# Human and Machine Haptics in Historical Perspective

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## 1. Origin of haptics

### *Haptic terminology*

*Haptics* is not a term well known to the public. It is derived from the Greek word 3psij-æ|, meaning "to come in contact with." As a scientific term it is traced to the German word *haptik* , as employed by M. Dessoir (1892) meaning "the study of touch and tactile sensations, especially as a means of communication " (Oxford English Dictionary).

Nowadays the term has expanded in scientific use beyond touch, embracing the breadth of the earlier Greek meaning — having to do with contact forces generally. In this meaning haptics includes not only cutaneous senses of force, which are distributed in time and space on the skin surface, but also the aggregations of skin contact forces to form vector resultants applied to the muscles and tendons and joints, sensed by different receptors in these structures. Thus haptics has come to include *kinesthesis* (sense of limb motion), and also *proprioception* (awareness of self, or sense of limb position relative to the body and gravity forces). Some researchers have used the term *tactual* to embrace cutaneous as well as muscle, tendon and joint sensing, restricting *tactile* to mean skin senses only, for example see Loomis and Lederman (1986). Others employ both *tactual* and *tactile* to mean skin sensing. The lay public's understanding of the term *touch* only adds to the confusion, since to many people it means only contact sensing on the skin, but to others it includes as well what they feel in and with their limbs. This profusion and confusion of terms may have discouraged scientific research in the field.

### *The place of haptics in natural and technological evolution*

Haptic capability is primitive on the evolutionary time scale. Early creatures had force sensitive skin or discrete structures such as hairs or antennae. For example, a *hapteron* (from the Greek 6pseim "to fasten" is an "organ of attachment by which certain aquatic plants or algae fasten themselves to rocks" (Oxford English Dictionary). In some cases it takes the form of a suction cup. Exteroceptor organs for vision and hearing generally came much later in evolution. Curiously, exactly the reverse occurred in human development of sensing technology. Edison is credited with inventing the telephone and grammophone (record player) early in 1900s. RCA scientists and others are credited with invention of television in the 1930s. Haptics, though of scientific interest to sensory psychologists and physiologists, did not have an equivalent technological implementation until very recently. In it may be said that currently artificial haptic sensing and display is nowhere close to the sophistication of artificial auditory and visual sensing and display.

## 2. Early psychophysiology of haptics

### *Sensory specialization or lack thereof*

As traced by the historian of sensation E.G. Boring (1950, p. 84), at least as far back as Aristotle mankind appreciated that there were five senses (sight sound, taste, touch and smell), and that touch was different from the other bodily senses. Boring quotes Aristotle, "By the peculiar object sense I mean a sense-quality which cannot be apprehended by a sense different from that to which it belongs, and concerning which that sense cannot be deceived, e.g., color is the peculiar object of vision, sound of hearing, flavor of taste. Touch, however, discriminates several sense qualities." In 1826 Johannes Mueller in Germany first wrote that each sense had its own specialized character or specific nerve energy. That doctrine had already been put forth privately by Sir Charles Bell in England (Boring, p. 27). Since there was little clarity about different sensory receptors and their locations in skin, muscle, tendon or joint at this point, there was natural confusion about a sense which mediated pressure, position awareness (both on the skin surface and of a limb in space), motion, vibration, texture, pain, heat, cold, tickle, itch, and so on. Curiously, at the same time touch was classed by some authors of the era along with taste and smell as a “simple sense” (Boring, p. 110).

