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Chapter 9
Hand Haptic Perception

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Abstract Haptic perception encompasses tactile feedback and kinesthetic feedback. The haptic experience of touching an object by hand conveys information to the human about the object's material properties such as stiffness, texture, and weight and its shape properties such as size, orientation and curvature. In this chapter, we review how these properties are perceived through the sense of touch.

Keywords Tactile feedback · Kinesthetic feedback · Time-delayed haptic feedback · Object material properties · Object shape properties · Exploratory hand movements

1 Introduction

The sense of touch is the first sensory modality that develops and becomes functional in humans [1]. Touch feedback, which is also called haptic feedback, encompasses tactile (cutaneous) feedback relying on skin stimulation and kinesthetic (force) feedback involving muscle stimulation. For instance, in any haptics-based shape recognition task, active touch and contour following stimulate the kinaesthetic sense while passive pressure sensing is a form of tactile sense. Together, tactile feedback and kinaesthetic feedback influence the human's ability to distinguish objects.

The haptic experience of a human subject when touching an object includes sensations such as stiffness, texture, and weight. These sensations define the material properties of the object and our hands are adapted to best perceive them through touch and manipulation, surpassing vision in terms of discrimination

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accuracy. On the other hand, size, orientation and curvature define the shape (geometric) properties of an object and can be perceived by both touch and vision. Sections 2 and 3 discuss the haptic recognition of material properties and shape properties of an object, respectively.

Haptic exploration of an object is a task-dependent activity meaning that it necessitates highly-specialized exploratory hand movements for detecting various object properties. For instance, rubbing, pressing and lifting an object can provide information regarding object texture, stiffness and weight, respectively. In Sect. 4, we will contrast and compare such active haptics-based movements against passive stimulation of fingers in terms of detecting object material and shape properties.

2 Haptic Recognition of Object Material Properties

2.1 Stiffness

Different objects in our environment have different stiffnesses. The perception of object stiffness happens through evaluating the object deformation in response to a force applied on it by the hand (finger) or another object. While by touching a compliant object we can receive both the force and the deformation information required for stiffness discrimination, our vision can provide additional information concerning the deformation of the object. However, the utility of vision will be limited if critical movements of the task are orthogonal to the view or are occluded by the hand that is trying to sense the contact force. Moreover, vision cannot supply any information about the hand-object contact force. Thus, haptic interaction with an object is crucial to estimating its stiffness.

Srinivasan and LaMotte compared the ability of the human hand to discriminate the softness of objects when human subjects were given tactile information, kinesthetic information, or both [2]. The purpose was to isolate the components of haptic information that enables the human to make this discrimination. To do so, three experiments were performed: (a) active touch with the normal finger, (b) active touch under local cutaneous anesthesia of the finger, and (c) passive touch where the objects were brought in contact with the passive fingerpad of the subject using a mechanical device. Thus, in these experiments, the subjects received both tactile and kinesthetic feedback, only kinesthetic feedback, and only tactile feedback, respectively. Two types of specimens were used: (1) rubber-type objects with variable stiffnesses, and (2) rigid objects supported by springs of various stiffnesses (called spring cells). These specimens were chosen to represent compliant objects with deformable and with rigid surfaces, respectively. In the experiments, it was seen that the subjects demonstrated very good softness discriminability for the rubber objects in the active touch experiments, while they showed poorer discriminability for the compliance of spring cells. Another result was that to discriminate pairs of rubber objects, tactile information alone was sufficient but kinesthetic information alone was not. Nonetheless, for discriminating pairs of spring cells, tactile information alone was not sufficient and both tactile and kinesthetic information were necessary. Such a difference in the sufficiency of tactile information for successful stiffness discrimination can be traced to the mechanics of contact of the fingerpad, which affect tactile information, as explained in the following: As a subject indents an object, the compressive contact force applied by the fingerpad on the object increases, causing the fingerpad to deform. Only in the case of objects with deformable surfaces, the resulting deformation of the fingerpad depends on the object stiffness. This explains why tactile information alone is not sufficient for discriminating pairs of spring cells, which have rigid surfaces.

