation support for cyclists," in *Proc. Int. Conf. Intell. User Interface (IUI)*, 2013, pp. 417–426.

[140] M. Prasad, P. Taele, D. Goldberg, and T. A. Hammond, "HaptiMoto: Turn-by-turn haptic route guidance interface for motorcyclists," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, Apr. 2014, pp. 3597–3606.

[141] J. Gay, M. Umfahrer, A. Theil, L. Buchweitz, E. Lindell, L. Guo, N.-K. Persson, and O. Korn, "Keep your distance: A playful haptic navigation wearable for individuals with deafblindness," in *Proc. 22nd Int. ACM SIGACCESS Conf. Comput. Accessibility*, Oct. 2020, pp. 1–4.

[142] A. Cosgun, E. A. Sisbot, and H. I. Christensen, "Evaluation of rotational and directional vibration patterns on a tactile belt for guiding visually impaired people," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Feb. 2014, pp. 367–370.

[143] T. Moriyama and H. Kajimoto, "HARVEST: High-resolution haptic vest and fingertip sensing glove that transfers tactile sensation of fingers to the back," *Appl. Sci.*, vol. 11, no. 3, p. 1298, Feb. 2021.

[144] G. Garcia-Valle, M. Ferre, J. Brenosa, and D. Vargas, "Evaluation of presence in virtual environments: Haptic vest and user's haptic skills," *IEEE Access*, vol. 6, pp. 7224–7233, 2018.

[145] Y. Kishishita, S. Das, A. V. Ramirez, C. Thakur, R. Tadayon, and Y. Kurita, "Muscleblazer: Force-feedback suit for immersive experience," in *Proc. IEEE Conf. Virtual Reality 3D User Interface (VR)*, Mar. 2019, pp. 1813–1818.

[146] A. Delazio, K. Nakagaki, R. L. Klatzky, S. E. Hudson, J. F. Lehman, and A. P. Sample, "Force jacket: Pneumatically-actuated jacket for embodied haptic experiences," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2018, pp. 1–12.

[147] S. Zhao, J. Lehman, A. Israr, and R. Klatzky, "Using haptic inputs to enrich story listening for young children," in *Proc. Int. Conf. Interact. Design Children*, 2015, pp. 239–242.

[148] C. Richards, R. Cahen, and N. Misdariis, "Designing the balance between sound and touch: Methods for multimodal composition," in *Proc. 19th Sound Music Comput. Conf.*, 2022.

[149] J. C. Duvall, L. E. Dunne, N. Schleif, and B. Holschuh, "Active 'hugging' vest for deep touch pressure therapy," in *Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput., Adjunct*, 2016, pp. 458–463.

[150] M. Al-Sada, K. Jiang, S. Ranade, X. Piao, T. Hoglund, and T. Nakajima, "HapticSerpent: A wearable haptic feedback robot for VR," in *Proc. Extended Abstracts CHI Conf. Hum. Factors Comput. Syst.*, 2018, pp. 1–6.

[151] L. Turchet, R. Nordahl, S. Serafin, A. Berrezag, S. Dimitrov, and V. Hayward, "Audio-haptic physically-based simulation of walking on different grounds," in *Proc. IEEE Int. Workshop Multimedia Signal Process.*, Oct. 2010, pp. 269–273.

[152] L. Turchet, P. Burelli, and S. Serafin, "Haptic feedback for enhancing realism of walking simulations," *IEEE Trans. Haptics*, vol. 6, no. 1, pp. 35–45, 1st Quart., 2013.

[153] P. Strohmeier, S. Güngör, L. Herres, D. Gudea, B. Fruchard, and J. Steimle, "BARefoot: Generating virtual materials using motion coupled vibration in shoes," in *Proc. 33rd Annu. ACM Symp. User Interface Softw. Technol.*, Oct. 2020, pp. 579–593.

[154] Y. Wang and M. A. Minor, "Design of a bladder based elastomeric smart shoe for haptic terrain display," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2014, pp. 1236–1241.

[155] T.-H. Yang, H. Son, S. Byeon, H. Gil, I. Hwang, G. Jo, S. Choi, S.-Y. Kim, and J. R. Kim, "Magnetorheological fluid haptic shoes for walking in VR," *IEEE Trans. Haptics*, vol. 14, no. 1, pp. 83–94, Jan. 2021.

[156] G. Millet, M. Otis, D. Horodniczy, and J. R. Cooperstock, "Design of variable-friction devices for shoe-floor contact," *Mechatronics*, vol. 46, pp. 115–125, Oct. 2017.

[157] C. Wang, D.-Y. Huang, S.-W. Hsu, C.-L. Lin, Y.-L. Chiu, C.-E. Hou, and B.-Y. Chen, "Gaiters: Exploring skin stretch feedback on legs for enhancing virtual reality experiences," in *Proc. Conf. Hum. Factors Comput. Syst. (CHI)*. New York, NY, USA: Association for Computing Machinery, 2020, pp. 1–14, doi: 10.1145/3313831.3376865.

