Haptic devices and illusions for augmented and virtual reality applications

by

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Abstract

The last decade has seen exponential growth in the need for a deeper dive into virtual and augmented environments. This can be achieved only through more sophisticated tactile illusions, provided by haptic devices. Firstly, in this work, the literature review on haptic devices is provided (Chapter 1), describing 85 publications in the period from 2010 to 2020. The review describes the technology based on the concept of "wearability level", providing its two-level classification. 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. In the second part of this work (Chapter 2), a new haptic device is proposed. Its design is based on the analysis of the review made in the first part. Therefore, this device aims to do a step further and expand the abilities to precede haptic technologies. Human studies were conducted to evaluate the performance of the new haptic device in different use cases. It reflects the best features of the reviewed systems, trying to be in the direction of future developments in this field.

Thesis Supervisor: Zhanat Kappassov
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Chapter 1

Literature Review

1.1 Introduction

Modern head-mounted displays (HMDs) deliver an impressive visual experience allow-
ing users to dive deep into a virtual environment (VE). This became possible thanks
to fast progress in computer graphics, optics, displays and motion tracking. Virtual
reality (VR) and augmented reality (AR) systems can visually render realistic 3D en-
vironments and virtual objects. However, there is still much work to be done before
people can fully interact with objects in a VE. For example, realistic object manipula-
tion, 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 [6].

The word *haptics* refers to the capability to sense a natural or synthetic mechanical
environment through touch [7]. 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 [7]. Cutaneous feedback is instead
related to the stimuli detected by low threshold mechanoreceptors under the skin
within the contact area [8]. Haptic devices are used to engage these types of feedback
and give users the feeling of touch (provide haptic illusions). They receive information
from a VE and act on the user through tactile feedback; at the same time, they send
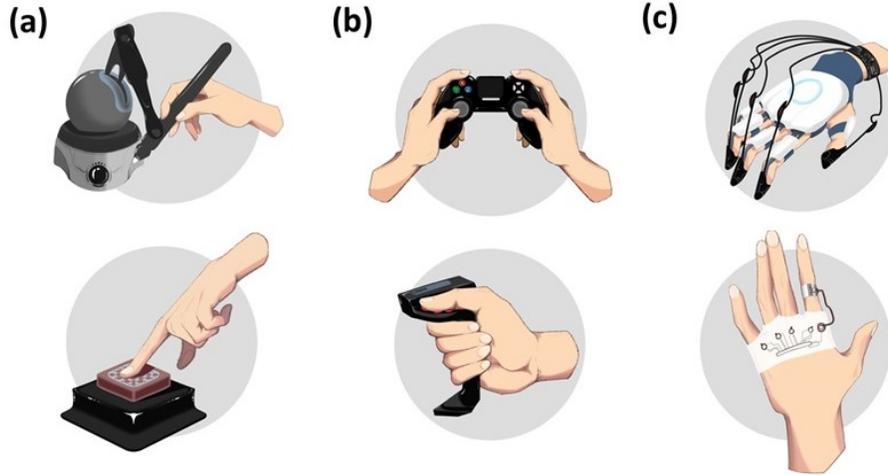
Figure 1-1: Taxonomy of haptic devices by wearability: (a) grounded haptic device; (b) hand-held haptic device; (c) wearable haptic device.

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 a limited workspace. Traditionally, kinesthetic devices are able to provide clear forces or torques to move the user's hand or resist motion [9]. They are widely used in industry and medicine for teleoperation tasks and other tool-based applications, e.g., using manipulator hands and dental drills [10]. Due to their limitations, grounded kinesthetic haptic devices are not suitable for our daily life where we interact with objects with our hands and perform simple actions such as grasp, touch, squeeze, push, click, slip through a surface.

To avoid the drawbacks of grounded kinestethic devices, the haptic feedback can be delivered through cutaneous feedback devices, as human fingerpads are rich in mechanoreceptors [11]. 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 [12]. 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).

1.1.1 Existing Review Papers

Previous reviews in this field focused on haptic devices [7, 9], wearable haptic interfaces [1] including exoskeletons and gloves [13,14], touch surfaces [15], and applications of haptic devices [10, 16, 17]. Some of them [1, 7, 9, 15] provide a background in the physiology of human sensory-motor control.

The first survey on haptic interfaces and devices was written by Hayward et al. [7] in 2004, providing 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. [9] reviewed the technology behind creating artificial touch sensations focusing on design, control and application of noninvasive haptic devices. Firstly, the authors of [9] introduced their 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. [1] 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 type of tactile stimuli, mechanical properties and interested body part.

Unlike [1], Wang et al. [13] 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 of [13] 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 [14] 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 in [13], as they are divided into traditional gloves (made of flexible fabric), thimbles, and exoskeletons. Finally, [14] analyzed characteristics and performance of existing commercial devices.

Bastogan et al. [15] reviewed another type of haptic devices - surface haptics. The categorization in [15] 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. [10] reviewed the applications of haptic systems in virtual environments. 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. [16] 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. [17] 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.

1.1.2 Motivation and Contribution

The main motivation for writing this manuscript 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. Also, the review part of this work demonstrates the key features on which beginning designers should focus while developing novel haptic devices. In this connection, the second part of this manuscript (Chapter 2) provides a practical example of the last.

Unlike [9], which classified haptic devices by design in three major categories (graspable, wearable and touchable), in this review I 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" [1]. 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 AppleWatch (Apple, USA) and Gear (Samsung, South Korea).

To represent this trend in the proposed taxonomy, I classify haptic systems by wearability level into three categories (see Figs. 1-2 and 1-1):

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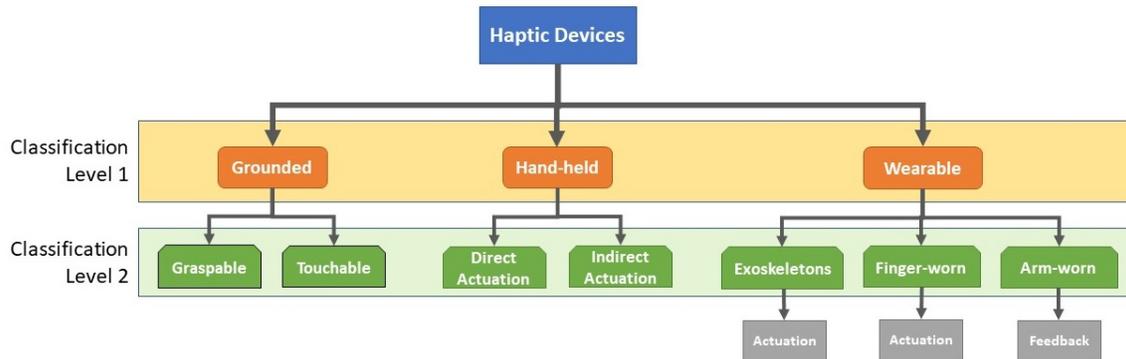
Figure 1-2: Two-level taxonomy of haptic devices based on wearability level (taxonomy level 1) and classification based on further characteristics (taxonomy level 2).

This specific taxonomy based on wearability level is, to the extent of my knowledge, a novel contribution. Furthermore, for all categories, I 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, I provide a table that summarizes the most important features of the 85 analyzed devices. For key features regarding different types of illusions related to object manipulation and perception (illusions of weight, shape, size, stiffness, texture), the applicable approaches are summarized.

1.1.3 Organization and Method

The remainder of this chapter is organized as follows. Grounded and hand-held devices are reviewed in Sections 1.2 and 1.3, respectively. Wearable devices are analyzed in separate sections: exoskeletons in Section 1.4, finger-worn devices in Section 1.5, and arm-worn devices in Section 1.6. A discussion of the applicability of the reviewed devices in various contexts and of the different types of tactile illusions is reported in Section 1.7, together with the conclusions. The discussion and conclusion further reflected in Chapter 2 where a new haptic device is introduced. Design and evaluation of the device revealed further in the second part of this thesis - Chapter 2.

The criteria used to select papers to be included in the review were the following:

(i) the approach described in the paper should be original; (ii) the authors should be presenting a newly built device, or an original modification of an existing device; (iii) the described haptic interface should provide either haptic illusions or novel haptic feedback for various tasks such as teleoperation and navigation; (iv) the paper is published in either an international journal or an international conference in English language from 2010 onward. In order to retrieve such papers from the literature, the following procedure was followed: first of all, I searched for relevant keywords, such as "haptic devices", "haptic technology", "tactile feedback", "haptic interfaces" and "wearable devices" in Google Scholar, ACM Digital Library, IEEEXplore, and Springer Link; afterwards, I analyzed (to possible find additional devices) the references cited in these papers, together with the papers that were citing them (via Google Scholar). As a result, 85 papers were found that satisfied the above-mentioned requirements.

1.2 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 1-1a). 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 A.1.

1.2.1 Graspable Devices

Graspable haptic systems (Fig. 1-1a, left) are traditionally kinesthetic devices, but some may provide cutaneous feedback through a held tool. Well-known commercial examples of tabletop graspable devices are Phantom (Sensable Technologies, USA) 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. [18] developed a haptic device that could be attached at 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. [19] 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 [20], 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. [21] 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 [22]. Unlike [21], the device presented in [22] 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 [21] and [22]) also has limitations such as high power consumption, strong cooling system requirement, and a consequent limited continuous interaction.

1.2.2 Touchable Devices

Touchable haptic devices (Fig. 1-1a, 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 [15].

TeslaTouch [23] is a touch screen device which provides a 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 "electostatic 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 illusions 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. [24]. The device conveys tangential forces in 2DoF when the user's finger is inserted in 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. [25] 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. [26]. The device is a 4×4 array of pins (tactors) moving perpendicularly to the fingerpad with amplitude of 2 mm. Each tactor (with 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) [27, 28] 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 outside, the fabric relaxes; when the two motors rotate towards 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 [5] introduced another approach of rendering virtual objects softness. The device combines vibrotactile feedback and pseudo-haptic effect delivered through a head-mounted display (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. [29] developed a texture display with vibrotactile feedback. The researchers placed materials with different textures on the top 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. [30] 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 pre-slide phase of soft object [31]. 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 [32], 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 propor-

tions. PATCH has a similar efficiency in displaying pulsing and stroking patterns as a voice-coil-actuated sleeve.

1.3 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 A.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. I 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.

1.3.1 Direct Actuation

Benko et al. [33] presented two hand-held controllers (*NormalTouch* and *Texture-Touch*) 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

Figure 1-3: Examples of Direct and Indirect Actuation Type hand-held devices.

