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Haptic Interfaces for Virtual Reality: Challenges and Research Directions

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ABSTRACT The sense of touch (haptics) has been applied in several areas such as tele-haptics, telemedicine, training, education, and entertainment. As of today, haptics is used and explored by researchers in many more multi-disciplinary and inter-disciplinary areas. The utilization of haptics is also enhanced with other forms of media such as audio, video, and even sense of smell. For example, the use of haptics is prevalent in virtual reality environments to increase the immersive experience for users. However, while there has been significant progress within haptic interfaces throughout the years, there are still many challenges that limit their development. This review highlights haptic interfaces for virtual reality ranging from wearables, handhelds, encountered-type devices, and props, to mid-air approaches. We discuss and summarize these approaches, along with interaction domains such as skin receptors, object properties, and force. This is in order to arrive at design challenges for each interface, along with existing research gaps.

INDEX TERMS Haptic interfaces, human-computer interaction, virtual reality.

I. INTRODUCTION

Pioneered by computer graphics expert Ivan Sutherland in the 1960s, virtual reality (VR) technology has become more and more prevalent in today's society [1]. Ever since its conception, advancements in computer graphics and audio synthesis have made virtual experiences look and feel more real. As a result, VR technology has since been used in various fields, such as entertainment, education, and rehabilitation. While the ability to simulate vision and sound in virtual environments is a crucial step towards achieving 'realism', the ability to touch and feel remains thoroughly underdeveloped. The more accurate term for technology that simulates touch is 'haptics'.

Foundation research in the field of haptics consists primarily of robots and manipulators developed for application in the nuclear industry, to enable the safe and remote handling of harmful materials [2]. With the conception of VR technology, research surrounding haptics has extended beyond its original purpose to also include rendering sensations of touch in the virtual environment. However, simulating touch has proved to be an incredible feat due to the need for accommodating complex human skin receptors, gestures, and various properties of objects. Recent studies have shown that the integration of haptic interactions in VR enables virtual objects to have more physical properties which, in turn, enhances user experiences [3]. This explains why the development of haptic interfaces has remained rampant throughout the years despite the challenges and limitations posed.

Hence, researchers have attempted numerous solutions to delivering realistic haptic feedback to users in the virtual world. To aid the development of more realistic haptic interfaces in this challenging area, two research questions were posed in this review. The first: what are the design challenges of haptic interfaces? The second: what are the research directions in the development of haptic interfaces? To answer both questions, this review systematically highlights popular approaches in developing haptic interfaces for VR ranging from wearables, handhelds, encountered-type devices, and props to mid-air approaches. Additionally, interaction domains are discussed in detail to help readers gain perspective on how best to stimulate realistic haptic interactions.

This paper also aims to address some of the limitations of recent surveys on haptic interfaces for VR [4], [5]. While the literature cited above discusses multimodal and commercial haptic interfaces, this work systematically addresses non-commercial haptic interfaces.

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TABLE 1. Human receptors. Adapted from Wang *et al.* [4], Feher [6], Hale and Stanney [7], Lederman and Klatzky [8], and Iheanacho and Vellipuram [9].

Receptor Type	Receptor Name	Modality [6]	Fibre Type [6]	Adaptation Rate [6]	Conduction Velocity (ms^{-1}) [6]	Sensitivity Range [8]	Location [6]	Receptive Field [9]	Skin Type [7]	Spatial Resolution [7]
Mechano-receptor	Meissner corpuscle	Low-frequency vibrations such as tap and flutter	A Beta (myelinated)	Fast	30 to 70	~5 to 40 Hz	Dermis, beneath the epidermis of non-hairy skin	Small	Glabrous	Fair (3-5mm)
	Pacinian corpuscle	High-frequency vibrations and transient pressure	A Beta (myelinated)	Fast	30 to 70	~40 to 400 Hz	Subcutaneous tissue, beneath the dermis	Large	Glabrous and hairy	Very poor (2cm)
	Ruffini ending	Proprioception and skin stretch	A Beta (myelinated)	Slow	30 to 70		Dermis	Large	Glabrous and hairy	Poor (1cm)
	Merkel disk	Light touches and textures	A Delta (myelinated)	Slow	12 to 30	Less than ~5Hz	Dermis, beneath epidermis	Small	Glabrous	Good (0.5mm)
Nociceptor	A Delta fibre	First pain	A Delta (myelinated)	Slow	12 to 30		Epidermis, the outermost layer			
	C fibre	Second pain	C (unmyelinated)	Slow	0.5 to 2		Epidermis, the outermost layer			
Thermo-receptor	Cold receptor	Cold	A Delta (myelinated)	Phasic and tonic component	12 to 30	5° C to 45° C	Dermis			
	Warm receptor	Warmth	C (unmyelinated)	Phasic and tonic component	0.5 to 2		Dermis			
Kinaesthetic receptor [7]	Muscle receptor/ muscle spindles	Muscle length/ muscle strength					Muscles			
	Tendon receptor/ Golgi tendon organs	Force/tendon stretch					Tendons			
	Golgi endings	Joint movement					Joint ligaments			

II. DOMAIN OF INTERACTIONS

To effectively identify research gaps and directions for future research, an overview of the range of possible modalities should be discussed. These include sensations that can be felt by receptors found in the human skin, object properties, and forces.

A. RECEPTORS

Essentially, the human sense of touch is made possible through cutaneous and kinaesthetic receptors found within and beneath the skin respectively. The receptors work in tandem to respond to pressure, pain, temperature changes, and force. This means that each receptor has unique characteristics, as summarised in Table 1.

As Table 1 shows, cutaneous receptors include cutaneous mechanoreceptors that respond to vibration, tactile sensations, pressure, and touch, nociceptors that respond to changes in temperature, and nociceptors that respond to intensified and forceful stimuli. Mechanoreceptors are also found in muscles, joints, and tendons that respond to various kinaesthetic modalities. These receptors are part of the somatosensory system and are categorised by their function, characteristics, and location. While this information may seem trivial, these attributes can aid in the development of more robust and effective haptic interfaces. Figure 1 is a diagrammatic representation of the various mechanoreceptors that can be found in the skin [6].

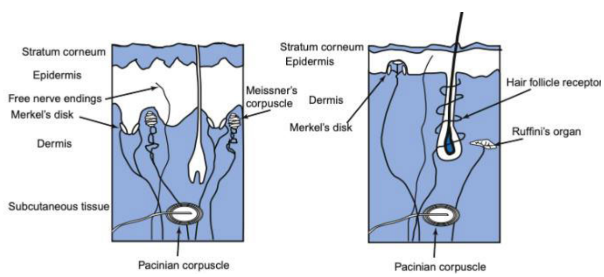

FIGURE 1. Mechanoreceptors in the skin [6].

Fibre type, for instance, consists of myelinated and unmyelinated varieties, which refers to the presence or absence of an insulating layer called the myelin sheath. This leads to a difference in the transmission rates of impulses along the nerves [10]. While more needs to be known as to whether this fact is significant in the design of haptic interfaces, Pacchierotti *et al.* [11] suggest exploiting unmyelinated fibres predominantly found in hairy skin that respond to gentle touches to stimulate caresses. The adaptation rates of each receptor also vary in terms of how it behaves when a constant stimulus is present. Receptors that are slow adapting continue to send impulses to the brain, as long as it detects a constant stimulus, while fast-adapting receptors only send an impulse when the stimulus is initially detected or removed [12]. Similarly, it is also unclear how this knowledge can aid in the development of haptic interfaces.

Furthermore, factors such as receptive fields, location, and sensitivity are also important when it comes to making executive decisions about the design of an interface. These decisions can range from the size of the device (to ensure it covers the receptive field), the type of interface to develop (handhelds or wearables, depending on the location of the receptors), to the kind of actuators to integrate into the device (actuators that support stimulation at a particular range of frequency). Apart from that, factors such as skin type and spatial resolution can be used to maximise the efficiency of an interface. According to Hale and Stanney [7], stimulation of textures should be focused on areas with non-hairy skin that have high spatial resolution, such as palms and fingers.