*Skin senses*

It was Ernst Heinrich Weber, Professor of Anatomy and Physiology at Leipzig (1818 et seq.) who published the first significant scientific work on touch (1834, 1846). He divided touch into component sensations of weight, location and temperature, and relegated other sense qualities of the skin to *das Gemeingenfuhl*, or “general sensation”. Weber experimented with the different touch qualities, including their interactions. For example he asserted that cold bodies appear heavier than warm bodies of equal weight. It was Weber, of course, with his famous compass test, who first noted that if two points of skin contact are separated by less than some distance they appear as one. He later refined this into the concept of differential threshold and performed many experiments on himself which he reported (1834) and which later led to the empirical “law” which bears his name. He also noticed that the same stimulus can give rise to two sensory qualities (e.g., both pressure and pain) simultaneously, and that in some cases two different stimuli (both pressure and pull on the skin) can effect the same sensory quality. He postulated specialized nerve endings but was not successful in identifying them. Weber and his colleagues at the time knew that nerves went from the skin to the brain, and so the mind was somehow involved, but there the mystery began (and still remains!).

Max von Frey, Dozent at Leipzig, proposed (Boring p. 425) that specialized nerve endings in the skin did exist and that they went to specialized areas in the brain. Nafe (1934), breaking from that accepted theory, proposed a pattern theory— that a quality of experience depends on the colocation of a number of separate nervous events. Melzak and Wall (1962) revised the pattern idea with much more electrophysiological and histological evidence, and their theory still stands. Sherrick and Cholewiak (1968) provide a good review of the skin senses.

When it comes to the perception of touch, one must make a distinction between active touch (where a person actively contacts and moves the skin relative to an environmental object) and passive touch (where the skin is fixed in position and the external object is moved into contact). The difference, of course, is the correlate kinesthetic and proprioceptive feedback one gets in active touch. Gibson (1962) was perhaps the first to articulate this difference. See Loomis and Lederman (1986) for a review of this distinction and touch perception generally.

It has long been evident that the skin senses share much with the sense of hearing. The sensorium of vibratory frequency is similar, for example. When impulsive stimuli are presented to the two ears slightly out of phase, the result is a sensation of phantom sound source, which appears to move left or right according to the time difference. A similar phenomenon, discovered by VonBekesy (1955), occurs on the skin when two vibrators are placed 10 cm apart and are out of phase. The vibration source (across the range 40-500 Hz) appears to move from one vibrator to the other as a function of phase. When isolated clicks are used in ears or on the skin the same phantom sensation occurs in either case moving from center to one side with about a one msec time separation.

*Muscle/joint senses*

For many years it was thought that our sense of limb motion was derived somehow from vision, and arguments by Helmholtz (1867/1925) reinforced that notion (see Jones, 1973). Sherrington (1900, p.1006 et seq.) vigorously opposed that idea, arguing that neither vision nor skin contributed much to sense of limb motion, though admitted to interactions with these other senses. Gradually over the next 50 years (and amazingly late compared to physiological understanding of the other senses) it became clear that there were ample and independent sensors in the muscles, tendons and joints— but it was far from clear how they worked together. Experiments to stimulate mu scle nerves of animals and observe correlates in the brain were confusing, at least until the gamma-efferent muscle fibers were discovered (Rose and Mountcastle, 1959). These mechanisms, in series with the primary muscles, tune the damping and effective sensation of muscle length. Recent decades have seen numerous experiments in both animals and humans, trying to understand this complex relationship. See Clark and Horch (1986) for a review.

*Mechanical impedance and human impedance control*

Impedance in general means force $F$ divided by velocity $V$, characterized by Newton's linear dynamical relation in terms of the properties mass $M$, friction $B$ and stiffness $K$ of the body being moved, i.e., in LaPlace notation,

$$\frac{F(s)}{V(s)} = Ms + B + \frac{K}{s}.$$

Impedance control refers to the effective mass, friction and stiffness properties determined by control gains within a human or robot arm. For example, a person can maintain a desired hand position (position control) by tightening both the agonist and antagonist muscles in the arm, thereby creating a large impedance (stiffness parameter in particular) to imposed force disturbances. Alternatively a person can resist an imposed force on the hand only enough to maintain force at some constant level (force control), which in this case means the hand will move as necessary. Theoretically a person or a robot can adjust control gains to achieve different relative amounts of mass and viscosity as well as stiffness anywhere along the scale from pure position control to pure force control. Since humans are limited in both force and extent of movement, they generally must compromise between position and force control, but with different muscles, controlling different degrees of freedom, they can provide their arms (or legs) with quite variety of impedance characteristics in the different degrees of freedom.

