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Haptics: The Present and Future of Artificial Touch Sensation

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Abstract

This article reviews the technology behind creating artificial touch sensations and the relevant aspects of human touch. We focus on the design and control of haptic devices and discuss the best practices for generating distinct and effective touch sensations. Artificial haptic sensations can present information to users, help them complete a task, augment or replace the other senses, and add immersiveness and realism to virtual interactions. We examine these applications in the context of different haptic feedback modalities and the forms that haptic devices can take. We discuss the prior work, limitations, and design considerations of each feedback modality and individual haptic technology. We also address the need to consider the neuroscience and perception behind the human sense of touch in the design and control of haptic devices.

1. INTRODUCTION

Haptics—the sense of touch—enables humans to perform a wide variety of exploration and manipulation tasks in the real world. In virtual worlds and robot teleoperation scenarios, this sense of touch must be artificially recreated by stimulating the human body (typically the hands) in a manner that produces the salient features of touch needed to enhance realism and human performance. This article focuses on the state of the art in design, control, and application of noninvasive haptic devices that generate artificial human sensations. There are two other main areas of haptic technology that are beyond the scope of this article but certainly deserve mention and can be further studied using the works listed in the Related Resources section at the end of the article: robot haptics (giving robots the sense of touch using force and tactile sensors and associated processing/perception algorithms; e.g., see Reference 1) and invasive haptic stimulation (creating haptic sensations in humans and other animals by electrically stimulating the peripheral nervous system or the brain; e.g., see Reference 2).

1.1. Applications of Haptics

It is difficult to imagine life without haptics, in part because it is such a natural and integral part of our lives. Without haptics, we would have great difficulty grasping and manipulating objects, be unable to determine many material or surface properties, and miss feeling the warmth of a loved one's hand. Thus, many of the applications of artificial haptics address scenarios where the sense of touch is lost or greatly diminished compared with the experience of a healthy person in the real world.

Certain highly specialized professions can use augmented haptic feedback, such as an astronaut teleoperating a robot outside the International Space Station to enable repair tasks while avoiding a dangerous human space walk, or a surgeon using a robot to perform a delicate procedure at a scale not achievable with the human hand. In such teleoperation scenarios, we often aim to give human operators a sense of "telepresence" such that they feel they are directly manipulating the environment with their own hands, rather than having their actions mediated by a robot and communication/control system.

In some cases, we seek to replace a sense of touch that was lost owing to disease or accident. An upper-limb amputee has completely lost the sense of touch through the loss of a hand; ideally, a prosthetic hand would sense haptic interactions between itself and the environment and relay that information back to the amputee, so that the amputee does not need to rely entirely on sight in order to manipulate objects.

A more universally experienced lack of haptics is in interactive computing. Computers, tablets, and smartphones have sensors to measure human inputs, but their outputs (displays) are limited primarily to the visual and auditory channels. As discussed below, vibration feedback has made inroads as a haptic display for human–computer interaction, but the quality of this interaction leaves much room for improvement, and many other promising haptic feedback modalities have yet to be implemented in commercial systems.

1.2. Human Haptic Perception

Unlike the four other senses (sight, hearing, taste, and smell), the sense of touch is not localized to a specific region of the body; instead, it is distributed across the entire body through the touch sensory organ, our skin, and in our joints, muscles, and tendons. The sense of touch is typically described as being divided into two modalities: kinesthetic and tactile. Kinesthetic sensations, such as forces and torques, are sensed in the muscles, tendons, and joints. Tactile sensations, such as pressure, shear, and vibration, are sensed by specialized sensory end organs known as mechanoreceptors that are embedded in the skin. Each type of mechanoreceptor senses and responds to a specific type of haptic stimulus.

The mechanoreceptors are characterized by their temporal resolution and the size of their receptive fields. Fast-adapting mechanoreceptors capture transient signals, and slow-adapting mechanoreceptors capture mostly static stimuli. For example, Meissner corpuscles are fast-adapting mechanoreceptors that respond to low-frequency vibrations and sense the rate of skin deformation (3). Pacinian corpuscles respond to a wider range of high-frequency vibrations and provide information about transient contacts (4). Merkel disks are slow-adapting mechanoreceptors that detect edges and spatial features (4). Ruffini endings sense skin stretch and allow for the perception of the direction of object motion or force (3).

The density of mechanoreceptors differs with the location on the body. Mechanoreceptors are more dense in the glabrous skin of the hands and feet than in hairy skin, which makes touch easier to localize on the glabrous skin (5). To create a truly effective haptic interaction, designers must account for the location dependency and specialization of the mechanoreceptors in creating both the device and the signals to drive it.

1.3. Haptic Devices

To introduce the breadth of haptic device design and control, we consider three major categories of haptic systems: graspable, wearable, and touchable. **Figure 1** gives examples of each of these types of systems.

Graspable systems are typically kinesthetic (force-feedback) devices that are grounded (e.g., to a table) and allow the user to push on them (and be pushed back) through a held tool. Graspable devices can also be ungrounded (e.g., using flywheels to provide inertial forces) or can be tactile devices that are held in the hand.

Wearable systems are typically tactile (cutaneous) devices that are mounted to the hands or other parts of the body and display sensations directly to the skin. They can provide cues such as vibration, lateral skin stretch, and normal skin deformation. They may also be body-grounded devices, such as an exoskeleton, that provide a kinesthetic cue to the user by creating a reaction

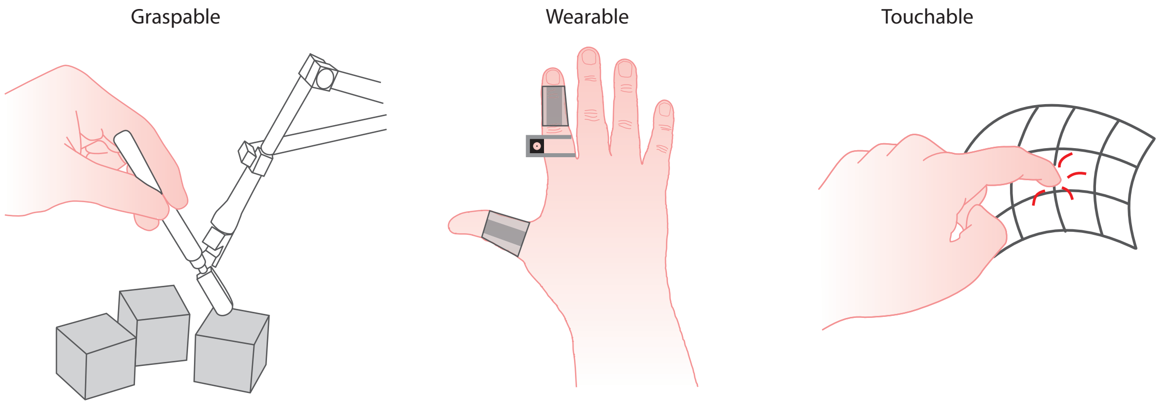

Figure 1

Examples of graspable, wearable, and touchable haptic systems. These three categories describe the breadth of interaction modalities for kinesthetic and cutaneous stimulation in interactive haptic devices.

force on a less sensitive part of the body. The wearability of the devices makes them attractive for use in mobile applications where users should be free and unencumbered to move about their environment.