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 [34]. 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 [35] 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 [35], it was shown that CapstanCrunch is better in rendering soft objects with low stiffness val-

ues, whereas CLAW is more realistic in rendering rigid objects.

Whitmire et al. [36] 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 [37] 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 similar form-factor was presented by Walker et al. [38]. This device, with 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 thumb and index fingers. 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 [39] is another hand-held controller, designed for providing orientation (cardinal directions) in VE. It is 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) [40] 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. [41] 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 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. [42, 43] 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.

1.3.2 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 was 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 [44]. DPHF is a mix of active haptic systems (which directly actuate the human limb) and haptic proxy objects. *Shifty*, presented in [44] is an example of 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 shape without even seeing it [45–49].

Transcalibur [50] 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 of [50] 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* [51]. 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 [52, 53]. 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* [53] rather than a shape illusion [50].

Heo et al. [52] 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 [53] uses only two jet-propellers, and provides a even greater thrust (up to 14 N). The device resembles a cylindrical handle with the jet propellers at the 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 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.

Thus far we have reviewed hand-held devices designed to be used with one hand or with two independent hands. Instead, Strasnick et al. [54] 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 differ in terms of linkage design.

Another haptic device for VR that utilizes a proxy object is *PIVOT* [55]. Although

the device is wrist-worn, it also comprises of 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.

1.4 Exoskeletons

The most typical form 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 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 to the user's body [1]. 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.
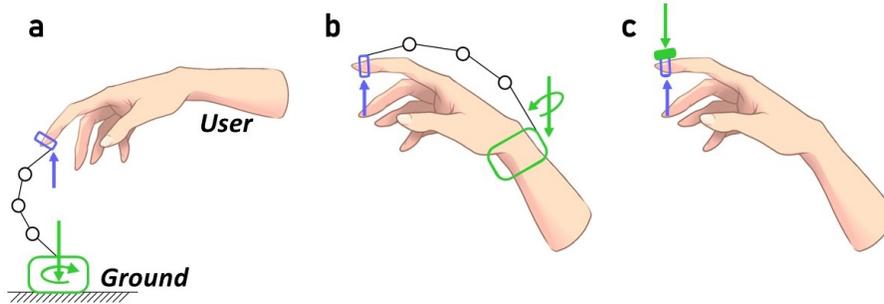
Figure 1-4: Schematics of different groundings of haptic devices: (a) world-grounded (i.e. tabletop) haptic device, (b) body-grounded kinesthetic device (i.e. exoskeleton), (c) finger-worn cutaneous device. The reaction forces are shown in green, actuation force in violet. Adapted from [1].

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. 1-4b). In order 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. 1-4c). However, as mentioned in [13], 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 (Dex-

tra Robotics, China) and CyberGrasp (CyberGlove Systems LLC, USA). These devices provide 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 number and complexity of mechanisms.

The previous review papers on haptic gloves and exoskeletons were considering a classification by haptic stimuli [1], actuation technology of haptic gloves for VR [14], pros and cons of existing force feedback gloves, and the design guidelines [13] and requirements of hand exoskeletons [56].

Pacchierotti et al. [1] 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. [14], 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. [13]. The paper presents 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 [13], 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 A.3, explored different approaches of delivering the sensation of grasping or gripping virtual objects.

Resistive Force

Cempini et al. [55]

Pierce et al. [54]

Locking Mechanisms

Wolverine [60]

DextrES [62]

Pneumatic Actuation

Zubrycki et al. [63]

ω-jet [65]
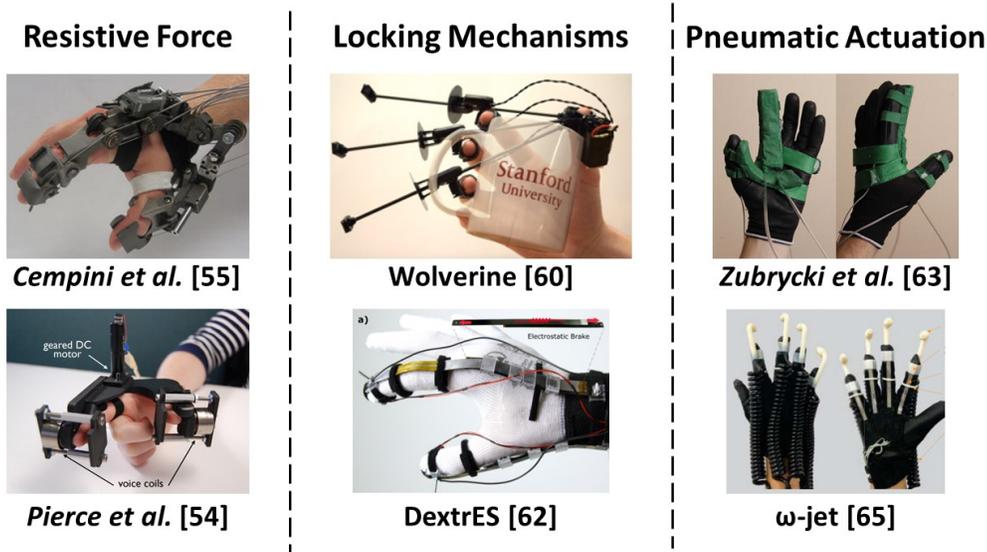
Figure 1-5: Examples of Resistive Force (left column), Locking Mechanism (central column) and Pneumatic Actuation (right column) type haptic gloves and exoskeleton devices.

1.4.1 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. [57] 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 thumb and index fingers 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. [58]. However, this device has more DoF and more complex kinematics compared to the device proposed in [57], 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 [59] is a hand exoskeleton system with force feedback for rendering the sensation of grasping a virtual object. The device has 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 a 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. [60] 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. 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 click buckle for ease of wearability. Each fingertip is powered by a DC motor located on the dorsum of the hand.

ExoTen-Glove [61] 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 actuation approach allows for lighter and less bulky exoskeleton structure as compared to [57,58,60]. 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, $W\Delta$ [62] is designed for providing force feedback to the user 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. $W\Delta$ has shown its efficiency in teleoperation by rendering contact forces sensed by a controlled robot end-effector.

1.4.2 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 conveys the sensation of rigid virtual objects.

Wolverine is an exoskeleton force-feedback device presented in [63], 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 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 [64] represents another approach for rendering virtual object grasping with a haptic exoskeleton. The device with a gripper-like form-factor [57, 58] combines a uni-directional brake mechanism [63] 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 locking mechanism was designed in the form of standard exoskeletons for the hand. The key unit of *DextrES* [65] 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 limbs 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.

1.4.3   Pneumatic Actuation

This type of devices use 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 [66] 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. [67] demonstrated an approach with pneumatic actuation using high pressure instead of vacuum as in [66]. Silicone elastomer actuators, placed inside a textile glove, are attached to the dorsal side of thumb and index fingers. 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* [68], 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 vental 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 [55]. Typically haptic gloves and exoskeletons are cumbersome and thus often limit the full range of wearer's motion. In addition, it requires a long time to put them on and to take them off [34].

1.5 Finger-worn Devices

Finger-worn haptic devices (also known as *thimbles*, and listed in Table A.4) mostly focus on the tactile stimulation of the fingerpads. Indeed, the latter contain the majority of tactile receptors within the human body [11], and most dexterous manipulation activities involve our fingertips [69]. 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 change 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 [2–4, 8, 12, 70–77], and shearing belt mechanisms [78–81]. Other less common approaches are moving tactors [82], and systems with electrical [83], thermal [75], vibration [84,85] and pneumatic [86] stimulation.

1.5.1 Moving Platform

(a)   **(b)**   **(c)**
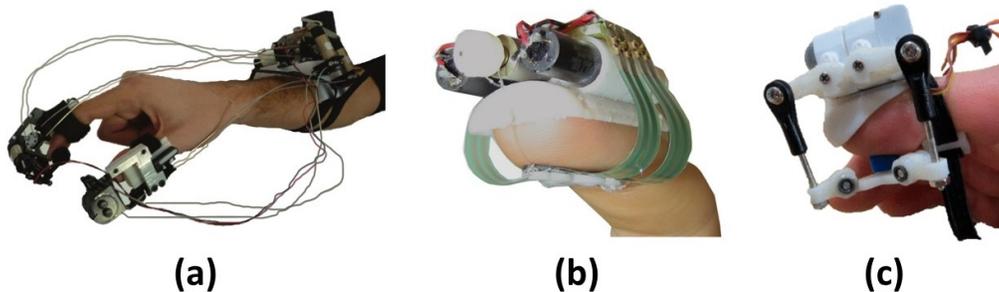
Figure 1-6: Finger-worn haptic devices of a moving plate type: (a) a heavy and bulky device with sheathed tendon actuation [2], (b) lighter and more compact devices with actuation through DC motors and gears/cables [3], (c) light and compact devices actuation through servomotors and rigid links [4].

Typically, moving-platform type devices possess a parallel mechanical structure (Fig. 1-6). 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. 1-6. The development of haptic thimbles of this type started from creating portable versions of the previously-available bulky grounded haptic thimbles (see, e.g, [87]). For example, Solazzi et al. [2] 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 [12, 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 [88] and [12] 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 [8, 76, 89]. In [73], [8] and [76], 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 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 cable-driven moving platform devices in terms of 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 [90]. Furthermore in [77], the functionality of the device from [90] was increased 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 [4, 74, 82] for better shear force provision. In [74] 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* [82], 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 a feeling of weight of a virtual object and roughness of virtual surfaces.

Lim et al. [91] 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 of virtual objects.

1.5.2   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. [78]. 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. 1-7). 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 normal force on the fingertip.

In *hRing*, Pacchierotti et al. [79] replaced the DC motors used in [78] with ser-
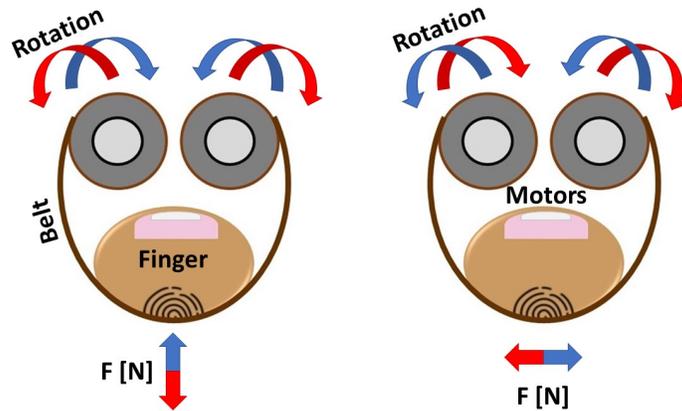
Figure 1-7: Working principle of shearing belt type haptic devices.

vomotors, 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 [81, 92], 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. [80, 93] 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 fabric-belt fingertip devices by 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. [94] presented a device with form-factor similar to a 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.

