Principles of haptic perception in virtual environments

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Introduction

During haptic interaction with *everyday environments, haptic perception relies on sensory signals arising from mechanical signals such as contact forces, torques, movement of objects and limbs, mass or weight of objects, stiffness of materials, geometry of objects, etc.* (Fig. 1a). In contrast, *haptic perception in Virtual Environments (VEs) relies on sensory signals arising from computer-controlled mechanical signals produced by haptic interfaces* (see Fig. 1b, the online animation [1] under Selected Readings and Websites, and [1, 2]). Haptic interfaces are programmable systems, which can reproduce mechanical signals that are normally experienced when haptically exploring real, everyday environments. Perhaps more importantly, haptic interfaces can create combinations of mechanical signals that *do not have* counterparts in real environments. This allows creating haptic VEs in which entirely new haptic sensory experiences are possible. As a result, it becomes feasible to investigate haptic perception and related phenomena, such as motor control, in entirely new ways. In this regard, interfaces do for haptic perception research what computer graphics does for human vision research. The importance of haptic technology extends beyond scientific research. This technology opens the door to new applications in a variety of fields.

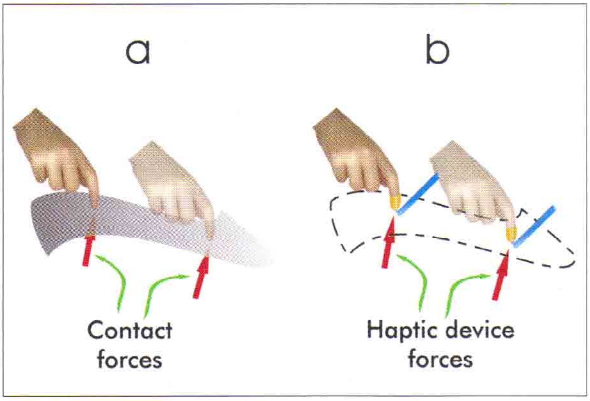

FIGURE 1.
(a) Haptic perception in everyday environments, *as when a perceiver explores a surface (the dark object here), involves mechanical variables such as contact forces, which arise from the physics of the haptic interaction scenario. (b) In contrast, haptic perception in* virtual environments *involves mechanical variables generated through haptic interfaces (here in blue, only part of the interface is pictured). Perceivers use haptic manipulandums (the golden, thimble-like part attached to the interface) to interact with interfaces. Under computer control, haptic interfaces produce mechanical variables (device forces) defining haptic virtual objects (the dashed surface). Note that during interaction with the virtual object, the perceiver's hand moves in an empty area of space.*

The main objective of this chapter is to discuss the essentials for effective use of haptic VEs in perception research and applications involving user testing. To illustrate this, the chapter also discusses some recent haptic perception discoveries in which haptic VEs played a key role. This chapter does not review the growing perception literature that uses haptic VEs. A full treatment of this literature would require an entire book of its own. Also, an important part of this literature can be consulted in several other chapters of this book. In this chapter, practitioners from fields such as neuroscience will find information to understand the similarities and differences between real and virtual haptic environments. Such practitioners will also find important information about designing and conducting perception experiments involving haptic VEs. This information would also benefit practitioners from areas such as engineering who are interested in haptic perception assessment in specific applications. The close interplay of basic research and engineering in haptic VEs has important implications for perception research and for haptic interface design. This is illustrated with examples of how haptic technology research contributes to our basic understanding of perception, and also of how perception research contributes to practical applications of haptic technology.

Haptic interaction, mechanical variables and haptic signals

Haptic perception relies on sensory signals arising from haptic interaction with a real or virtual environment. Haptic interaction involves mechanical (or haptic) variables such as forces, torques, masses, motions, stiffness of materials, etc. Note that mechanical variables arise from the environment, but also from the body of the person (i.e., the *perceiver*) that haptically interacts with the environment. For example, haptic interaction involves motion of limbs, as when actively moving a hand/arm when exploring a surface (Fig. 1a). When touching objects, contact forces between limbs and objects coexist with limb movement, as when lightly pressing down on a rigid surface while exploring it (Fig. 1a). In this example, mechanical variables involving the perceiver's body (hand/limb motion) are related to mechanical variables (contact forces) arising in part from mechanical characteristics of the environment (the surface's rigid material). This interplay between mechanical variables arising from environment and perceiver is an essential characteristic of haptic interaction, and has important roles in haptic perception. More generally, this interplay relates a perceiver's *actions* (such as precisely-controlled hand movements) to the *environment's reactions* (such as the motion of an object when pushed by a perceiver). Note that the interplay is bi-directional, as the environment's reactions may have an effect on subsequent actions by the perceiver. For example, when haptically exploring an object, the object may deform when squeezed or move when pushed. As a result, subsequent haptic exploration actions would need to be adjusted accordingly.

During haptic interaction, a given mechanical variable may or may not supply information that contributes to haptic perception. Throughout this chapter, a mechanical or haptic variable that supplies important information for haptic perception will be interchangeably called a *mechanical* or *haptic signal*. One or more mechanical variables or haptic signals define a *haptic stimulus*. A haptic environment consists of one or more haptic stimuli, which define the haptic properties of entities such as objects. A haptic object or environment is *virtual* if it is created through haptic technology. A haptic environment is *real* if it is not created through haptic technology. To further clarify important terminology, 'mechanical variable' and 'haptic variable' will be used interchangeably throughout.

The physics of haptic interaction and its importance in haptic perception

Haptic interaction is a process subject to the applicable laws of physics, such as those of dynamics [3]. This is because the laws of physics quantitatively describe the behaviour and characteristics of mechanical signals and variables present during haptic interaction. Physics describes haptic variables and signals in terms of mathematics. As haptic perception relies on haptic interaction, a thorough understanding of the relevant physics is essential to investigate how different mechanical signals contribute to haptic perception.