Touchable systems are encountered-type displays that allow the user to actively explore the entire surface. They can be purely cutaneous devices that change their tactile properties based on location, such as a surface with variable friction. Touchable devices can also be hybrid cutaneous and kinesthetic devices that change their shape, mechanical properties, and surface properties.

For each of these categories, the mechanism of haptic feedback can vary. The remainder of this review is organized mainly by these mechanisms, discussing kinesthetic devices (Section 2), skin deformation devices (Section 3), vibration (Section 4), and haptic surfaces (Section 5). In addition, owing to the increasing research and commercial interest in haptics for virtual and augmented reality, we include an additional discussion of this application (Section 6).

2. KINESTHETIC DEVICES

Kinesthesia refers to the sensation of movement and force and is typically associated with force-displacement relationships. Receptors involved include muscle spindles, which transduce muscle stretch, and Golgi tendon organs, which sense change in muscle tension. Stimulating these receptors can produce the illusion of movement and/or force. Kinesthetic or force-type haptic devices are defined by their ability to apply force about a joint such that movement (and resistance of that movement) is possible. Historically, kinesthetic feedback represented the bulk of haptic research in terms of device design and rendering algorithms. Interestingly, less is known about human kinesthesia, especially proprioception (the sense of self, usually referring to the sense of bodily movements), than about cutaneous sensing. This disparity is likely due to the complexity of developing experimental platforms for high-degree-of-freedom (high-DoF) force-displacement relationships on the scale and precision of human force sensing and motor control. Kinesthetic haptic devices are challenging to design and control because of this impressive human dynamic range, but they are the basis for a huge body of literature.

2.1. Traditional Kinesthetic Haptic Devices

The Phantom Premium haptic device (originally commercially available from SensAble Technologies) was a milestone in the field, because it enabled three DoFs of high-force and high-bandwidth force feedback with very low free-space impedance (6) [in other words, great Z-width (7)]. Numerous other kinesthetic haptic devices, from one-DoF knobs to six-DoF manipulandums, have been developed, with significant research effort put toward ensuring the realism and stability of virtual environments rendered via programmed force-displacement relationships.

Traditional kinesthetic devices designed using rigid links are no longer considered at the forefront of novel haptic device design, in large part because many of the research problems have been solved and the relatively high cost–benefit ratio has lacked commercial potential. Yet there are some novel designs and new rendering approaches worth briefly reviewing here. One design concept to consider is the choice of control formulation: admittance versus impedance control. Admittance control devices can apply much larger forces to the human operator for applications such as rehabilitation, albeit with differing control challenges from impedance devices. Alternatively, one can design devices that mechanically resist movement in controllable directions; cobots are a great example of this (8). Improvements to rendering techniques (9) and better understanding of human perception and cognition in the context of different haptic rendering algorithms (10) will also continue to refine the capabilities of kinesthetic haptic devices.

2.2. Low-Cost Kinesthetic Devices

Many kinesthetic devices have focused on high-DoF systems using the highest-quality motors with high force and low friction and cogging, linkages made from high-performance engineered materials such as carbon fiber, and low-friction bearings at joints. However, a new generation of kinesthetic haptics research is seeking to determine the minimal requirements for compelling haptic displays.

For example, haptic devices are being designed for use in education, where one or two DoFs can be sufficient to explain physical and mathematical phenomena in an intuitive, hands-on manner. For integration into classrooms, such devices should be inexpensive, robust, and perhaps even assembled by students or teachers. Haptics researchers are taking advantage of new and popular manufacturing techniques such as 3-D printing (11) and layered manufacturing to make haptic devices more accessible to nonengineers. The conflicting goals of low cost and high performance generate important research questions for haptic device designers as well as those interested in the application of haptics in training environments. For example, we do not fully understand how the accuracy of perception of mechanical properties via a haptic device affects learning or understanding of a concept or task (12).

2.3. Body-Grounded Kinesthetic Devices

Exoskeletons are typically body-grounded kinesthetic devices. How they should be designed and controlled in order to optimize performance for applications such as rehabilitation and user assistance is the subject of current research, which integrates design, control, biomechanics, and neuroscience (13). For example, hand-grounded devices can assist surgeons in steadying an instrument for medical tasks (14). An exciting design development in exoskeletons has been the use of soft robotic techniques and pneumatic actuation to make exoskeletons lighter, cheaper, and more adaptable to the human body (15, 16).

We differentiate body-grounded kinesthetic devices from wearable tactile devices by whether the device allows forces across a movable human joint. Pacchierotti et al. (17) provided a taxonomy that clarifies this difference. **Figure 2** shows how world-grounded kinesthetic haptic devices, exoskeletons (body-grounded kinesthetic devices), and wearable tactile devices differ in their grounding.

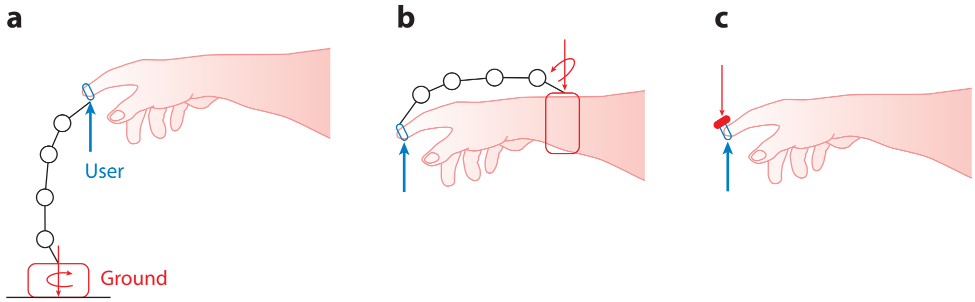

Figure 2

Schematic connections between grounds and haptic device user contact points for (*a*) world-grounded kinesthetic haptic devices, (*b*) exoskeletons (body-grounded kinesthetic devices), and (*c*) wearable tactile devices. Blue arrows indicate forces and torques applied to the user, and red arrows indicate reaction forces and torques at the ground. Figure adapted from Reference 17; © 2017 IEEE, reprinted with permission.

2.4. Multimodal Haptics

Kinesthesia has been successfully integrated with tactile (especially vibrotactile) feedback as well as other sensory modalities (particularly vision and sound) to produce compelling effects with less stringent requirements for the fidelity of force rendering. The force display of any kinesthetic haptic device is limited by the system's sampling rate, computational time delays, and quantization of position measurements (18).

