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Haptic Interfaces

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1. INTRODUCTION

Haptics is concerned with information acquisition and object manipulation through touch. Haptics is used as an umbrella term covering all aspects of manual exploration and manipulation by humans and machines, as well as interactions between the two, performed in real, virtual, or teleoperated environments. Haptic interfaces allow users to touch, feel, and manipulate objects simulated by virtual environments (VEs) and teleoperator systems (Salisbury & Srinivasan, 1992). The keyboard, mouse, and trackball are familiar, passive, haptic interfaces that sense a user's hand movements. Although they apply forces on the user's hand upon contact and consequently provide tactual sensation, the forces are not under program control. Active haptic interfaces, such as desktop robots and exoskeletal gloves with force feedback, are more sophisticated devices that have both sensors and actuators. In addition to transducing position and motion commands from the user, these devices can present controlled forces to the user, allowing him or her to feel virtual objects as well as control them. This chapter focuses on such devices.

This is an exciting time for the field of haptics. Within approximately 10 years of significant research activity, commercial efforts have brought simple, active haptic interfaces into mass production. Research efforts on a range of more sophisticated devices have intensified. The success of these endeavors depends on finding application tasks where haptics adds significant value and, from a design viewpoint, on achieving an optimal balance between the human haptic ability to sense object properties, fidelity of the interface device in delivering the appropriate mechanical signals, and computational complexity in rendering the signals in real time. Accordingly, this chapter discusses the usefulness of haptic displays in virtual environments (section 2), the human haptic system (section 3), and current interface hardware (section 4). Algorithms for estimating and rendering force feedback are covered in chapter 6 of this volume. VE-assisted teleoperation is treated specifically in chapter 48 of this volume.

Locomotion interfaces, which may actively display forces to the user, are covered in chapter 11 of this volume. Previous overviews of this field can be found in Burdea (1996), Srinivasan (1995), Youngblut, Johnson, Nash, Wienclaw, and Will (1996), and Srinivasan and Basdogan (1997).

2. ADVANTAGES OF ACTIVE HAPTIC INTERFACES

The gap between performance in the world and in a simulation is familiar to most computer users. In the real world, the placement, orientation, and scaling of a rectangle can be indicated in one quick gesture using the thumb and index fingers of both hands, and a rubber band to mark the perimeter. In a simulation (e.g., MacDraw) the same process must be performed in three steps using a mouse, requiring about 10 times longer (Fitzmaurice, Balakrishnan, Kurtenbach, & Buxton, 1999). A similar gap exists in VEs, both in terms of physical realism and task performance. For example, the phrase *virtual reality* typically conjures an image of a user with one passive VR glove that senses joint angles of a few fingers and position/orientation of the hand, through which the user can convey his or her intentions to the computer. However, in tasks such as surgical simulation or virtual sculpting, the glove would be inadequate. Two-way communication between the user and the computer enabled by force feedback would be absolutely necessary in order to simulate the "feel" of the organs or the clay as they are manipulated. In contrast to vision and hearing, haptics is the only modality that permits this bidirectional information transfer between the user and virtual environment. Current excitement in developing haptic interfaces arises from applications like these, and others like those listed below (from Srinivasan & Basdogan, 1997):

- *Medicine:* surgical simulators for medical training; manipulating micro and macro robots for minimally invasive surgery; remote diagnosis for telemedicine; aids for the disabled such as haptic interfaces for blind users (see chaps. 47–51, this volume).
- *Entertainment:* video games and simulators that enable the user to feel and manipulate virtual solids, fluids, tools, and avatars (see chap. 55, this volume).
- *Education:* giving students the feel of phenomena at nano, macro, or astronomical scales; "what if" scenarios for nonterrestrial physics; experiencing complex data sets (see chaps. 45–46, this volume).
- *Industry:* integration of haptics into CAD systems such that a designer can freely manipulate the mechanical components of an assembly in an immersive environment (see chaps. 52–54, this volume).
- *Graphic Arts:* virtual art exhibits, concert rooms, and museums in which the user can login remotely to play the musical instruments, and to touch and feel the haptic attributes of the displays; individual or cooperative virtual sculpting across the Internet.

The need for active haptic interfaces clearly depends on the task at hand, and can be classified as follows:

1. Active haptic interfaces are absolutely required for some tasks: Many medical procedures (for example, administering epidural anesthesia, palpating for cancerous lumps) are intrinsically haptic tasks. Haptic displays are required to simulate such tasks for training, because sensing of forces arising from tool-tissue interaction is critical for success. Another intrinsically haptic VE task is testing the ease of manual assembly of complex mechanisms before they are manufactured (Nahvi, Nelson, Hollerbach, & Johnson, 1998). In addition, active haptic

interfaces make VEs accessible to visually impaired users. Current VEs are almost entirely visual, therefore inaccessible to the roughly 0.75 million visually impaired users in the United States. The United States Congress has called for "every-citizen interfaces to the country's information infrastructure" (National Research Council, 1997). As VEs become more common in education and industry, it will be interesting to see whether the Americans with Disabilities Act is extended from the real environment to include virtual worlds.

2. Active haptic interfaces can improve a user's sense of presence: Haptic interfaces with 2 or fewer actuated degrees of freedom are now mass-produced for playing PC video games, making them relatively cheap (about $100 at the time of this writing), reliable, and easy to program. Although the complexity of the cues they can display is limited, they are surprisingly effective communicators. For example, if the joystick is vibrated when a player crosses a bridge (to simulate driving over planks) it can provide a landmark for navigation, and signal the vehicle's speed (vibration frequency) and weight (vibration amplitude). Haptic cues have also been developed to augment graphical user interfaces to windows operating systems, both Microsoft Windows (Immersion, 2000) and Linux/Unix (Miller & Zeleznik, 1999). Free source code for haptic effects for desktops and games are available. Most manufacturers of general-purpose, active interfaces also sell haptic authoring software. A few examples are the Ghost Toolkit for the Phantom (SensAble Technologies, 2000), Immersion Studio for the FeelIt mouse (Immersion, 2000), and the VirtualHand Studio for the CyberGrasp force feedback glove (Virtual Technologies, Inc., 2000). Just one haptic interaction (for example, handling a real plate in a VE) can significantly improve a user's expectations about the solidity and weight of all objects in a VE (Hoffman, 1998).