A human operator may try to perform stiffness discrimination using a teleoperated robot and through a haptic user interface that both controls the robot and displays the robot-object contact forces to the operator in the form of haptic (force) feedback. Since such a haptic telemanipulation system engages the operator's sense of touch, one would expect similar task performance as in direct touch. An interesting issue arises from the presence of a non-negligible time delay in the communication media between the user interface and the teleoperated robot, which happens in long-distance teleoperation. While the usefulness of haptic feedback in no-delay teleoperation has been established, e.g., in [3] and [4], the loss of temporal coincidence between the human operator's motions and the ensuing reflected forces in delayed teleoperation may confuse the operator so much so that the force feedback becomes useless or even misleading. To assess the value of providing haptic feedback to the user during delayed teleoperation, researchers have studied the effect of delay on the human's perception of the relative stiffness of virtual spring-like surfaces simulated by reflecting forces proportional to the user's virtual surface indentations. Subjected to a forced-choice paradigm (i.e., distinguish the stiffer of the two surfaces or identify them as having the same stiffness), users perceived the surfaces to be stiffer than actual under delayed force feedback and the stiffness overestimation increased for larger delays [5, 6]. The effect of crossing the boundary of a force field, where local stiffness is ill-defined, on the perception of delayed stiffness has also been studied [7]; note that stiffness is the local derivative of the force field. It has been found that subjects interacting with delayed force fields underestimate (overestimate) stiffness if they do not move (do move) across the boundary of the elastic field.

2.2 Texture

As a human draws a finger across the surface of an object, he/she receives information not only regarding the shape properties of the object, but also about the texture of the surface. Perception of texture is a multidimensional experience that encompasses roughness as its most prominent aspect. There are, however, other aspects of texture of a surface besides its roughness. Hollins et al. performed experiments to examine the dimensionality of surface texture perception [8]. In the experiments, 17 tactile stimuli were moved across the index fingers of the subjects in a direction perpendicular to its surface with constant speed. Out of the 17 stimuli, seven were thin or flexible materials such as wax paper, cardboard, smooth plastic or sand paper that were mounted on blocks of wood. Other stimuli were the surfaces of rigid objects such as a rubber eraser, Styrofoam, brick, or leather wallet. The stimuli presented to the subjects did not have any curvature and a random noise source masked out the faint sounds of contact between the finger and the stimuli. After each test, a subject was asked to sort the presented object into several categories on the basis of perceived similarity. Using multidimensional scaling methods and the data collected from the subjects, the study showed that subjects' judgments of surface texture can be represented in a perceptual space. Subjects' ratings of each stimulus fit into two (and possibly three) dimensions. The two robust and orthogonal dimensions were found to be roughness-smoothness and hardness-softness, and the third less robust dimension was judged to be compressional elasticity (springiness) of the surface—see Fig. 1. The warm-cold and sticky-slippery scales were not found to be independent of those for roughness and hardness. The study concluded that it is unlikely to have fewer than three dimensions in the perceptual space for texture.

Later, Picard et al. also investigated the perceptual dimensions of tactile stimuli [9]. Unlike Hollins et al. whose study involved passive stimulation of a static finger, Picard et al. allowed active exploration of objects by a dynamic finger. In the experiments, subjects were asked to use a lateral motion procedure to sort 24 car seat materials with different tactile properties on the basis of perceived similarity (free-sorting task). Their analysis showed that the tactile texture space did not exceed four dimensions: soft/harsh, thin/thick, relief, and hardness. While the first two dimensions may be qualified as separable, the last two dimensions were found to be related to the soft/harsh dimension. The hardness dimension was found to be close to the soft/harsh dimension as the two dimensions use similar exploratory hand movements to seek substance information about objects. This study did not identify roughness as a perceptual dimension although it is semantically close to harsh.