In the 1990s, Srinivasan et al. (19) showed that visual rendering could significantly alter haptic perception. For example, when a virtual wall is displayed with a certain mechanical stiffness, a classic stiffness-rendering algorithm based on Hooke's law states that the force displayed (f) should be stiffness (k) multiplied by the penetration into the wall (x): $f = kx$. If the cursor representing the haptic device's position is visually allowed to penetrate the wall (thus matching the haptic rendering algorithm), the user will perceive a less stiff wall than if the visual display is modified to make the cursor stop at the surface of the wall. (We revisit the dominance of vision over haptics in Section 6.)

Lower-fidelity kinesthetic haptic systems can also be enhanced by combining low-frequency force with high-frequency vibration feedback. In the real world, when we tap on a hard surface with a finger or even a stylus, we feel not only kinesthetic force, but also high-frequency vibrations resulting from the contact event. In a virtual environment, playing those vibrations with either the kinesthetic device motors (20, 21) or a separate vibrotactile motor (22) can increase the perceived hardness of a surface.

2.5. Applications

Kinesthetic haptic devices have yet to find their "killer app," since the high-DoF devices that are most compelling are expensive and not amenable to commercialization. Popular applications for researchers have been medical simulation, rehabilitation, and computer-aided design. Attempts have also been made at developing force-feedback joysticks for gaming applications, but the use of kinesthetic feedback in these fields has not yet achieved widespread commercial success. A subtle but common application of kinesthetic feedback in a consumer product is in the dashboard control/navigation system in some high-end automobiles.

Teleoperation of robots that are remote in distance or scale can enhance human performance or keep humans safe when performing tasks in dangerous environments. Typically, haptic feedback for teleoperation has focused on kinesthesia, in large part because sensing force is simpler than sensing distributed tactile information. Applications include situations in which remote operation of a robot is desirable owing to challenges in access (especially distance and danger) and large differences in scale relative to typical human manipulation.

3. SKIN DEFORMATION DEVICES

The kinesthetic force-feedback devices described in the preceding section represent a fairly complete haptic experience because they not only display large forces but also stimulate the skin through the held tool, effectively providing tactile feedback in addition to the actively controlled kinesthetic feedback. In the last decade, researchers began to examine whether providing only the tactile component of contact forces would have advantages for the size, wearability, and cost of haptic devices without detracting from the perception that net forces are being applied to the body. Prattichizzo et al. (23) called this "cutaneous force feedback" and acknowledged the removal of the kinesthetic forces as a form of "sensory subtraction."

3.1. Lateral Skin Deformation

Skin deformation is a promising feedback modality in which a shear force is applied to the user's finger pad, similar to the skin deformation that occurs naturally during haptic interactions. This method takes advantage of the finger's increased sensitivity to shear forces compared with normal forces (24). In addition, two DoFs of shear can be displayed, enabling directional cues. In order to display shear force, a device contacts the skin, presses on it to ensure sufficient friction, and moves laterally to deform the skin in shear. Researchers have investigated the ability to discriminate direction through both lateral skin stretch and lateral skin slip (25–27). Guzererler et al. (28) investigated the sensitivity to skin stretch on the palm in different speeds and displacements, and Bark et al. (29) and Wheeler et al. (30) showed that skin deformation is effective in communicating proprioceptive information when used on the forearm.

Such skin deformation can be achieved with or without an aperture, which changes the manner in which the device is grounded to the body (**Figure 3**). Many lateral skin deformation devices have been created using aperture-based grounding, where the finger is grounded on an outer aperture while a tactor moves against the skin, because it allows easy grasping without any associated donning or doffing process. Aperture-based devices, although limited in workspace and DoFs by the aperture constraints, can still provide sophisticated multi-DoF feedback, as demonstrated by Guinan et al. (31), who used multiple devices with two-DoF tactors to convey five-DoF directional cues.

Much of the work on lateral skin deformation has focused on passive perception of the skin deformation feedback cues. Only in recent years have researchers begun to focus on superimposing lateral skin deformation with dynamic force-feedback stimuli. Provancher & Sylvester (32) found that rendering a small amount of skin stretch by moving a high-friction tactor against the skin of the finger pad could increase the perception of friction. Quek et al. (33) extended this idea using an aperture-based one-DoF device and found that adding skin deformation to kinesthetic force feedback causes increased perception of stiffness. Further work by Quek et al. (34), using a three-DoF device that combined skin stretch with normal indentation, demonstrated that dynamic force information could also be perceived in multiple DoFs. A more complicated six-DoF device design was later used by Quek et al. (35) to provide force and torque information in teleoperated tasks using the da Vinci surgical robot. These works show that an assortment of skin deformation feedback DoF configurations, including two-DoF, three-DoF, and six-DoF devices, can supplement force feedback (34–37).

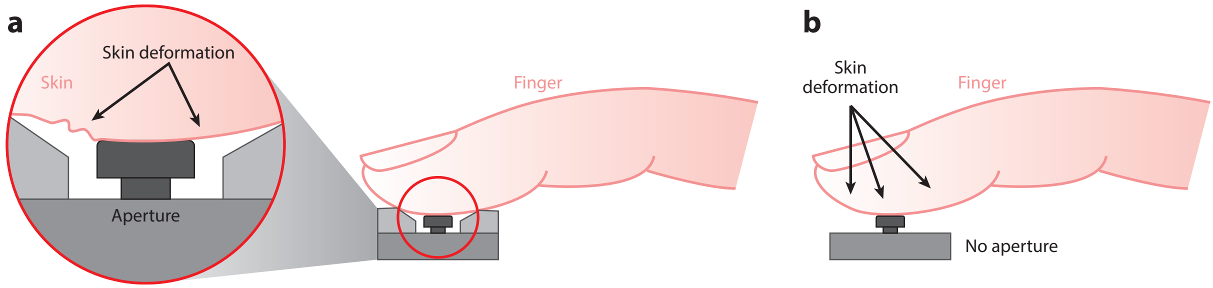

Figure 3

Skin deformation feedback achieved by moving a point in contact with the skin in the normal (into the skin) or lateral (parallel to the skin) direction. (*a*) Skin deformation with an aperture constraint that localizes the deformation. (*b*) Skin deformation without an aperture constraint, which can provide a stronger sensation because more mechanoreceptors are engaged. Figure provided by William Provancher.

Despite a large body of work demonstrating the efficacy of combining skin deformation with kinesthetic feedback, determining how users perceive lateral skin stretch feedback as a complete substitute for force feedback is still an open question. Schorr et al. (38) found that these skin deformation cues could be used to discriminate between various levels of stiffness without any underlying kinesthetic cues. In subsequent work, Schorr et al. (39) showed that this form of feedback performs similarly to kinesthetic feedback during a teleoperated palpation task.