A full, quantitative characterisation of haptic interaction in terms of physics may become difficult in some cases, especially when many haptic signals/variables are simultaneously present. This may happen, for example, when haptic interaction involves multiple fingers, or when objects react to perceiver actions in complex ways. However, characterising haptic interaction in terms of physics allows identifying such complexities in detail and, more importantly, allows simplifying the haptic interaction scenario so it becomes tractable and remains meaningful for haptic perception experiments. As we will see, this is especially important for experiments using haptic technology, because *the physics of haptic interaction is a major basis for creating haptic VEs.*

Haptic virtual environments and perception research: the essentials

Haptic perception in real and virtual environments relies on the physical aspects of haptic interaction, but also on how the perceiver's nervous system processes information arising from interaction. However, in this chapter we will concentrate on factors directly related to mechanical variables and signals present during haptic interaction.

A full understanding of haptic perception requires controlling the haptic stimuli occurring during interaction with an environment. Typically, this involves systematically controlling and/or varying the haptic signals/variables that define the stimuli. For example, when investigating haptic perception of shape, important factors such as forces experienced when touching objects should be controlled and/or systematically varied.

This is a challenging task in general. Important mechanical signals/variables have been traditionally difficult to measure and control during haptic perception experiments. For example, contact force control during haptic exploration is possible to achieve in some cases (e.g. [4]), but has been difficult to obtain in general. As a result, many important aspects of haptic perception have remained barely explored until very recently.

Today, advances in haptic technology [1, 2, 5] allow exerting considerable control over important mechanical variables in haptic perception experiments. In this chapter, only the essentials of haptic technology will be discussed. This discussion will concentrate on the aspects of the technology that are of greater importance for perception research. For more information on haptic technology, consult the chapters by Bergamasco, Hayward and Hirzinger in this volume.

Haptic technology allows producing computer-controlled haptic signals/variables that a perceiver experiences through a variety of tools called manipulandums, which resemble thimbles (Figs 1b and 3b), pens (Fig. 2b), plates (Fig. 4), as well as joysticks, driving wheels, etc. [1]. To experience haptic variables, a perceiver wears or handles the manipulandums. Manipulandums are physically attached to computer-controlled mechanisms, which generate the haptic variables. Mechanisms and manipulandums are essential parts of a *haptic device* [1, 2]. The region of space in which a manipulandum can move is the haptic device's *workspace*. Note that the workspace is physically constrained by the device's mechanism. That is, the manipulandum can only move as far as the mechanism allows. Typical workspaces are three-dimensional, with volumes in the order of 100 cm^3 or larger.

Generally speaking, a haptic device can be classified as passive or active. Passive devices include those in which a perceiver applies energy to the device (for example, through applied forces and motions), and computer-controlled dissipation of this energy is provided by the device [1]. In contrast, *active devices* supply computer-controlled energy to perceivers, typically in the form of forces [1, 2]. The engineering of an active device includes the following basic components:

a) Actuators, such as electric motors, provide the energy needed to generate haptic signals such as forces. Actuators apply this energy to the device's mechanism and manipulandum.

b) Sensors, measuring the current state of the device, which typically includes the workspace position of the manipulandum and its orientation.
c) Power sources and electronics to drive the actuators and operate the sensors.
d) Electronics and control software enabling communication between the device and external control computer(s).
e) Software toolkits to control the device.

Software written with these toolkits runs on the external control computer, allowing real-time, programmable control of the device's haptic signals. This software implements *haptic rendering algorithms*. These algorithms precisely define the characteristics of haptic VEs and haptic *virtual objects* (VOs). Haptic rendering software is analogous to graphics rendering software. Together, haptic device hardware and software define a *haptic interface*. Virtual objects and environments created through haptic interfaces are 'virtual' because they are purely computational entities which are, so to speak, sculpted through the haptic device. Intuitively, this works as follows for isotonic, active haptic devices [1], in which the position of a manipulandum is sensed and used to compute programmable forces. Consider the case of a perceiver that uses a pen to poke into a flexible rubber surface (Fig. 2a). The physics of the contact between pen and surface involves several mechanical variables, among them contact forces and hand/pen displacements. When poking into the surface, the perceiver experiences the contact forces through the pen. The surface deforms when poked, and the perceiver's hand and pen are simultaneously displaced.

This real haptic interaction scenario can be reproduced through a haptic interface. For this, the perceiver holds a pen-like haptic manipulandum (Fig. 2b). The position of the manipulandum's tip is sensed in real-time (a thousand times *per second* or more) by the haptic device's sensor electronics. This positional information is sent to the external computer that controls the device. The positional information is monitored by the computer's haptic rendering software. When the perceiver moves the manipulandum's tip into the workspace location in which the haptic rendering software defines a virtual surface, the perceiver contacts the virtual surface and must experience adequate, simulated contact forces. The haptic rendering software computes these forces by using a *contact model* [5] (for example, a set of equations) of the mechanical interaction between, in this case, a pen and a *virtual rubber surface* (Fig. 2b, dashed surface). The rendering software then sends force control commands to the haptic device, and the device's actuators physically produce the computed contact forces. The perceiver experiences these forces through the manipulandum (Fig. 2b). When the manipulandum is withdrawn from the workspace zone in which the virtual surface is defined, the rendering software stops device forces. The perceiver no longer touches the virtual surface. Note that, excluding the manipulandum (and, indirectly, the device), the perceiver is not touching any physical object at all, but is only experiencing device forces. For an illustration of haptic rendering, watch the online animation [1] under Selected Readings and Websites at the end of the chapter.

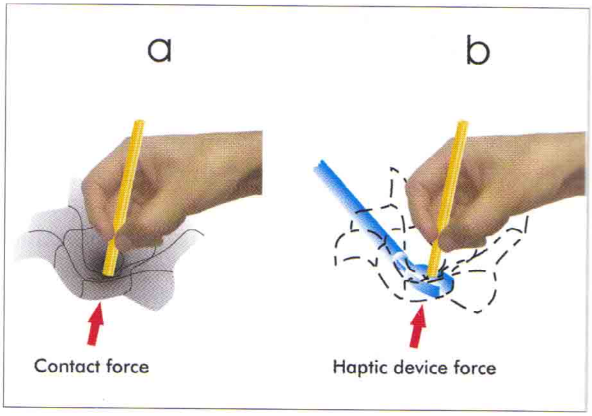

FIGURE 2.
A perceiver interacts with (a) real and (b) virtual deformable objects through a pen-like manipulandum. Both interaction scenarios involve similar mechanical variables, such as hand displacements and forces.