The roughness percept is generally believed to reflect the separation between raised elements that form the textured surface. For the underlying neural representations of roughness, readers are referred to [9]. Klatzky and Lederman studied the perception of roughness when a rigid structure was placed between the skin and the textured surface [10]. Subjects made roughness judgments through a stick-like probe held in the fingertips or a rigid fiberglass sheath mounted on the fingertip. Task performance under these rigid structures was compared to that with the bare finger (i.e., direct contact). A result of this study was that although discrimination was best with the finger, the rigid structures led to greater perceived roughness for the smoothest stimuli. The two experimental conditions in the above study (contact with a rigid structure versus direct touch) were different in the vibratory coding of roughness by the rigid structure. Vibration is highly important when a human operator uses a teleoperation system to explore a surface. For instance, the user needs to receive critical vibratory information associated with making contact with a rigid surface for teleoperation realism. The study by Klatzky and Lederman supports the use of vibro-tactile cues to display roughness when direct skin contact with an environment is not possible.

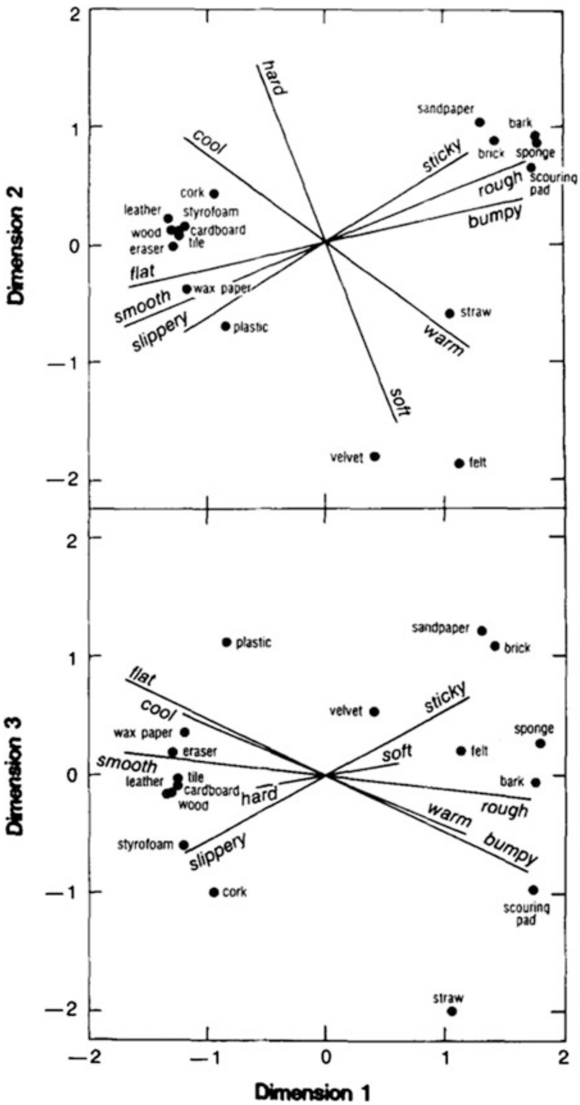

Fig. 1 Three-dimensional space viewed along the third dimension (*top*) and the second dimension (*bottom*) [8]

2.3 Weight

Ernst H. Weber (1795–1878) performed experiments that measured the sensitivity of the human hand in weight perception, which is limited in nature, and studied whether weight perception was more due to the tactile feedback resulting from holding an object or the kinesthetic feedback resulting from lifting an object. Subjects were made to lift different weights and asked if they could detect a difference between the two. Searching for the smallest perceivable difference—the "just-noticeable difference"—a 1 to 40 ratio between a standard weight and a different weight was found to be noticeable when subjects lifted weights (i.e., invoking both tactile and kinesthetic feedback). However, when the weights were rested on a subject's skin (i.e., providing tactile feedback only), the just-noticeable difference became a ratio of 1 to 30. This simply means that using both tactile and kinesthetic information results in more sensitivity to small weight differences.