3.2. Wearable Skin Deformation Devices

Although the tactile feedback devices discussed above act on different parts of the body, most of them focus on the finger pad owing to the great density of mechanoreceptors present there (38). A large body of work has investigated the use of small, wearable, finger-grounded devices for deforming the finger pulp. Although there are many ways that these devices could be classified, one way is to distinguish between the devices that render indentation normal to the finger pad (often with control of orientation as well) and those that provide lateral translation (often with normal indentation as well).

Recently, researchers have investigated the effects of wearable finger-grounded tactile haptic devices that can move an end effector against the surface of the finger pad (**Figure 4**). One category of these devices compresses a platform normally against the finger pad in addition to changing orientation (44–46). These devices have been used to provide normal force sensory substitution to the finger pad during teleoperation with the aim of preserving stability and improving transparency (23, 41, 47, 48). Such devices are well suited to displaying orientation information but are not necessarily capable of displaying arbitrary lateral forces. That is, the display of lateral force is directly coupled with differential normal forces at each attachment point of the finger-pad platform.

Another category of wearable fingertip haptic devices focuses on designs that move a high-friction tactor element, similar to that used in previous aperture-based skin deformation research, against the finger pad. These designs, while less appropriate for displaying orientation information, are appropriate for the display of lateral forces (49). Leonardis et al. (42) developed a wearable servo-actuated three-DoF skin deformation device with revolute–spherical–revolute (RSR) kinematics. The device was used to render contact forces in a virtual pick-and-place task and resulted in decreased grasping forces when compared with no haptic feedback. While the device has impressively small dimensions, the tactor translational motion has inherently coupled changes in orientation that cause the end effector to roll across the finger pad, possibly affecting the display of lateral finger-pad forces. Other devices (43, 50) decouple these DoFs in a similar package.

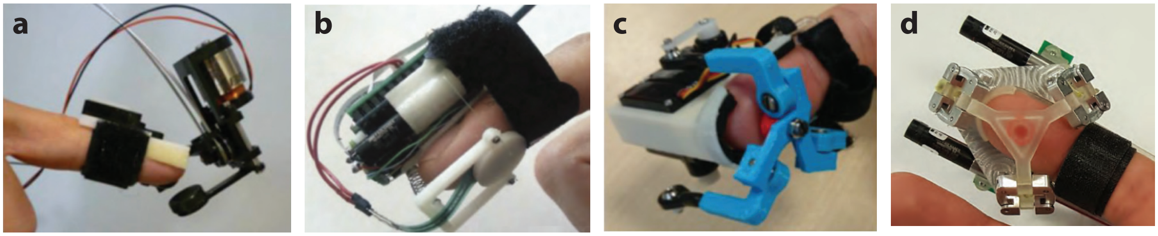

Figure 4

Recently developed wearable haptic devices that invoke skin deformation without an aperture. Panel *a* reproduced from Reference 40; © 2010 IEEE, reprinted with permission. Panel *b* reproduced from Reference 41; © 2014 Association for Computing Machinery, reprinted with permission. Panel *c* reproduced from Reference 42; © 2015 IEEE, reprinted with permission. Panel *d* reproduced from Reference 43; © 2017 IEEE, reprinted with permission.

4. VIBRATION

Haptic feedback in consumer products is usually synonymous with vibration feedback. Vibrations provide an added dimension to gaming by simulating the sensation of collisions or driving over a rough surface, the buzzing of a phone allows us to stay in contact and receive private notifications of messages even when in meetings, and vibrations have been used to simulate the feel of a button click. Similarly, much haptics research has focused on the use of vibration to display information, help the user complete a task, and add realism to virtual environments. Vibration's popularity can be explained by the widespread availability of actuators and the ease with which they can be integrated into systems. The actuators' small size, light weight, and low cost mean that vibration systems are easily scalable and can potentially display large amounts of information to users.

4.1. Human Vibration Sensing

Humans have two distinct types of mechanoreceptors that sense vibration, each of which is responsible for sensing a specific frequency band. In glabrous (nonhairy) skin, the lower-frequency vibrations (5–50 Hz) are sensed by the Meissner corpuscles, while the higher-frequency vibrations (40–400 Hz) are sensed by the Pacinian corpuscles (3). During interactions with physical objects, the Meissner corpuscles sense the rate of skin deformation caused by the slipping of a grasped object or by surface discontinuities and edges moving under the finger (3). The Pacinian corpuscles sense high-frequency vibrations caused by transient contacts with an object, as in collisions or a tool dragging across a textured surface (4).

Common vibration actuators, such as eccentric rotating mass motors or linear resonant actuators, typically produce vibrations at frequencies above 100 Hz, which primarily activate the Pacinian corpuscles. The Pacinian corpuscles have large receptive fields (4), so it is difficult for users to distinguish actuators that are placed close together. This issue of discriminability is further compounded by the propagation of vibrations through the skin (51). Pacinian corpuscles do not have directional sensitivity, so humans cannot distinguish the direction of high-frequency vibrations (52).

The density of both Pacinian and Meissner corpuscles in glabrous skin is high (3), which lends itself well to easily perceivable haptic feedback cues. However, the spatial density of the Pacinian corpuscles is significantly reduced in hairy skin (5), and the Meissner corpuscles are completely absent (53). Instead, hairy skin contains C-tactile afferents, which are rapidly adapting mechanoreceptors that respond preferentially to slow, stroking touch (53). Haptic designers must understand the methods and limits of human haptic sensing to create haptic systems that effectively stimulate the mechanoreceptors to achieve the desired sensation.

4.2. Information Display

Traditionally, vibration has conveyed binary information using a simple on–off state change. Arrays of these actuators can convey directional information, usually with one actuator used for each DoF. These arrays of tactors are typically mounted directly on the body (54), with common locations being the hand (55), arm (56), and torso (57, 58). Array size and actuator placement are limited by the ability of the user to distinguish the cues from multiple actuators. This distinguishability is limited both by the receptive fields of the Pacinian corpuscles and by the propagation of vibration through the skin (51). Owing to differences in the distribution of Pacinian corpuscles in glabrous and hairy skin, arrays of actuators can be denser when mounted on the hand than when placed on other parts of the body, such as the torso or the forearm (5).

Vibrotactile cues can also help users correct errors when completing a task. Feedback is provided if the user moves away from a desired set point or if their motion deviates from a desired trajectory. The vibration can be displayed to direct the user to move either away from the cue (repulsive feedback) or toward the cue (attractive feedback). Research has shown that users do not exhibit a preference for either repulsive or attractive feedback (59), but they may respond more quickly to attractive feedback (60). Error correction systems have been incorporated into handheld devices (61), prosthetic hands (62), and wearable bands (63) in order to guide users toward desired locations or body positions. Vibration has also been used to correct user error when following trajectories for upper-arm motions (64) and during surgery (65).