Isotonic haptic devices are currently the most common type of device. Other haptic devices, known as *isometric devices*, measure forces applied by a perceiver to produce manipulandum displacements [1]. Unless otherwise noted, in the rest of this chapter the term 'haptic device' will refer to isotonic devices, and 'haptic interface' will refer to interfaces that include isotonic devices.

The importance of haptic devices in perception research

From the point of view of perception research, perhaps the most important characteristic of haptic devices is their capability to generate programmable haptic variables and signals that relate to perceiver's actions. Four key reasons for the importance of this capability are:

i) It allows reproducing real-world haptic signals to create, for example, virtual versions of real objects.
ii) It allows to dynamically change the mechanical properties of VOs. This allows creating, for example, VOs that, on command, change their shape and/or physical size (e.g., growing or shrinking), or become stiffer or softer to the touch. Other possibilities include VOs that move around the workspace in experimenter-controlled ways, or multiple VOs that interact with one another and also with the perceiver.
iii) It allows creating VOs that *do not exist in nature*. For example, it is possible to create haptic interaction scenarios in which mechanical variables relate in normally impossible ways to perceiver actions.
iv) In principle, it allows relating perceiver actions to haptic signals in a quantitative manner. For example, computer-controlled haptic signals experienced by perceivers (as well as the movement of the haptic manipulandum under perceiver control), can be recorded in the external control computer for detailed analysis.

Such capabilities are probably impossible to achieve without haptic technology. These capabilities offer many opportunities for perception research, especially the capability to create normally impossible haptic objects/environments. Using these in perception research has allowed discovering new, important characteristics of haptic perception and, more generally, of brain function. An example of this will be discussed later in this chapter.

Haptic interface characteristics and their importance for perception experiments

Haptic interaction with real objects may or may not involve tools, while interaction with VOs nearly always involves tools (manipulandums) at the present time. Understanding the characteristics of these tools and related device engineering allows using them effectively for designing haptic perception experiments and other applications.

Haptic interaction in the real world is extremely rich in terms of the mechanical variables typically present. As a consequence, a haptic device that can reproduce all aspects of real haptic interaction is not feasible at the present time. Haptic devices can currently generate only certain haptic variables or signals, particularly forces. Haptic interface engineering largely defines the characteristics of the virtual haptic interaction scenarios that can be simulated. Some of these characteristics relate to device mechanics, actuators and/or sensors, some to rendering software, and some to both. Additional hardware and software may compensate for an interface's limitations, or expand interface capabilities, as we will see later in the chapter.

In what follows, a discussion of key aspects of haptic interface engineering will be presented. The discussion will highlight the importance of interface engineering in perception research and perceiver assessment. This discussion applies fully to isotonic haptic devices. However, excepting those issues related to contact force production, this discussion also applies to active devices in general.

Tools are used to interact with haptic virtual objects

Many human activities involve tool use. Handwriting is an example. However, many other activities are tool-free, and involve direct contact between skin and objects. Object palpation is an example of this. However, when using haptic interfaces to simulate activities that are normally tool-free, a manipulandum still needs to be used. This is because haptic variables created with interfaces need to be mechanically delivered to the perceiver through manipulandums. However, manipulandum use may have an effect on haptic perception. Much of the rich cutaneous information that is present in real-world haptic interaction is not available when exploring VOs through manipulandums. For example, when sliding a fingertip along the surface of a real object, there is substantial cutaneous information available to perceivers. This includes skin deformation and/or indentation related to surface features such as texture, shape and the surface's material properties (for example, surface stiffness). More generally, skin deformation is related to local stress fields arising from fingertip-surface mechanical interaction. Although pioneering research work to provide such cutaneous information is underway (e.g., [6]), analogous cutaneous information is generally not available when interacting with virtual surfaces through manipulandums. However, perceivers using manipulandums have access to cutaneous information arising from the mechanics of skin-manipulandum interaction. Depending on the manipulandum and the task at hand, this cutaneous information may approximate the cutaneous information available when using analogous tools to perform real-world tasks. For example, similar cutaneous information may be available when touching real objects with a pen (Fig. 2a), and when touching VOs with a pen-like manipulandum (Fig. 2b).

Normally present thermal information (such as that available when touching a cold steel surface) is also typically absent during interaction with VOs. Also, manipulandums have always some inertia and, typically, weight, which are not present in a real, tool-free haptic scenario. These manipulandum-related differences during interaction with real and virtual objects should be taken into account when using haptic technology in perception research. Experiments may systematically explore how these differences may affect perception in specific situations. However, note that manipulandum-related differences during interaction with real and virtual objects are not disadvantages *per se*. They also offer experimental opportunities. For example, simple manipulandums can be used to learn how perception is affected by loss of cutaneous cues. Then, more sophisticated interaction with VOs can be introduced, for example, by systematically using different manipulandums and/or devices providing computer-controlled cutaneous information, such as the one described in [6].

A fixed number of independently-actuated forces or torques are available for virtual object interaction

Many haptic devices generate only one computer-controlled force vector, typically with three Cartesian components. This force is applied at a single manipulandum location. This location typically defines also the manipulandum-VO contact point. In the example above, computer-controlled force is applied at the tip of the pen-like manipulandum (Fig. 2b). In addition to computer-controlled force, some devices also generate torques along different axes.

Real-world haptic interaction typically involves many independent, or nearly independent, forces acting together. For example, consider the case in which a perceiver grasps a small, rigid cylinder with the thumb and index finger (Fig. 3a). During interaction, different forces are applied to each finger. When simulating an analogous two-finger interaction with a VO, a common solution involves two haptic devices (Fig. 3b). Each device generates one independently-controlled force. For more complex virtual interaction scenarios, some multifinger haptic devices have been developed [1, 7].