1.5.3 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 [1].

Maereg et al. [84] 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 [95]. 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 control of voltage of 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 focuses on providing tactile stimuli to the most sensitive part of the skin - the fingerpad. Gaudeni et al. [85] 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 [85], 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 freeing 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 [83] 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 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 [96], Moscatelli et al. [97] and Dhong et al. [98], 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. [99] 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 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. [100] 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 system is rather low and thus TCP-based stimuli are less effective in interactions with a virtual wall than VCA-based stimuli.

1.6 Arm-worn Devices

Arms as possible location for haptic feedback have been used less than hands, possibly due to lower density of mechanoreceptors [101]. 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 VE and real world, or to change the tactile feeling of real objects by augmenting them with virtual textures [85].

The application of these haptic devices can be split into two categories: guiding (e.g. navigation, telemanipulation) [102–107] and enhancement of tactile perception [108–111]. 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 type of stimuli, wrist-worn bracelet-type devices can be divided into vibrotactile, skin stretch and compression, and thermal, as detailed in the following.

Vibrotactile Feedback **Skin Stretch & Compression Feedback** **Thermal Feedback**
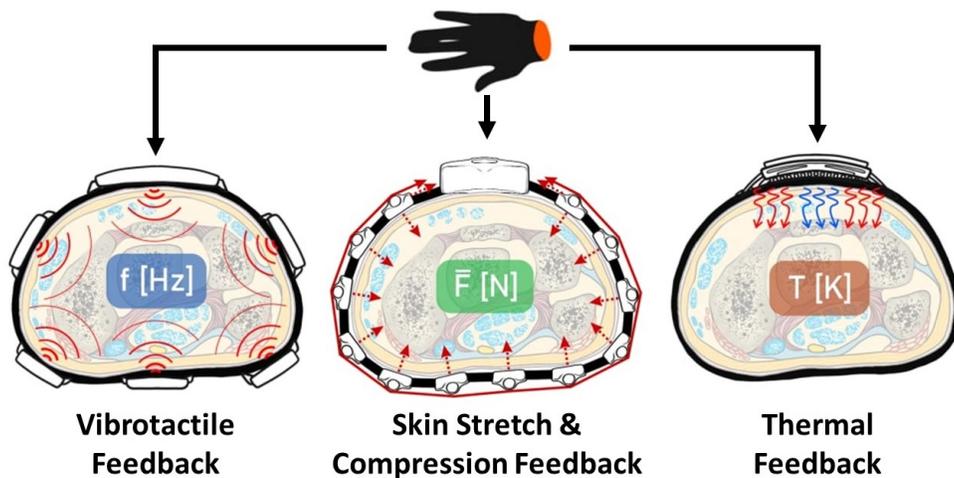
Figure 1-8: Schematics of three actuation types of arm-worn haptic devices put on the cross-section of the forearm: (a) vibrotactile feedback, (b) skin stretch and compression feedback, (c) thermal feedback.

1.6.1 Vibrotactile Feedback

As observed for previous tactile devices discussed in this literature review, 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 [102] used haptic bands called *Hapi Bands* for guidance in Yoga postures.

Panëels et al. [103] introduced a tactile bracelet for navigation tasks. The device has the form of a wristwatch, and is equipped with six electromagnetic actuators arranged in circle that provide vibrotactile feedback. The navigational information is delivered via combination of vibration patterns including duration, pauses, frequency, amplitude, position and number of tactors.

Another haptic wristband for navigation was described in [104], where vibrotactile feedback is provided to navigate a user during human-robot guidance. The actuation is performed by three cylindrical vibro-motors, which provide a haptic signal when the human deviates from the planned trajectory.

Haptic wristbands have shown effectiveness in performing teleoperation tasks. Bimbo et al. [112] 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. [113] 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 actuation force of 1 N.

In the field of AR/VR hand interactions, Pezent et al. presented a haptic wrist-

band called *Tasbi* [110, 111]. The bracelet's hardware consists of six linear resonant actuators (LRAs) evenly distributed around the circumference of the 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.

1.6.2 Skin Stretch and Compression Feedback

The high sensitivity of human skin to tangential stretches motivated the development of haptic bands with skin stretch feedback [106–109, 114, 115]. In comparison, compression feedback provides less attention-demanding, and more prolonged background feedback [116, 117].

Caswell et al. [118] 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. [114] 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. [106] 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 [117], is a haptic bracelet that providing 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 [116]. 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.

Moriyama et al. [108] 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 two DoF (normal and lateral) force to the dorsal (corresponding to thumb) and volar (corresponding to index finger) sides of the wrist, respectively.

A novel wearable skin stretch device for the upper limb called *hBracelet* was developed to improve telepresence during remote control of a robot-manipulator [109]. 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 1.5.2), 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. [119] have combined the shearing-belt approach with vibrotactile feedback by attaching four equidistant vibration motors on an elastic fabric belt. Thus, the forearm-worn haptic device can provide three types of cutaneous feedback - skin-stretch, compression and vibrotactile.

Raitor et al. [105] 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 [115]. Kanjanapas et al. [115] 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 normal force at different contact points.

Wu and Culbertson [120] developed a haptic forearm-worn sleeve with pneumatic actuation, which provides 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. [107] 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 self-movement along the user's forearm. The system hardware is made of four interlinked segments, each containing a wheel powered by a servomotor.

1.6.3 Thermal Feedback

Thermal feedback is another cutaneous stimulus that can be used as additional communication channel or as method of enhancing virtual experience. From the physiological point of view, the face is the most thermally sensitive region on 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 [121]. 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 [121, 122]. Also, people react to cold stimuli quicker than to warm stimuli due to the difference in the conduction velocities of their afferent fibers [123].

Tewell et al. [124] 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 [125] 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. [126] 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 [127] 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.

1.7 Discussions

Chapter 1 of this paper has reviewed research trends and applications of haptic devices, categorizing them based on the concept of wearability. Using this taxonomy, Table A.6 summarizes the use of different stimuli in the reviewed applications, linking them to different types of haptic illusions or guiding interfaces. Among those of the latter type, there are devices that convey haptic stimuli to guide a user in tasks such as teleoperation and navigation, and to provide notifications. The use of haptic feedback in these applications helps to concentrate on the main task and decreases the load from visual and auditory channels. These devices usually require a pre-training session for the user to learn tactile patterns and reach an acceptable level of performance. Arm-worn devices are used in almost the totality of guidance applications.

Despite all recent advances, there are still gaps and challenges to be addressed, which I will discuss in the following, also hinting at recommendations for potential research directions.

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 of the 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 A.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 review 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 my opinion, is the main gap to be filled in future research. Indeed, in order to attract users in real-life applications, it is my 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.

Referring to the table, the design specifications of an ideal haptic device can be proposed by combining different features from these four devices. For example, the first device, CLAW [34], 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. However, its main drawback is that it is hand-held. Grabity [64] 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 [60] would benefit from the presence of additional stimulation methods to render weight and texture. Finally, the finger-worn moving-platform type device from [90] has the potential to render weight using the shearing force delivered by the platform. Also, the weight sensation can be delivered by asymmetric vibration of its motors, but this method requires the use of multiple devices. Despite the wearability and light weight of haptic thimbles, kinesthetic feedback is required

for proper size rendering.

Integrating the sensors from these four devices can constitute a considerable challenge, mostly due to limited space availability. However, 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.

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Chapter 2

Novel haptic device

2.1 Introduction

As a result of the literature analysis (Section 1.7), it was decided to create a haptic device of the arm-worn type. The reason for this choice can be highlighted here again. Firstly, this type of haptic device allows for a combination of multiple actuation techniques (e.g. compression, vibrotactile, thermal, and skin-stretch feedback). Also, such placement on a human body (wrist and forearm) does not strongly restrict device size and complexity compared with haptic thimbles. Finally, relocation of haptic feedback from the fingertips to other locations on the body can enable haptic interaction with mixed reality virtual environments while leaving the fingers free for other tasks. However, human arms have a lower density of mechanoreceptors [101] which may be challenging for complex haptic renderings (e.g. shape and texture of virtual objects).

I propose to design a wrist-worn haptic device (Fig. 2-1) that will provide meaningful feedback to the user – but without the need of creating perfectly realistic sensations. The new haptic bracelet and evaluation of its performance in rendering haptic cues, particularly in providing haptic feedback during virtual object manipulation tasks, are presented in Chapter 2 of the manuscript.

One of the main challenges in this research is not only to evaluate user experience with this form-factor of the haptic device but also to understand how to effectively

map haptic feedback from the fingertips to the wrist for two-finger (e.g. index finger and thumb) manipulation during in virtual environment.
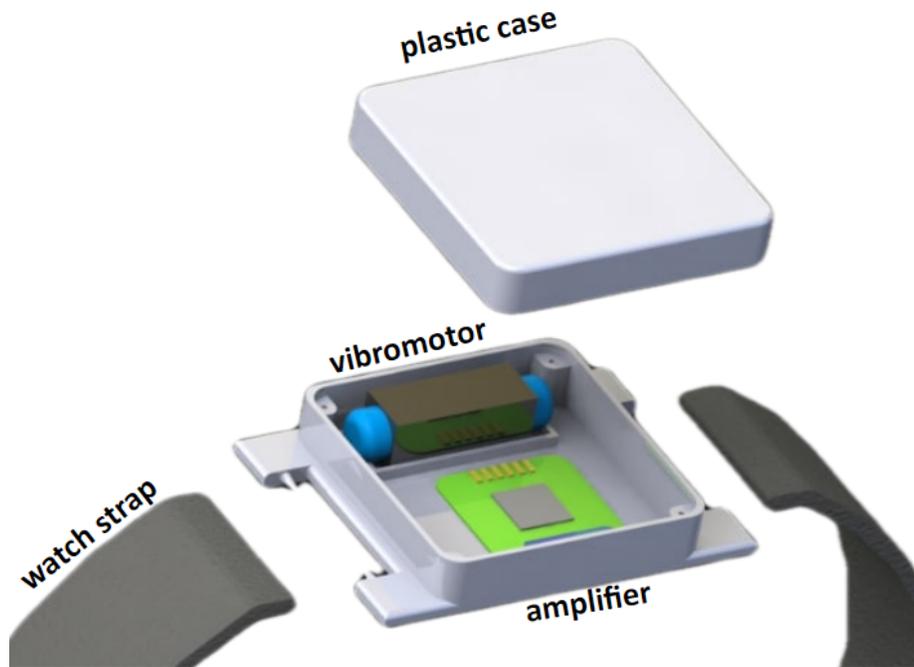
Figure 2-1: Render of CAD model

2.2   State of the art

A haptic device designed to be worn on the wrist/arm has been already shown in Chapter 1.6. Devices discussed in that section have various types of actuation, and feedback and are dedicated to different tasks. Nevertheless, the most popular and habitual type of actuation which is coming into a mind when talking about haptics - vibrotactile - was not widely studied in the state-of-the-art wrist-worn devices.