Finally, vibration can be used to provide information about events that occur at a distance, namely during teleoperation. With such systems, the user controls the motion of a robot remotely but is unable to feel the forces or vibrations experienced by the robot. Researchers have sought to use vibrations to convey to the user information about the interaction between the robot and its environment. This information transfer requires sensors on the robot (e.g., a force sensor or accelerometer) and an actuator on the master controller (66). Systems have been created to provide cues for remote surgery (67) and for teleoperation of a robot (68, 69).

4.3. Haptic Icons

Haptic designers often rely on vibration as a simple binary cue (on or off) in vibrotactile arrays. However, vibration signals can be much more expressive and can present a wider range of information by altering the amplitude, frequency, rhythm, and envelope of the vibration (70). By altering these parameters, designers can create distinct haptic icons to relay abstract information, such as the urgency of a message or the identity of the sender. These haptic icons are especially useful in applications where providing the same information through visual or auditory means is not feasible or ideal. However, one downside of haptic icons is that the mapping from the sensation to the meaning is often abstract, so the user must learn the meaning behind the icon. Recognizing and interpreting these abstract cues may cause a delay in the user's response to the cue. Despite this downside, haptic icons are a promising method for creating a large set of distinguishable haptic cues that present information to the user. Researchers have studied how to best create distinct haptic icons based on human tactile perception (71), and tools have been created for designing and testing distinct icons (72).

Vibrations can also be used to display less abstract information, such as emotions. Patterns of vibrations can be accurately matched to emoticons (73, 74) and emotions from facial expressions (75). Similar to traditional haptic icons, these haptic emoticons are created by modulating the temporal properties of the vibration signal. They still require training to successfully match the cue to its intended meaning, but the mapping may be more intuitive because haptics can affect the emotional state of the user (76).

4.4. Vibrotactile Illusions

In addition to displaying static sensations at discrete locations on the body, multiple vibration actuators can also display illusory sensations, such as motion. The key to these haptic illusions is the shape of the signals and the timing and spacing between individual actuators. Apparent tactile motion, which was first described by Burtt (77), is the sensation that vibration travels in a continuous motion across the skin. This illusion is created by controlling the length and delay of actuation between individual actuators in a linear array. It has been successfully implemented in a wearable navigation system (58) and in both one-dimensional (78, 79) and two-dimensional (80) holdable devices.

A second haptic illusion created with vibration is the phantom tactile sensation. In this illusion, two vibration actuators are activated simultaneously, and the user experiences a phantom vibration sensation between the two actuators (81). The location of the phantom vibration is dependent on the relative amplitudes of the two actuators. Israr & Poupyrev (82) combined the apparent motion and phantom tactile sensation illusions to create smooth, two-dimensional tactile strokes with a sparse vibrotactile array using an algorithm they called the Tactile Brush.

Another haptic illusion created with vibration actuators is sensory saltation, or the "cutaneous rabbit," which was first presented by Geldard & Sherrick (83). In this illusion, a series of short vibration pulses are successively presented at three discrete locations on the skin, and the user feels as though a rabbit were hopping along the skin in a continuous motion. An illusory hop is felt midway between the actuators. This illusion is quite robust (84) and can be expanded to two dimensions (85).

4.5. Asymmetric Vibrations

Vibrations have also been successfully used to generate a pulling sensation by creating an asymmetric vibration profile. These profiles are created by generating a large positive acceleration pulse followed by a small negative acceleration pulse. Although the net force generated by the system is zero, the user senses the large pulse more strongly than the small pulse, resulting in the sensation of being pulled in the direction of the large pulse.

The first systems to apply asymmetric vibrations were large mechanical devices that used a slider–crank mechanism (86, 87) or spring (88) to move a mass with a specified motion profile. Other systems have used an asymmetrically moving handle (89, 90). More recently, researchers have turned to using smaller vibration actuators, including a linear resonant actuator (91), voice coil (92–94), or speaker (95), to generate the asymmetric vibrations (**Figure 5**). These linear vibration actuators rely on current sent to an electromagnet to move a mass to generate the desired vibration. The small size of these actuators has allowed the asymmetric vibration principle to be expanded to systems with multiple degrees-of-direction cues (94). The perception behind this ungrounded pulling sensation is an area of active study, but researchers have hypothesized that it is created by asymmetric lateral skin deformation that is sensed by the Meissner corpuscles (93). Other researchers have proposed that the pulling sensation is induced by vibrations in the tendons (95). Research into the perception of the sensation has indicated that the perceived strength of the pulling sensation increases with the motion of the hand holding the actuator (96).

4.6. Vibrations for Increased Realism

Vibration has also been explored as a means of adding realism to virtual interactions. Vibration is naturally produced during many interactions with the physical world, especially those that occur through a tool. The human sense of touch excels at sensing and interpreting these vibrations to gather information about interactions and the physical world (97). Vibrations produced when dragging across a surface encode its roughness (98), and vibrations produced during tapping encode its hardness (21). However, these high-frequency vibrations are missing during traditional haptic rendering owing to limitations in the algorithms and devices (21, 99).

Researchers have worked to capture and recreate these high-frequency vibrations to create more realistic and immersive virtual environments. Complete physics-based simulations to generate these vibrations are too computationally complex for real-time rendering (100). Therefore, rather

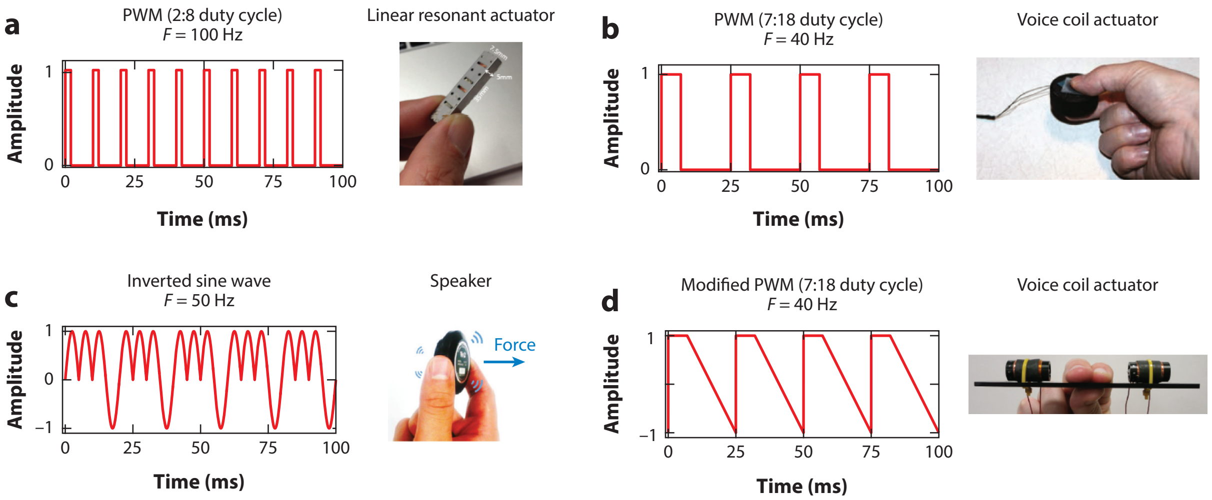

Figure 5

Examples of ungrounded asymmetric vibration systems: (*a*) a Traxion system that uses a linear resonant actuator driven with a pulse-width modulation (PWM) signal, (*b*) a voice coil driven with a PWM signal, (*c*) a speaker driven with an inverted sine wave signal, and (*d*) a voice coil driven with a modified PWM signal. All signal amplitudes shown are individually normalized. Panel *a* adapted from Reference 91; © 2013 Association for Computing Machinery, reprinted with permission. Panel *b* adapted from Reference 92; © 2014 Springer Nature, reprinted with permission. Panel *c* adapted from Reference 95; © 2016 IEEE, reprinted with permission. Panel *d* adapted from Reference 93; © 2016 IEEE, reprinted with permission.