3. Active haptic interfaces can improve performance by providing natural constraints: In VEs, selecting and repositioning objects without haptic cues can be surprisingly difficult. Without force feedback, a user trying to set a simulated coffee mug down on a simulated table top is likely to merely push the mug through it. To overcome these difficulties, force-free interaction metaphors have been developed. For a review see Mine, Brooks, and Sequin (1997). The names of these metaphors generally suggest how they work (e.g., "extender grab," "spring widget," "virtual chopsticks"). Although these methods appear adequate for many tasks, they usually demand more visual attention than the same action would in the real world. A haptic interface is a more straightforward solution that may reduce the visual attention required of the user. Force feedback also can improve accuracy and rate of spatial input. For example, during a virtual a pick-and-place task force feedback cut positioning errors in half while speeding performance by about 20% (Noma, Miyasato, & Kishino, 1996).

4. Active haptic interfaces can reduce "information clutter": Unlike speakers and video monitors, haptic displays don't generally clutter a user's environment with unnecessary information. A good example of this property is a pager set to vibrate rather than beep. This haptic display provides only the right message ("You have a page"), to the right person (the owner), at the right time. This specificity is likely to become more important as embedded processors make more real-world objects intelligent and active. The same considerations suggest that haptic displays may reduce information clutter in VEs of increasing complexity.

3. HUMAN HAPTIC SYSTEM

In the real world, whenever an individual touches an object, forces are imposed on the skin. The net forces as well as the posture and motion of various limb segments are conveyed to the brain as *kinesthetic* information (the term *proprioceptive* is approximately equivalent; see endnote 2 in chap. 7, this volume), conveyed by multiple sources such as receptors in the joints, tendons, and muscles. This is the means by which the coarse properties of objects, such as large shapes and springlike compliances that require hand or arm motion in probing them, are sensed. In addition, the spatial and temporal variations of the force distributions within the contact region on the skin are conveyed as *tactile* information by several types of receptors embedded in the skin. Fine texture, small shapes, softness, and slipping of surfaces are felt through the tactile sensors. The temperature of the skin, which, in turn, is related to the temperature and thermal properties of the object, is also sensed through specialized tactile sensors.

In addition to the tactile and kinesthetic sensory subsystems, the human haptic system consists of the motor system that enables active exploration or manipulation of the environment and a cognitive system that can link sensations to perception and action. In general, a tactual image is composed of both tactile and kinesthetic sensory information, and is controlled by motor commands based on the user's intention. Because of the large number of degrees of freedom, multiplicity of the subsystems, spatially distributed heterogeneous sensory receptors, and the sensorimotor nature of haptic tasks, the human haptic abilities and limitations that prescribe the design specifications of haptic interfaces are difficult to quantify.

Haptic interfaces in VE or teleoperation systems receive the intended motor-action commands from the human and display tactual images to the human. A successful haptic interface represents a good match between the human haptic system and hardware for sensing and display. The primary input–output variables of the interfaces are displacements and forces, including their spatial and temporal distributions. Haptic interfaces can therefore be viewed as generators of mechanical impedances that represent a relationship between forces and displacements (and their derivatives) over different locations and orientations on the skin surface at each instant of time. In contact tasks involving finite impedances, either displacement or force can be viewed as the control variable, and the other is a display variable, depending on the control algorithms employed. However, consistency among free-hand motions and contact tasks is best achieved by viewing the position and motion of the hand as the control variable, and the resulting net force vector and its distribution within the contact regions as the display variables.

Because the human user is sensing and controlling the position and force variables of the haptic interface, the performance specifications of the interface are directly dependent on human abilities. In a substantial number of simple tasks involving active touch, one of the tactile and kinesthetic information classes is fundamental for discrimination or identification, whereas the other is supplementary. For example, in the discrimination of length of rigid objects held in a pinch grasp between the thumb and the forefinger (Durlach, Delhorne, Wong, Rabinowitz, & Holherbach, 1989), kinesthetic information is fundamental, whereas tactile information is supplementary. In such tasks, sensing and control of variables such as fingertip displacements are crucial. In contrast, for the detection of surface texture or slip, tactile information is fundamental, whereas kinesthetic information is supplementary (Srinivasan, Whitehouse, & LaMotte, 1990). Here, the sensing of spatiotemporal force distribution within the contact region provides the basis for inferences concerning contact conditions and object properties. Both classes of information are clearly necessary and equally important in more complex haptic tasks.

Detailed reviews of the human haptic system are available, focusing on position sense (Clark & Horch, 1986), skin sensitivity (Sherrick & Cholewiak, 1986), and perception (Loomis & Lederman, 1986). In this section a brief overview focused on issues relevant to haptic interfaces is provided. Sections 3.1 and 3.2 are excerpted from Srinivasan (1995) and summarize briefly the psychophysical results available on human haptic abilities in real environments at two levels: (1) sensing and control of interface variables and (2) perception of contact conditions and object properties. These results are also gathered in tables in the Appendix of this chapter. Although humans can feel heat, itch, pain, and so forth, through sensory nerve endings in the skin, these sensations are not discussed here because the availability of practical interface devices employing them is unlikely in the near future. This section concludes by emphasizing some features of the human haptic system that can provide guidance for haptic interface design (see section 3.3).

3.1 Sensing and Control of Interface Variables

3.1.1 Limb Position and Motion

A large variety of psychophysical experiments have been conducted concerning the perception of limb position and motion (Clark & Horch, 1986; Jones & Hunter, 1992). It has been found that humans can detect joint rotations of a fraction of a degree performed over a time interval of the order of a second. The bandwidth of the kinesthetic sensing system has been estimated to be 20 to 30 Hz (Brooks, 1990). It is generally accepted that human sensitivity to rotations of proximal joints is higher than that of more distal joints. The just noticeable difference (JND) is about 2.5 degrees for the finger joints, 2 degrees for the wrist and elbow, and about 0.8 degrees for the shoulder (Tan, Srinivasan, Eberman, & Cheng, 1994). In locating a target position by pointing a finger, the speed, direction, and magnitude of movement, as well as the locus of the target, can all affect accuracy. In the discrimination of length of objects by the finger-span method (Durlach et al., 1989; Tan, Pang, & Durlach, 1992), the JND is about 1 mm for a reference length of 10 mm, and increases to 2 to 4 mm for a reference length of 80 mm, thus violating Weber's law (i.e., JND is not proportional to the reference length). In the kinesthetic space, psychophysical phenomena such as anisotropies in the perception of distance and orientation, apparent curvature of straight lines, non-Euclidean distance measures between two points, and others have been reported. For reviews, see Fasse, Kay, and Hogan (1990), Hogan, Kay, Fasse, and Mussa-Ivaldi (1990), and Loomis and Lederman (1986).