Efficient manipulation of an object requires its accurate weight information, which as shown by Weber first requires manipulation (lifting) of the object. A practical solution to this paradox lies in using our past experience about object properties such as its size. Larger objects tend to weigh more (not considering environments such as under water or outer space). As such, research has shown that the size of an object influences the perceived weight of the object—this is referred to as size-weight illusion. As a result of the size-weight illusion, different sized objects of the same mass are perceived to have different masses. Ellis and Lederman conducted experiments to assess the extent to which haptic cues (physical weight) and visual cues (size/volume) about an object influence weight perception [11]. In a first set of experiments called haptics + vision experiments, subjects could see an object while picking it up to evaluate its heaviness. In a second set of experiments called haptics-only experiments, blindfolded subjects were asked to haptically estimate the weight of objects. Haptic cues alone were found necessary and sufficient to generate a size-weight illusion that has almost the same strength as that generated under both haptic and vision cues. In fact, as seen in Fig. 2, for objects of the same physical weight (904, 350, or 140 g), the perceived weight decreased as the volume increased under both haptics + vision and

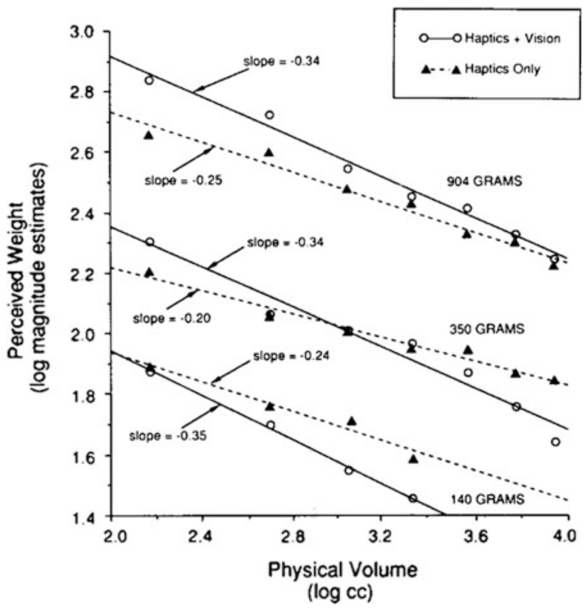

Fig. 2 Mean magnitude estimates of weight versus the physical volume for each modality [11]

haptics-only modalities. Such a strong size-weight illusion produced in the haptics-only condition showed that vision is not a necessary condition for this illusion to exist. The size-weight illusion is a primarily haptic phenomenon rather than a case of vision influencing haptic processing. The size-weight relationship can be used, for instance, in a robotic setting for lifting objects of unknown masses by finding an initial estimate of the object weight based on the size information obtained from the grasp action.

Later, Ellis and Lederman showed that weight perception is more broadly affected by a subject's expectation based on knowledge and past experience [12]. In experiments, golfers and non-golfers were presented with real and practice golf balls that had been tampered with to have different weights. It was found that golfers, who expect a weight difference between ball types, judged practice balls to weigh more than real golf balls of the same weight. On the other hand, non-golfers, who expect no weight difference between ball types, judged practice and real balls of equal weight to weigh the same.

3 Haptic Recognition of Object Shape Properties

3.1 Size

Humans can evaluate the size of an object using both vision and touch. They demonstrate a well-known tendency to overestimate the length of a vertical line compared to a horizontal line of the same length—this is referred to as the vertical-horizontal illusion and is very robust in vision [13]. The vertical-horizontal illusion has also been reported in the haptic modality in both blindfolded sighted and blind subjects [14], meaning that subjects overestimate vertical extents and underestimate horizontal extents when trying to judge sizes based on touch. As shown by Suzuki and Arashida, the vertical segment of an inverted T is perceived to be 1.2 times longer than the horizontal segment when using touch to judge the size [15]. Interestingly, the horizontal segment will be overestimated when the inverted-T figure is rotated by 90°, meaning that the segment that is divided into two parts (i.e., the horizontal segment in the inverted T and the vertical segment in the rotated inverted T) is underestimated [16]. The extent of the vertical-horizontal illusion in touch has been shown to depend on the object tracing motions made by the hand and the size and orientation of the explored object. For instance, Gentaz and Hatwell found an increase in the length overestimation with the inverted T when subjects used the index finger of the dominant hand to explore the object instead of free exploration by both hands [14].