than create models to simulate the vibrations from physics principles, many researchers have instead worked to directly model the vibrations produced from interactions with the physical surfaces in a process known as data-driven modeling (101). Data-driven models seek to capture the output response of a system (e.g., force and acceleration) given user inputs (e.g., position, velocity, and force).

Researchers captured and modeled vibrations to simulate the feel of interactions such as cutting (102) and tapping (21). The most promising and widespread application of haptic data-driven modeling has been to capture the feel of a textured surface. The simplest and most direct approach to this has been to play back the recorded vibrations directly (103, 104). Direct playback of signals, however, often fails to fully capture the complexity of the real interaction. Following the principle of distal attribution, for the virtual interaction to realistically mimic the real interaction, the rendered signals must behave in a physically appropriate manner and must match the motions made by the user (105). Therefore, the power and frequency content of the rendered signals must change if the user's force or speed changes in the virtual environment. This behavior of the rendered signals requires that more complex models of the recorded data be created before rendering.

In one of the first examples, Okamura et al. (20) modeled the vibrations from patterned textures as data-driven decaying sinusoids that depend on the user's speed and applied force. Similarly, Guruswamy et al. (106) created texture models based on a spatial distribution of infinite-impulse-response filters that are fit with decaying sinusoids. Researchers have also created haptic texture models using autoregressive models that depended on the user's normal force and scanning speed (107, 108).

Traditional kinesthetic haptic devices do not have a high enough bandwidth to accurately recreate the high-frequency vibrations needed for realistic texture modeling. Therefore, the majority of researchers opt to use a dedicated vibration actuator, such as a voice coil, that is capable of accurate and high-bandwidth vibration output. Some researchers who focus on the feel of textures with a bare finger instead of through a tool opt to render the texture vibrations with a variable-friction surface display (109).

4.7. Midair Vibration

The above-mentioned applications of haptics all require that the actuators directly contact the user to transfer the mechanical signals to the skin. However, there has been recent interest in exploring midair haptics, i.e., displaying haptic sensations to the user as they explore a virtual object in free space without contacting the actuators. Focused ultrasound beams can be used to create a localized sense of pressure on the fingertip in midair. An array of ultrasound transducers generates a focal point by individually controlling the phase and intensity of each transducer in a phenomenon known as acoustic radiation pressure. The radiation pressure is modulated at 1–1,000 Hz, so users often report experiencing a vibratory-like stimulus in addition to the localized pressure (110). This property of the signal has been exploited to provide midair localized vibration to the body (111). The same principles have also been used to create floating screens with touchable icons (112), multipoint haptic feedback (113), and three-dimensional shapes (114).

5. HAPTIC SURFACES

Another perspective on the creation of haptic experiences is that they should be real-world surfaces that can be actively explored by a human, enabling simultaneous kinesthetic and cutaneous feedback. Such haptic surfaces would ideally feel just like natural objects in the environment, except that they can arbitrarily change shape, mechanical properties, and surface texture. Owing to limitations in scale, dimensionality, size, and weight of sensors and actuators, this ideal cannot be perfectly achieved. However, through a combination of clever use of material properties and control coupled with sensory illusions, several approaches are maturing and emerging to generate highly compelling surface displays.

5.1. Pin Arrays

The traditional method of recreating a surface has been to control the vertical displacement of pins laid out in a two-dimensional array. Because of the linear actuators, this rendering is often limited to 2.5-dimensional shapes—each “pixel” in the tactile image is a physical pin attached to a linear actuator that can move up and down to render 2.5-dimensional shapes. A variety of technological approaches have been applied for actuation: DC motors with lead screws, rotational servos, pneumatic actuators, and shape-memory alloys. For the majority of these displays, the large number of actuators means that shape control primarily involves downsampling the desired shape to the resolution of the display and positioning each element accordingly. The SmartMesh multiloop mechanism (115) is based on extendable links arranged in a double-layer square grid, and the formable object (116) uses a parallel rigid-body structure with kinematics optimized to render basic shapes like cylinders and spheres. For a bed-of-pins display consisting of hydraulic actuators arranged along the rows and columns of an array, the resolution of the interface can more feasibly be increased because the number of actuators scales linearly rather than polynomially with the size of the array (117). Another way of achieving perceived vertical displacement with simpler actuation is to laterally bend a pin using a piezoelectric bimorph (118). Although each pin shears (as opposed to normally displacing) the skin, the created strain field can feel like a normal displacement. Interaction techniques and applications have been examined with large shape

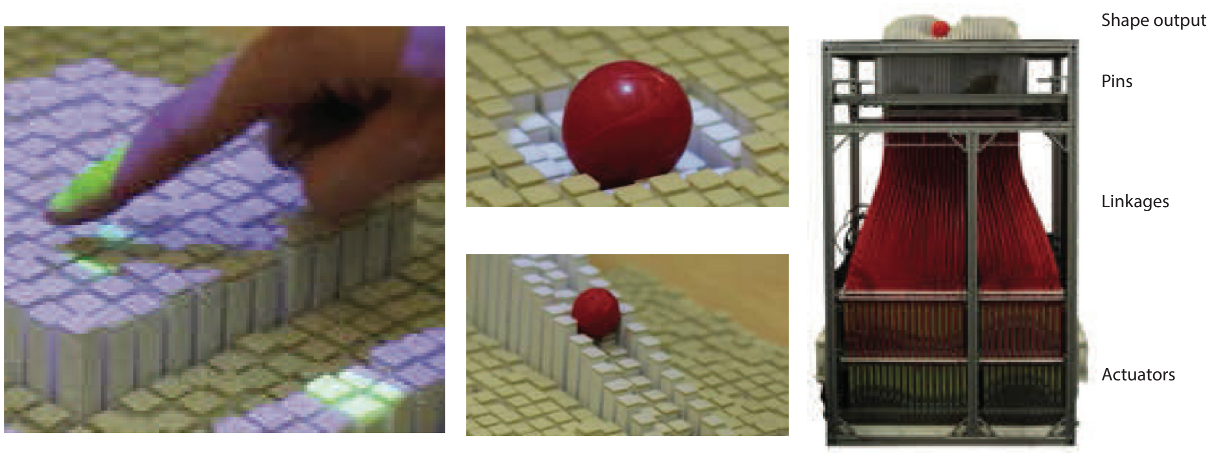

Figure 6

Large-scale pin array. This device can be used in conjunction with projection to create visuo-haptic environments, teleoperated via three-dimensional measurements of human movement, and used as a distributed manipulator for objects placed on the surface. The pins are driven by a large array of underlying motors and linkages. Figure adapted from Reference 119; © 2013 Association for Computing Machinery, reprinted with permission.