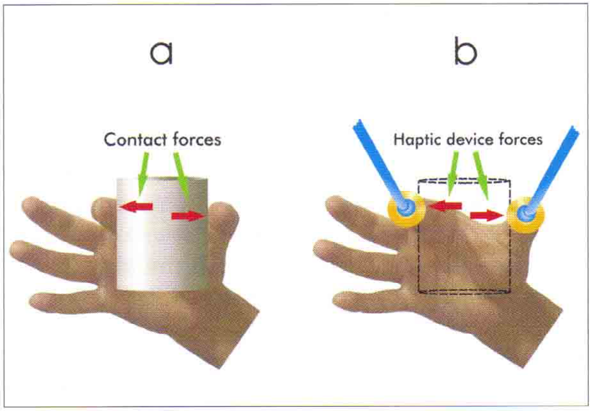

FIGURE 3.
A perceiver grasps a real cylinder (a) and a virtual one (b). In the real case, the perceiver experiences contact forces. The virtual cylinder is created with forces generated with two haptic devices (the blue machines in b); only part of the interfaces is pictured. Each device has its own manipulandum (the golden, thimble-like parts).

Haptic devices generate mechanical variables and signals with finite magnitudes

Isotonic haptic devices generate mechanical signals through actuators such as electric motors. The actuators transform one form of energy (e.g., electricity) into mechanical energy. This energy manifests itself as the device's mechanical signals (e.g., forces or torques). Actuators have a limited mechanical-energy output capability. As a result, only a finite range of, for example, force can be generated. Maximum forces vary from device to device. Typically, maximum forces are in the order of ten Newton, which is close to the weight of 1 litre (or quart) of water. As a consequence, VOs created with isotonic devices tend to feel somewhat soft, spongy. In contrast, isometric devices can produce rigid (highly stiff) VOs. However, it is difficult to use an isometric device to simulate touching an empty space. This is much simpler to do with isotonic devices, because they tend to feel very light when handled. Typically, perceivers can produce considerably more force than isotonic haptic devices. As a result, a perceiver can literally penetrate a haptic VO when applying enough force.

However, note that finite device forces are not a disadvantage *per se*. Perfectly rigid objects are idealisations. Many real objects may noticeably deform depending on the forces you apply during manipulation. Also, if rigid objects are needed for an experiment, haptic augmented reality setups may be used (see later in this chapter).

Haptic device forces vary in discrete steps

Typically, device forces are represented with a limited number of bits. As a result, forces vary in discrete steps. The magnitude of the smallest force step varies depending on the interface, but values in the order of 10 mN (or better) can be achieved [8].

Only selected aspects of haptic interaction are typically sensed through a haptic interface

Haptic interfaces have a limited number of sensors. During operation, interfaces typically sense the three-dimensional workspace position of one point on the manipulandum. Typically, the device applies forces to the manipulandum at this same location. Over time, changes in this point's position reflect actions performed by the perceiver. Depending on the interface, other aspects of interaction may be sensed. This may include the spatial orientation of the manipulandum, and/or the state of control buttons placed on the manipulandum. The resolution of sensed variables is finite, as they are represented with a limited number of bits. When sensing manipulandum position, resolutions in the order of 10 µm can be achieved [8], although common commercial devices have resolutions in the order of 40 µm [8]. This can be particularly important in applications requiring high spatial resolution, such as haptic texture rendering [8]. In addition to variables that are actually sensed, interfaces may also estimate other variables such as manipulandum velocity. Generally, such estimates should be used with caution due to potential variability. Haptic interface manipulandums can be specially made to add extra sensing capabilities, such as torque sensing. Possible perceptual consequences of such enhancements should be thoroughly evaluated. For example, the enhanced manipulandum may have substantially increased weight.

Haptic interaction with virtual objects involves a discrete number of events executed a high number of times *per second*

A digital movie displayed on a computer screen is not the same as a natural visual scene. However, both can be remarkably similar to the eye. Unlike the natural scene, the movie consists of a series of still images that are typically displayed tens of times *per second*.

Haptic interaction with VOs has analogous aspects. During typical operation, a haptic device reads the state of its sensors, and sends the readings to a computer. The computer uses the readings as inputs to a haptic rendering program, which in turn sends control commands back to the device to generate haptic signals such as forces. To create VOs, these sensing, communications and force-production events are executed repeatedly. These events constitute the *haptic rendering control cycle* (HRCC). The execution rate of this HRCC depends mainly on i) haptic rendering computational load, ii) the processing speed and resources of the computer that executes the rendering, iii) the communication latency between control computer and haptic device and, iv) the computational load from any other active tasks running on the control computer, including network and operating system overhead. Significant delays introduced at any of these elements will affect the HRCC execution rate.

The HRCC execution rate is clearly an important variable for perception experiments. In general, the HRCC is executed with a frequency of 1 kHz or faster. Slower execution rates result in substantial, easily noticeable delays between perceiver actions and device force production. This negatively impacts the perceived realism of many VOs. However, the perceived realism of VOs is a complex, multidimensional phenomenon that requires further research. An adequate HRCC execution rate depends on factors such as hand velocity during haptic interaction, the temporal and spatial response of the human haptic system to a variety of stimuli such as displacements and forces, the characteristics of specific VOs, as well as the tasks in which the objects are used (e.g. [8]). A good rule of thumb is to execute the HRCC as fast as possible. Depending on the haptic device and the computer hardware available, it is possible to execute the HRCC at 4 kHz or faster.

For haptic perception experiments, a high, constant, rock-solid HRCC execution rate is extremely desirable in general. Otherwise, VO quality could vary during experiments, with perceptual consequences that can be difficult to assess. This is a demanding, but achievable objective, particularly when using control computers with highly-customisable operating systems (OSs) such as Linux, or real-time OSs.

Note that some cycle variability may be unavoidable, and generally tolerable, during deployment of haptic technology in applications other than perception experiments. However, this depends on the application.

The events happening when touching real and virtual objects: similarities and differences

This discussion applies to VOs created with isotonic haptic devices. Although similar events occur when touching real or VOs, there are important differences which will be discussed here in more detail. For simplicity, this discussion will consider a perceiver that uses a single fingertip to interact with a real or VO. It will also be assumed that real or VOs do not move away when touched, although their surface may deform when touched. Real and VOs are assumed to be of a large size compared to the perceiver's fingertip. It is also assumed that objects' surfaces have texture features that are small when compared to the size of the fingertip's surface. First, the events occurring when touching a real object will be discussed. Then, the analogous events occurring when touching a VO will be presented, and the differences between the real and virtual cases will be highlighted. Note that the important events described here extend to more general situations involving interaction with multiple fingers, for example. Note also that the following discussion illustrates only the main factors involved in the relevant physics of interaction. Plain language is used instead of mathematics. This was done to make this material accessible to most readers. However, this discussion is not a substitute for a detailed analysis of the physics of a specific interaction scenario.