For example, when playing ping pong accurate position control must be maintained, but when catching a baby, one makes the catch soft (low stiffness) to minimize deceleration (and hence force on) the baby. In writing on a chalk board one maintains stiff position control up-down and left-right, but one maintains soft impedance against the chalk board so that the force will be relatively constant in spite of body movements toward and away from the board. In recent years significant progress has been made in impedance theories and models of human limb movement and related perceptions (see Hogan, 1980; Hogan, 1989)

## 3. Handles and transfer functions

### *Handles*

Perhaps the first engineering of haptic systems was in hand controls — power operated controls for automobiles and aircraft. In the first experimental power steering systems the human simply operated a hydraulic valve to modulate flow into a cylinder connected to the steering linkage, and the externally imposed force on the car's wheels provided no force feedback at all to the driver. Simple spring loading, of course, helps by giving the driver a force cue in adition to a position cue.

During and after World War II aircraft engineers recorded many instances of pilots confusing hand controls because the knobs were similar in shape and their eyes were too busy to watch their own hands. Experiments were performed to find sets of knob shapes which are most quickly and correctly discriminated by haptic senses alone. Figure 1 illustrates one set of recommended knob shapes.

### *Transfer functions*

During this same period much effort was made to determine the human pilot's transfer function (between visual pitch or roll indication and hand-actuated control position). The motivation was that, since the pilot was part of the aircraft control loop, in order to ensure control loop stability, one could not simply worry about aircraft dynamic response to control commands. One had also to know the pilot's dynamics from aircraft pitch and roll back to hand control position. After a decade of research on this problem McRuer and his coworkers (1967) established the so-called crossover model (here stated in the frequency domain notation)

$$\frac{X(jw)}{E(jw)} = \frac{K}{jw} e^{jwT}$$

where $X$ is the actual pitch or roll, $E$ is displayed error in pitch or roll, $K$ is loop gain, $T$ is time delay, and $jw$ is the Fourier variable. This surprisingly simple model states that the combined open-loop dynamics of human and aircraft together act like a simple integrator with a time delay, the latter being mostly the reaction time of the pilot. In other words, the human compensates for the aircraft dynamics to make the servo loop behave nicely. This model has been widely applied in a number of manual tracking contexts, many outside of aviation. In the author's laboratory Weissenberger (1962) was probably first to derive the human transfer function with tactile pressure stimulus on the fingers as the input (with no visual stimulus). Not surprisingly, his results fit the McRuer model nicely.

Control handle vibrators have been used in a number of manual control applications, for example so-called *stick shakers* are used in aircraft to warn pilots of dangerous flight regimes. Fenton (1966) employed a tactile vibrator stimulus to warn an automobile driver that he was getting too close to a lead car.

## 4. Haptics in sensory/motor aids for the handicapped

*Haptic aids for the deaf*

One of the first technological aids for the deaf evolved from research by the famous mathematician Norbert Wiener and the eventual MIT president and US presidential science advisor Jerome Weisner, namely Project Felix (1949). Their technique was to map spectral information of speech into five frequency bands, displayed respectively by vibrators to the five fingers of a hand.

Wiener also called attention to two brothers who had come to him and shown him how they could communicate with one another by touching each others' larynx and feeling the speech vibrations. This technique came to be called the Tadoma method. It was later adopted by many other deaf, and was regularly taught to students at Perkins School for the Blind in Watertown, Massachusetts.

*Haptic aids for the blind*

The idea of sensory substitution (displaying to a human sense information that is normally mediated by a different human sense) was first applied in a major way in an effort to helping the blind to read. Louis Braille (1809-1852), blinded at the age of three, invented the haptic reading system which bears his name. Various combinations of six raised dots represent individual letters, numbers, or common combinations of letters (Figure 2). Braille note-taking devices have been common for most of this century. However, learning to read Braille is difficult for many blind persons.