Pezent et al. [111] demonstrated their haptic bracelet efficiency in rendering virtual object stiffness. Moreover, they combined both vibrotactile and normal force (squeeze) feedback. Bimbo et al. [112] did the same for rendering stiffness of collided objects during robot teleoperation tasks. Others [103, 104, 119] utilized vibrations to direct and navigate users. However, the above-mentioned publications did not study such aspects as proper placement of the wrist-worn device on the human arm (e.g. volar or dorsal side), and actuation strategy for different types of applications (e.g. Virtual Environment, navigation, notifications).

Several researchers have investigated placing vibrotactors (or tactors) on the wrist and arm. Chen et al. [128] compared placing planar arrays of tactors on the dorsal versus the volar side of the wrist. Matscheko et al. [129] further studied arranging tactors dorsally versus radially, concluding that placing tactors around the wrist circumference was best.

This thesis contributes by studying the effectiveness of mapping haptic feedback from the fingertips to the wrist for two-finger (e.g. index finger and thumb) manipulation in VR, and showing which actuation strategies can be applied to use one device for different types of applications such as manipulation in VE, enhancing music listening experience, navigation, and haptic notifications.

2.3 Hardware Design

The haptic device represents a bracelet with two active structures placed on the dorsal and volar sides of the user's wrist (Fig. 2-2). Each active structure is a 3D-printed plastic case (Ultimaker 2+ Extended, PLA) containing a voice-coil actuator (model Haptuator Mark II, Tactile Labs Inc., Canada) and type-D audio amplifier (Adafruit PAM8302). Both active structures are attached to a regular rubber watch strap. The strap has multiple holes which makes the bracelet suitable for almost all sizes.
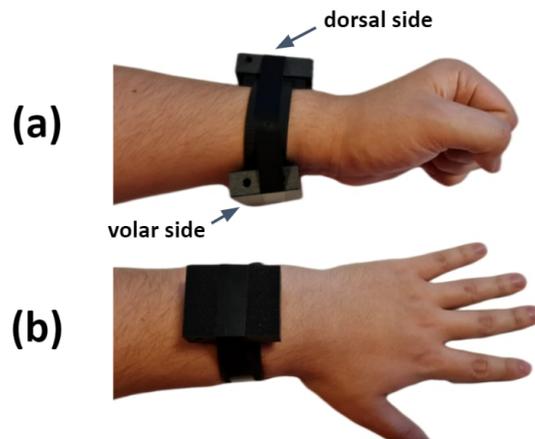
Figure 2-2: Haptic bracelet on wrist: (a) side view, (b) top view
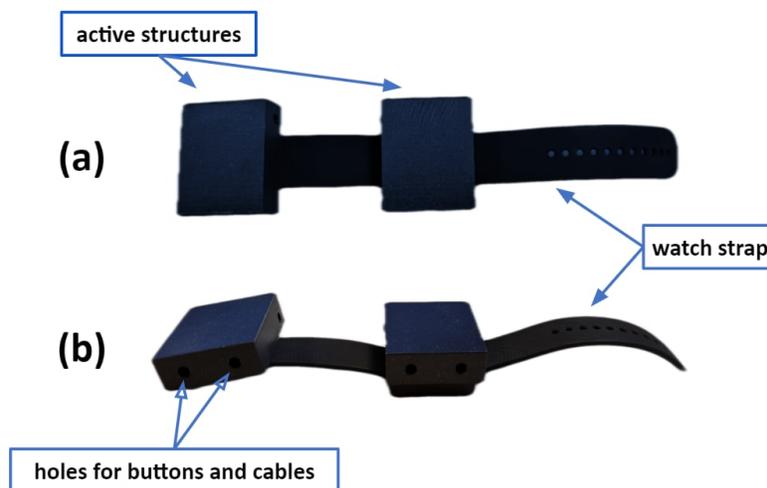
Figure 2-3: Haptic bracelet: (a) top view, (b) side view

The system is powered by a digital microprocessor-based board (model Teensy 3.2, Paul Stoffregen and PJRC, USA). The board has 2 analog outputs which allow using

one controller for both dorsal and volar actuators. The use of the audio amplifiers allows using the full power of actuators along with their wide bandwidth range (90 Hz - 1000 Hz).
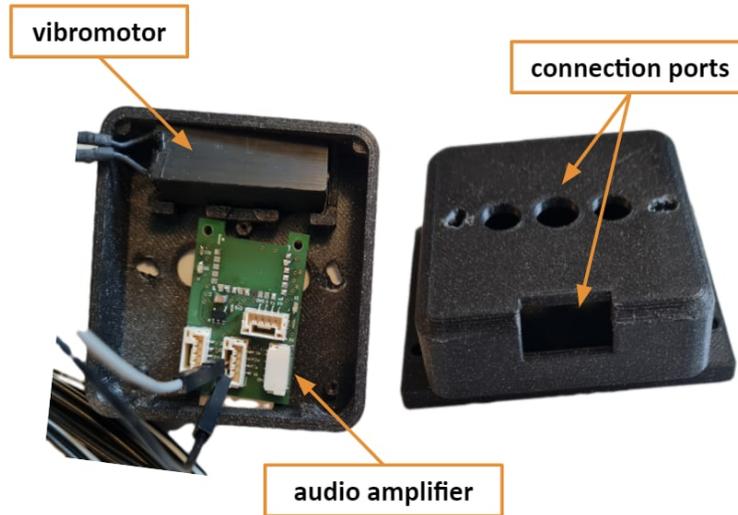
Figure 2-4: First prototype of the haptic bracelet: (left) inside the case, (right) cover part.

Figures 2-4 and 2-1 show the inner part of the bracelet. The VCA is oriented along the length of the arm and firmly fixed inside between the main case and cover. At the place of motor attachment, I have put a thin piece of silicone to make isolation and prevent the noise. In this project, I am not focusing on presenting the high-end product, therefore some limitations can be noticed. For example, the controller is placed separately, wires can be seen for users, and the system is powered through a cable, not a battery. These can affect on overall user experience, for example having different mass (210 g) and shape (two cubic structures, $50{\times}50{\times}12$mm each) from an ideal market-available device.

2.4   Stimuli

The haptic device provides vibrotactile feedback to its wearer through two voice-coil actuators. VCAs can be controlled with different strategies, e.g. to generate synchronous similar signals, generate asynchronous similar signals, or generate independent signals. The strategy is selected according to the corresponding application (Fig. 2-5).
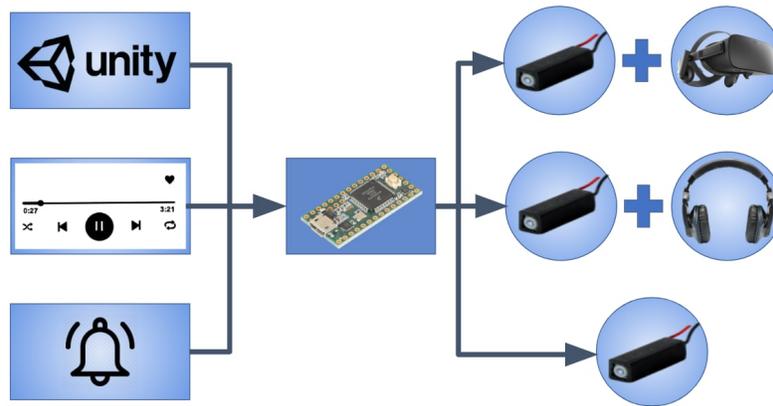
Figure 2-5: Three types of applications: (1) VR/AR: haptic + visual feedback; (2) Music: haptic + audio feedback; (3) Notifications: only haptic feedback.

Surpassing previously mentioned wristbands, the new haptic bracelet is designed to be applicable for a wide range of use-cases with simple hardware. Particularly in this manuscript, I consider (1) providing haptic illusions of stiffness and weight of manipulated virtual objects, (2) enhancing the music listening experience, and (3) providing haptic notifications. Each of these applications addresses its stimulation approach.

2.4.1   Virtual Environment

Here, the main purpose of the device is to enhance immersion into a virtual/augmented world, by providing realistic haptic cues during some actions or events. In this manuscript, success in delivering two different haptic illusions is studied as well as an evaluation of the proper placement of actuators or proper mapping of haptic stimuli from fingertips (of index finger and thumb) to the wrist. The proposed mapping

approach is based on the placement of tendons linked to the index finger and thumb. Index finger movement corresponds to a tendon on the ventral side of the wrist, and thumb movement corresponds to a tendon closer to the dorsal side of the wrist. Thus, stimulation of places close to the tendons could create a reasonable mapping for users to understand (Fig. 2-6).
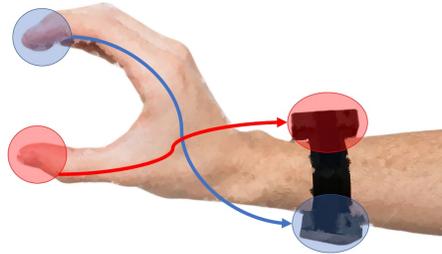
Figure 2-6: Illustration of mapping