[158] D. Schmidt, R. Kovacs, V. Mehta, U. Umapathi, and S. Kohler, L.-P. Cheng, and P. Baudisch, "Level-ups: Motorized stilts that simulate stair steps in virtual reality," in *Proc. 33rd Annu. ACM Conf. Hum. Factors Comput. Syst.*, 2015, pp. 2157–2160.

[159] D. Zanotto, L. Turchet, E. M. Boggs, and S. K. Agrawal, "SoleSound: Towards a novel portable system for audio-tactile underfoot feedback," in *Proc. 5th IEEE RAS/EMBS Int. Conf. Biomed. Robot. Biomechatronics*, Aug. 2014, pp. 193–198.

[160] J. Anlauff, T. Kim, and J. R. Cooperstock, "Feel-a-bump: Haptic feedback for foot-based angular menu selection," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2018, pp. 175–179.

[161] M. Schirmer, J. Hartmann, S. Bertel, and F. Echtler, "Shoe me the way: A shoe-based tactile interface for eyes-free urban navigation," in *Proc. 17th Int. Conf. Hum.-Comput. Interact. With Mobile Devices Services*, Aug. 2015, pp. 327–336.

[162] H. Kerdegari, Y. Kim, and T. J. Prescott, "Head-mounted sensory augmentation device: Comparing haptic and audio modality," in *Biomimetic and Biohybrid Systems (Living Machines)* (Lecture Notes in Computer Science), vol. 9793, N. Lepora, A. Mura, M. Mangan, P. Verschure, M. Desmulliez, and T. Prescott, Eds. Cham, Switzerland: Springer, 2016, doi: 10.1007/978-3-319-42417-0_11.

[163] M. Berning, F. Braun, T. Riedel, and M. Beigl, "ProximityHat: A head-worn system for subtle sensory augmentation with tactile stimulation," in *Proc. ACM Int. Symp. Wearable Comput. (ISWC)*, 2015, pp. 31–38.

[164] O. B. Kaul and M. Rohs, "HapticHead: A spherical vibrotactile grid around the head for 3D guidance in virtual and augmented reality," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2017, pp. 3729–3740.

[165] M. K. Dobrzynski, S. Mejri, S. Wischmann, and D. Floreano, "Quantifying information transfer through a head-attached vibrotactile display: Principles for design and control," *IEEE Trans. Biomed. Eng.*, vol. 59, no. 7, pp. 2011–2018, Jul. 2012.

[166] D. Escobar-Castillejos, J. Noguez, L. Neri, A. Magana, and B. Benes, "A review of simulators with haptic devices for medical training," *J. Med. Syst.*, vol. 40, no. 4, pp. 1–22, Apr. 2016.

[167] Y. Ujitoko and Y. Ban, "Survey of pseudo-haptics: Haptic feedback design and application proposals," *IEEE Trans. Haptics*, vol. 14, no. 4, pp. 699–711, Oct. 2021.

ADILZHAN ADILKHANOV (Member, IEEE) received the M.Sc. degree in robotics from Nazarbayev University, Nur-Sultan, Kazakhstan, in 2022. He is currently working as a Research Assistant with the Department of Robotics and Mechatronics, Nazarbayev University. He is a coauthor of three conference and journal papers. His research interest includes haptic devices.

MATTEO RUBAGOTTI (Senior Member, IEEE) received the Ph.D. degree in electronics, computer science, and electrical engineering from the University of Pavia, Pavia, Italy, in 2010.

He was a Lecturer in control engineering at the University of Leicester, Leicester, U.K., and a Postdoctoral Fellow at the University of Trento, Trento, Italy, and at IMT Institute for Advanced Studies, Lucca, Italy. Since 2018, he has been an Associate Professor of robotics and mechatronics with Nazarbayev University, Nur-Sultan, Kazakhstan. He has coauthored more than 60 technical papers in international journals and conferences in the fields of control theory and robotics. His current research interests include robot control and motion planning, and physical human–robot interaction. He is a Subject Editor of the *International Journal of Robust and Nonlinear Control*, and is a member of the Conference Editorial Boards of the IEEE Control System Society and of the European Control Association.

ZHANAT KAPPASSOV (Member, IEEE) received the degree in radio-engineering from the Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russia, and the Ph.D. degree in robotics from the Institute of Intelligent Systems and Robotics, Sorbonne Université (formely Université Pierre et Marie Curie), Paris, France. He was at the Industrial Technology Research Institute, Taiwan. He is an Assistant Professor with the Robotics Department, Nazarbayev University. His current research interests include tactile sensing that involves robot physical interaction and dexterous manipulation. He serves as a reviewer for IEEE journals and conferences. His Ph.D. thesis was nominated as the Best Ph.D. Thesis 2017 by the GDR Robotique Association, France.

• • •