Bliss (1969) developed a commercial device for manually scanning alphanumeric characters on a printed page and converting them to vibrotactile sensations. This gave the blind person direct access to the printed page. These days character-recognition-to-speech conversion is the most popular system, but of course is not usable by the deaf-blind.

Tactile maps have been in common use for many years as aids for the blind in finding their way around buildings or city streets. Several investigators have converted video images to tactile images by doing pixel conversion to raised pins, vibrators or air jets. In one experiment with vibrators arrayed on the subject's back corresponding to video pixels there was a claim that subject could get some sense of a picture. Unfortunately acceptable spatial resolutions for this form of sensory substitution has never been achieved. "Seeing" complex visual patterns from tactile force patterns imposed on the skin does not seem to work even when resolutions are high.

Much more satisfactory have been hand-held wands or body-attached devices by which the blind user can point a light or radar beam in a particular direction and get a return vibration signal as to the light or sound emanating from or the distance to the physical environment in that direction (Russel, 1971). In this case the user is actively pointing rather than passively receiving, and the information pattern is much simpler — two factors that make it workable.

The so-called long cane, an aluminum or glass fiber rod with a handle, has been a superb mobility aid for a blind person trained in its use. The idea is to tap on the sidewalk or floor with the cane where the next step will occur at the same time one is making a present step, providing one step advance notice of whether there is an obstacle or a down-step. Mickunas and Sheridan (1963) explored the use of cane tapping cues in negotiating an obstacle course. They systematically damped the handle of such a cane, or allowed the shank or tip to bend, and learned that trained blind users can function with any one of vibration, position or transient force cues (corresponding respectively to handle, shank and tip). But when all such cues disappeared simultaneously the blind traveler is helpless.

*Haptics in prosthetics and orthotics*

Haptics is also important for artificial limbs (prosthetics) and limb braces (orthotics). In the former both skin and muscle/tendon senses are missing for the lost limb segments, while in the latter there may be some residual skin/muscle/tendon sensation (but usually it is missing because nerves have been severed or diseased). The need is to provide some artificial haptic sensation to correspond to that which would occur in a normal person. It is a challenge to find a functional skin/muscle/tendon site which correlates to the lost site in the terms of "body image association." In some cases prosthetic arms employ a form of sensory substitution within the haptic domain, for example, magnitude of vibration to indicate the elbow angle. An interesting application of the VonBekesy phenomenon cited above was employed by Mann and Reimer (1970) to display to the skin of the wearers to indicate angular position of a prosthetic arm elbow joint.

A related development is the powered exoskeleton, a set of articulated limb braces (a kind of robot the user wears over his clothing). The idea is to enable the user to lift weights and do work much in excess of what he normally would do, for example in loading a truck. Mizen (1964) and coworkers of Cornell Aeronautical laboratory built such a "man amplifier" (Figure 3), and there have been various efforts to improve upon this idea. Presumably the wearer would receive at each limb some force feedback which is a fraction of the total force exerted. The other forces (by Newton's first law) would be supported by the ground or other base element of the exoskeleton. Cornell claimed such a device would be safe for a man to lift 1600 pounds six feet in the air. Many, however, felt that the dangers outweighed (!) the advantages, and the project was discontinued.

*Haptic handicaps of special purpose clothing*

For developers of surgical gloves, gloves for soldiers in the arctic, and gloves for space extra-vehicle-activity (EVA) and deep ocean diving suits, it would be ideal if materials could be found which are puncture and tear-proof, provide thermal and pressure barriers as needed, and yet provide no barrier to touch. Unfortunately serious compromises have had to be made, and mechanics of how hand coverings distort tactual perception have only recently been studied rigorously.