The first is an illusion of virtual object stiffness. Two approaches are evaluated - single-finger interaction (e.g. pressing a button), and two-finger object manipulation (e.g. object squeezing). Unlike in [111] where the wrist-worn haptic device $Tasbi$ uses both vibrotactile and compression forces to render the softness of the virtual button, the haptic bracelet presented in this work delivers this cue through vibration only. In this case, the stimulus vibration of a single actuator where the frequency is proportional to index finger displacement towards (normal to) a virtual button (Fig. 2-7 left). In two-finger object manipulation, both actuators are working independently with frequencies being proportional to the displacement of a corresponding finger. Overall, the generated stimulus is a frequency modulated signal as in my previous work [5] - the frequency of the oscillation is modulated by the rate of change of the
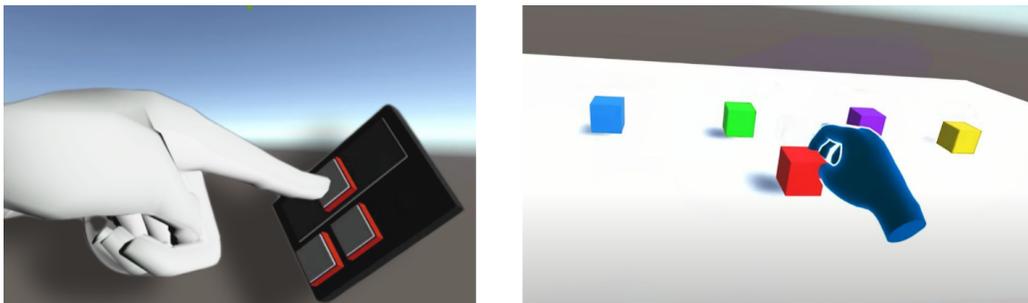
Figure 2-7: Virtual Environment: (left) pressing buttons with different stiffness level, (right) object manipulation (squeezing/lifting).
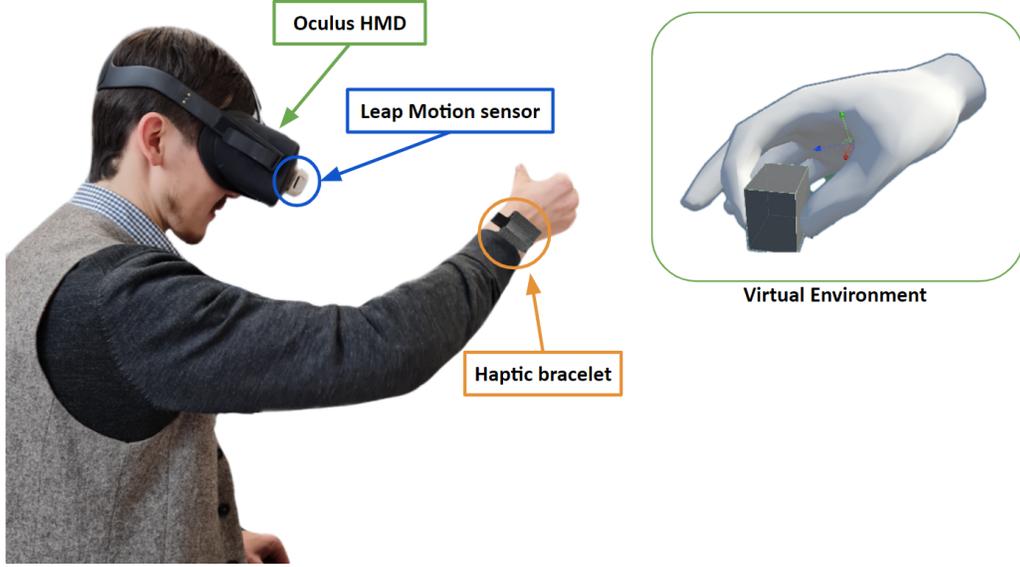
Figure 2-8: Experimental procedure: a user wearing VR headset is using the haptic device to perform the task. User hand movement is synchronized with the virtual environment displayed at the top-right corner.

applied force so that the desired lateral displacement of the coil is

$$p_h(t) = A \cdot sin(2\pi \cdot M_h \cdot F_N(t)) \tag{2.1}$$

where M_h, A, and F_N are the frequency modulation coefficient, the amplitude, and normal force respectively. However, unlike in [5], the device presented in this thesis does not contain any force sensors. Therefore, the force rate is replaced by the rate of change of each of the fingers (that squeeze a virtual object) inclination. This finger inclination is captured by Leap Motion Controller (Ultraleap, USA) attached to an HMD (Fig 2-8).

The second is an illusion of virtual object weight (Fig. 2-7 right). The illusion is achieved by running two motors simultaneously and playing the same signal on each of the actuators. The signal is the same as in Eq. 2.1, but the frequency is oppositely proportional to object weight, while the amplitude is directly proportional to the weight. For all VE applications, the haptic feedback from the wrist-worn device is combined with pseudo haptic feedback delivered through HMD.

2.4.2 Music

The second use-case of the novel wrist-worn haptic device is augmented audio experience. The bracelet is needed to mimic the audio signal which is being streamed to headphones. Here, I am referring to already existing devices used for richer music listening. The device is called *Basslet* (Lofelt GmbH, Germany) and represents a subwoofer in a watch-like form factor that works alongside headphones. Basslet recreates a strong bass vibration from the music played on a smartphone. The haptic band presented in this manuscript can be used similarly. However, I have added one more actuator to the volar side of the user's wrist. Further in this manuscript (Sec. 2.5.2), I will evaluate to what extent a double-actuator configuration improves the music listening compared to a Basslet-like configuration with a single actuator (Fig. 2-9).

2.4.3 Notifications

The third type of application is providing notifications through vibrotactile feedback. Here, the haptic cues are not accompanied by any other feedback (visual or audio). Different kinds of haptic notifications (or haptic icons) can be rendered by different patterns and combinations. Thus, vibromotors can be actuated synchronously or
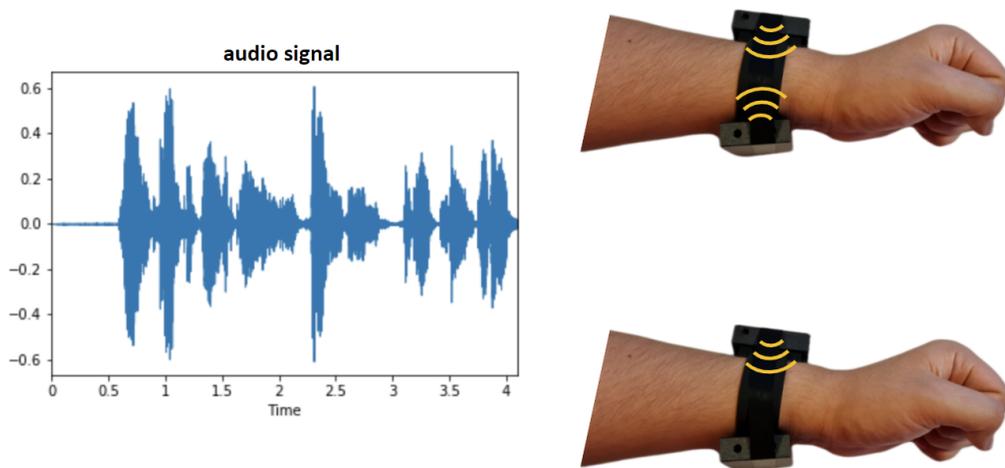
Figure 2-9: Enhanced music listening experience: (top) double-actuator configuration, (bottom) single-actuator configuration.
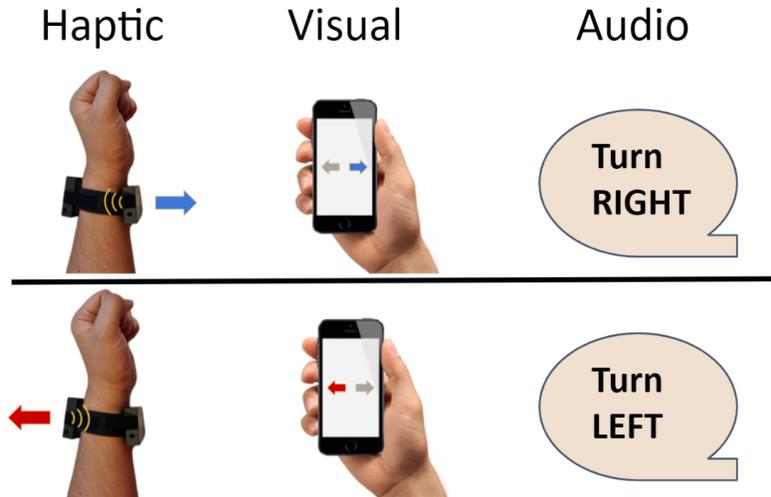
Figure 2-10: Notifications for navigation

asynchronously depending on a haptic icon.

In this project, two kinds of haptic notifications are tested. The first type is used for navigation. The principle is shown in Fig. 2-10. The second type is a more complex haptic cue aimed at rendering rotation around the wrist axis. As it can be seen from Fig. 2-11, this effect is achieved by generating short chirp signals on each actuator with little delay between them.
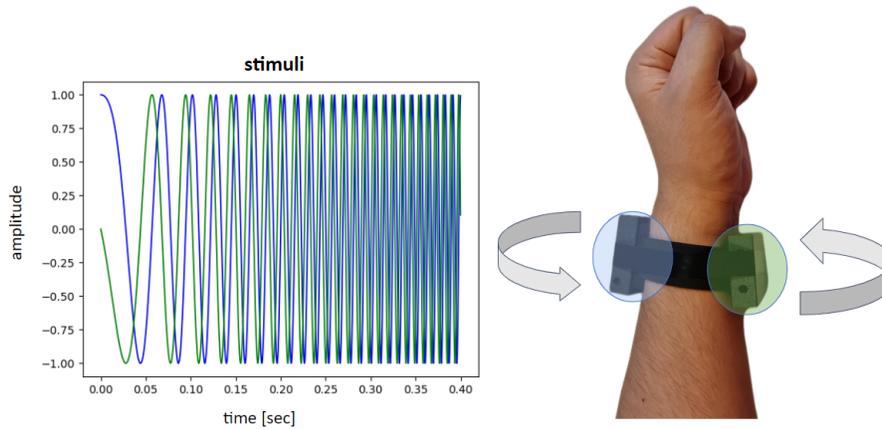
Figure 2-11: More complex notification

2.5   Perceptual Evaluation

This study aims to evaluate the effectiveness of a new haptic device in delivering tactile cues both in terms of convenient signal rendering and place of actuation including the mapping strategy. To properly conduct this evaluation, experimental evaluation with human subjects is required. Therefore, ten volunteers (6 male and 4 female, 8 right-handed and 2 left-handed) were involved in experiments 2.5.1 and 2.5.3, and twenty (11 male and 9 female, 17 right-handed and 3 left-handed) volunteers - for experiment 2.5.2. Subjects (7 male and 3 female) were chosen randomly regardless of their familiarity with technologies in the field of this research. None of the participants reported any physical injuries or mental disorders, specifically in visual or haptic perception abilities. Instructions were provided to each participant in written and verbal forms before the procedure started. Subjects were asked to remove gloves, watches, bracelets, and jewelry if any as they may cause discomfort during the experiment.