B. OBJECT PROPERTIES

Since our sense of touch makes discerning object properties possible, attributes such as object dimensions, compliance, texture, and temperature should also be considered when developing haptic interfaces. Table 2 shows what each attribute encompasses.

TABLE 2. Object properties.

Attribute	Property
Dimension	- Shape - Size - Weight
Compliance	- Soft - Hard
Texture	- Smooth - Rough
Temperature	- Hot - Cold

Lederman and Klatzky [13] classify hand gestures according to how each object's properties are perceived. For instance, when exploring textures, we tend to do so by moving our fingers in a back-and-forth motion. Alternatively, we apply pressure to determine the compliance of an object, we initiate contact with an object to determine its temperature, we lift an object to determine its weight, we enclose our fingers around an object to determine its size or we make contact with an object's edge to determine its shape. From here, we can conclude that when it comes to simulating object compliance, texture, and heat, cutaneous stimulation of a single finger is generally sufficient for users to perceive these object properties. On the other hand, spatial dimensions such as shape, size, and weight would require more than just cutaneous stimulation. This means that when developing haptic interfaces to replicate an object's spatial dimensions, device design should also accommodate gestures such as grasping and lifting.

Furthermore, human haptic perception for these properties is also limited with specific thresholds that are often low, which is appropriate, considering how sensitive the human touch is. Kappers and Tiest [14] present these limits in terms of discrimination thresholds and complementing performance in their review.

C. FORCES

Compared to human mechanoreceptors and the perception of object properties, discussions regarding haptic force perception are less advanced thus far. Hence, this section aims to provide a brief overview of force perception to promote research advances in this area. Specifically, to evaluate the limitations of human force perception and how it impacts the development of haptic interfaces in virtual environments.

Tiest and Kappers's [15] review provides a comprehensive summary of findings related to force perception. This review focuses on the perception of force in various magnitudes and directions. However, the literature discussed in their review primarily features studies that assume the subject is completely still, which does not correspond to how we interact with objects in real-world scenarios. Hence, further research should be carried out on how we perceive contact forces instead, which is more natural and prevalent in day-to-day interactions. Table 3 overviews contact forces and their definitions [16].

TABLE 3. Contact forces.

Type of Force	Definition
Air Resistance	A type of frictional force encountered by objects as they travel through air.
Applied	A type of force applied on an object by another object.
Frictional	A type of force exerted by a surface to an object as it moves across it.
Gravitational	A type of force in which an immensely large object pulls another object towards itself.
Normal	A type of force exerted by a stable object onto another object in contact.
Spring	A type of force exerted by a stretched spring on an attached object.
Tension	A type of force transmitted through a string when it is pulled on by forces on opposite ends.

III. METHODOLOGY

A. RESEARCH QUESTIONS

To support the aim of this review, the following research questions were posed.

RQ 1. What are the main design challenges of haptic interfaces for virtual reality?

RQ 2. What are the research gaps pertaining to haptic interfaces for virtual reality?

To answer the research questions above, we referred to best practices for systematic reviews by vom Brocke *et al.* [17] and Paré *et al.* [18]. A standard protocol was also employed when selecting literature to be included in the review.

B. DATA SOURCES

To gather appropriate literature for this review, databases such as ACM, IEEE, MDPI, Sage, and Wiley were searched for relevant articles. To ensure quality, literature on haptic interfaces for virtual reality was gathered from academic journals and conference proceedings.

C. SEARCH PROCESS

In the early stages of conducting this review, we used a combination of keywords including "haptics" and "interfaces" but found these search terms to be too broad. Since the application of haptics has been proposed for many aspects ranging from interfaces for the visually impaired to haptic-enabled physical machines and general haptic user interfaces, haptic interfaces for virtual reality were largely overshadowed. Therefore, we eventually decided to use the combination of "haptics" and "virtual reality" instead. This process resulted in 2764 papers which were further narrowed down by the screening process.

D. SCREENING PROCESS

To start, the initial 2764 papers were narrowed down to 451 by excluding papers that were published before the year 2015. From there, duplicate papers and those with only an abstract were also excluded, bringing the total down to 322. The screening process then continued with the examination of each article's title, keywords, and abstract. At times of uncertainty, the entire article was read to ensure that it was relevant to the research questions. This brought the total down to 39 papers.

IV. HAPTIC INTERFACES FOR VIRTUAL REALITY

This section highlights existing works that focus on delivering haptic feedback to users in the virtual environment. As seen in Figure 2, haptic interfaces discussed here include handhelds, wearables, encountered-type devices, physical props, and mid-air approaches.

However, due to the lack of official guidelines for what constitutes a handheld, wearable, and so on, existing interfaces included in this part of this review were arranged into individual sections based on specific inclusion criteria, as listed in Table 4.

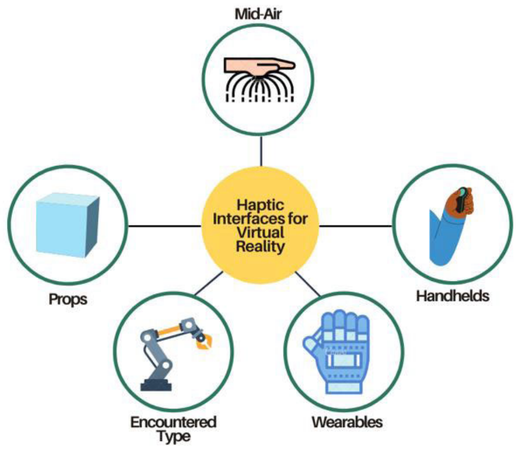

FIGURE 2. The various types of relevant haptic interfaces in this review.

TABLE 4. Inclusion criteria for haptic interfaces.

Interface	Inclusion Criteria
Handhelds	- Includes novel devices that are typically held, generally resemble a controller. - May also include attachments or add-ons that enhance haptic feedback of default controllers.
Wearables	- Includes novel devices that are typically worn. - These devices can be worn on the user's fingers, wrists, hands, or anywhere on the body.
Encountered types	- Includes novel devices that can provide haptic feedback on demand. - Typically includes the use of robotic arms, drones, or specialized devices with an end effector attached. - May also include techniques that aid in enhancing the encountered-type approach.
Physical props	- Includes the use of physical props placed in the physical space aligned to virtual objects in delivering haptic feedback. - May also include techniques to improve the use of physical props in delivering realistic haptic feedback.
Mid-air	- Includes novel devices that employ transducers in delivering ultrasonic vibrations through air. - Includes novel devices that exploit the properties of air in delivering haptic sensations. - May also include tools to address the limitations of mid-air haptics.

A. HANDHELDS

With the recent surge of commercial VR consoles like the Oculus Rift, HTC Vive, and Sony Playstation VR, more people are now able to experience virtual simulations from the comforts of their own homes. Often, these consoles feature a handheld controller that utilizes sensors to track and simulate hand movements. However, to promote mass adoption, the manufacturing cost of these devices is often kept low and affordable. This is greatly reflected in the design of the handheld controllers that only allow simplified input capabilities and basic vibrotactile haptic motors. In other words, the inbuilt vibrotactile actuators in these controllers are only capable of providing basic buzzing sensations [19]. In the paragraphs below, recent studies related to handheld haptic interfaces are discussed. The studies highlighted all have a similar purpose, which is roughly to provide varying sensations via a handheld interface, to increase realism in virtual worlds.

Strasnick *et al.* [20] proposed an attachment that links both right and left controllers to mimic stiffness in order to compensate for the lack of realistic feedback. Specifically, the attachment aims to increase the spatial relationship between both controllers for two-handed activities such as holding a rifle, playing the trombone, and firing a bow. The attachment utilizes a chain consisting of ball-and-socket elements with linear actuators on both ends connected to the controllers. To provide realistic simulations, stiffening of the chain is necessary, which is made possible by the linear actuators that retract the cables compressing the ball-and-socket elements. This increases the friction at each joint of the chain, effectively simulating the sensation of stiffness. Testing the attachment with 12 participants, it was found that virtual experiences feel more realistic with the attachment than without it for almost all the activities.