## 5. Haptics in teleoperation

Haptics has played a key role in teleoperation technology from the beginning. Haptics in teleoperation naturally has much in common with haptics in aids for the handicapped. Teleoperation here means any artificial device by which a human can apply forces to and receive feedback from a real but remote physical environment. Teleoperation can be continuous with no computer mediation in the loop, in which case it takes the form of a master-slave (isomorphic position-to-position) teleoperator. Alternatively teleoperation can be controlled through a joystick (angular position of joystick or other hand-controller maps to teleoperator end-point rate). Human supervisory control (telerobotics) means that a human commands a computer which in turn commands position or force to the teleoperator. In either case haptic feedback can be critical.

*Force-reflective telemanipulation*

While hand tools date to the dawn of mankind, and simple elecromechanical and hydraulic cranes and earth moving machines (these are all teleoperators) existed since the last century, modern teleoperation can be traced to just after World War II and the development of servomechanisms. Just after the war much federal money went to developing plants and facilities for nuclear power and the remote handling of radioactive materials. In 1948 the Argonne National Laboratory, under the leadership of Raymond Goertz, designed the Model 1 mechanical master-slave manipulator. It was a seven-degree-of-freedom bi-lateral (symmetrical) metal tape transmission pantograph device. It operated through a leaded glass wall but yet afforded excellent force reflection from the remote gripper to the operator's hand. A 1954 modification (Model 8) was manufactured commercially and continues to be used today.

In that same year Goertz (1954) also built an servo-electric master-slave manipulator (E-1), where transmission was by electric wire of arbitrary length rather than by metal tape (Figure 4). Bilateral in this case meant that for each degree of freedom any position difference between master and slave was converted to a electric motor force pushing forward on the slave and backward on the master (becoming force feedback on the operator's hand corresponding to that felt on the master). This marvelous feat of engineering (one prototype of which, the E-2, still resides in the author's laboratory) set the tone for much of the teleoperator development to follow, including force feedback.

Ralph Mosher (1958) and coworkers at General Electric Company, built the Handyman, the first bilateral electrohydraulic master-slave manipulator. It had ten degrees-of-freedom for each of two arm-hand combinations and allegedly could lift 75 pounds at its weakest position. Force feedback was similar to that for the Argonne electric telemanipulator. However, because of its vacuum tube amplifier technology, its twenty servo circuits posed reliability problems; rumors at the time suggested that they never all worked simultaneously.

The NASA Space Nuclear Propulsion project mandated a number of hazardous environment teleoperation activities, a series of meetings which for the first time brought together people from nuclear industry and government remote handling projects, workers in the neophyte space and undersea teleoperation projects, researchers from universities, and others. A series of documents (Johnsen and Corliss, 1967; Corliss and Johnsen, 1968) chronicled developments as of that point. The importance of haptics was becoming appreciated by the design engineers.

As teleoperators developed for space, undersea and other applications, it became clear that force feedback is essential for some tasks, not for others. For position control in free space, particularly if movements are slow, force feedback provides little advantage, and for that reason space manipulators have continued to employ mostly joystick control with no force feedback. However, resolved force and touch feedback have proven essential in terms of speed and error prevention for most handling and assembly tasks, and are best provided by master-slave position control. For a review of this area see Sheridan (1992).

*Teletouch*

Strickler (1967), in the author's laboratory at MIT, built what is believed to be the first tactile sensor for a master-slave manipulator (Figure 5). Up to that time force feedback had all been resolved force, i.e. the resultant of all forces applied to the slave arm/hand forced the corresponding linkage in the master arm/hand to push back on the human operator. The principle of Strickler's devicewas quite simple: a local force at any point on the gripper surface deformed a flexible mirror which optically reflected a regular grid pattern back though a coherent fiber bundle. Touch patterns became clearly (visually) evident distortions of the grid pattern. Since no satisfactory high resolution tactile pattern display existed then (one can argue that it still does not), touch-to-vision substitution seemed most appropriate.