Events happening during interaction with real objects

i) Typically, prior to contact with the object, the perceiver's fingertip does not experience major external forces. Usually, external forces are restricted to the minimal air resistance that occurs when limbs are displaced. External forces may become significant during strong wind, when operating in a denser medium such as water, or in the presence of acceleration, as when travelling aboard aircraft. These cases will not be discussed here.

ii) In general, when a perceiver's fingertip touches an object, the perceiver actively applies forces ('perceiver-applied forces') to the object. Following the physics of the interaction, the object also applies contact forces ('object-related forces') back to the perceiver's fingertip.

Perceiver-applied forces originate mainly from perceiver's muscle contractions, and/or the mass and acceleration of perceiver's limbs. Also, due to elastic mechanical characteristics of fingertip skin and subcutaneous tissue, as well as those of tendons and muscles involved in finger, hand and arm control, some energy originating from object contact may be stored in these tissues. When released, this energy may contribute to perceiver-applied forces.

On the other hand, object-related forces depend on factors including the following ones:

a) The forces applied by the perceiver. Let us illustrate this with a special case in which a rigid object is slowly touched under nearly frictionless conditions. This is approximated, for example, when touching a large, slippery piece of ice. In this case, by Newton's Third Law, object-related contact forces are equal in magnitude to the forces applied by the perceiver when pushing down onto the object, but have the opposite direction. Note that perceiver-applied forces may vary over time: the perceiver may apply more or less force when pushing down onto the object. When this happens, as a consequence of Newton's Third Law, object-related contact forces are automatically adjusted. Object-related contact forces remains equal at all times to the forces with which the perceiver pushes down onto the object.
   In the special case discussed and in general, perceiver-applied and object-related contact forces may vary not only over time, but also spatially. That is, forces are applied at all the spatial locations in which a perceiver contacts objects during haptic interaction. Such spatial locations vary during interaction. This is important, because perceivers use stereotyped exploratory procedures involving different spatial patterns of hand movement [9]. As a result, different exploratory procedures may be associated with different spatial patterns of contact force.

b) The physical properties of the object's surface. For example, when touching a rigid object that has a rough surface, significant frictional forces will be typically present as a result.

c) The mechanical state of the object, particularly at the contact area. For example, if a rubber ball was previously touched, and its shape deformed as a consequence, mechanical energy was stored in the ball's material. This energy is released in part when the ball regains its former shape. If a perceiver touches the ball at this point, the ball's stored energy may contribute to the object-related contact forces experienced by the perceiver.

d) The mechanical properties of the perceiver's fingertip and body. For example, the fingertip may be lubricated, or the skin of the fingertip may be more or less rough. Both factors would influence frictional contact forces.

e) The mechanical interaction between the fingertip and the object. This includes all preceding factors, and also the relative movement between the object and the perceiver's fingertip. Frictional forces depend on this relative movement. Also, during movement, the total contact area between object and fingertip may vary. This would also change frictional forces.

Events happening during interaction with virtual objects

In a broad sense, touching VOs involves events that are digital (i.e., discrete) versions of events happening when touching real objects. Let us discuss them in detail.

i) Before contacting a VO, the perceiver may experience several mechanical effects resulting from haptic device characteristics. These effects may include damping, backlash and the inertia of the manipulandum [10]. Typically, there are also gravity effects related to the masses of different parts of the haptic device. Gravity effects are approximately compensated for through counterweights or software. Because of the potential impact on perceiver performance, the design of devices typically attempts to minimise these undesirable mechanical effects. However, as these effects depend on the specific interface, adequate technical information should be requested from the manufacturer.

ii) The mechanical effects in i) are still experienced during the following events. When a perceiver's fingertip touches a VO, the interface generates computer-controlled forces, which are experienced by the perceiver through the haptic manipulandum. Device forces define *virtual-object-related contact forces* (VOCFs), which in many cases are analogous to object-related forces experienced when touching real objects. The features of VOCFs are jointly determined by the engineering of the haptic interface, and by the haptic rendering software that the experimenter writes to control the interface. This means that, to a considerable extent, VOCFs can behave in whatever manner the experimenter finds useful for his/her purposes. This allows for a wide range of possibilities. Note that the haptic rendering software must precisely define *all* aspects of haptic interaction with the VO. This includes sensing manipulandum position to computationally detect when and where the perceiver contacts a VO (a process called *collision detection* [5]), and how the object will react to this contact. The software must also detect when the perceiver has ceased touching the object.

Let us examine further how haptic interface engineering contributes to similarities and differences in the events happening when touching virtual or real objects. Compare the following to the equivalent cases discussed above for real objects.

a) Typically, perceiver-applied force is not sensed during interaction with VOs. As a result, real-world relationships between perceiver-applied and object-related forces may be simplified when touching VOs. A typical strategy for this computes VOCFs from manipulandum position and a linear spring model [5]. This strategy may be reasonably applied in some situations. However, simulating rigid objects in this, or analogous ways, is problematic. For example, it is possible to increase the stiffness of the spring model to approximate a rigid object, but this would result in unstable device behaviour, which produces unwanted device vibration and audible noise [5]. This approach is also limited by the maximum force that the device can generate, which may be easily overcome by perceiver-applied forces.

Spring-model contact forces and related approaches are very useful in many applications, such as user interface design, for example. However, in perception experiments it may be necessary to use rigid objects. Note again that isometric haptic devices can simulate contact with rigid VOs [1].

b) When touching VOs, the mechanical properties of the perceiver's fingertip would not have, in general, the same interaction effects that they have when touching real objects. For example, when touching real objects, lubricating the fingertip results in reduced frictional forces. When operating a haptic interface, a lubricated fingertip will not result in reduced virtual friction forces. Note, however, that different states of fingertip lubrication could be systematically simulated through haptic rendering computations, but this would be a different experimental situation. In this case, the perceiver's fingertip would not be physically lubricated. Instead, the haptic rendering software would use a model of fingertip lubrication when computing VOCFs.