Other than attachments, researchers have also designed novel handheld devices to increase the functionality of default controllers. Benko *et al.* [21] proposed two controllers that allow users to feel the texture of surfaces. The first one, called *NormalTouch*, utilizes a platform that tilts and adjusts its height according to the surface height and orientation of a virtual object. Three servo motors are used to actuate the platform, arranged in a 3-Degrees of Freedom (DoF) manner. The servo motors are attached to revolute joints, which are then attached to spherical joints under the platform. The second one, called *TextureTouch*, utilizes a four-by-four pin array to render the texture of a particular surface. A rack-and-pinion mechanism, along with a servo motor, is used to actuate individual pins in the array. Both devices feature a finger pad to deliver the sensations to users. The results from this study showed positive feedback from 12 participants who expressed that both controllers made interacting with objects in the virtual environment feel more realistic. However, feedback from participants also showed that the use of pin arrays is more suitable for objects with finer details, while the use of the versatile platform is more suitable for objects with a larger surface area.

Consequently, Whitmire *et al.* [22] proposed a novel controller called the *Haptic Revolver* that allows users to experience realistic touches, shear forces, texture, and shape in the virtual environment. This is made possible by a wheel actuator that is systematically raised and lowered underneath the user's fingers, depending on the type of surface encountered in the virtual environment. A servo motor is used to move the wheel up and down while a DC motor spins the wheel. These sensations are delivered with the help of a rendering engine that utilizes wheel description files, which control how the wheels should behave when the user's finger encounters the surface of a particular virtual object. The controller is also highly customizable, allowing developers to interchange wheels to suit one's application. The handheld controller was evaluated with the aid of 11 participants, with scenes that feature a card table, a keyboard, and a painting. Mean realism ratings of the controller from the trial session greatly surpassed those of the typical vibrotactile controller.

Aside from touch, researchers have also attempted to fit as many interactions in a single package as possible. For example, Choi *et al.* [23] designed a multifunctional controller called *Claw* that allows users to experience realistic grasps, touches, and triggers in a virtual environment. The handheld greatly resembles a claw, where users grip the handle with their little, middle, and ring fingers, rest the thumb on the thumb rest, and place their index finger in the provided opening at the top of the controller. For user input, the controller features buttons and detects thumb movements with a proximity sensor. This enables the controller to change into modes ranging from "touch", "grasp", to "trigger". When it is detected that the thumb is on the thumb rest, the device switches to "grasp" mode where the handheld then physically adjusts the distance between the thumb and the index finger according to the size of the virtual object. When it is detected that the thumb is not on the thumb rest, the handheld switches to "touch" mode where it then renders surface textures with a voice coil actuator (VCA) positioned underneath the fingertip. If the user picks up a gun in the virtual environment, the handheld switches to "trigger" mode, which locks the user's arm in a set position. A revolute hinge coupled with a spring return enables the simulation of triggers. Testing the handheld controller with 12 participants, it was found that the average scores for realism, usability, interface, and performance were in the positive range.

While the approaches mentioned succeeded in replicating common interactions, Lee *et al.* [24] claim that the proposed solutions failed to provide intricate and nimble manipulations of virtual objects. More specifically, according to them the aforementioned techniques only allow for arm and wrist-based as opposed to finger-based object manipulations which are also common in real life. Hence, they proposed a controller called *TORC* that not only renders object textures, but also allows users to more accurately rotate and position objects in the virtual environment. The controller is held with the thumb, index, and middle fingers, resembling a "puppet" stance. Users can glide across the trackpad present underneath the thumb for dexterous interactions. VCAs and force sensors were also present under each finger to produce sensations when the user squeezes, shears, or turns an object. The output of the force sensor is amplified to drive the VCA, producing vibration bursts depending on changes in force, thereby simulating proprioception and force. For testing, 16 participants were asked to locate and rotate a key in a keyhole using the controller. The participants relayed that the controller had a better touch proxy because it allows finger-based manipulations that were previously not possible with a conventional controller.

Taking on another path, Zenner and Krugger [25] proposed a handheld controller that is capable of simulating drag and weight shifts in the virtual environment. The controller works by dynamically changing its shape to resemble a fan depending on the scenario. To enable the sensation of rotational inertia and drag to the user, the controller periodically changes its surface area. This is made possible by servo motors placed on each arm at the top of a commercial fan that opens and closes. With the aid of 18 participants, they found that the proposed controller provided more realism compared to a standard one. The authors suggest that the controller can be used in many scenarios, including but not limited to sports, handling of tools, and flying.

Fujinawa *et al.* [26] developed handheld controllers that are specific to the virtual experience. The authors argued that handheld controllers with predefined shapes are less immersive because users can perceive the shapes. Hence, by applying the shape perception model, the authors were able to design controllers of varying shapes such as a sword, a tennis racket, and a guitar. To design a custom controller, one is required to input parameters such as the handle and the target virtual model. With these parameters, the system produces a computer-aided design model which can then be fabricated with a 3D printer or a laser cutter. The custom controllers were tested with the help of 5 participants. Participants were required to determine and perceive which controllers matched the shape that was presented to them in the virtual environment. Results showed that most of the controllers were matched with their corresponding shape, indicating that the system was successful in complementing controllers of a specific shape with the visual presented in the virtual environment.

Chen *et al.* [27] proposed controllers that are embedded with arrays of tactile pins. The device is cylindrically shaped with a joystick attached to one end for user input. Inside the device, individual pin arrays were arranged in columns where every column is placed at a 45° angle from the adjacent column. To ensure the pin arrays were able to cover as much surface area as possible, they were also arranged in cardinal directions. Ten participants were brought in for testing where they were then exposed to stimuli such as shootings from an action game and a rainy virtual environment. Data were then obtained from the verbalized responses of the participants. Results showed that the proposed system could stimulate sensations with good accuracy.

B. WEARABLES

Another popular form of haptic interface for virtual use is wearables. Since they are generally worn by the user, these devices should be compact, light, and comfortable to handle. In the paragraphs below, recent studies related to wearable haptic interfaces are discussed. The studies highlighted all have a similar purpose, which is generally to provide varying types of feedback via a wearable interface, to increase realism in the virtual environment.

Choi *et al.* [28] developed a device called *Wolverine* that is worn on the fingers of the user to simulate realistic grasps in the virtual environment. The device is worn on 4 fingers, where the base is mounted to the thumb with rods that are mounted horizontally on the index, middle, and ring fingers. Depending on the size of the virtual object, sliding mounts are locked at specific locations on the rod with the help of a directional brake mechanism, initiated by a DC motor. When the user grasps an object in the virtual environment, the DC motor is turned on to pull a wire that is attached to a lever, stretching the elastic tendon into a taut stance, effectively engaging the brake mechanism, and jamming the rods at a certain position. Once the user stops grasping the object, the brake mechanism is unlocked with the aid of another elastic tendon that pulls the lever back out. Preliminary findings showed that the device can perform a wide range of motion (20-160mm) and stiffness (162N/mm), which enabled the rendering of 75% of the objects from the YCB Object Set.

Other than grasping, Choi *et al.* [29] also developed a wearable device called *Grabity* that can simulate weight. The device is worn on the thumb and gripped at the same time with both the thumb and index finger. To make interactions seem more realistic, the device provides inertia, stiffness, and gravitational feedback. Touches are replicated with conventional symmetric vibrations provided by a voice coil actuator. The grasping mechanism is like the study discussed in the previous paragraph, except this approach utilized a unidirectional brake system instead. In exchange for elastic tendons, *Grabity* used 2 magnets. For replicating weight, pads that touch the user's fingers are asymmetrically stretched. This is possible due to horizontal movements made by the magnet present in the voice coil actuator. Basically, a range of weights can be replicated by adjusting how the magnet vibrates. In a test with 5 participants, users were able to differentiate between different weights in the virtual environment. However, users were unable to determine the heaviest object due to intense vibrational cues.