Investigations of the human ability in controlling limb motions have typically measured human tracking performance with manipulanda having various mass, spring, and damping characteristics (Brooks, 1990; Jones & Hunter, 1992; Poulton, 1974; Sheridan, 1992). The differential thresholds for position and movement have been measured to be about 8% (Jones & Hunter, 1992). Human bandwidth for limb motions is found to be a function of the mode of operation: 1 to 2 Hz for unexpected signals; 2 to 5 Hz for periodic signals; up to 5 Hz for internally generated or learned trajectories; and about 10 Hz for reflex actions. For a review see Brooks (1990).

3.1.2 Net Forces of Contact

When a person contacts or presses objects through active motion of the hand, the contact forces are sensed by both the tactile and kinesthetic sensory systems. Overall contact force is probably the single most important variable that determines both the neural signals in the sensory system, as well as the control of contact conditions through motor action. It appears that the JND for contact force is 5% to 15% of the reference force value over a wide range of conditions involving substantial variation in force magnitude, muscle system, and experimental method, provided that the kinesthetic sense is involved in the discrimination task (Jones, 1989; Pang, Tan, & Durlach, 1991; Tan et al., 1992). In closely related experiments exploring human ability to distinguish among objects of different weights, a slightly higher JND of about 10% has been observed. For reviews see Clark and Horch (1986) and Jones (1986). An interesting illusion first observed in the late 19th century by Weber and reviewed more recently (Sherrick & Cholewiak, 1986) is that cold objects feel heavier than warm ones of equal weight. In experiments involving grasping and lifting of objects using a two-finger pinch grasp (Johansson & Westling, 1984) it has been shown that individuals have exquisite control over maintaining the proper ratio between grasping and lifting forces (i.e., the orientation of the contact force vector) so that the objects do not slip. However, when tactile information was blocked using local anesthesia, this ability deteriorated significantly because individuals could not sense contact conditions such as the occurrence of slip and hence did not apply appropriate compensating grasp forces. Thus, good performance in tasks involving contact requires the sensing of appropriate forces, as well as using them to control contact conditions. The maximum controllable force that can be exerted by a finger pad is about 100 N, and the resolution in visually tracking constant forces is about 0.04 N or 1%, whichever is higher (Srinivasan & Chen, 1993; Tan, Srinivasan, Eberman, & Cheng, 1994).

3.2 Perception of Contact Conditions and Object Properties

Although humans experience a large variety of tactile sensations when touching objects, these sensations are really combinations of a few building blocks or primitives. For simplicity, normal indentation, lateral skin stretch, relative tangential motion, and vibration are the primitives for conditions of contact with an object. Surface microtexture, shape (mm size), and compliance can be thought of as the primitives for the majority of object properties perceived by touch. The human perception of many of these primitives is through tactile information conveyed by mechanoreceptors in the skin.

Considerable research effort has been invested on psychophysics of vibration perception and electrocutaneous stimulation using single or multiple probes. For a review see Sherrick and Cholewiak (1986). These studies are mostly directed at issues concerned with tactile communication aids for individuals who are blind, deaf, or deaf and blind, areas that are beyond the scope of this chapter. A comprehensive list of references describing such tactile displays can be found in Kaczmarek and Bach-y-Rita (1993) and Reed, Durlach, and Braida (1982). In designing these devices, human perceptual abilities in both temporal and spatial domains are of interest. The human threshold for the detection of vibration of a single probe is about 28 dB (relative to 1 μm peak) for 0.4 to 3 Hz. It decreases at the rate of -5 dB/octave for 3 to 30 Hz, and decreases further at the rate of -12 dB/octave for 30 to about 250 Hz, after which the threshold increases for higher frequencies (Bolanowski, Gescheider, Verrillo, & Checkosky, 1988; Rabinowitz, Houtsma, Durlach, & Delhorne, 1987). Spatial resolution on the finger pad, as measured by the localization threshold of a point stimulus, is about 0.15 mm (Loomis, 1979), whereas the two-point limen is about 1 mm (Johnson & Phillips, 1981).

To answer questions concerning perception and neural coding of roughness or spatial resolution, precisely shaped rigid surfaces consisting of mm-sized bar gratings (Lederman & Taylor, 1972; Morley, Goodwin, & Darian-Smith, 1983; Phillips & Johnson, 1981a, 1981b; Sathian, Goodwin, John, & Darian-Smith, 1989), embossed letters (Phillips, Johnson, & Browne, 1983; Phillips, Johnson, & Hsiao, 1988), or Braille dots (Darian-Smith, Davidson, & Johnson, 1980; Lamb, 1983a, 1983b) have been used in psychophysical and neurophysiological experiments. For a review see Johnson and Hsiao (1992). The perception of surface roughness of gratings is found to be solely due to the tactile sense and is dependent on groove width, contact force, and temperature but not scanning velocity (Loomis & Lederman, 1986). Some of the salient results on the perception of slip, microtexture, shape, compliance, and viscosity are given below. Humans can detect the presence of a 2 μm high single dot on a smooth glass plate stroked on the skin, based on the responses of Meissner-type rapidly adapting fibers (RAs; LaMotte & Whitehouse, 1986; Srinivasan, Whitehouse, & LaMotte, 1990). Moreover, humans can detect a 0.075 μm high grating on the plate, owing to the response of Pacinian corpuscle fibers (LaMotte & Srinivasan, 1991). Among all the possible representations of the shapes of objects, the surface curvature distribution seems to be the most relevant for tactile sensing (LaMotte & Srinivasan, 1993; Srinivasan & LaMotte, 1991). Human discriminability of compliance of objects depends on whether the object has a deformable or rigid surface (Srinivasan & LaMotte, 1995). When the surface is deformable, the spatial pressure distribution within the contact region is dependent on object compliance, and hence information from cutaneous mechanoreceptors is sufficient for discrimination of subtle differences in compliance. When the surface is rigid, kinesthetic information is necessary for discrimination, and the discriminability is much poorer than that for objects with deformable surfaces. For deformable objects with rigid surfaces held in a pinch grasp, the JND for compliance is about 5% to 15% when the displacement range is fixed, increases to 22% when it is roved (varied randomly), and can be as high as 99% when cues arising out of mechanical work done are eliminated (Tan et al., 1992; Tan, Durlach, Shao, & Wei, 1993). Using a contralateral-limb matching procedure involving the forearm, it has been found (Jones & Hunter, 1992) that the differential thresholds for stiffness and viscosity are 23% and 34%, respectively. It has been found that a stiffness of at least 25 N/mm is needed for an object to be perceived as rigid by human observers (Tan et al., 1994). See the tables in the Appendix for a summary of these results.