Before experiments, the Collaborative Institutional Training Initiative (CITI) Program's Health Information Privacy and Security course were completed. After that, the protocol of the experiment (NU-IREC 357/06012021) was approved by the Institutional Research Ethics Committee (IREC) of Nazarbayev University.

2.5.1   Virtual Environment

Stiffness illusion - pressing button

There are two experiments in this subsection that study device performance in delivering stiffness illusion. The first of them is focused on single-finger interaction with a virtual object - pressing a push-button. In [111] it was already proven that haptic feedback combined with the visual channel can give realism to this action. Therefore, in this experiment, I put more effort into understanding if it is possible to achieve the same result with a simpler setup (e.g. vibrotactile feedback only, one or two actuators). Moreover, I strive to explore if the mapping strategy proposed in the previous section will suit this task.
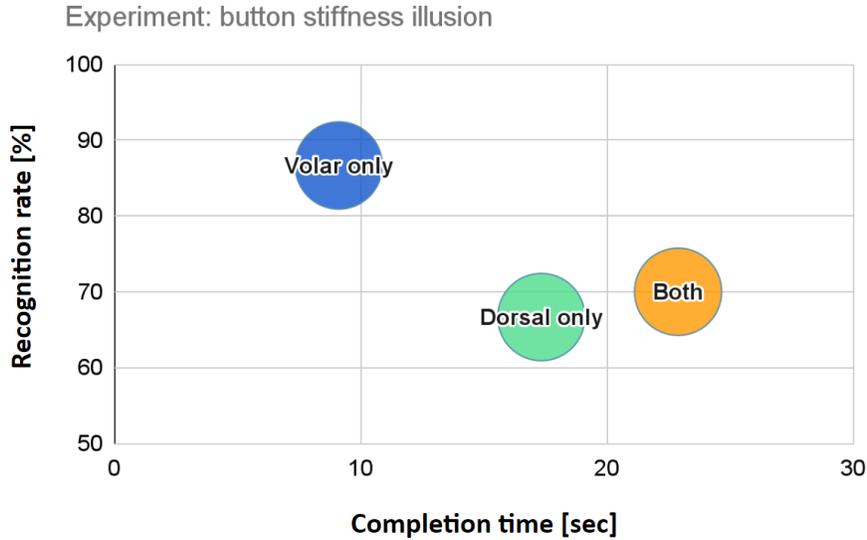
Figure 2-12: Experiment on stiffness illusion - pressing a push button. Three different actuation places are evaluated by measuring success of button recognition and completion time.

Three different actuation places were chosen to be compared - vibration only on the volar side, only on the dorsal side, and on both sides of the wrist. The experimental procedure is following. A subject takes a seat, wears the HMD with Leap Motion sensor, and takes some trials in pushing a virtual button to understand the movement - necessary hand displacement and displacement rate. Then, the panel with three buttons appears in VE (Fig. 2-7 left). The dimensions and color of the buttons are the same, whereas the stiffness level is different. M_h parameters for tactile stiffness rendering are equal to 5 for soft, 2 for medium, and 0.5 for the firm button. The task is to differentiate the buttons by stiffness level as soon as possible. Subjects can press buttons with the index finger as many times as they need and verbally tell the button name (e.g. "soft", "medium", "firm"). This procedure was repeated for all three mapping variants. As a result, two parameters were measured - the number of correct buttons recognized and time spent.

Figure 2-12 shows the results of this study. It can be seen that providing haptic cues on the volar side only helped to differentiate buttons with the highest average accuracy (86.67%, stdev = 0.843) and the shortest average time (9.2 sec, stdev = 2.625). On the other hand, actuation on the dorsal side only leads to the lowest

average recognition accuracy (66.67%, stdev = 1.333) and an average completion time of 17.2 sec (stdev = 2.427). The longest average time spent on recognition belongs to the option with two vibrating actuators (both dorsal and volar at the same time) - 22.9 sec (stdev = 2.260). The average recognition rate with this option is equal to 70% (stdev = 1.197).

Stiffness illusion - squeezing object

The second experiment in this subsection that studies device performance in delivering stiffness illusion is focused on a two-finger manipulation task - squeezing a virtual object with the index finger and thumb. In my previous research [5], it was already demonstrated that vibrotactile feedback on the fingertips of the two fingers causes the illusion of squeezing a soft object. Therefore, this experiment aims to study if it is possible to achieve the same result by relocating tactile cues. The mapping strategy is mentioned in the previous section.

The procedure is the same as in the previous experiment. However, in this experiment, a testee sees the virtual world as in Figure 2-7 (right). The task is to differentiate objects by their stiffness. The first part of the experiment was conducted with the grounded haptic device $VibeRo$ [5]. The verbal responses were recorded. After, the second part of the experiment was conducted with the new wrist-worn haptic device. Again, verbal responses were recorded. It was allowed to squeeze objects as many times as necessary. Since the performance of two devices is compared, recognition time is out of interest.

Figure 2-13 shows the results of the experimental evaluation. It can be seen that the haptic bracelet follows the same trend as VibeRo - firm vibrations are more clear to users. Moreover, on average, the results of the haptic bracelet were a little bit higher than of VibeRo: for soft vibration level - 74.8% vs 70.1%, for firm vibration level - 85.9% vs 84.7%. For pure visual feedback (no vibration), the results are almost the same since there is no effect of a haptic device.

A pairwise one-way ANOVA was performed using R statistical software (aov() function) to calculate the significance of the results of our measurements. In other
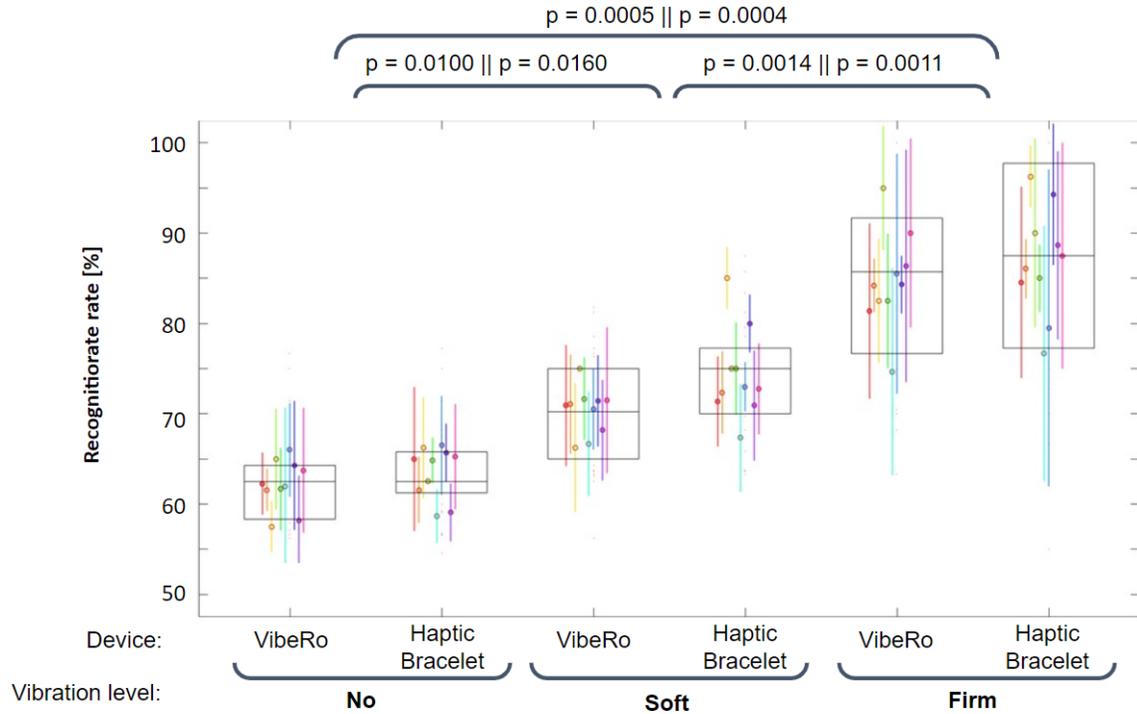
Figure 2-13: Experiment: stiffness illusion - squeezing object. Comparison of two devices - VibeRo [5] and new haptic bracelet

words, mean recognition rate values of all subjects regarding each vibration level (no vibration, i.e. $M_h = 0$, "soft", i.e. $M_h = 5$, and "firm", i.e. $M_h = 2$) were taken to analyze subjects perception of object stiffness. According to ANOVA, the difference of data in all pairs of vibration levels within a device is statistically significant. For example, the pairwise comparison at the given conditions between the cases of $M_h = 5$ ("soft") and $M_h = 2$ ("firm") revealed statistically significant difference – the probability of getting these values by chance is 1.4% ('*': p=0.0014) for VibeRo and 1.1% ('*': p=0.0011) for the haptic bracelet.

Weight illusion

In this experiment I am interested in how well can the haptic bracelet simulate the weight of a virtual object. In Chapter 1 of this manuscript, various haptic devices demonstrated their ability to render the illusion of the weight of a virtual object. Different approaches to providing haptic feedback were studied for such kind of application. According to Table A.6, the most popular way of delivering an illusion
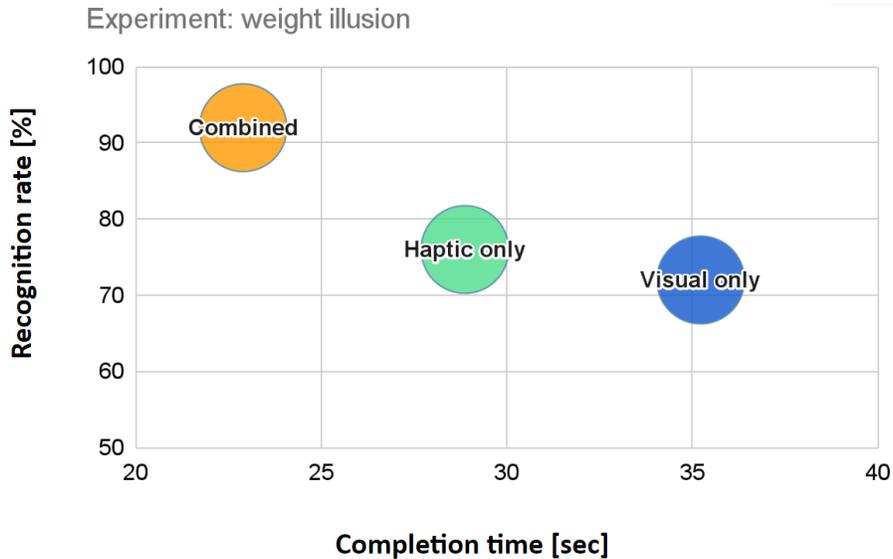
Figure 2-14: Results of the weight illusion experiment.

of weight is skin-stretch feedback. Among vibrotactile feedback, only one device demonstrated this feature - *Grabity* [64] (exoskeleton type). Grabity stimulates each fingerpad (index finger and thumb) with vibrations to simulate the weight of a virtual object. Finally, none of the existing bracelets can generate this haptic illusion. Therefore, this experiment aims to explore to what extent it is possible to utilize a wrist-worn haptic device for this type of application. Unlike previous experiments, this experiment is not considering a mapping strategy since the same vibrotactile feedback is generated by both actuators at the same time.