Consequently, Yem and Kajimoto [30] proposed a wearable device called *FinGAR* that targeted human mechanoreceptors. This means that the device is built to replicate four modes of stimulation which are hardness, friction, macro roughness (uneven and relief), and fine roughness (rough and smooth). The device is worn on the user's thumb, index, and middle finger. A DC motor is used to deliver high-frequency vibrations to the finger pad to simulate skin deformation, while an electrode array is used to deliver low-frequency vibrations to simulate pressure. Specifically, the authors aimed to determine whether motor rotations, motor vibrations, cathodic currents, and anodic currents can be used to successfully replicate any of the four modes of stimulation. Results from the study showed that sensations of macro roughness and hardness earned the highest scores when motor rotations and cathodic stimulation were applied. As for fine roughness and friction, high- frequency motor vibrations earned the highest scores.

To provide tactile and heat feedback in the virtual environment, Kim *et al.* [31] utilized the Arduino microcontroller and Leap Motion sensor in building a haptic interface. The wearable device features a wristband module with two fingertip units that resemble a band-aid. The prototype is currently able to provide virtual sensations to only the thumb and index fingers. The Leap Motion sensor is used to capture hand motions and transmit the physical motions as data values to the Arduino-powered wrist module via Bluetooth. These data values are then used to determine whether the system should deliver vibrations or heat to the user's fingertips. A vibrator motor and a resistor are responsible for the transmission of vibrations and heat respectively. Test findings suggest that the haptic feedback felt by users is natural with minimum delay between actual interaction and feedback.

Another wrist-based haptic device called *Tasbi* was proposed by Pezent *et al.* [32], which is capable of vibrotactile and squeeze feedback. Design of the device incorporates a band that is made up of six vibrotactile units. Instead of delivering sensations to the user's fingers and hand to convey stiffness, the device renders vibrotactile cues that resemble a squeeze throughout the band. Furthermore, the squeezing sensation is also made possible by a DC motor and a gearbox that drives the two-sided spool to create tension in the cord surrounding the user's wrist. The aim of the study was to determine whether the combination of different haptic and visual modalities can produce more accurate feedback. To find out, the authors carried out a test by making users push buttons of variable stiffness in a virtual environment. Results showed that the integration of squeeze, vibrotactile and visual stimuli can produce realistic effects. This shows that wrist-based interfaces can be a viable solution when it comes to generating intuitive haptic sensations.

Salazar *et al.* [33] proposed a wearable device that can replicate bulges and holes as well as smooth and soft surfaces. The device is primarily worn on the index finger. Two servo motors and a fabric belt are used to transmit sensations of pressure and skin stretch. When the motors rotate in opposite directions, the belt moves up and down, which delivers a varying amount of force to the finger. When both motors rotate in similar directions, the belt delivers sensations of shear force to the finger. The authors carried out a total of three experiments with the aid of the Novint Falcon device to provide kinaesthetic feedback. Each of the three experiments had 14 participants. Firstly, the authors wanted to determine whether the combination of cutaneous and kinaesthetic feedback can replicate feelings of stiffness. The experiment was carried out by making participants identify the stiffer of two pistons. Most participants conveyed that the combination of both types of feedback did somehow replicate feelings of stiffness. Secondly, participants were made to identify bulges and holes in the virtual environment. The authors employed both the skin stretch and varying pressure rendering techniques to produce the shapes. Findings indicate that both methods work well, but holes rendered with varying pressure showed better results than when rendered with skin stretches. Thirdly, participants also had to determine the friction of a particular surface. To replicate a slippery surface, the device stretches the skin towards the motion of the user's finger. For sticky surfaces, the skin is stretched in a way that contradicts the motion of the user's finger. However, participants were not convinced of the presence of slippery or sticky surfaces during the experiment. Nevertheless, this device can be useful for use in the medical field to simulate the feel of a body or a cyst.

Aside from finger and wrist-based haptic interfaces, Cai *et al.* [34] designed a glove that is capable of delivering thermal feedback and material identification to users in the virtual environment. The glove features airbags that are in constant contact with the palm and fingers. Hot and cold chambers are used to produce varying sensations of heat to stimulate different material types and temperature changes. The chambers are made out of foam boxes and Peltier modules to maintain the temperature of the hot chamber at 68 °C and the cold chamber at 2 °C. A pneumatic control module pumps air from the room and mixes air from both chambers to replicate different temperatures. The usability of the glove was tested with 12 participants, which required them to interact with objects such as copper, glass, hot and cold water. Results showed that the participants were able to differentiate between the virtual objects with an accuracy of 87%.

As opposed to the rest of the wearable devices highlighted in this section, Fang *et al.* [35] developed a device called *Wireality* based on string haptics. The device simulates interactions with virtual objects by programmatically locking retractable wires that are attached to the user's fingers and the module that is worn on the shoulder. This enables the user's hands and individual joints to be arrested in the air, accurately replicating interactions with walls and furniture. The locking mechanism is made possible with a ratchet gear and solenoid pawl to lock the spring-loaded cables in place. To test the feasibility of the system, participants were asked to interact with virtual objects such as a sphere, a wall, and a pole. Results from the study showed that the device provided more realistic interactions compared to a basic vibrotactile handheld controller. However, because the device is attached to a shoulder module, it did not receive good ratings in terms of freedom of movement and comfort.

C. ENCOUNTERED TYPES

Encountered-type devices aim to provide more natural haptic feedback in the virtual environment by freeing the user's hands of any controllers and wearable devices. More specifically, encountered-type haptic interfaces "bring" the desired feedback to the user in an on-demand manner [36]. For instance, Araujo *et al.* [37] used a robotic arm to deliver sensations of textures. The end of the robotic arm is equipped with cardboard modules that can simulate textures such as shoes and clothes by attaching various types of fabrics to the endpoints. Physical stimuli such as temperature and airflow are simulated with a Peltier pad and a fan respectively. Elements of a control panel are simulated by attaching buttons and sliders to the endpoint. A depth camera is used to determine the user's hand location. When the user touches an object in the virtual environment, the robotic arm is programmed to move and align to the position of the object. When the user goes on to touch another object in the virtual environment, the grip of the robotic arm rotates to dynamically render the corresponding tactile feedback. No formal testing has yet been done to evaluate the system, but early observations suggest that users are surprised by the realistic feedback it provides.

Similarly, Takizawa *et al.* [38] proposed a system that can simulate objects of various volumes and rigidities at different positions. The system is a grounded device that features an array of balloons that acts as the end effector. To simulate objects of varying rigidity, a linear actuator with the help of a syringe regulates the air pressure inside the balloon. For instance, soft objects can be replicated with a balloon of low pressure and hard objects with a high-pressured balloon. To alter the volume of the balloon, a funnel is used to aid in the control of the balloon's exposed surface area. This is so the balloon can easily move in and out of the tube, making it easy to adjust the volume of the balloon to match the virtual object. Lastly, with the use of a linear actuator and a flexible tube, the position of the balloons can be altered. A string placed along the tube that is controlled with a pulley and motor appropriately bends the tube to adjust the vertical and horizontal position of the balloon. While no user testing has been done to date, the authors suggest that the system can be used to replicate livers (for surgery simulators) and clay.

Kim *et al.* [39] utilized reachability maps to increase the limited workspace that is commonly associated with grounded encountered-type haptic interfaces. This limit is caused by the need to simulate haptic feedback for entire walls or large structures with limited physical space. Hence, the maps were pre-computed by sampling and discretizing possible orientations and space boundaries with nonlinear optimization. Essentially, the map is used to determine whether the position of the user's hand is inside the appropriate boundaries. If so, the position of the manipulator is updated along with the avatar hand. If not, the manipulator stays idle and waits for the next updated hand position. The system is implemented with a 7-DoF manipulator with an acrylic panel attached as the end effector. To test the system, participants were asked to open doors in the virtual environment. Results showed that the system garnered positive feedback in which the interaction felt realistic and natural.