Fyler (1981), again in the author's lab at MIT, demonstrated a technique for mapping an object by "poking around in the dark" — what one does when looking for an object in a dark room. Since a computer can kinematically keep track of each of a series of discrete contact points (end point of a manipulator), those points can be plotted on a computer screen as viewed from any visual angle. By graphically connecting the points and making a shaded solid from it, one can get a closer and closer approximation as more contacts are made, and in fact use this feedback to guide the teleoperated contactor where next to touch.

Since early experiments in supervisory control, where a human operator commands a telerobot to perform some action until specified sensory conditions are met, touch sensing has been paramount as one type of conditional (e.g., move in X direction until contact is made).. For example, Jet Propulsion Lab of Califormia Institute of Technology has developed control strategies for use in space where hard contact forces and sudden accelerations can be disastrous. In one implementation, as the telerobot moves through space the arm/hand is stiff to achieve good position control, but as it approaches object the end-point stiffness suddenly diminishes to achieve soft contact.

*Haptic feedback under time delay*

Coping with time delay in a force feedback system poses a very special haptics problem. Every control engineer knows that negative feedback loops abhor time delays, since when the loop gain exceeds unity at that frequency where the delay causes a 180 deg phase shift, the feedback becomes positive rather than negative. Then, even in the absence of input energy, any energy within the loop increases without bound — in other words drives the system to instability. If there is no force feedback, that is, only visual feedback in a teleoperator loop, the human learns to "move-and-wait", i.e., make a discrete open-loop move and then wait for visual feedback before making another move. This takes time but does not cause instability. However, with force feedback, any loop delay means the force acts on the master (or rate-control handle) at a time later than when the coresponding movement is made as an intended control action. In other words, the force becomes a force disturbance on the master or handle. This might be tolerable, except for the fact that such forces necessarily go right beck into the control loop, and at the critical frequency will necessarily drive the loop unstable for the reasons cited above.

## 6. Robotic haptics

Primitive micro -switch touch sensors have been used since the earliest experiments with autonomous robots, where their signals, rather than being sent to a human, were sent to a computer controller. For example Henry Ernst's MH-1 (1961) was programmed to move sideways to a block, then, upon contact, move up and over the block, open its gripper, move down, close its gripper until contact, then place the block as directed.

*Wedging and jamming*

Placing a peg in a hole with tight clearance has always been seen as a haptic feat, and it had not been well understood why people have trouble doing that (or closing a drawer or any similar assembly task). Robots have had even more difficulty. Whitney (1989) and Simunovic (1975) are credited with developing the definitive theory of so called *wedging* and *jamming*, two different ways an assembly can fail. Wedging is entirely a matter of friction, and occurs when the friction cones of opposing contact points on opposite walls of a hole intersect inside the peg. Jamming is a combination of insertion forces and contact reaction forces. Wedging and jamming are eliminated intuitively by manually relaxing or reversing imposed forces, wiggling or vibrating, and so on. In robotic systems it is a matter of implementing stiffness control so that wedging and jamming forces are minimized at the same time the insertion is being made.

*Remote center compliance*

A unique invention by which a machine can perform assembly with tight fits is the remote centered compliance (RCC) device (Watson and Drake, 1975) (Figure 6). It is a passive implementation of stiffness control which "creates the behavior of a force feedback algorithm in which the diagonal entries in the feedback matrix represent stiffness rather than damping coefficients". In essence there are spring loaded elements which simultaneously allow compliance in both rotation and lateral translation but maintain stiffness in forward translation. For straightforward peg-in-hole insertion tasks an RCC is far cheaper and more effective than active impedance control. The RCC has been used for assemblies having 60 millionths of an inch clearance.

*Optimizing touch strategy*

Touch is used in a robotic context to regulate force in assembly and to make contact "softer" when approaching objects, both as described above. But it has also been used to do pattern recognition, the machine intelligence equivalent of the Fyler experiment described above. For example, Schneiter and Sheridan (1990), in a Monte Carlo simulation experiment, determined what strategy is best for one-point contact probing of a convex object, given that it is one of several objects whose size and shape are known, to determine an optimal strategy (in terms of least number of contacts) by which to positively identify the object and its orientation.