3.3 Aspects of the Human Haptic System That Have Special Relevance to VE Hardware

A few aspects of the human haptic system that pertain to the design of haptic interface hardware deserve special attention. The following points are addressed:

1. A haptic precision gradient suggests that interface hardware deployed at distal body segments (e.g., fingertips) provides more benefit than interface hardware deployed proximally (e.g., shoulder).
2. A perceptual emphasis on transient stimuli suggests that users may tolerate considerable drift errors in haptic display hardware.
3. The human tendency to move the preferred hand with respect to the nonpreferred hand (rather than the world) suggests that two-handed interfaces offer significant advantages over one-handed.
4. The wide range of information transfer rates for different methods of manual communication suggests the importance of developing efficient "haptic languages" for interaction with virtual environments.

3.3.1 Distal to Proximal Gradient in Precision

Given the importance of the fingertips for manipulation, it is reasonable to use them as a reference for describing more proximal body segments. Viewed this way, one finds a consistent gradient in performance, such that the skin and segments closer to the fingertip can be sensed and controlled more precisely than those closer to the trunk. This trend holds for detecting indentation of the skin and fingertip displacement, resolving position targets and rate of information transfer.

Gradient in tactile resolution: On the distal half of the fingertip humans can sense slow indentations of about 20 microns, sense vibrations (~250 Hz) of about 0.1 microns, distinguish separate points until they are within about 1 mm, and sense translations as small as 0.15 mm. At more proximal points on the limbs and trunk, sensitivity in all of these categories is poorer. For example, on the upper arm, vibration amplitude must be about 10 times larger to be detected, and slowly applied forces must be about 2 times larger. This distal to proximal gradient generally holds, but the tongue and lips are a notable exception. See Sherrick and Cholewiak (1986) for a review.

Gradient in detecting movement: A similar precision gradient is observed in detecting fingertip displacement. See Clark and Horch (1986) for a review. If the fingertip is moved passively at the speed humans normally use for pointing, then a displacement of about 0.3 mm can be detected if movement is constrained to the distal finger joint. If the movement is constrained to the elbow joint, detection requires about twice as much fingertip displacement (0.6 mm), and at the shoulder, twice as much again (1.2 mm; Hall & McCloskey, 1983). Thus, in terms of linear displacement of the fingertip, the distal segments again show higher sensitivity.

Gradient in resolving position targets: If participants are asked to discriminate or reproduce fingertip locations, they can typically distinguish about three targets when movement is constrained to 70 degrees of flexion of the middle joint of the index finger (Clark, Larwood, Davis, & Deffenbacher, 1995). This makes each target about 25 mm wide (one third of the corresponding range of fingertip displacement). Although participants can distinguish more targets over the angular range of motion of the more proximal joints, this precision does not compensate for the increased displacement of the fingertip these joints permit. Thus, flexion of the most proximal index finger joint allows participants to resolve fingertip targets about 40 mm wide, the wrist about 70 mm, the elbow about 100 mm, and the shoulder about 80 mm (Clark et al., 1995). Again, more distal segments generally show higher precision.

Gradient in pointing speed: If participants actively point with the limb, they can specify about 4.2 to 4.5 bit/sec using the finger joints with a tool held in a pen grasp (Balakrishnan & MacKenzie, 1997). If movement is constrained to a more proximal joint (wrist abduction), the rate decreases by about 30%, to about 4 bit/sec. Other studies report the same trend with far steeper gradients. An extreme example is Langolf (1976), in which they report 38 bit/sec with fingers only, 23 bit/sec with wrist and fingers, and 10 bit/sec with shoulder and elbow. The neck is estimated to provide only about 4 bit/sec (Card, Mackinlay, & Robertson, 1991). One suspects that this gradient is due to the increasing rotary inertia of limbs as the axis of rotation is shifted proximally, and also due to the fact that the human body seems to have more precise sensing and control hardware deployed at the distal body segments. In this case, more distal segments show higher rates of information transfer.

Implications for haptic interfaces: Since the bandwidth of human motor performance typically limits bandwidth of haptic input devices (Card et al., 1991), these results suggest that interfaces that sense finger movement may allow users to perform more quickly than they can with interfaces that only sense movement of the palm or arm. Human-computer interaction (HCI) developers have had mixed success with attempts to speed spatial input by including the fingers (Balakrishnan & MacKenzie, 1997; Zhai, Milgram, & Buxton, 1996).

A second consequence of the haptic precision gradient is that the quality of simulations is not degraded unduly when forces that ought to be grounded in the world are grounded on more proximal segments of the body. (See section 3.3.2 for a more detailed explanation of force grounding). CyberGrasp illustrates this body-grounded approach. This device renders forces on the fingertips that mimic what a user would experience handling objects in the real world. However, forces are grounded on the back of the hand, so the device fails to render appropriate torques about the wrist, elbow, or shoulder joints. Still, it provides a satisfactory haptic simulation, probably because it addresses the distal body segments (fingers), where the haptic system has greatest sensitivity. Experiments (Richard & Cutkosky, 1997) show that just rendering fingertip forces (i.e., grounding force on the middle phalanx) provides cues that lead participants to stop at virtual walls with penetration depths comparable to those achieved by world-grounded haptic interfaces that display appropriate torques around all joints.

3.3.2 *Perceptual Importance of Change*

Broadly speaking, haptic sensors in skin and muscle perform like systems of second order or higher. That is, the response of the sensor depends on both rate and magnitude of stimulus. Perhaps because haptic input emphasizes higher time derivatives, the precision of human haptic output also depends strongly on time. Over short intervals (< 1 sec), fine displacements can be sensed and controlled. However, over longer intervals (1 sec to 1 min) the haptic system alone does not generally notice or correct for substantial position errors (> 1 cm of fingertip displacement; Clark & Horch, 1986).

This emphasis on higher time derivatives is also apparent in the difference between the small, rapid displacements of a passive limb that can just be detected, and the 10- to 100-fold larger errors in actively reproducing pose of the same limb. The shoulder joint illustrates the trend. Here a fingertip displacement of about 1.2 mm can be detected (Hall & McCloskey, 1983), but for participants to reproduce target positions reliably with the shoulder, the targets at the fingertip must be about 70 times wider (80 mm; Clark, Larwood, Davis, & Deffenbacher, 1995).

Implications for haptic interfaces: This laxity in absolute position sensing may offer the haptic interface designer some leverage. For example, many active interfaces can probably be recentered at 1 to 10 mm/sec (up to a few centimeters) without attracting a user's attention or degrading the quality of the interaction. This could help compensate for the limited workspace of many devices.