To further increase the limited workspace that comes with grounded interfaces, researchers have also come up with encountered interfaces that are ungrounded. For instance, Yamaguchi *et al.* [40] utilized drones with an attached end effector at the front and back of the device. For testing purposes, the researchers attached papers to the drone to simulate monsters and made participants grasp a secondary object that acted as the sword. With that, it is then necessary to determine the position of both the drone and the grasped object with a motion capture system. This is done so that the position of the drone can be aligned to the position of the object in the virtual environment. To determine the effectiveness of the system, participants were requested to draw lines with the grasped object on the wall in the virtual environment. Findings indicate that the system successfully allows participants to draw lines with utmost precision.

Consequently, Hoppe *et al.* [41] utilized quadcopters to deliver both active and passive feedback. To do so, various modules were attached to the quadcopters to simulate interactions with various objects. The materials used to fabricate the modules were not specified. The system also comprises a motion-tracking device that determines the position of both the user and the quadcopter. These data are then sent to a backend core to ensure that the quadcopter and the image produced in the virtual environment are aligned properly. To test if the system increases the sense of presence, participants were asked to interact with a balloon in the virtual environment. To simulate a balloon, a semi-circular module was attached to the quadcopter. Results showed that, compared to using a handheld controller, the quadcopter system was rated higher for realism.

Abtahi *et al.* [42] also utilized quadcopters in providing haptic feedback. To facilitate the process of ensuring the quadcopter aligns to the object in the virtual environment, the positions of all objects are first mapped. Then, the intersection between the trajectory of the user's hand and the virtual environment is calculated to determine specific areas that can be interacted with. The system also compensates for offset errors by retargeting the user's hands with visuohaptic illusions. The authors also took multiple precautions to ensure the system is safe. These precautions ranged from developing an algorithm to avoid collisions, a tutorial scene for users, to deliberately decreasing the moving speed of the quadcopter. The system was tested with 9 participants in a virtual boutique scene. To simulate sensations of texture, a piece of fabric was attached to the quadcopter. A hanger was also attached to the quadcopter to simulate touching a hanger in the virtual environment. To simulate carrying a box, the quadcopter was encased in a grilled cage with the fans turned off, thereby turning it into a passive prop. Most participants found the experience realistic and enjoyable.

To provide support for various types of haptic interactions, Huang *et al.* [43] proposed a setup resembling a ''hula hoop'' with different props attached. Props can be reconfigured depending on the requirements of the application with the provided prop cartridges. Users stand on a turntable surrounded by the hoop-shaped setup that automatically rotates to align the correct prop when the user touches a specific object in the virtual environment. The system considers the user's gaze as well as hand-eye coordination in predicting the next prop to position in front of the user for reduced response time. The haptic retargeting technique is also used, where either the position of the object or the user's hands is slightly changed to ensure that the prop correctly aligns to the virtual object. A total of 12 participants were recruited to test the feasibility of the system, using custom-made props to simulate shooting an enemy down, driving a ship, and fishing. Most participants agreed that the system provided realistic haptic feedback.

D. PHYSICAL PROPS

While encountered-type devices are useful in terms of being able to provide haptic feedback in an on-demand manner, implementing them may incur large costs due to the need for robotic arms and drones. Therefore, some developers may opt for the use of physical props instead to reduce extra complications and costs. For instance, Matsumoto *et al.* [44] utilized a square table to simulate a pentagon-shaped table through the redirected walking technique, which changes the perceived shape of an object. In redirected walking, users are redirected to walk on a different path in real life but are made to believe that they are walking on the same path in the virtual environment by adding translations to their head movements. While this approach is still under development with no testing done yet, the authors propose applying rotational operations when the user turns around the corner of the square. Humans can only perceive rotations ranging from 67.2° to 112.5° in the virtual environment. Since the angle of a pentagon is 72°, it is within range, making it possible for users to perceive a pentagon from a square table.

Consequently, McClelland *et al.* [45] proposed a device that can change its shape to simulate both two-dimensional and three-dimensional objects in the virtual environment. The device integrates four rectangular panels hinged together with twist potentiometers at every axis. This produces a plane-shaped device that can be bent and folded at each hinge. To test the feasibility of the device, the authors recruited 20 participants and asked them to choose a shape within the limitations of the device. Some example shapes that can be replicated with the device include a notebook, tablet, smartphone, and pen. Participants were then asked to utilize the device to replicate the shapes that they have chosen. They expressed positive feedback in terms of user-friendliness, responsiveness, and the ability of the device to imitate various shapes. However, participants also noticed that the device could not be folded completely flat, which reduced the sense of realism. The size of the device also did not match the size of the object in the virtual environment, further reducing the sense of realism.

Cheng *et al.* [46] also utilized a foldable board that can be folded in half on a larger scale, along with a pendulum that was suspended from the ceiling. Together, both props were used to simulate various objects in the virtual environment, such as a chair, a suitcase, a railing, and a group of flying enemies. The authors recruited 12 participants to test the feasibility of the props with a demonstration. The demonstration consisted of rooms that featured both props in various scenarios ranging from fixing a short-circuited cable, handling a fuse box, to turning on a reactor. In all scenarios, the props were re-used by making sure they overlapped in every room visited in the virtual environment. Compared to virtual experiences that do not feature any haptic feedback, the props received positive feedback from participants in terms of user satisfaction and realism.

Similarly, Calandra *et al.* [47] utilized off-the-shelf LEGO Mindstorms EV3 Core building blocks to make props that can be reconfigured on demand. Therewith, a virtual scenario is developed that features several stages of stabilizing a nuclear reactor. To ensure that the props are correctly repurposed after every stage, encoders are used to check their state, and data are sent to the Unity game engine after their use. Once the state of a prop changes, it will then be manually repurposed for other tasks in the virtual environment. For example, encoders in props that have servomotors are used to gather rotational data. Sensors were also connected to the LEGO Intelligent Brick to send data regarding the state of a button or the rotation of a doorknob. With the use of commercial building blocks, the authors were able to deliver passive haptic feedback for common interactions such as pushing, pulling, rotating, pressing, inserting, and joining.

White *et al.* [48] developed props that can be used to enhance the experience of a baseball simulation. Four props of increasing complexity were developed to test whether the simulation experience varies with the use of these different props. A total of 42 participants were asked to carry out baseball-related tasks with an HTC Vive controller, a normal baseball bat, a weighted prop that resembles a baseball bat, and another version of the weighted prop with vibrotactile feedback. A Wi-Fi-enabled circuit board was used to detect if a hit is registered in the virtual environment. Once a hit is detected, these data are sent to the circuit board, activating the vibration motors attached to the prop. The authors suggest that the weighted prop can replicate sensations of inertia when the user swings the baseball bat. Additionally, the weighted prop that incorporates vibrotactile feedback can imitate the sensations of successfully hitting a baseball. Participants experienced significant improvements during the simulation with the weighted prop that features vibrotactile feedback.

Valkov *et al.* [49] incorporated motors in developing a prop that can simulate friction. The prop is circular, with four omnidirectional wheels on the bottom, with an infrared receiver to receive data used to determine how the prop should behave. The prop is programmable, making it reconfigurable for different scenarios. Sensations of friction are produced by rotating the motors with a microcontroller unit. Electrical power generated by motor rotation is used to rotate rotors in the opposite direction. This short cuts the motor, causing noticeable braking, making it harder for users to move the prop across a surface, thereby simulating friction. To test the feasibility of the system, 15 participants were asked to move the prop across a table set up to determine the areas in which the authors have purposely applied friction. Participants were able to perform with a 75% success rate.

Strandholt *et al.* [50] used actual carpentry tools such as a hammer, screwdriver, and saw for a carpentry-based simulation. By attaching a Vive Tracker onto the tools, the position of the object in the real world was aligned to the object in the virtual world. Additionally, secondary props like planks were also brought in to provide more realistic haptic feedback. A total of 20 participants were asked to hammer a nail, saw a plank, and use a screwdriver in the virtual environment to test the feasibility of the system. For instance, participants were asked to drive a screw into a plank with a screwdriver. This was done with an actual screwdriver attached with a Vive Tracker and an actual plank. The position of both objects was then mapped to the virtual world. In the virtual environment, the screw was animated to look like it was driven into the plank. Results showed that the perceived realism for all three actions was much better when both the tool and the secondary prop were used as opposed to using just a conventional controller.