The procedure is the following: a testee is asked to wear the haptic bracelet and an HMD with a Leap Motion sensor being attached to it. On the screen, a subject sees the same scene as in the previous experiment (Fig. 2-7 right). However, objects are the same but non-squeezable, so it is only possible to lift them vertically. Moreover, it is not necessary to use only two fingers. Here, the task is to differentiate five objects by their weight. Subjects are allowed to lift objects as many times as necessary, but tasks must be completed as soon as possible. Thus, both recognition rate and completion time are taken into account for the analysis.

The graph in Figure 2-14 demonstrates the result of this experiment. It can be seen that the highest recognition rate of 92% (stdev=0.843) is achieved by a

combination of pseudo haptic feedback (visual channel - animation) and the haptic feedback. Also, this option allowed for the quickest completion time - 22.9 sec (stdev=2.260). The second-best result belongs to pure haptic stimulus - 76% recognition rate (stdev=1.032) with a completion time of 28.7 sec (stdev=2.316). Interestingly, pure visual feedback demonstrated relatively high result - 72% recognition rate (stdev=1.150) with completion time of 35.8 sec (stdev=2.443).

2.5.2 Music

In this experiment, more people (twenty) were tested because there is no need of using VE and the HMD which makes the process easier compared with other experiments in this project. For this experiment, I did not apply any signal processing for the generated haptic stimulus - VCAs were simply replicating the audio signal streamed to headphones. Three cases of haptic feedback are studied - single actuation on the dorsal side of the wrist, actuation on both sides (dorsal and volar) at the same time and no actuation.

Subjects were asked to wear the haptic bracelet on preferable hand and wear headphones. Then each of three different music tracks of three different genres (classic, hip-hop and techno) were played three times - one time per haptic configuration. The sequence of haptic configuration is random. After each track was played subjects were asked which of the haptic configuration is preferable.

The results are shown in Table 2.1. Analysis of this data reveals that the haptic bracelet is able to enhance the music listening experience. However, the difference between the single-actuation option and the double-actuation option is not significant. Subjects could not distinguish reasonable changes between two haptic modes. However, among the three genres, the majority of testees preferred to use the double-actuation mode of the haptic bracelet while listening to hip-hop. This can be explained by a high density of low-frequencies (basses) in this type of music which are easier to perceive.

Table 2.1: Result of responses during the music experiment

music	no haptic feedback	one actuator	two actuators	no difference
classical	5%	20%	25%	50%
hip-hop	0%	5%	75%	20%
techno	0%	15%	20%	65%

2.5.3 Notifications

There are two experiments in this subsection that aim to explore effectiveness of the haptic bracelet in rendering haptic notifications. Two types of haptic notifications are presented in this project - notifications for navigation and notification through rendering pattern of rotation around the wrist.

In the first experiment, I am comparing three types of guidance for navigation - visual, audio and haptic. The visual guidance is displayed on a screen as it happens in daily life. The audio guidance is delivered verbally through a speaker. The haptic guidance is delivered through vibrations on either the dorsal or volar side of the wrist in correspondence to the direction of movement and depending on the hand chosen for wearing the device. In this project, for the left hand: vibration on the dorsal side means turning left and on the volar side – turning right (Fig. 2-10); for the right hand – vice-versa. The subject received 10 guidance per each type - 5 commands to turn left and 5 commands to turn right. After each command/notification, the subject had to push on the corresponding arrow on the keyboard. Both reaction time and correctness were measured in this experiment.

Figure 2-15 shows the result of this experiment. While it is difficult to differentiate the correctness rate of each notification method, the average reaction time is easily recognizable. The best result belongs to visual guiding - 100% of recognition rate with the best average reaction time - 0.274 sec. The haptic guiding has the lowest correctness rate (93%), but the reaction time (0.341 sec) is quicker than audio's (0.425 sec). Overall, the result of haptic notification for navigation purposes are convenient. This make the haptic bracelet suitable not only for VE application mentioned earlier but also for guiding tasks.

Despite the success in rendering cues for navigation, these haptic notifications
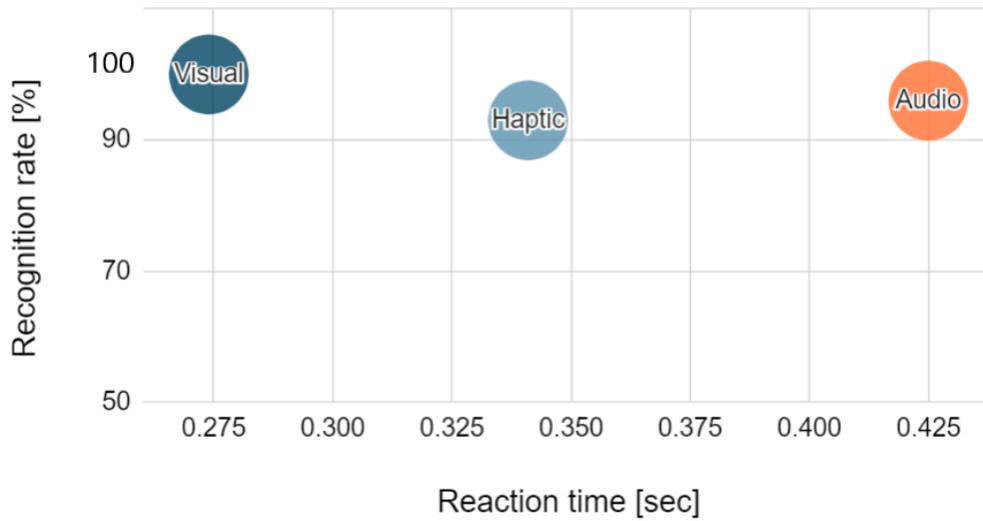
Figure 2-15: Results of the navigation experiment.

remain relatively simple. Thus, the second experiment of this subsection is addressed on evaluation of effectiveness in rendering more complex haptic icons. Here, I chose the haptic stimulus that causes the feeling of rotational signal around the wrist (Fig. 2-11). In this experiment subject were asked to verbally transmit the direction of the "rotation" - clockwise or counter-clockwise. During the experiment, it became clear that the results are meaningless. Testees were confused by this haptic rendering. There are several reasons for this failure. Firstly, the orientation of actuators inside the haptic bracelet is not suitable for this type of stimulation. Secondly, it can be said that the number of actuators around the wrist is less than needed.

2.6   Conclusion

In this MS thesis, I have reviewed the existing haptic devices, and, analyzing the reviewed material, I came up with my own vision of a novel haptic device. A more explicit discussion of the literature review can be found in the first Chapter.

In this Chapter, I have proposed a new haptic device of wrist-worn type (referring to the introduced taxonomy). This haptic bracelet uses vibrotactile actuation to render various haptic effects for different applications. Therefore, the unification of haptic devices for a variety of use-cases is the main contribution of this project. Another novelty introduced in this manuscript is a qualitative perceptual evaluation of the mapping strategy which allows using the human wrist for the generation of haptic cues initially intended for fingertips. Finally, this paper extends our previous work [5] for virtual object manipulation. Specifically, it was described that the capability of a new haptic device to enhance the quality of perceived haptic clues representing the softness of an object being squeezed in the VE seen in an HMD.

Regarding the Virtual Environment application, it was revealed that the haptic bracelet is able to provide convenient haptic illusions for both single- and two-finger manipulation of soft virtual objects. Particularly, the experiment with button stiffness illusion demonstrated the most effective option of stimuli generation for such rendering. Results show that users can easily and correctly recognize different button stiffness when the vibrotactile feedback takes place on the volar side of the wrist. Results of the second experiment give insights into two important things. Firstly, the haptic bracelet that maps haptic cues from the fingertips to the wrist is able to give the same performance as the grounded haptic device which was designed especially for this purpose. Secondly, as for VibeRo, the new haptic bracelet is more efficient in generating the illusion of relatively firm deformable objects. Finally, both experiments support my hypothesis for the proper tactile mapping (Fig. 2-6). The significance of the obtained experimental data is assured by pairwise one-way ANOVA.

In addition to the haptic effect of object stiffness, this project introduces a new haptic effect for wrist-worn haptic devices – weight illusion. This effect was previously

rendered either by vibrotactile or skin-stretch feedback on fingertips. Despite this fact, results of the experiment with weight illusion support the idea that a combination of pseudohaptics and vibrotactile cues can enhance virtual object manipulation in terms of perceiving the weight of lifted objects.

Another application of the haptic bracelet is "feeling" music. Despite that this use-case of haptic wrist-worn devices is not new, this project contributes by comparing different combinations of placing actuators and studying the effectiveness of the augmented audio signal in playing different genres of music. Results of this perceptual evaluation show that people prefer listening to music when the haptic device is on. However, it is difficult to state that the number of active vibro-actuators matters for all genres of music tested but one – hip-hop.

The third application of the new haptic bracelet is not new for this type of device. However, this paper contributes by studying novel types of haptic icons and comparing the effectiveness of delivery of navigation guidance in this way. At the first, it was understood that the placement and orientation of actuators in this device are not suitable for the type of haptic notification proposed here. For the latter, the results of the experiment show that despite the high recognition rate of haptic notifications, this type of information is still less accurate than the visual one. It can be concluded that the haptic bracelet will suit well as an additional source for navigation guidance.

2.6.1 Limitations and Future work

As was already mentioned, some of the proposed applications were not successfully executed by the novel haptic device. Some of them are explained by anatomical issues of the human body, whereas others failed due to hardware limitations. While some of these limitations are easily fixable, e.g. orientation of actuators inside the bracelet, others raise more complex issues. For example, the addition of at least one more actuator will significantly change the overall structure. Also, it should be taken into account that some limitations could affect the obtained results. For example, many testees reported that "it would be better to increase the attachment of the device to the skin" - change or redesign straps. This problem was temporarily resolved by

wrapping isolating tape on top of the device and wrist circumference.