3.3.3 *Bimanual Frame of Reference*

Humans naturally perform many manual tasks by setting a frame of reference with the nonpreferred hand (e.g., positioning a piece of paper) and then operating the preferred hand in this frame (e.g., writing on the paper; Guiard, 1987). This preference also affects the precision of a user's performance with haptic interfaces. For positioning tasks, errors of the preferred hand are typically about twofold smaller relative to the nonpreferred hand (~ 50 mm) than they are relative to the world (~ 100 mm; Mine, Brooks, & Sequin, 1997). It is not yet clear how much of this improvement is simply due to subtracting out sway of the torso and how much is due to the participant's experience with this sort of manipulation in the real world. Regardless of the source of improvement, the effect is robust. Participants can perform spatial input in about half as much time (Hinckley, Pausch, & Proffitt, 1997) when the preferred hand operates in the frame of the nonpreferred hand. These results suggest that two-handed interfaces offer about a two-fold improvement in speed and accuracy.

3.3.4 *Factors That Determine Rates of Information Transfer*

Coordination of movement: Since inertia of the limbs limits the rate of motor production to less than 5 Hz, and the precision of motor output typically limits information transfer to a few bits per joint, rapid information transfer depends on coordination of multiple joints. Work thus far (Zhai & Milgram, 1998) has shown that humans performing a one-handed 6 degree-of-freedom (DOF) docking task tend to set position of a grasped object first (simultaneously adjusting 3 DOF), and then specify orientation separately (simultaneously setting 3 more DOF). In these experiments, the haptic interface paradigm (position versus force input to the computer) did not have much effect on this basic division of labor. However, these efforts have provided some useful tools for haptic interface development—generic techniques for measuring how well humans can specify different kinematic parameters simultaneously. Advances in HCI require finding these kinematic parameters, and developing hardware that can transduce them.

Codes for information transfer: When a motor activity is more complicated than just pointing, the code used to transmit information has a large effect. The same fingers that are used to send Morse code at about 3 bit/sec can be used to type at about 14 bit/sec, transmitting information about 2,000-fold faster. See Appendix for information transfer rates for different modes of manual communication. Coding is comparably important for manual reception of information. Advances in HCI require finding rich codes for haptic input and output that users can learn quickly and easily.

4. CURRENT HARDWARE

In performing tasks with a haptic interface, the human user conveys desired motor actions by physically manipulating the interface, which, in turn, displays tactual sensory information to the user by appropriately stimulating his or her tactile and kinesthetic sensory systems. Thus, in general, haptic interfaces can be viewed as having two basic functions: (1) to measure the positions and contact forces (and time derivatives) of the user's hand (or other body parts) and (2) to display contact forces and positions (or their spatial and temporal distributions) to the user. Among these position (or kinematic) and contact force variables, the choice of which ones are the motor action variables (i.e., inputs to the computer) and which are the sensory display variables (i.e., inputs to the human) depends on the hardware and software design as well as the tasks for which the interface is employed. Typically, the user's hand position is sensed by the interface and contact forces computed by rendering algorithms are displayed to the user.

A primary classification of haptic interactions with real environments or VEs that affects interface design can be summarized as follows: (1) free motion, in which no physical contact is made with objects in the environment; (2) contact involving unbalanced resultant forces, such as pressing an object with a finger pad; (3) contact involving self-equilibrating forces, such as squeezing an object in a pinch grasp. Depending on the tasks for which a haptic interface is designed, some or all of these elements will have to be adequately simulated by the interface. For example, grasping and moving an object from one location to another involves all three elements. The design constraints of a haptic interface are strongly dependent on which of these elements it needs to simulate. Consequently, the interfaces can be classified according to whether they are force-reflecting or not, as well as by what types of motions (e.g., how many degrees of freedom) and contact forces they are capable of simulating.

An alternative but important distinction in haptic interactions with real environments or VEs is whether an object is touched, felt, and manipulated directly or with a tool. Which of these two types of interactions is supposed to be simulated seriously affects the complexity in the design of a haptic interface. Note that an ideal interface, designed to provide realistic simulation of direct haptic exploration and manipulation of objects, would be able to simulate handling with a tool as well. Such an interface would measure the position and posture of the user's hand, display forces to the hand, and make use of a single hardware configuration (e.g., an exoskeleton with force and tactile feedback) that could be adapted to different tasks by changes in software alone. For example, displaying forces on the fingers and palm when they were in proper position for grasping a hammer would simulate wielding this tool. However, the large number of degrees of freedom of the hand, extreme sensitivities of cutaneous receptors, together with the presence of mass, friction, and limitations of sensors and actuators in the interface make such an ideal impossible to achieve with current technology. In contrast, an interface in the form of a tool handle, for which reconfigurability within a limited task domain is achieved through both hardware and software changes, is quite feasible. Thus, one of the basic distinctions among haptic interfaces is whether they attempt to approximate the ideal exoskeleton or employ the tool-handle approach.

Another distinction concerning haptic interfaces has to do with whether the device "grounds" forces on the body or on the world. A "body grounded" device, such as a hand exoskeleton, is capable of simulating some forces (e.g., the resistance of a tennis ball to squeezing with the thumb and forefinger), but cannot simulate all forces (e.g., the torque about the user's shoulder due to the weight of the ball). In principle, a "world grounded" device, such as a desktop robot could simulate both types of forces, but is generally not portable. User performance with the two types of force grounding have been compared for some tasks (Richard & Cutkosky, 1997) and found roughly equivalent.

4.1 Current Technology

Compared to audio (see chap. 4, this volume) and video (see chap. 3, this volume) hardware, haptic interface hardware for VEs is in an early stage of development. Many of the devices available today have been motivated by needs predating those of VE technology. Simple position/motion-measuring systems have long been employed to provide control inputs to the computer. These have taken many forms, such as those that involve contact with the user without controlled force display (e.g., keyboards, computer mice, trackballs, joysticks, passive exoskeletal devices) and those that measure position/motion without contact (e.g., optical and electromagnetic tracking devices). Applications motivating development of these devices have ranged from the control of equipment (e.g., instruments, vehicles) to biomechanical study of human motion (e.g., gait analysis, time and motion studies).

The early developments in force-displaying haptic interfaces were driven by the needs of the nuclear energy industry and others for remote manipulation of materials (Sheridan, 1992). The force-reflecting teleoperator master arms in these applications were designed to communicate to the operator information about physically real tasks. The recognition of the need for good-quality force displays by early researchers (Goertz, 1964; Hill, 1979) continues to be relevant to today's VE applications. However, the dual challenges of making free motion feel unimpeded but making virtual surfaces feel stiff requires hardware with low friction, low apparent inertia, and very high bandwidth. Although Sutherland's (1965) pioneering description of VEs included force-reflecting interfaces, development of practical devices has proven difficult.