Azmandian *et al.* [51] employed both world and body manipulation techniques to reduce the number of physical props required for a simulation. In the case of world manipulation, the virtual world is moved or slightly offset to ensure that virtual and physical objects align. As for body manipulation, the position of certain virtual body parts like the arms is also slightly moved to ensure that virtual body parts and prop align. In both techniques, dynamic retargeting is the key to ensuring that the prop can be re-used for various circumstances. For instance, the sensations of a circular arc can be re-created in the virtual environment with just one cube-shaped prop. This is an example of the world manipulation technique where the virtual world is translated slightly to the left as the user touches the circular arc in the virtual environment, so as to create an illusion of many cube-shaped props. Similarly, the body manipulation technique allows one cube-shaped prop to be used to represent three cubes arranged horizontally through slightly retargeting the virtual hands. This is done by translating the entire body to the right in the virtual environment, making it seem like there is more than one cube on the table. Twenty participants were recruited to experience four simulations, namely body manipulation, world manipulation, a hybrid of both techniques, and a control where users used a wand to interact with the cubes. The hybrid technique produced the most realistic experience for participants.

E. MID-AIR HAPTICS

Mid-air interfaces eliminate the need to wear, hold or set up external props and devices to receive haptic feedback. Instead, feedback is transmitted through a device that features a panel of ultrasonic transducers often arranged in grids of varying sizes. These transducers are modulated in such a way that the phase delay between the actuators creates interference patterns in the sound waves that are then propagated into the air [52]. This results in focal points that are relatively higher in pressure compared to the surroundings, allowing users to feel vibrotactile sensations [53]. However, while the use of transducers is common in providing mid-air haptic feedback, it is important to note that haptic sensations can also be transmitted "airborne" in other ways.

Sand *et al.* [54] developed a device to provide mid-air tactile feedback that is attached to a head-mounted display. The device is built with an array of transducers arranged in a 16-by-8 two-dimensional grid. Additionally, the device includes a field-programmable gate array board capable of 64-resolution pulse width modulation accompanied by a soft-core processor. The entire system is then connected to a workstation with a universal serial bus port. Together with a motion tracker that tracks hand movements, the workstation controls the generation of tactile haptic feedback. To test the system's feasibility, 13 participants were asked to interact with a virtual numeric keyboard with and without haptic feedback. While the system did not enhance or degrade performance, participants still preferred the haptic feedback provided by the setup compared to no feedback at all.

Also utilizing transducers, Matsubayashi *et al.* [55] developed a system that allows for multi-fingered virtual object manipulation. Interactions are simulated by producing a floating image of the virtual object on an autostereoscopic display. The behaviour of the image produced on the display is dependent on the user's hand gestures or movements that are determined with a depth sensor. To create more realistic interactions, the system also takes pressure distribution into account by constantly altering the waves transmitted by the transducers at high speeds, depending on the state of contact of the user's fingers and the virtual object. For testing the feasibility of the system, 10 participants were asked to grasp and lift virtual cubes. The system was arranged in a box-shaped setup in which transducers were placed all around the top, bottom, left, and right borders of the box. Facing the user was an autostereoscopic display. The depth sensor was placed below the display, enabling tracking of hands to render appropriate tactile feedback from the transducers. Participants could complete tasks presented to them with relative ease. Furthermore, they felt that the experience was realistic, owing to the pressure distribution feature.

Rather than use regular transducers that are often bulky, heavy, and rigid, van Neer *et al.* [56] proposed an alternative solution that applies polymers. These novel transducers are produced through a printing process that involves the use of piezoelectric membranes. The authors state that the materials used are lighter, more flexible, and thinner than typical solutions. This is ground-breaking as it allows for a mid-air interface that can be bent and integrated into curved surfaces to cover a larger surface area than a standard grid. While no user testing was done, haptic feedback of the prototype in performance tests indicated that the transducers were not only feasible but also realistic.

To increase the range of the standard two-dimensional grid-based device that provides mid-air haptic feedback, Howard *et al.* [57] proposed a tiltable mount capable of offering two degrees of freedom (2-DoF). The system is relatively low-cost, and is not only capable of increasing the workspace, but also improving the quality of rendered haptic feedback by dynamically reorienting itself. This allows haptic sensations to be delivered from multiple angles and directions. To effectively integrate the module with the virtual environment, the position of the device in the real world must first be calibrated to align with the interactable object in the virtual world. Other than that, the position of the user's hand is also tracked with a motion sensor to ensure haptic sensations are delivered in the correct direction. A feasibility test with 15 participants showed that the system effectively increased workspace and improved feedback.

Han *et al.* [58] developed a device that enhances the teleportation experience in the virtual world. The device features two modules that provide a variety of haptic sensations. The cold module is capable of dispelling sensations of mist, raindrops, and wind while the hot module dispels sensations of heat and hot air. The mist sub-module consists of ultrasonic mist makers and a fan placed in a tank containing water. To generate raindrops, micro-aperture atomizers produce water droplets. To simulate wind blows, a high-speed electric fan is used. To produce heat and hot air, infrared lights and heat blowers are utilized. At this time of writing, no user test had been done yet to determine system feasibility.

Similarly, Sasaki *et al.* [59] utilized rotors to develop a device capable of delivering mid-air haptic feedback. The device resembles a pole with a multirotor attached to each end. The setup, consisting of two quadrotors mounted on each side of a rod, generates linear and rotational forces that can be used to enhance virtual experiences such as paddling through a river, flying, falling from a high place, and weightlifting. Furthermore, by controlling the intensity and timing of each rotor, sensations such as bumping an object or recreating water dynamics are possible too. However, user testing has not been done to evaluate feasibility of the system.

Romanus *et al.* [60] expounded a mid-air haptic technology that incorporates three different technologies – virtual reality head-mounted displays, wearable biosensors as well as ultrasonic transducers. These devices allow users to see, touch, and feel a representation of their own beating heart. The devices are set up in such a way that the hologram is updated dynamically to change the haptic and visual feedback of the beating heart. The biosensor monitors the user's heart rate which is used as input for the haptic feedback modulation frequency and animation speed of the beating heart. To mimic the user's heartbeat, a circle sensation is projected onto the user's palm using ultrasound. Two different haptic modalities were designed to achieve this project's purpose, one with a pulsing intensity and one with a pulsing radius. The pulsing intensity is created by changing the intensity of the haptic feedback on the circle sensation, whereas the pulsing radius is produced by changing the radius of the circle projected on the palm.

Ultrasonic phased arrays are also capable of producing textures in VR objects. To do so, Beattie *et al.* [61] extracted fine and macro roughness features from images of material surfaces and rendered them through an autocorrelation function, Discrete Fourier Transform (DFT), and Power Spectral Density (PSD). The roughness of a texture was determined by fitting a slope to the frequencies of the PSD function. For instance, a rapidly decaying slope indicates that the image is a smoother texture, whereas a slower or flatter slope indicates a rougher texture. Hence, by mapping the haptic intensity of the ultrasonic array to the slope, the sensation of textures can be produced. This initial step towards ultrasonic haptic textures presents a new paradigm in augmented and virtual reality experiences, where users can not only touch but also feel digital objects.

V. CHALLENGES (RQ1)

Figure 3 shows all haptic interfaces discussed in this review. With this visible increase of novel haptic interfaces, design-based challenges are imminent. This section aims to answer the first research question posed, which is to identify design challenges for each type of haptic interface.

A. HANDHELDS

Handheld haptic devices are generally simple to use, compact and cheap to manufacture [62]. With a simple form factor that embraces the "grab and go" design philosophy, it is no surprise that handheld controllers are the default interface accompanying commercial virtual reality hardware. As a result, handhelds have their own set of challenges as discussed below.

Adaptability. Handheld haptic interfaces are built with accessibility in mind, to cater to the public without the need for extensive training. With that said, handhelds should also be flexible enough to adapt to various hand sizes. This can be done by implementing adjustable hinges throughout the controller.