displays (e.g., **Figure 6**), with a focus on supporting remote collaboration (119–121). However, shape displays using the bed-of-pins approach remain limited by their 2.5-dimensional nature and the fact that they are often large, table-scale devices owing to the size of their actuators.

5.2. Deformable Crust Devices

Rather than filling the volume of a shape with the body of a pin, one can control the shape of a surface directly. This is the idea behind deformable crust topologies (122). A particularly promising approach for creating deformable crusts is through an actuation approach often used in soft robotics: pneumatics. For example, pneumatic soft composite actuators can undergo complex shape changes with a single DoF (123). Particle jamming can be used to control the stiffness of segments of a robot to lock segments, allowing for locomotion or shape changes (124, 125). Particle jamming and pneumatic composites can be used for new human–computer interfaces (126, 127). A combination of particle jamming cells on a nominally flat surface with air pressure applied from below can create a surface with controllable and distributed geometry and mechanical properties (128) (**Figure 7**).

5.3. Variable-Friction Surfaces

Given the shape of a surface, how do we control what it feels like? In the pin array and deformable crust examples, the stiffness of the surface can be directly controlled. However, texture and friction are also important to display realistic surfaces. This has been accomplished in recent years by modulation of surface friction, which effectively displays changing shear force as the skin (usually the fingertip) slides over a surface (**Figure 8*a***). These displays change the friction between a human finger and a plate by vibrating the plate at high (ultrasonic) frequencies (131, 132). When the plate vibrates, the friction between the finger and the plate is drastically lower than it is when the plate is static. The vibration frequencies (dozens of kilohertz) are high enough that they cannot

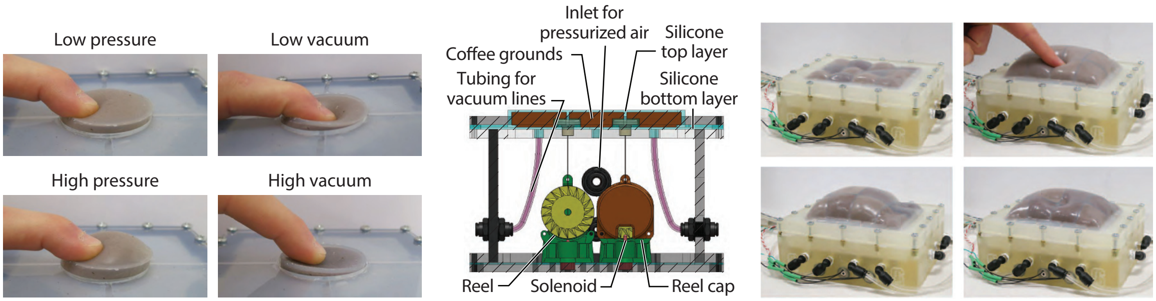

Figure 7

Deformable crust using pneumatics and particle jamming. The pressure underneath the crust can raise and lower a cell, and the vacuum inside a cell filled with granular material (in this case, coffee grounds) changes the hardness of the cell. Multiple cells can be combined in an array with reels and solenoids to control the outlay of string pulling down on the crust at points between the cells. This results in a surface with controllable shape and mechanical properties. Figure adapted from Reference 128; © 2015 IEEE, reprinted with permission.

be heard or felt directly by a human. Measuring the position and speed of a finger touching the surface enables the friction to be modulated in order to display walls, textures, etc., on the surface.

Another way to modulate friction uses changing electrostatic forces (109, 130) (**Figure 8*b***). Here, the normal force between the finger and surface depends on the attraction of electrostatic force, which is not strong enough to feel in the direction perpendicular to the surface but changes the effective friction enough to display similar walls and textures. The effect is not typically as strong as with vibrations, but electrostatics has the advantage that it uses no moving parts. Inherent in these approaches is that the surface must be actively explored by the finger(s), and the surface can dissipate energy only by resisting fingertip movement. There is a way to actively push on the finger, akin to what a traditional kinesthetic haptic device does: An actuator moves the plate laterally under the finger while friction is high, imparting a force to the finger. Since the lateral motion cannot go on forever, the system can be reset by lowering the friction using either the ultrasonic vibration or electrostatic technique and relocating the plate to its original position, ready to display to the finger again (133). In the future, this effect might be achieved passively with clever microstructure design of materials.

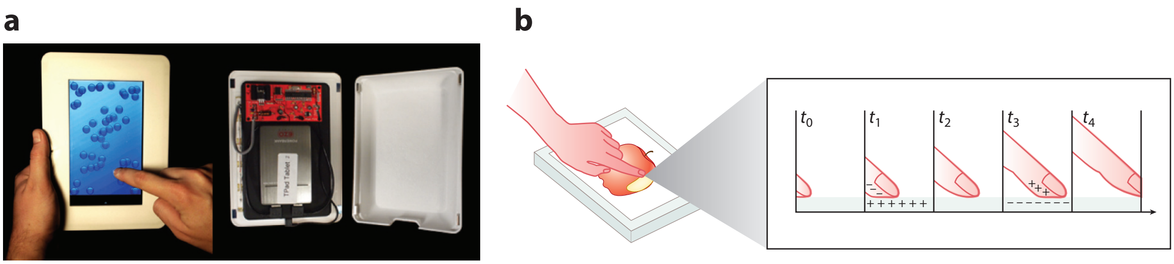

Figure 8

Variable-friction surfaces. (*a*) The open-source Tactile Pattern Display (TPaD) tablet. This tablet operates by vibrating the glass surface ultrasonically, which changes the friction between the finger and the surface and thus changes the shear force felt as a finger slides across the surface (as described in Reference 129). (*b*) Electrostatic vibration. This approach changes the friction by using electrostatic force to attract the finger to the surface. Although the forces are too small to feel directly, they change the friction felt by the user as the finger slides over the surface. Panel *a* provided by Joe Mullenbach. Panel *b* adapted from Reference 130; © 2010 Association for Computing Machinery, reprinted with permission.