A wide variety of devices are under development in companies and universities worldwide. A rough breakdown of major types of haptic interfaces that are currently available or being developed is as follows:

1. Ground-based devices
    - Joysticks, mice, steering wheels, flight yokes
    - Tool-based (pen or instrument)
2. Body-based devices
    - Flexible (gloves and suits worn by user)
    - Exoskeletal (jointed linkages affixed to user)
3. Tactile displays

4.1.1 *Ground-Based Devices*

Joysticks are probably the oldest of these technologies and were originally conceived to control aircraft. Even the earliest of control sticks, connected by mechanical wires to the flight surfaces of aircraft, unwittingly presented force information about loads on flight surfaces to pilots. In general, these devices may be passive (i.e., not force reflecting), as in joysticks used for cursor positioning, or active (i.e., force reflecting), as in many of today's modern flight-control sticks. Many ground-based devices are now commercially available:

1. Force-reflecting joysticks are now commercially available in a wide range of prices and capabilities. Low-cost devices ($100–$1,000) with 2 actuated DOF are targeted primarily toward video games (Microsoft Sidewinder, Immersion Impulse Stick, I-Force). Devices with more DOF are produced in smaller quantities, generally have higher precision, and cost more ($1,000–$10,000). Joysticks with 3 actuated DOF include the Immersion Impulse Engine 3000 and Cybernet PER-Force 3DOF. More dof are available in the Cybernet PER-Force Handcontroller (6 DOF). Force-reflecting mice with 2 actuated DOF are also commercially available at low cost (e.g., Immersion FeelIt mouse, about $100). The video-game industry has also led to mass production of steering wheels with 1 actuated DOF, and flight yokes with 2 actuated DOF.
2. Pen-based force-reflecting interfaces are now mass-produced for general-purpose work. The Phantom (from SensAble Technologies) is a popular commercial desktop interface that comes in a variety of sizes, with either 3 or 6 actuated DOF. At the time of this writing, units are in the price range of about ($13,500–$61,000).
3. Force-reflecting surgery simulators are also in mass production. The Immersion Laparoscopic Impulse Engine drives the tips of surgical tools to simulate laparoscopic procedures. It offers 3 actuated DOF (5 sensed) for about $9,000. The Freedom-7 (with 7 actuated DOF) appears to be near market. Dedicated telesurgery systems (e.g., the Intuitive Surgical daVinci system) incorporate multiple hand-masters with 4 to 7 DOF per hand, but full force-feedback has not yet been implemented. The current price range is about three quarters to a million dollars.

These devices represent the commercial fruition of decades of research on teleoperation hand masters. For reviews of this field see Jacobus, Riggs, Jacobus, and Weinstein (1992), Meyer, H. L. Applewhite, and Biocca (1992), Brooks (1990), McAffee and Fiorini (1991), Honeywell, Inc. (1989), and Okamura, Smaby, and Cutkosky (2000). For reviews of the ergonometrics of hand controllers (shape, switch placement, motion and force characteristics, etc.) see Brooks and Bejczy (1985). For a review of actuator technologies see Hollerbach, Hunter, and Ballantyne (1992) and chapter 11 (this volume).

Notable applications of force-reflecting hand controllers to VEs include project GROPE at the University of North Carolina (Brooks, Ouh-Young, & Batter, 1990). In this simulator, the Argonne Mechanical Arm (ARM), and more recently the Phantom, were used successfully for force reflection during interactions with simulations of molecule docking. Haptic interactions with data from a scanning tunneling microscope have also been simulated (Taylor, 1994). The MIT Sandpaper is a 3-DOF joystick that is capable of displaying virtual textures (Minsky, Ouh-Young, Steele, Brooks, & Behensky, 1990). In Japan, notable desktop master manipulators have been built at Tsukuba University (Iwata, 1990; Noma & Iwata, 1993), ATR Laboratories in Kyoto (Noma et al., 1996), and Tokyo Institute of Technology (Walairacht, Koike, & Sato, 2000). At the University of British Columbia, high-performance hand controllers have been developed by taking advantage of magnetic levitation technology (Salcudean, Wong, & Hollis, 1992). At McGill University, the 2-DOF Pantograph has been developed for desktop applications, and the Freedom 7 has been developed for surgical simulation (Hayward, Gregorio, Astley, Greenish, & Doyon, 1997; Ramstein & Hayward, 1994). In conjunction with MPB technologies, the Freedom-6S hand controller has also been developed (MPB, 2000). PER-Force hand controllers were developed in conjunction with NASA

(Cybernet, 2000). The Phantom (Massie & Salisbury, 1994) was developed at MIT. Hand controllers that provide dynamically reprogrammable passive constraints have been developed at Northwestern University (Colgate, Peshkin, & Wannasuphoprasit, 1996) and Grenoble University (Troccaz-J & Delnondedieu-Y, 1996). A hand controller with very high peak stiffness has been developed at the University of Washington (Adams, Klowden, & Hannaford, 2000).

One of the most complex force-reflecting devices built to date is the Dexterous Teleoperation System Master designed by Sarcos, Inc., in conjunction with the University of Utah's Center for Engineering Design and the Naval Ocean Systems Center (NOSC). Although it is primarily ground-based, by having attachment points at the forearm and upper arm of the user it has the advantages of an exoskeleton, such as a large workspace comparable to that of the human arm. This device utilizes high-performance hydraulic actuators to provide a wide dynamic range of force exertion at relatively high bandwidth on a joint-by-joint basis for 7 DOF. Another high-performance force-reflecting master is a ground-based system for teleoperated eye surgery built by Hunter, Lafontaine, Nielsen, Hunter, & Hollerbach (1990). At Harvard, a planar manipulator has been developed to study precision teleoperation with a pinch grasp between the thumb and the index finger (Howe, 1992).

4.1.2 Body-based Devices

Body-based devices fit over and move with the limbs or fingers of the user. Because they are kinematically similar to the arm and hands that they monitor and stimulate, they have the advantage of the widest range of unrestricted user motion. As position-measuring systems, body-based devices (gloves, suits, etc.) are relatively inexpensive and comfortable to use. A few of the more common commercially available gloves include the VTI CyberGlove, and the iReality 5th glove. Depending on the manufacturer and model, these typically resolve 5 to 23 DOF to approximately 1 degree. The FakeSpace Pinch Glove takes a different approach, detecting contact between the tips of two or more digits.