Compactability. As handhelds are supposed to be compact for better handling, the ever-present challenge is to fit as many features into the device as possible. This is exacerbated by the popularization of multimodal haptic interfaces. For instance, the device should be able to support rendering of all types of feedback, such as thermal, pressure, vibration, texture, and skin stretch. Moreover, rendered sensations should also be easily recognizable and differentiable without much training [5].

Double Hand Manipulation. Furthermore, with the increase of single novel handheld devices, more research should be done to enable double hand manipulation. From a design perspective, this means that researchers should consider factors like manufacturing costs for a pair of handhelds instead of just one. Apart from that, the pair should also be able to work synchronically to efficiently imitate double-handed interactions.

B. WEARABLES

Wearable haptic interfaces are generally designed to be compact and comfortable in order not to impede the movement of

FIGURE 3. A visual summary of haptic interfaces discussed.

users [63]. This is why compared to other haptic interfaces, wearable systems are mainly used to aid inpatient rehabilitation so as to reduce joint loads, identify movement disorders, and improve walking strength and stability [64], [65]. The need for small, user-friendly, and comfortable wearable systems has raised some design challenges for developers and researchers alike. These challenges are discussed below.

Adaptability. Since actuators in these systems require close contact with the user's body to efficiently deliver sensations, size-adaptable wearables become necessary. The design of wearable systems should also account for skin stretch and deformations that may occur during use [66]. The system must be able to adapt and predict unwarranted movements of users to allow for more realistic experiences. Ultimately, when repeatedly faced with such situations, the device is expected to still perform well without any loss of functionality or damage.

Compactability. The need for compact wearables also means that hardware such as actuators and sensors should be nimble enough to fit into tight crevices on the body. This is especially true for gloves, considering how small the surface area of each finger is. With such requirements, fitting the actuation for different types of sensation could also be a challenge. In other words, instead of employing different actuators to render distinct sensations, researchers should focus more on developing multimodal actuators instead.

Weight. Factors such as weight should be considered too when developing novel wearable systems or actuators without sacrificing functionality. Since wearables are worn, weight can also be an issue when it comes to user comfort. Comfort is important to ensure that virtual experiences are as realistic and immersive as possible.

C. ENCOUNTERED TYPES

Unlike handhelds and wearables, encountered-type haptic interfaces aim to free the user from the need to handle or wear another device. Instead, sensations are delivered by directly bringing stimuli to the user. Therefore, in terms of design challenges, factors such as comfort and size become less important in encountered-type interfaces compared to handhelds and wearables. The challenges for this particular interface are discussed below.

Degrees of Freedom. The main challenge is to increase the degree of freedom without incurring major costs or complexities to the setup. This is especially necessary for setups that implement robotic arms or novel systems that usually have end effectors attached to deliver haptic feedback.

Kaluschke *et al.* [67] found that devices with 6-DoF outperformed 3-DoF devices in terms of feedback quality and control intuitiveness. This means that future encountered-type interfaces should strive for a better degree of freedom as the need for more realistic haptic interfaces increases.

Consequently, setups that implement drones also have their fair share of challenges, as discussed below.

Power Consumption. Drones should be able to carry loads without sacrificing flight durations in order not to have virtual experiences cut short during use.

Safety. Additionally, drones should have safety features that protect users from their propellers.

Noise. Loud noise emitted from drones can be another challenge as it may ruin immersion on the user's part.

Regardless of the use of drones, all encountered-type interfaces will face the following challenge.

Synchronicity. Since encountered-type interfaces rely on robotic arms and drones that approach the user to deliver haptic sensations, synchronicity between the interface and the virtual object is necessary. This means that the interface should be able to align with objects in the environment to provide realistic virtual experiences.

D. PHYSICAL PROPS

The use of physical props to deliver sensations is also known as passive haptics. With props, complex hardware is not needed, which enables the delivery of realistic haptic feedback at a low cost [68]. Nevertheless, utilizing props to deliver haptic sensations may be challenging, as discussed below.

Tangibility. The main design challenge for physical props comes from the need to appropriate more than one object in an entire virtual scene. Hence, the challenge is to develop more tangible props that can be reused for multiple scenes. Ideally, the prop should be able to transform into multiple props without the need for much tweaking.

Synchronicity. Similar to encountered-type haptic interfaces, the use of passive props also requires synchronicity between the props and the virtual objects. However, aligning props to their virtual counterpart could be challenging because, unlike robotic arms and drones, props are mostly non-programmable.

E. MID-AIR HAPTICS

Mid-air interfaces are highly compelling due to their ability to deliver haptic sensations without direct contact. This allows users to interact with interfaces or digital content with hand gestures or movements in the air. However, despite being able to improve user engagement, sensations delivered mid-air pose their own design challenges, as discussed below.

Transmission Range. For mid-air haptic interfaces, vibrotactile feedback is delivered to users from a panel of ultrasonic transducers. This means that compared to other interfaces discussed in this review, the transmitting and receiving range for haptic sensations are limited to the size of the panel. Hence, the main challenge is to increase the rendering space so as not to limit the movement of users. While this can be achieved by using more than one panel, the cost of employing multiple panels does not make this approach ideal.

Cost. Currently, the cost for an individual transducer is about 1 USD when bought in bulk [69]. Not including the need for other electronic parts, an array containing just 100 transducers would cost 100 USD. The need to amplify each transducer will require relatively complex circuitry, further increasing costs. Therefore, the challenge is to minimize the number of transducers or simplify transducer design to lower costs.

VI. RESEARCH DIRECTIONS (RQ2)

Other than design challenges, haptic interfaces for virtual reality have limitations regarding their supported domains of interaction. As such, this section aims to answer the second research question posed, which is to discuss identified research gaps.

Physiology. Most existing haptic interfaces highlighted in this review are designed to simulate haptic stimuli. While it is unnecessary for encountered-type and physical prop-based interfaces to prioritise the individual characteristics of each receptor, handhelds, wearables, and mid-air haptic interfaces need to do that. This is because the latter interfaces deliver haptic stimuli by directly contacting the skin. Despite not prioritising the characteristics of human receptors, studies on some existing approaches report positive feedback (as discussed thoroughly in section IV above), but it would be interesting to also recreate some of these methodologies by taking physiological factors into consideration. This is further supported by Basdogan *et al.* [70], who suggest that despite advances in tactile rendering, existing algorithms are unable to provide a sense of realism due to limited understanding of human tactile perception. Hence, this section aims to shed some light on how understanding physiological characteristics may improve haptic interfaces.

As Table 1 shows, each receptor has its specialized characteristics. For instance, unmyelinated and myelinated fibres differ in terms of the presence and absence of myelin. Myelin acts as an insulator for electrical impulses, which speeds up the conduction of action potential. An action potential is an impulse that is generated when information passes through nerve fibres. The conduction velocity of unmyelinated fibres ranges from 0.5 to 10 m/s while the conduction velocities of myelinated fibres can reach up to 150 m/s [71]. Interestingly, conduction velocity is affected by age, temperature, height, finger circumference, and gender. According to Stetson *et al.* [72], conduction velocity decreases as one ages, at lower body temperatures, as height increases, and as finger circumference increases. Also, females were found to have lower conduction velocities compared to males. Hence, these factors should be considered when developing haptic interfaces, to ensure that generated haptic feedback via actuators is properly transmitted regardless of differing anthropometric factors.

Moreover, the adaptation rate of receptors in Table 1 refers to how rapidly a receptor adapts to a constant stimulus [12]. Fast adapting or phasic receptors halt the transmission of impulses when the strength of the stimulus remains constant. This allows the body to ignore a constant stimulus that is unimportant. Slow-adapting or tonic receptors transmit impulses for as long as the stimulus is present. These receptors are used to monitor parameters that must be continuously evaluated such as barometric pressure. As mentioned, it is currently unclear how this affects the development of haptic interfaces. This could be useful when developing interfaces that need to conserve power. When working with fast-adapting receptors, actuators can be halted after a certain period. Thus, research should be done to determine whether this is feasible.