Using haptic technology in the design of perception experiments

As we have seen, haptic technology offers exciting capabilities for investigating haptic perception and interaction in general. This section will discuss specific issues related to designing and performing experiments using haptic technology. This discussion will not be exhaustive, but will attempt to present issues of wide applicability involving current and, hopefully, future developments in haptic technology.

Perceiver issues

Physical demands of experiments

As perceivers interact with a computer-controlled mechanical system during experiments, tests may tend to be physically demanding for perceivers. The experimenter should have this in mind when designing the experiments, and ensure that adequate rest breaks are periodically provided to perceivers to help minimise possible effects of fatigue. It is also desirable to limit the total duration of a testing session. This duration depends on the actual experiment but, from experience, a testing session lasting about an hour and a half is reasonable for experiments involving forces of about 1 Newton, with rest breaks after each 10–15 min of actual testing.

Perceiver safety during experiments

Haptic devices may accidentally hit perceivers if not handled properly. This could happen if a perceiver suddenly loosens his/her grip on the manipulandum while the haptic device is generating force. To avoid this, and before the experiment starts, perceivers must be carefully instructed not to loosen their grip on the manipuladum, except when told to do so by the experimenter, which will only happen in safe, tested conditions. Also, perceivers should be told not to hold the manipulandum too tightly. This would help avoid accidents and also minimise perceiver fatigue. Some interfaces will automatically turn off forces when the manipulandum moves above a certain velocity. It is necessary to ensure that such a safety mechanism is actually in place. Otherwise, it is necessary to program it into the haptic rendering software used in experiments. It is also advisable to physically locate the haptic interface at a safe distance from the perceiver's face. To further ensure perceiver safety, all experiments must be reviewed and approved by a supervisory ethics committee, and perceivers must provide informed consent in writing prior to testing.

Individual variations

There are wide individual variations in hand and finger sizes. As a result, haptic manipulandums may be more or less effectively used by some perceivers. For example, some perceivers may find it difficult to use some thimble-like manipulandums, as their fingertips may not fit or perhaps fit too loosely for effective manipulation. It may be necessary to find ways to adjust the manipulandum, and also to assess how this may affect experiments. The manufacturer of the device may offer special manipulandums to deal with this. It may be necessary also to adjust haptic interface force levels, so that perceivers with different physical strengths can perform the tests comfortably. Due to individual variations such as these, it is frequently useful to design within-subject tests for experiments.

The instructions given to perceivers and related, unwanted expectations

For successful experiments, it is critically important that perceivers receive substantially the same instructions about how to perform experimental tasks. For this, instructions should be carefully prepared prior to testing and, preferably, in writing. A full discussion of instructions is beyond the scope of the chapter, but there is some information that, in general, should not be provided to perceivers in the instructions, and which should also be avoided during perceiver recruitment. In particular, *perceivers should not be told that in the experiments they will manipulate or interact with virtual objects*. Perceivers provided with this information will have potentially undesirable expectations about the experiments, which may greatly affect their performance. For example, instead of concentrating on performing experimental tasks, some perceivers will think that some or all of the stimuli are *fake*, and try to guess which stimuli are the fake ones, or why they are fake.

It is also necessary, in general, to minimise other undesirable perceiver expectations. Such expectations can arise from allowing perceivers to visually inspect the experimental setup, including the haptic interface. As a result of this, most perceivers will understand that they will not interact with real objects, but with a machine that simulates objects. Ideally, perceivers should not be allowed to see the setup or haptic interface. This can be accomplished by using a screen or similar arrangement to block visual information. It is also important to avoid touch cues about the setup and haptic device. For example, perceivers may notice from touching the haptic manipulandum that they will not be exploring real objects. This can be avoided by using *haptic augmented reality* setups (see later in this chapter).

Other perceiver expectations or assumptions

Perceivers tend to assume that device forces reflect characteristics of VOs, instead of assuming other possibilities, such as force effects related to the mechanical properties of the manipulandum. For example, when experiencing spring-like device forces, perceivers tend to relate the forces to VO deformation. Perceivers generally do not assume that forces could result from touching a rigid VO with a springy manipulandum, for example. It is clear that many factors shape these assumptions, such as previous experience with real objects. Assumptions like these should be carefully considered by the experimenter when designing tests or analysing results, as assumptions may influence perceiver behaviour. Informally querying perceivers after testing may also help identify such assumptions. On the other hand, perceiver assumptions may be useful in areas such as perception-based haptic rendering, for example, as a potential source of ideas for new rendering methods. Perceiver assumptions may also suggest new phenomena in haptic perception and/or cognition, and in related areas.

Perceiver practice

Perceiver performance may be affected by unfamiliarity with the experimental setup. Providing enough practice trials prior to formal testing helps correct this.

Haptic interface issues

Many important interface issues have been discussed above. Here, some additional issues will be discussed. Strategies to deal with these and with previously discussed issues will be outlined.

Device noises

The level of mechanical noise present during normal device operation varies from device to device. It is necessary to ensure that perceivers do not receive unwanted experimental cues from these noises. Sometimes, screens used to block visual cues also help reduce noises. If this does not help, perceivers may wear earplugs or headsets delivering wide-band noise.

Device overheating

Device actuators such as motors may overheat, typically when using relatively high force levels during extended periods of time. Some devices include safety measures to help prevent permanent actuator damage from overheating. These measures, however, may interfere with experiments. For example, devices may include low-level software that shut them down automatically. To do this, instead of actually sensing actuator temperature, such software may estimate the energy that actuators dissipate as heat during operation, as well as estimating the time needed to cool actuators through device inactivity. As a result, physically cooling the actuators may not allow restarting device operation immediately. Simple solutions to avoid this include using lower levels of force, and avoiding situations in which large forces are continuously exerted during long periods of time. Rest breaks usually help achieve this. Generally, such problems may be easily found and solved during pilot tests. More drastic solutions may sometimes be needed, such as replacing device driving electronics [11].