Body-based devices with rigid exoskeletons afford force display and slightly more accurate pose sensing, typically at the expense of greater bulk. For a review of the design issues in exoskeletal devices see Shimoga (1992). At the time of this writing, one force reflecting exoskeleton is in mass production (the VTI CyberGrasp). Research on body-based force reflecting hand exoskeletons has been ongoing for decades. See Okamura et al. (2000) for a review. Some current designs are notable. The Rutgers Portable Dextrous Master (Burdea, Zhuang, Roskos, Silver, & Langrana, 1992; Fabiani, Burdea, Langrana, & Gomez, 1996), is a light, simple exoskeleton that grounds fingertip forces on the palm rather than the back of the hand. A light, cable-based, 2-DOF, body-grounded hand controller (HapticGEAR) for immersive VEs has been developed at Tokyo University (Hirose, Ogi, Yano, & Kakehi, 1999). A force-reflecting hand master that senses and controls fingertip position (but not joint angles) is under development at Johnson Space Center (Sinah, Endsley, Riggs, & Millspaugh, 1999). Regardless of the exact mechanical design, providing force feedback with body-based hand controllers remains a difficult problem, placing great demands on minimizing actuator size to make the control bandwidth of the device commensurate with human haptic capabilities.

4.1.3 Tactile Displays

While the display of net forces is appropriate for coarse object interaction, investigators have also recognized the need for more detailed displays within the regions of contact. In particular, the display of tactile information (e.g., force distributions for conveying information on texture and slip), though technically difficult, has long been considered desirable for remote manipulation (Bliss & Hill, 1971).

Very crude tactile displays for VEs are now in mass production. The Aurora Interactor uses a voice coil to display vibration through a vest or seat cushion. CyberTouch, by VTI, is another vibrotactile transducer made to mount on the backs of the fingers. A 1.25-inch diameter vibrotactile transducer has been developed by Engineering Acoustics, Inc., and applied to the torso for a situational awareness display (Raj, McGrath, Rochlis, Newman, & Rupert, 1998). The Displaced Temperature Sensing System from CM Research displays temperature changes to the fingertip. Although they are not designed expressly for VE applications, electromechanical Braille cells are also commercially available (American Foundation for the Blind, 2000) and are being actively developed (Petersen, 2000).

Research on tactile display systems in the last two decades has been motivated in part by efforts to convey visual and auditory information to deaf and blind individuals (Bach-y-Rita, 1982; Reed et al., 1982), and more recently to simulate tissue palpation during minimally invasive surgery (Howe, Peine, Kontarinis, & Son, 1995; Moy, Singh, Tan, & Fearing, 2000a).

Many of these displays have the general appearance of pin or balloon arrays, often with an antialiasing membrane between the pins and fingertip skin. A variety of actuators have been employed, including DC solenoids (Frisken-Gibson, Bach-Y-Rita, Tompkins, & Webster, 1987), shape memory alloys (Howe et al., 1995), compressed air (Moy, Wagner, & Fearing, 2000b), piezoelectric vibrators (Chanter & Summers, 2000), and electrorheological fluids (Monkman, 1992). Also under development are micromachined tactile displays that stimulate skin with tangential tactors (Ghodssi, Beebe, White, & Denton, 1996), electrical current (Beebe, Hymel, Kazcmarek, & Tyler, 1995), or tangential force due to electrostatic attraction (Tang & Beebe, 1998). A review of principles and technical issues in vibrotactile and electrotactile displays can be found in Kaczmarek and Bach-y-Rita (1993) and Shimoga (1992).

Some interesting alternatives to the rectangular array are under development. Researchers have developed an array of concentric rings that simulates compliant surfaces by controlling the rate at which the skin contact area spreads as normal force is applied to the display (Ambrosi, Bicchi, De Rossi, & Scilingo, 1999). A "grasp blob" is also under development (Aldridge, Carr, England, Meech, & Solomonides, 1996). This device consists of a grasped, fist-sized bag that can be depressurized rapidly, compacting the particles within it into a solid mass.

4.2 Hardware Summary

Computer keyboards, mice, and trackballs are the simplest haptic interfaces and are being widely used to interact with computers. Position-sensing gloves and exoskeletons without force reflection are also available on the market but are used mainly for research purposes. Among the force-reflecting desktop devices, joysticks, mice, small robots, and surgical simulators are commercially available. Force-reflecting exoskeletons are harder to design for adequate performance, and only a few are commercially available. Tactile displays offer particularly difficult design challenges because of the high density of receptors in the skin to which they must apply the stimulus. Basic (1-DOF) tactile stimulators are now available for VEs, whereas tactile arrays for VEs are still in development.

5. FUTURE WORK

Design specifications for haptic interfaces depend on the biomechanical, sensorimotor, and cognitive abilities of humans. Therefore, multidisciplinary studies involving biomechanical and psychophysical experiments together with computational models for both are needed in order to have a solid scientific basis for device design. Perhaps to a lesser extent, neurophysiological studies concerning peripheral and central neural representations and the processing of information in the human haptic system will also aid in design decisions concerning the kinds of information that need to be generated and how these should be displayed. A major barrier to progress from the perspectives of biomechanics, psychophysics, and neuroscience has been the lack of robotic stimulators capable of delivering a large variety of stimuli under sufficiently precise motion and force control.

5.1 Hardware Development

For the foreseeable future, it appears progress in haptics will be limited by the development of new actuator hardware. It is now clear that active interfaces with two and perhaps three DOF are commercially sustainable. It remains to be seen whether devices with 4 or more active DOF eventually become general purpose computer peripherals or remain limited to specialized applications like surgical simulation.

Hardware for displaying distributed forces on the skin remains an especially challenging problem. Exploration of novel technologies is needed for quantum improvements in miniature rotary and linear actuators. Shape memory alloys (SMAs), piezoelectrics, microfluidics, and other microelectromechanical systems (MEMS) for tactile display all warrant further investigation. Mechanical flexibility is another major challenge in the development of general-purpose wearable tactile displays. The human skin is a dynamic environment subject to bumps, scratches, and deformations due to flexion of the body segments. To put an array of actuators on it in a package that does not break or encumber an active user may require methods for manufacturing or embedding actuator arrays in flexible substrates, a challenge MEMS technology is only beginning to address.

5.2 Methods of Stimulation

The right balance of complexity and performance in system capabilities is generally task dependent. In particular, the fidelity with which tactual images have to be displayed, and motor actions have to be sensed by the interface depends on the task, stimulation of other sensory modalities, and interaction between the modalities. Experimenting with available haptic interfaces, in conjunction with visual and auditory interfaces, is necessary to identify needed design improvements. Design compromises and tricks for achieving the required task performance capabilities or telepresence (immersion) need to be investigated (see chaps. 21, 22, and 40, this volume). One of the tricks might be the use of illusions (such as visual dominance) to fool the human user into believing a less than perfect multimodal display (DiFranco, Beauregard, & Srinivasan, 1997; Srinivasan, Beauregard, & Brock, 1996). Techniques such as filtering the user's normal tremor or the use of sensory substitution within a modality (e.g., the use of tactile display to convey kinesthetic information) or among different modalities (e.g., visual display of a force) need to be developed to overcome limitations of devices and limitations of the human user, perhaps to achieve supernormal performance. To tackle the ever-present time delays, efficient and reliable techniques for running model-based and real-time controls concurrently are needed.