Furthermore, factors such as receptive fields should also be taken into account when developing haptic interfaces. While receptors with larger receptive fields detect stimuli over a wide area, the perception is less precise [73]. This explains why the finger, which is required to detect fine detail, consists of densely packed mechanoreceptors with small receptive fields (10 square mm) [73]. For areas like the back and legs with large receptive fields, the hot spot where stimulation produces the most intense response is usually located in the centre, directly over the receptor [73]. This information can be used to develop whole-body haptic interfaces apart from just the hands. With that said, more research should be done to determine the hot spots of other body parts, such as the chest, stomach, and feet.

Factors like spatial resolution also differ for each mechanoreceptor, as seen in Table 1. Mechanoreceptors with high spatial resolution can better detect physical stimuli that are closely spaced [74]. Similarly, this information can be used when developing haptic interfaces by leveraging areas with high spatial resolutions for more intricate and nimble physical stimulations. All in all, it would be helpful if human physiology experts and engineers could work together to find out how to utilize every characteristic of individual receptors to properly develop haptic interfaces that are more efficient and realistic.

Multimodality. As for the various types of object properties, a golden standard for a device that can stimulate them all remains mostly unachievable. However, research by Rossignac *et al.* [75] and Stanley and Okamura [76] suggests that the concept of digital clay is possible to a certain extent. However, both of those studies on developing deformable surfaces were limited to accommodating changes in properties like shape and size. It would therefore be interesting to expand this work by including pin arrays or other mechanisms that could also simulate texture, temperature, and compliance.

A true multimodal interface should possess the following abilities:

1. Adapting to various shapes and forms on demand.
2. Simulating various types of surface and object textures.
3. Simulating various thermal sensations and temperatures.
4. Simulating weight.
5. Simulating various types of contact forces.

Therefore, the real challenge here is to fit all these features into a compact interface without substantially sacrificing functionality, cost, or complexity.

Realism. Some existing haptic interfaces discussed in this review also managed to effectively simulate shear forces, rotational forces, and stiffness. However, as mentioned, more research should be done on how humans perceive contact forces, which are more common in real life. This can then be used to develop haptic interfaces that simulate real-life situations better. For example, the act of lifting a cup of coffee may seem simple on the outside. However, on the inside, this simple action is made possible by receptors in the wrists, shoulders, elbows, and multiple joints in the fingers. If one is sitting, the back is also involved to help brace against the movement. Not to mention, the cutaneous receptors on several fingers that are in contact with the cup are also involved to respond to the stimulation. The back-and-forth action of moving the cup towards the mouth and back to the table means that the position of the muscles and joints is constantly changing. The shifting position of the hand also changes the way inertia affects receptors under the skin [77]. Hence, by breaking down which parts are involved when carrying out an action, realistic tactile feedback can be delivered by focusing on stimulating these areas. Work can also be done to create a trigger map of some kind for common interactions, so as to speed up this process.

Accessibility. More haptic interfaces should be developed to help improve accessibility for the visually impaired. For example, Wong *et al.* [78] developed a haptic-audio-based online shopping platform to enable the visually impaired to autonomously shop online. The authors utilized the Novint Falcon to enable visually impaired users to perceive the shape, dimension, and texture of objects they wish to purchase. However, due to the stationary nature of the Falcon, the working range of the device is limited to an area of 10 square cm [79]. Hence, with the implementation of haptic interfaces that can provide larger working ranges as well as more realistic feedback, the visually impaired will be able to shop online independently and effectively. It is also important to consider the requirements of visually impaired users. The developed interface should not be too complex and should be easy to manoeuvre and use, without the sense of vision.

Haptic Water. Another obvious gap is the lack of haptic interfaces that can simulate the sensations of interacting with a body of water. Reuvekamp *et al.* [80] utilized the FCS Haptic Master device to simulate shallow waves on a water surface.

The 3-DoF device is capable of rendering stiffness and force. Users mainly interact with the handle as shown in Figure 4. To create sensations of waves in the virtual environment, the authors programmed the device to simulate gravitational, viscous, and upward forces. For gravitational force, the authors programmed the device to simulate a force pointing downwards that is constant. For viscous force, the device was programmed with a damper object based on extent of submersion. The upward force was simulated with the aid of two springs, one pushing the device away and another pulling it in. More specifically, as the object touches water, the pulling spring starts to work, and as the object submerges, the pushing spring starts to work. As of today, no user testing has been done to assess the feasibility of this system.

FIGURE 4. The FCS Haptic system.

Another prominent attempt to simulate water comes from Ikeno *et al.* [81], who simulated the experience of pouring water from a bottle. To do so, the authors modelled and measured real vibrations to reproduce the sensation of water pouring out from a Japanese sake bottle. The authors developed a device with a vibrotactile actuator and attached it to a makeshift sake bottle. As with the FCS device, no user testing has been done to evaluate the feasibility of this system.

The studies highlighted above show that efforts to simulate sensations of water are still in their infancy. Hence, more research should be done to mitigate this issue. The challenge is to develop an interface that is capable of reproducing accurate sensations of interacting with water, in a portable form that does not restrict user movement. Factors such as temperature should also be considered when simulating water. Thus, the interface should feature various types of actuators to replicate the multimodal characteristics of water. This is another challenge, as fitting as many actuators as possible in a device could lead to complexity, cost, and portability issues.

Haptic Frameworks/Models. Easily adaptable models and frameworks should be developed to enhance the process of building haptic interfaces. According to Schneider *et al.* [82], the challenges hapticians face are multifaceted, owing to the multisensory and vertically integrated nature of haptic experiences and the need to collaborate with individuals from different disciplines, places, as well as design-related problems.

The vertically integrated nature of haptic experiences means that any changes made to a single haptic component may require some kind of an overhaul to the entire system. This is because often, actuator components need to physically interact with other components present in the system. Hence, these components are tightly coupled and are highly dependent on one another. This issue can be mitigated by developing frameworks that support modularity to provide some degree of separation between the components present in a system. Modularity could also be useful when it comes to customization, which is another challenge hapticians face when developing haptic interfaces. Modularity would allow individual modules to be independently replaced according to the user's wants and needs without affecting the entire system. Furthermore, the need to synchronize modalities is also a challenge in providing fast feedback. This is largely attributed to the accumulation of latency in the computational pipeline. Thus, frameworks should be developed to allow easy access to and management of the computational pipeline.

The field of haptics is interdisciplinary. Experts from fields such as engineering, physiology, psychology, and computer science must work together to ensure haptic experiences are built well. If developers wish to commercialize their products, a sales representative is needed to carry out demos that are often complicated. Hence, frameworks should be developed to enable and integrate interdisciplinary research. Another possible solution is to develop modular frameworks specific to each field, to make collaborations more seamless.

Most design-related challenges stem from needing to understand user requirements. Often, users themselves find it too difficult to understand their own needs. Furthermore, user evaluation is often low-level and lacks real-world testing. Therefore, frameworks for surveys that properly gauge user requirements and user evaluation should be developed as well.

VII. CONCLUSION

With advances in haptic and VR technology, more and more researchers have come up with interfaces that provide the sense of touch in virtual environments. However, due to the complex nature of the human somatosensory system, development of realistic haptic interfaces can be challenging. Hence, this review highlights some interaction domains, including receptors, object properties, and forces to aid future researchers in developing more realistic haptic interfaces. Additionally, haptic devices for VR ranging from wearables, handhelds, encountered types, props, and mid-air interfaces are discussed to determine design challenges for each type of interface. Finally, this review goes on to discuss research directions, including better consideration of physiology when developing haptic interfaces, requirements for multimodality, considering contact forces to deliver realistic haptic sensations, tackling accessibility, simulating sensations of interacting with water, and building adaptable haptic frameworks that simplify development of haptic interfaces.

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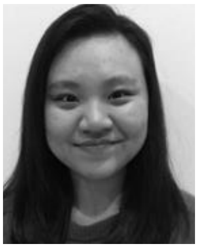

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