Device limitations and strategies to deal with them

When evaluating the purchase of haptic devices/interfaces for experiments, up-to-date, detailed technical information should be requested from manufacturers, especially about those features that matter the most for the experiments at hand. More information may be gathered from colleagues, the literature or from online resources such as the Haptics-L mailing list and the International Society for Haptics (see [2, 3] in Selected Readings and Websites). Three important examples of device limitations will be mentioned here, with strategies to deal with them.

a) Variations in nominal resolution of manipulandum position sensing. Nominal resolution may vary in a significant, systematic way throughout the workspace [8]. Depending on the experiment, this may or may not be an issue. If this is an issue, experiments can be designed so that the manipulandum operates only in the workspace region in which resolution varies the least (typically, the centre of the workspace). If this is not feasible, then VOs should be presented in different parts of the workspace, so that overall, possible effects of nominal resolution variability are averaged out, or isolated during data analysis.
b) Nominal forces may systematically vary across the workspace. This can be due to actuator drive electronics [11], which can be corrected by replacing the electronics. Up-to-date information about this should be requested from device manufacturers.
c) Limitations when simulating the physics of real world haptic interaction. It is common to use simplified contact models when perceiver-applied forces are not sensed. An open issue is how such simplifications may affect haptic perception, as real and simplified virtual scenarios may be very different, physically and perceptually. Because of this, relating perception of VOs to perception of real objects may be difficult.

A possibility to deal with c) consists in using interfaces to create haptic VOs that coexist with real physical objects. By analogy with the equivalent case for visual displays [12], such setups might be called *Haptic Augmented Reality* (HAR) setups. HAR setups might be also called Haptic Mixed Reality setups. An example of a HAR setup is shown in Figure 4. This setup uses an isotonic device for investigating haptic perception of shape. Here, a perceiver interacts with a real, rigid object (Fig. 4). The rigid object is carefully designed and machined, so its geometrical features are known. The manipulandum has wheels, rolls on top of the rigid object, and is mechanically constrained so it always remains vertical to the object's surface, as shown in Figure 4. The manipulandum is always in contact with the object, and includes a sensor that measures the force that perceivers apply when lightly pushing down on the manipulandum's plate (this force is called the 'perceiver-applied normal force', Fig. 4). Following Newton's Third Law, this perceiver-applied force is balanced by a corresponding object-related force.

This HAR setup has several advantages: i) the physics of the interaction with the rigid object is very simple, which allows identifying the most important physical aspects of the interaction, and expressing them precisely and quantitatively; ii) this allows knowing which haptic variables to sense; iii) the setup allows selectively modifying real-world mechanical variables through the haptic interface; iv) this allows creating normally impossible, paradoxical combinations of real and virtual objects, and to use them to probe perception in new ways; v) the setup allows relating perception of real objects to that of VOs; vi) for experimental purposes, finite haptic interface forces can be used more effectively. Let us see how these advantages are achieved in the current HAR setup. From the physics of the interaction [13], it is found that, when exploring the real, rigid object in this setup, object-related lateral forces (along the horizontal direction of movement, Fig. 4), depend mainly on i) perceiver-applied normal force (Fig. 4) and ii) the local geometry of the real object (under the very low friction conditions used here). By design, this local geometry is always known. It is given by the precisely-machined surface of the real object. As the position of the manipulandum is sensed, it is always possible to recover the current local

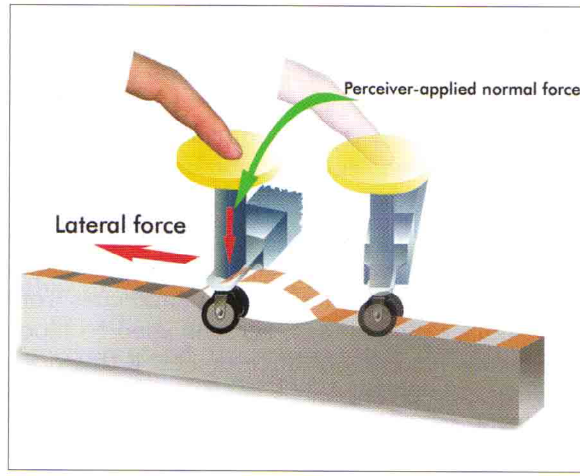

FIGURE 4.
A haptic augmented reality (HAR) setup, in which real and virtual objects coexist. A perceiver applies a normal force through his/her fingertip to hold the haptic manipulandum (golden plate) down. The perceiver rolls the attached haptic device (in blue, only part of the device is shown) on top of a real, rigid object (grey bar). Simultaneously, the haptic device generates net, computer-controlled lateral forces corresponding to a virtual bump (the red, dotted figure). This paradoxical, haptically augmented object combines the geometry of a hole (grey bar) with the lateral forces of a bump. This paradoxical object is typically perceived as a surface with a bump.

geometry in real-time. Perceiver-applied normal force (Fig. 4) is sensed in real-time also, so object-related lateral forces can always be known from the physics of the interaction and the sensed variables. As a result, haptic interface forces can be added in real-time to object-related lateral forces. The resulting net lateral force is experienced by perceivers through the manipulandum. When the haptic interface does not generate lateral force, perceivers experience only the object-related lateral forces arising from the natural interaction with the object. However, haptic interface forces can be designed so that a variety of different, paradoxical combinations of mechanical variables are achieved. For example, under haptic interface control, net lateral forces can correspond to those experienced when touching an object with a bump, even when the perceiver's hand moves along the surface of a real object with a physical hole (Fig. 4). More generally, in this way important lateral force cues can be decoupled from the geometry of real objects, and the perceptual contributions of each of these cues can be investigated separately, with surprising results. For example, the stimulus shown in Figure 4 is typically perceived as a surface with a bump. In this and other, paradoxical situations, shape perception depends on lateral force cues, and not, as previously thought, on geometrical cues such as fingertip trajectories during exploration. Such paradoxical objects are not experienced in the real world, and are probably impossible to generate without haptic interfaces or equivalent apparatus. These findings suggest that lateral force, under some conditions, is the effective stimulus for haptic shape perception. Alternatively, these findings suggest that lateral force elicits illusory haptic shapes [13, 14]. Research also suggests that these findings may apply to more general situations, for example, to elicit the perception of ascending a slope during locomotion on flat surfaces [15]. Overall, these findings indicate that lateral forces alone can elicit perception of shape. As a consequence, from the perceptual point of view, lateral forces as used here define haptic virtual objects. Therefore, this HAR setup uses real objects combined (or augmented) with lateral-force-based VOs [13]. Clearly, in addition to lateral-force VOs, other types of haptic VOs could be used in HAR setups.