Heller et al. studied whether the haptic horizontal-vertical illusion in the case of 2-D forms would generalize to 3-D objects [17]. They experimented with objects that had round or square bases and dowel rods projecting above them at heights equal to the widths of the horizontal bases—see Fig. 3. It was found that with free

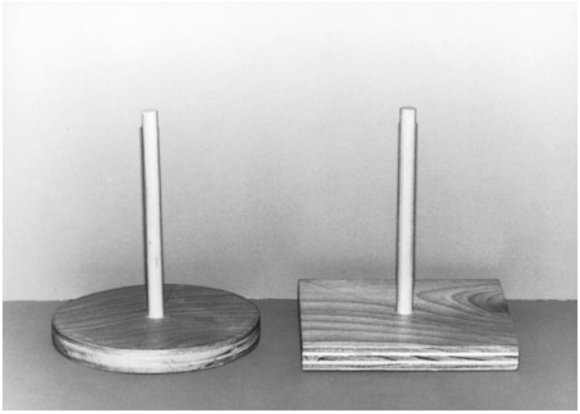

Fig. 3 3D objects with *round* and *square* bases and dowel rods projecting above them in [17]

haptic exploration to judge the size, the horizontals were overestimated by the subjects. This is referred to as negative illusion because it is contrary to the vertical-horizontal illusion.

3.2 Orientation

Proper spatial orientation of objects enables human subjects to recognize them through the sense of touch. In general, upright shapes are more easily recognizable than tilted shapes. Orientation is of particular importance in alphabet recognition, a prime example of which is reading Braille characters across the page from left to right based on the sense of touch. If a subject's hand is tilted, recognizing upright Braille characters becomes difficult [18]. Similarly, rotating the Braille characters can cause the reader to misinterpret the letters and words because of the misalignment between the finger and the characters [19]. Past research has shown a relationship between the orientation of the Braille page and the recognizability of Braille characters. Heller et al. measured the performance of both congenitally blind and blindfolded sighted individuals in reading non-rotated and rotated (by 180°) Braille letters [20]. While all subjects did worse on the 180° rotated Braille page, the blind subjects had less difficulty compared to the sighted subjects in terms of recognizing the rotated letters. Also, Ungar et al. found that while rotated Braille letters and words reduced the speed and accuracy of Braille recognition, experienced Braille readers could adjust to rotated characters in the presence of a context such as a set of words that are all in the same line [19]. Thus, for the highest speed and accuracy of character recognition through the sense of touch, Braille needs to be presented horizontally.

3.3 Curvature

Shape perception in 3D often happens through a combination of vision and haptics. The curvature of an object at any point on its surface is the reciprocal of the radius of curvature at that point. Similar to the overestimation of linear extents discussed in Sect. 3.1, Heller et al. have shown a haptic vertical-horizontal illusion in perception of convex curves [21]. Kappers et al. performed experiments to study the active haptic identification of 3D objects represented by quadric surfaces [22]. Each object was defined by a quantity describing its shape ("shape index") and a quantity describing its overall curvature ("curvedness")—see Fig. 4. In the experiments, both the shape index and curvedness were found to significantly impact the haptic shape identification. In fact, when the curvedness of test surfaces were kept constant, concave surfaces (negative shape index) led to a larger variation in the subjects' shape recognition response than convex ones (positive shape index). Also, it was found that surfaces with a high curvedness were identified more easily than those with a low curvedness. Further experiments with constant and with random curvedness yielded identical results (i.e., not knowing the curvedness had no influence on the subjects' response about the shape index), meaning that curvedness and shape index are not confounded from a psychophysical perspective.