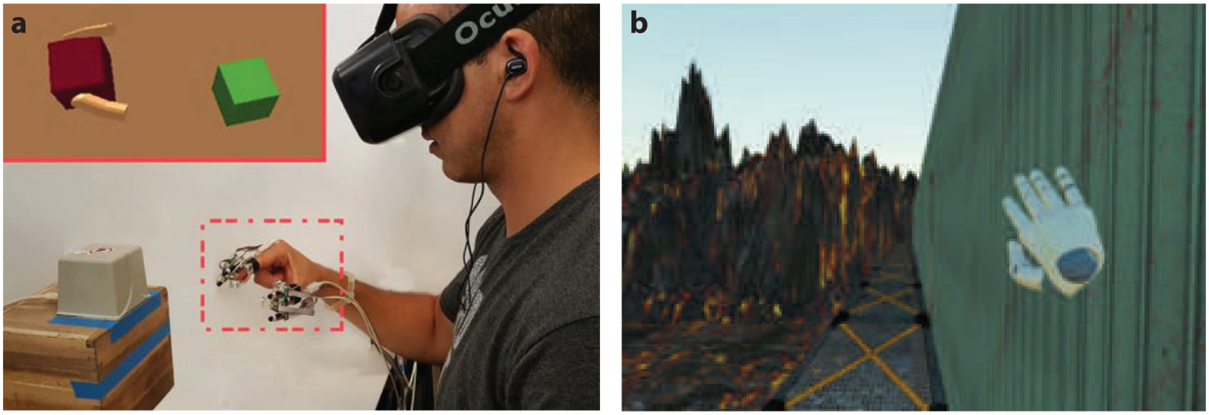

Figure 9

Virtual-reality scenarios. (*a*) A grasp-and-lift task with combined tactile and visual information to display virtual mass. (*b*) Haptic redirection. This technique can invoke tactile interaction with static walls in a virtual environment in conjunction with a warped graphical display to give the illusion of straight-line movement even when the actual movement is curved. Panel *a* reproduced from Reference 50; © 2017 Association for Computing Machinery, reprinted with permission. Panel *b* reproduced from Reference 134.

6. INTEGRATION WITH VIRTUAL AND AUGMENTED REALITY

Head-mounted virtual-reality displays, with associated movement tracking and the development of creative virtual-reality content, have recently led to significant interest in using haptics to enhance the quality and accessibility of virtual experiences. Indeed, the lack of realistic haptic feedback is a significant barrier to immersivity during object contact and manipulation in virtual reality—it is terribly disappointing to reach toward a highly compelling (graphically) rendered virtual object, see your fingers close around it, and feel . . . nothing. The spell of virtual reality is broken. Here, we explore the haptics-related approaches that have been successfully used or are in development to enhance interaction with virtual worlds (**Figure 9**).

6.1. Encountered-Type Haptic Devices

An encountered-type haptic device produces physical environments for the user to explore directly with his or her entire hands rather than relying on the user to hold an intermediary device through which they receive haptic feedback (135). The active surfaces described in the preceding section fall into this category, but there is much work to be done to seamlessly integrate encountered-type haptic devices with virtual reality. One of the main reasons to use an encountered-type haptic device with virtual reality is that the human user will see the graphically rendered environment, not the haptic device. This means that the haptic device does not need to have any realistic physical appearance and is required to feel right only at the point(s) of contact. However, this presents a significant sensing and control challenge: predicting where the user will want to touch the virtual environment as the hand approaches an object, such that the haptic device can position and shape itself as needed in order to provide the desired haptic experience.

6.2. Pseudohaptics

Visuo-haptic illusions seek to use haptic illusions (136) and the overall dominance of the visual system (137, 138) to create haptic feedback with passive props and visual feedback (139). This pseudohaptic feedback can be used to render the perception of friction, stiffness, size, and weight. Researchers have also sought to combine visuo-haptic illusions with active haptic feedback systems. Pseudohaptics through visual feedback is effective in augmenting cutaneous active haptic feedback for increased stiffness rendering (140). Spatial manipulation with single-point, underactuated kinesthetic haptic devices has been augmented with visuo-haptic feedback to increase the perception of rotation alignment (141). Ban et al. (142) have investigated actively changing a single physical ridge on a passive shape to influence haptic perception of bumps or other features on a surface. However, this space has not been explored fully, especially with regard to integration with encountered-type shape-changing interfaces, which can allow for many types of haptic exploratory procedures.

6.3. Haptic Retargeting

Haptic retargeting combines the concepts of encountered-type haptic devices and pseudohaptics described above. Moving the visual representation of the hand in the virtual environment, even if the felt environment is flat, can imply curvature (143). This same effect can be used to display angular information (144). Taking advantage of visual dominance in proprioception enables the use of visual stimuli to exaggerate the angular displacement of the head, which can be used for redirected walking (**Figure 9*b***). More recently, this effect coupled with spatial warping of the visually perceived hand location has been used for redirected touching (145) and grasping of shape primitives (146).

7. CONCLUSION

As the role of technology in communication, training, and entertainment increases, so does the number of potential applications of haptics. Haptics has already shown great promise in mobile communication and gaming, although the expressiveness of many commercial haptic devices has been limited. The potential impact of haptics is greatest in areas where the sense of touch is critical to the task or situation (e.g., remote surgery and prosthetic limbs), where touch can replace visual or auditory cues (e.g., mobile communication and navigation), and where touch can enhance virtual interactions (e.g., virtual reality and gaming). One of the largest factors limiting the impact of the field of haptics has been the availability and expressiveness of hardware. Commercially available actuators designed exclusively for haptic output are limited, which leads many researchers to develop their own haptic devices using off-the-shelf components. The key to developing functional and effective haptic hardware is to focus on the perceptual capabilities of the human sense of touch during the design process. This human-centered design paradigm results in haptic hardware that more effectively stimulates the mechanoreceptors to display the desired sensations.

FUTURE ISSUES

1. How will we identify and understand the perceptual basis of new haptic illusions to facilitate the design of haptic systems with minimal sensing and actuation? Two key challenges will be identifying haptic illusions that are robust across users and determining the ideal actuation parameters for creating the strongest illusion.
2. Can we enable consumer haptic devices by decreasing cost, size and weight, and power requirements, potentially via the use of novel actuators and smart materials? The challenges here will be reducing the size of haptic actuators while maintaining bandwidth, force output, range of motion, and important degrees of freedom; powering haptic actuators in mobile and wearable devices; and enabling wireless communication with and control of haptic devices.

3. Is it possible to create predictive models of human perception and cognition surrounding touch feedback, in order to decrease reliance on exhaustive human user studies? Past psychophysics studies have focused on human touch perception at a small number of locations on the body, including the hand, so it will be useful to expand our existing knowledge of touch perception to cover other body locations. In addition, there is currently no standardized metric for evaluating the output characteristics of haptic devices.

DISCLOSURE STATEMENT

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