Besides achieving paradoxical combinations of haptic signals, HAR setups allow overcoming other potential limitations of haptic interfaces. For example, finite haptic device forces result in VOs whose nominal boundaries can be penetrated when perceiver-applied force overcomes device forces. As a result, manipulandum trajectory under perceiver control may not accurately reflect the nominal geometry of VOs. When using HAR setups, these inaccuracies can be eliminated through the use of precisely-machined rigid objects. Also, perceivers' exposure to unwanted cues about the workings of the experimental setup can be eliminated when using HAR setups. In the example just discussed, perceivers can be thoroughly instructed about using the setup without their being aware of the haptic interface at all. This is generally difficult to do when using a haptic interface alone. Perceiver safety may also benefit from HAR setups. In the example discussed here, it is mechanically difficult that the haptic manipulandum accidentally contacts perceivers. *Finally, as HAR setups involve real and virtual objects, it is possible to investigate perception of a continuum of stimuli ranging from real objects to purely virtual ones* [13]. This allows relating perception of VOs to that of real objects, which is generally difficult to achieve otherwise.

In general, instead of using haptic interfaces to generate all the relevant mechanical variables in an experiment, interfaces can be used to selectively modify the variables present during interaction with real objects. This allows for better control of important experimental cues. In a sense, using real objects in HAR setups constrains the ways in which haptic interfaces are used. Therefore, it could be thought that HAR setups limit the applicability of haptic interfaces, for example, by severely constraining device workspace. This is not so. For example, a realistic, precise HAR setup can be used first to understand the perceptual contributions of important haptic signals. Then, this basic understanding can be used to design a purely virtual haptic environment (with no real objects involved, as in [17], for example), that approximates the features of the related HAR setup. This purely virtual environment can exploit to the full the capabilities of haptic interfaces, and can be used to test a variety of more complex situations. Perceiver performance in the HAR and purely virtual cases can be compared and further understood. For example, the HAR setup discussed above has been used as the basis to investigate the role of contact force in active and passive touch perception, in experiments involving only purely VOs that move across a

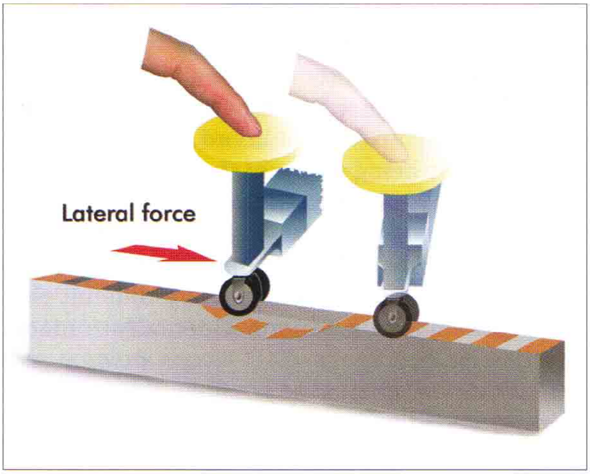

FIGURE 5.
A haptic augmented reality (HAR) setup in which a real, flat, rigid object (grey bar) is combined with net lateral forces generated through a haptic device (the blue machine, shown here only in part). The net lateral forces correspond to those of a virtual hole (the red, dotted figure). This geometrically flat, paradoxical haptic object is typically perceived as a surface with a hole.

workspace [16]. Such VOs allow controlling lateral forces during object exploration in passive and active touch situations, which is very difficult to achieve with real objects. These experiments with purely virtual objects are justified by, and rely on, results obtained with the HAR setup described above.

Extending interface capabilities through haptic perception: perception-based haptic rendering

As we have just seen, haptic perception of shape can be modified considerably through haptic device forces. In another example of this, when exploring a flat, rigid surface while simultaneously experiencing the lateral forces of a hole (Fig. 5), perceivers do not experience touching a flat surface, but one with a hole [13]. We can see that, as happens in other sensory modalities, greatly simplified stimuli can elicit compelling perception of complex objects. This has been found, for example, in haptic perception of shape [13, 14, 17, 18], and texture [19]. These findings contribute to understanding how haptic perception works, but also allow simplifying the technology needed to render haptic objects for different applications. For example, as lateral forces can elicit perception of shape when exploring flat surfaces, this means that lateral forces can *haptically render* virtual shapes, without the need to simultaneously provide perceivers with the geometrical information present in real objects. This can be achieved through devices with planar workspaces [13, 14], instead of using more complex devices with three-dimensional workspaces. This promising field, in which the properties of human perception are applied to haptic rendering, is frequently called *perception-based haptic rendering*.

Summary

Haptic VEs do for haptic perception research what computer graphics does for vision research. Haptic interaction with VEs allows investigating perception and related phenomena in totally new ways. This includes creating haptic objects that do not exist in the real world. The level of stimulus control provided by haptic VEs allows relating perception to mechanical signals in a quantitative way. This is difficult to achieve otherwise. The close interplay between haptic technology and perception research is a constant source of advances in both fields. Clearly, human perception research benefits greatly from haptic technology and, conversely, haptic technology benefits greatly from human perception research. Current and future advances in both fields offer potentially important opportunities for understanding haptic perception and related phenomena, as well as their underlying neural implementations (e.g., see [4–6] in Selected Readings and Websites). This can contribute much to highlight and understand the profound importance of these commonly underrated phenomena [20]. Haptic technology also offers considerable scientific and technological potential when used in combination with other technologies such as visual or auditory digital displays. This potential is largely untapped.

Acknowledgements

I thank Lorena Robles-De-La-Torre for preparing the figures, and Vincent Hayward for insightful comments.

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