For future work, we envision rethinking current limitations and utilizing improved components to reach higher performance of the hardware. Moreover, as mentioned in Chapter 1, other means of haptic feedback can be combined with vibrotactile feedback to cover a wider range of possible applications.

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Appendix A

Tables

Table A.1: Grounded Haptic Devices
* - considered grounded due to water tanks; ** - speed of heating/cooling; *** - time for filling/emptying.

Device	Type	Purpose / Haptic Illusion	Kinesthetic Feedback	Cutaneous Feedback	Actuators	Max Force
[18]	graspable	teleoperation	Force Dimension Omega.3	normal/tangential skin deformation	(x3) servomotors (Futaba S3154 RC)	10 N
[19]	graspable	stiffness perception	Phantom Premium 1.5	skin stretch	(x1) DC motor (Portescap 16G88214E)	2 N
[20]	graspable	teleoperation	N/A	skin stretch	(x6) layers of EAP (3M VHB 4910 acrylic film)	1.6 N
[21]	graspable	3D shapes	force due to EMF	N/A	(x9) electromagnetic coils	2 N
[22]	graspable	3D surface exploration	force due to EMF	N/A	(x3) electromagnetic coils	0.959 N
[23]	touchable	textured surfaces	N/A	electrovibration	(x1) capacitive-based touch sensing panel (3M Microtouch)	-
[24]	touchable	directional cues, friction	N/A	skin stretch	(x2) Flexinol SMA wires	3 N
[25]	touchable	teleoperation	N/A	temperature feedback	(x4) Peltier Elements	**14.4°C/sec **18.7°C/sec
[26]	touchable	surface relief	N/A	normal skin deformation	(x16) DC motors (Namiki SLC07-17)	-
[27] [28]	touchable	softness	N/A	normal/tangential skin deformation	(x2) DC motors (Remax 2561:1 3W, Maxon Motros)	20 N
[5]	touchable	softness	N/A	vibrotactile	(x1) VCA (Haptuator Mark 2)	-
[29]	touchable	material roughness	N/A	vibrotactile	(x1) VCA (X-1740, Aoyama Special Steel Co., Japan)	-
[30]	touchable	object slippage	N/A	skin stretch	-	-
[32]	*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

Table A.2: Hand-Held Haptic Devices. * - weight without controllers or trackers.

Device	Purpose	Kinesthetic Feedback	Cutaneous Feedback	Actuators	Mass
[33]	surface shape rendering	extrusion of the platform	tilt of the platform	(x3) servomotors (Hitec HS-5035HD)	150
[33]	rendering shape of virtual objects and surface structure	N/A	4x4 pin-array	(x16) servomotors (Hitec HS-5035HD)	600 g
[34]	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
[35]	softness of touched and grasped objects	resistance force	N/A	(x1) coreless motor (E-flite EFL9052)	-
[36]	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
[37]	in-hand interaction - texture, compliance	N/A	vibrotactile	(x2) VCA (Dayton Audio DAEX9-4SM)	-
[38]	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
[39]	orientation in VE	N/A	pressure vectors using pin array	(x15) solenoids in each hand (DC0410, Yong Ci Neng Co.)	-
[40]	size, shape and stiffness of a virtual object	opening/closing wings to change the angle	N/A	(x2) servomotors (TowerPro SG92R)	65 g
[41]	softness of haptic proxy objects	N/A	vibrotactile	(x1) VCA (Tectonic Elements TEAX19C01-9)	-
[43]	tele-micromanipulation, microassembly	force feedback on fingertips	N/A	(x1) coreless motor (DCX10L, Maxon Motor)	40 g
[44]	rendering weight/shape of virtual hand-tools	DPHF - weight shifting	N/A	(x1) stepper motor (NEMA-14 type)	440 g
[50]	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
[51]	objects with different scale/ material/fill state	DPHF - weight shifting + air resistance	N/A	(x2) servomotor (MG996R)	598 g
[52]	rendering forces of varios directions and magnitudes	DPHF - propeller-induced propulsive forcce	N/A	(x6) brushless motors (2600KV T-Motor F40 III)	692 g
[53]	dynamic weight motion illusion	DPHF - propeller-induced propulsive forcce	N/A	(x2) brushless motor (KV3900)	1069 g
[54]	stiffness rendering	extension/retraction of the connecting cable	vibrotactile (Vive controller)	(x2) servomotors (Actuonix L12-R Micro Linear Servo)	*673 g
[54]	stiffness rendering	lock/unlock of ball joints and hinge	vibrotactile (Vive controller)	(x3) servomotors (FEETECH FS5115M)	*793 g
[54]	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
[55]	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

Table A.3: Exoskeletons and Gloves.
* - weight without actuating block placed on the forearm.

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

Table A.4: Finger-Worn Haptic Devices.
Type: MP - moving platform, SB - shearing belt, OT - other types.

Device	Type	Haptic Feedback	Haptic Illusion	VE	Actuators	Mass
[2]	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
[12]	MP	skin stretch	stiffness	-	(x3) DC motors (Faulhaber 0615S)	35 g
[8]	MP	skin stretch + vibrotactile	palpation (robotic surgery)	VR	(x3) servomotors (Pololu SubMicro) + (x1) vibromotor (Force Reactor, Alps Electric)	-
[76]	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)	-
[90]	MP	skin stretch + vibrotactile	surface exploration, softness	VR	(x3) servomotors (HiTech HS-5035HD)	25 g
[4]	MP	skin stretch	object manipulation	VR	(x3) servomotors (HK-282A RC)	16 g
[74]	MP	skin stretch	weight, stiffness, friction	VR	(x2) DC motors (Faulhaber 0615S)	32 g
[77]	MP	skin stretch + force feedback	teleoperation	VR	-	42 g
[82]	MP	skin stretch	surface exploration & weight	VR	(x2) DC motors (Maxon RE8)	22 g
[78]	SB	skin stretch	gravity & grip force	-	(x2) DC motors (Maxon RE10)	35 g
[79]	SB	skin stretch	stiffness	VR/AR	(x2) servomotors (HiTech HS-40)	15 g
[84]	OT	vibrotactile	stiffness	VR	(x1) ERM vibromotor (Precision Microdrives 310-113)	-
[85]	OT	vibrotactile	surface texture	VR/AR	(x1) VCA (Bone Conductor Transducer, Adafruit)	9.6 g
[83]	OT	vibrotactile + electrical	hardness, friction, fine & macro roughness	-	(x1) DC motor (Maxon 118386) + (x1) 4×5 electrode array	15 g
[99]	OT	force feedback	contact & softness	-	HC-DEAs (VHB 4910, 3M)	-
[100]	OT	skin stretch	contact/non-contact	-	TCP actuators	14 g

Table A.5: Arm-Worn Haptic Devices

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

Table A.6: Haptic devices with different feedback types for rendering particular haptic illusions, 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	[64]	[18], [4,8,74] [78,82,91]	[110]			[55]		[44,50,51]		[52,53]
shape		[2,3,70,71,73] [77,90]	[26]			[60], [33] [34,36]			[21,22]	
size						[34,35,40] [57,58,61] [60,66,67] [77]	[59] [63–65]	[44,50,51]		[53]
stiffness	[5], [41], [64] [76,90] [83,84]	[19,20], [74]	[28], [110] [80,81] [99]			[35,40,54] [57,58,66] [60,61,67]				[68]
texture	[29], [34,37] [73,76,85] [90,95]	[33,36]	[26]		[23] [83]					
teleoperation	[109,112,119]	[106,109,119] [38]	[109,119] [105]	[25]		[43]				
navigation	[103,104]	[24], [39] [115,118]		[124,126]						
notification	[102]	[114]	[32], [113] [116,117]	[32] [120,125–127]						

85

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

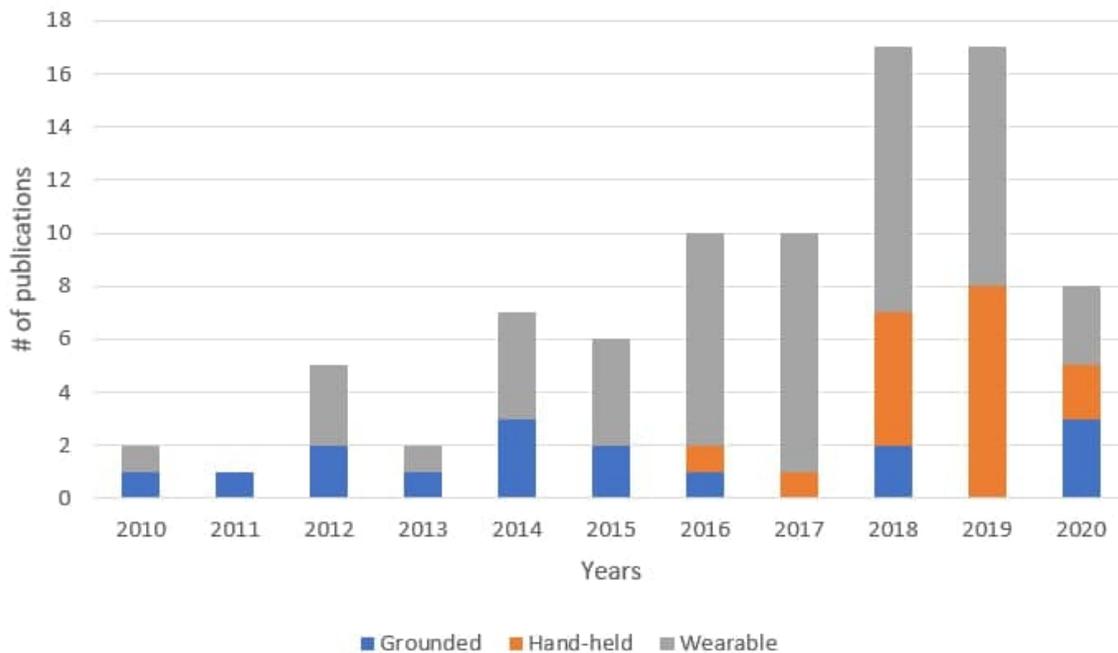| device	weight	shape	size	stiffness	texture
[34] CLAW		RF	RF		V
[64] Grabity	V		LM	V	
[60] Jo et al.		RF	RF	RF	
[90] Chinello et al.		SS		V	V

Appendix B

Figures

Figure B-1: Number of publications by year. Subdivisions by wearability: grounded (blue), hand-held (orange), wearable (grey).

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