5.3 Evaluation of Haptic Interfaces

Evaluation of haptic interfaces is crucial to judge their effectiveness and to isolate aspects that need improvement. However, such evaluations performed in the context of teleoperation have been so task-specific that it has been impossible to derive useful generalizations and to form effective theoretical models based on these generalizations. There is a strong need to specify a set of elementary manual tasks (basis tasks) that can be used to evaluate and compare manual capabilities of a given system (human, robotic, VE) efficiently. Ideally, this set of basis tasks should be such that (1) knowledge of performance on these tasks enables one to predict performance on all tasks of interest and (2) it is the minimal set of tasks (in terms of time consumed to measure performance on all tasks in the set) that has this predictive power (Durlach, personal communication, 1990).

In this void, some tasks have become de facto standards, including point-to-point movements (i.e., Fitts' task, Balakrishnan & MacKenzie, 1997), target selection (Card et al., 1991), and docking (Zhai, Milgram, & Drascic, 1993), measured in terms of mean completion time, RMS error, and information transfer rates. For basic input devices like joysticks and mice, a task-based ISO9000 standard has been proposed (Douglas, Kirkpatrick, & MacKenzie, 1999). However, it is not clear how well these measurements extrapolate to devices intended for tasks more complicated than pointing.

Some progress has been made in developing a standard set of physical measurements for devices (e.g., workspace, degrees of freedom, force range, precision, etc.). A standard set of physical measurements is proposed by Hayward and Astley (1996). Although these physical measurements are clearly necessary, at this point in the development of haptic interfaces they are probably not sufficient to guide device development. For example, a device might perform brilliantly at displaying shoulder torque (a physical measurement), but if this parameter is not very effective at helping the user complete many tasks or feel immersed the device may not really be "good." Measures of the relative perceptual importance of force and position cues at different body sites during different tasks are also required in order to ascertain what stimuli are worth displaying to the user.

TABLE 5.1
Mechanical Properties of Human Upper Limb

Degrees of Freedom	
Shoulder	4 (shrug, flexion, abduction, rotation)
Elbow	2 (flexion, pronation)
Wrist	2 (flexion, pronation)
Each digit	4 (abduction + 3 flexions)
Bandwidth of motor system[1]	
Unexpected signals	1–2 Hz
Periodic signals	2–5 Hz
Reflex actions	10 Hz
Minimum hand closure time	0.09 seconds
Fingertip forces[2]	
Typical pinch grip	1–10 N
Controllable	Up to 100 N
Control resolution	0.05 to 0.5 N
Grasp force range	50–500 N

[1] (Brooks, 1990).
[2] (Tan et al., 1994).

TABLE 5.2
Mechanical Impedance of Human Upper Limb

Passive elbow[1]		
	Up to 2 Hz	~ 0.02 (N · m)/rad)
	10 Hz	~ 0.1 (N · m)/rad)
	100 Hz	~ 5 (N · m)/rad)
	1000 Hz	~ 100 (N · m)/rad)
Lumped response of index finger pad and segments		
	"Relax"[2]	0.14–0.4 N/mm
	"Resist force as much as possible"[2]	0.30–0.86 N/mm
	Straight[3]	0.8–2.2 N/mm
	Flexed[3]	0.4–2.0 N/mm
Lumped response of finger pad and digits during pen grasp[2]		
	"Relax"	0.34–1.25 N/mm
	"Resist force as much as possible"	0.79–2.41 N/mm
Lumped response of finger pad to pseudo-static plate indentor[4]:		
	Physiologic range of finger pad indentation	~ 3 mm
	Stiffness at initial contact (0–1 mm)	~ 0.1 N/mm
	Upon further indentation (1–2 mm)	~ 0.4 N/mm
	Upon further indentation (2–3 mm)	~ 1.0 N/mm
	Indentations > 3 mm	10–100 N/mm

[1] (Jones, Hunter, Lafontaine, Hollerbach, & Kearny, 1991).

[2] (Buttolo, 1996) Measured 30 ms after start of force ramp at 0.1–0.5 N/s. Stiffness of pen grasp is six- to sevenfold greater than index finger alone. Precision of position control improves two- to threefold.

[3] (Milner & Franklin, 1995).

[4] (Gulati & Srinivasan, 1996).

TABLE 5.3
Tactile Sensation[1]

Indentation threshold	
Static	20 μm, 0.3 mN/mm^2
10 Hz	10 μm
250 Hz	0.1 μm
Feature detection	
Texture	0.075 μm (improvement due to lat scanning)
Single dot	2 μm
Normal force when detecting features	0.4–1.1 N (typical), 0.3–4.5 N (observed range)
Temporal resolution	
Time between successive taps	10 ms
Bandwidth sensed	0–1000 Hz
Reaction time	70 ms to 500 ms (reflexive slip to threshold detection)
Spatial resolution	
Lateral localization	0.15 mm
Lateral 2-point limen	1 mm at fingertip
Hot/cold	
Detection threshold for temperature change	0.01°C/s
Reaction time	300–900 ms
Persistent hot	> 40°, (pain > 48°)
Persistent cold	< 20°, (pain < 15°)

[1] For source details see Sherrick and Cholewiak (1986), Srinivasan (1995).

TABLE 5.4

Active Touch Including Tactile, Kinesthetic, and Motor Systems[1]

Parameter	*(JND)*
Length	10% or less
Velocity	10%
Acceleration	20%
Force	7%
Compliance	8% (rigid surface, piano key)
Compliance	3% (deformable surface, rubber)
Viscosity	14%
Mass	21%
Rigidity perception	25 N/mm or greater

[1] For source details see Beauregard, Srinivasan, and Durlach (1995) and Chen and Srinivasan (1998)

TABLE 5.5

Information Transfer Rates Through the Hands[1]

Method for manual production	Rate (bits/sec)
Morse code	1.8–3.6
Handwriting	3.5–7 (estimated)
Finger spelling	7–11
Typing	7.2–14.4
Court stenography	13.5–27
Signing with ASL	15–30
Method for manual reception	
Kinesthetic Morse code	0.9–1.4
Tactual reception of finger spelling	8.1–?
Tactual reception of spoken English (Tadoma)	11.2–22.5
Tactual reception of ASL	11.7–23.4

[1] Gathered in Reed and Durlach (1998).

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