## 7. Virtual haptics

What is popularly called *virtual reality* is actually as old as mankind, for people have always been story tellers and actors. The technological media of books, radio, audio recordings and TV have enabled the rendering of various virtual realities, and computer graphics is just another form of rendering. However haptics has not shared in these renderings of virtual reality.

*Positioning in virtual space*

Of course the joystick, the light-pen, the track-ball and (slightly later) the mouse were widely used as soon as the first mini-computers appeared in the 60s to communicate hand position to the computer. The VPL data glove, employing optic fibers to measure bend of each finger relative to the wrist and a Polhemus electromagnetic transducer to measure wrist position in six DOF, was the first widely applied commercial product in haptic VR to signal multi-finger position in free space. The somewhat more accurate EXOS exoskeletal device incorporated a set of Hall effect goniometers for measuring corresponding angles at each finger joint, and also used a Polhemus at the wrist for establishing the baseline position of the hand relative to a fixed reference.

*Force feedback in virtual space*

The first test of virtual force feedback known to the author was an unpublished experiment by James Bliss at MIT in the 1960s in which an X-Y plotter applied forces to the finger of a human subject in such a way as to provide a virtual groove. The first known demonstration of virtual touching and grasping in all 7 DOF was an experiment in the author's lab by Winey (1981) in which the E2 manipulator master acted on a virtual environment in which objects could be compressed or picked up — and because of the force reflecting nature of the system, forces could be "felt" (see Fig. 7). The PHANToM, widely adopted by the early 90s, has became the standard for haptic feedback of forces in multiple DOF from a virtual environment.

*Cutaneous feedback in virtual space*

As of this writing virtual haptic feedback to the skin is still very primitive. Patrick (1990), using an EXOS device to measure hand position, and on the thumb and forefinger a vibrator to generate haptic feedback from virtual environment (Figure 8), demonstrated how a subject could "reach out and touch something" which did not really exist.

## 8. Holes in the history of haptics

Behavioral and biological scientists seem to have appreciated the complexity of haptics from early on, and recognized the importance of active touch as compared to passive touch. But they have yet to understand how haptics works in the nervous system — in terms of the many sensors and muscles which interact. One reason may be that evolution had much longer to differentiate into a variety of sensors spatially distributed throughout the body and highly integrated with motor mechanisms — within the same organism Hearing and vision, by contrast, are relatively separate physically and functionally from other structures and mechanisms within the body. Haptics now poses a considerable scientific challenge with respect to tissue mechanics, physiology of the many and varied receptors in the skin, muscle, tendons and joints, and the psychology and neurobiology of how receptor stimulation generates the many different sense qualities.

Until the 1950s, and probably because the dismal state of its science, haptics was mo stly ignored by technologists, except for those few concerned with power assist in vehicle steering and spring loading in manual tracking. Now, fifty years later, it is a "hot" area, though there is much catching up to do to come close to the science and engineering of audio and video technology. Devices for resolved (aggregated) force sensing and display have become available, and to a lesser extent so has spatially distributed touch sensing. We have not succeeded much with touch displays (to the skin, that is, not to the eyes) nor do we understand much about improving robotic handling performance by tactile sensing. The challenge is evident.

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**Illustrations**

Figure 1. A set of hand controls shaped designed for tactile discrimination.
Figure 2. The Braille alphabet.
Figure 3. Mizen's man-amplifier prototype.
Figure 4. Goertz's E2 electromechanical manipulator and/or Mosher's Handyman electrohydraulic manipulator and/or Goertz's Model 8 mechanical master slave manipulator
Figure 5. Strickler's early touch sensor and touch display.
Figure 6. Illustration of the principle of remote center compliance.
Figure 7. Winey's experiment with virtual force feedback from a virtual environment.
Figure 8. Patrick's experiment in virtual cutaneous haptics.
A PHANToM arm (well covered in other chapters?)