4 Active Haptic Exploration Versus Passive Stimulation

To arrive at a basic understanding of how humans perceive objects, psychologist James Gibson carried out experiments using cookie cutters of different shapes such as square, star, etc. [23]. First, in a set of passive stimulation experiments, the

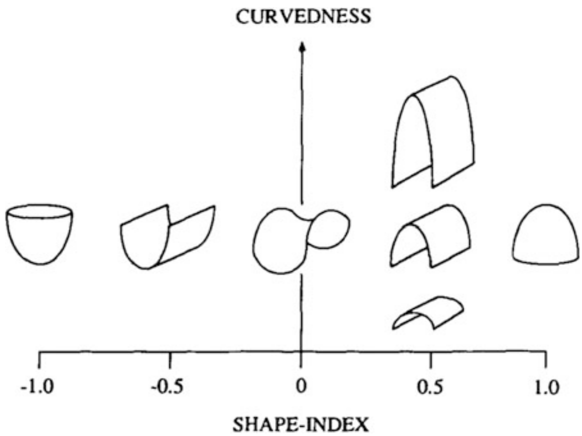

Fig. 4 The shape index can indicate a *concave spherical paraboloid* (−1), a *concave cylinder* (−0.5), a *hyperbolic paraboloid* (0), a *convex cylinder* (0.5), or a *convex spherical paraboloid* (1). The curvedness can range from a flat surface (0) to an extremely curved surface (infinity) [22]

cutters were pressed on the palm of a still hand of a blindfolded subject. Next, in a set of active exploration experiments, the subject was allowed to feel the cutter by his/her finger. The rate of correct identification of the shape of objects rose from 29 to 95 % from the passive stimulation to the active exploration conditions. This means that object shape perception is much more accurate when fingers are used to actively explore the object as the subject will receive feedback both from the fingers (cutaneous feedback) and from the arm and hand muscles (kinesthetic feedback). For further details on the advantages of active touch, the reader can refer to [24].

Lederman and Klatzky showed that in active exploration of objects, various subjects systematically performed appropriate hand movements (called exploratory procedures) depending on the task at hand [25]. The purpose of their experiments was to find links between desired knowledge about objects and the exploratory movements performed by subjects. After classifying the procedures for each task, they found that in free exploration a procedure is used that is necessary, sufficient, and optimal for the given task. Their experiments found several consistently applied associations between task and procedure including identifying object texture through lateral motion, identifying object hardness by applying pressure, identifying object temperature through static contact, identifying object weight by unsupported holding, identifying object global shape and volume through enclosure by fingers, and identifying object exact shape by following the object contours—see Fig. 5.

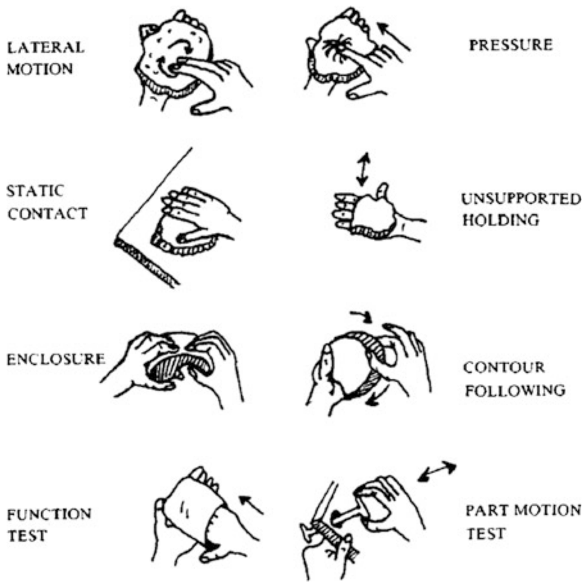

Fig. 5 Exploratory procedures (EPs) and associated property(ies) that each EP is optimal at providing. Adapted from [25] with permission of the authors

5 Concluding Remarks

In this chapter, we considered how an object's material properties such as stiffness, texture and weight are perceived through the sense of touch. For shape properties, we considered the effects of object size, orientation and curvature on object recognition. Finally, we briefly compared the effects of passive stimulation of fingers versus active movements of finger on the human's ability to detect object material and shape properties. The interested reader is also referred to [24] for additional studies.

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