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Survey on Communication through Touch

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Contents

1 Introduction

The tactile channel is adept at extracting information present in naturally occurring tactile sensations (e.g., appreciating the texture of a fabric). Information can also be conveyed by tactile stimuli that are artificially produced with a view to provide for human-computer interaction (e.g., the "buzz" of a cell phone). Another possibility is to seek to replicate naturally occurring sensations for virtual reality applications as in a training simulator. Human-computer interaction technology (HCI) already leverages touch for information transfer. For instance, the click experienced when a character is entered on a keyboard informs the user of the occurrence of the event. However, it is only recently that HCI has attempted to use touch to close the communication loop from the computer to the human in a programmed manner. Typically, computer interfaces rely mostly on vision and audition to supply information [37], when, in fact, people spontaneously and unconsciously rely on touch to explore and experience their environment [74].

The design of artificial tactile feedback is a new research area with exciting applications. In HCI, artificial tactile feedback aims at communicating contextual information. Such interactions take advantage of the touch channel to provide information with minimal distraction to the awake individual. Consider how the sensation of a sharp edge experienced while holding a glass is an indication that it is likely cracked. Similarly, devices able to supply tactile feedback artificially could communicate status information (e.g., to indicate the presence of a message) or instructions to navigate in an unknown environment (e.g., "turn right").

There is growing demand for communication through touch because of the increased number of opportunities in a wide range of areas such as entertainment (e.g., computer paddles), medical technologies (e.g., virtual surgery training, sensory substitution), research (e.g., study of perception), and many more. Research on tactile displays has been focused mainly on devices that apply normal indentation to a user's fingertip. In most cases, this is achieved through the vertical movement of miniature pins against the skin to reproduce small-scale shapes or textures. In general, however, artificial tactile feedback can be supplied by electromechanical devices, called *tactile displays*, which operate according to a wide variety of principles.

In this report, we first consider early and recent research on the development of artificial tactile communication. Then, we review current models of the encoding of tactile information in humans before examining the state-of-the-art for tactile displays[1]. While much remains to be discovered, we believe that these findings can guide the design of an artificial language for touch. We conclude with a summary of guidelines and insights collected from the literature on touch.

[1] Our review is limited to cutaneous touch, i.e., related to the stimulation of the skin. We are mainly concerned with the mechanical deformation of the skin and leave out pain and temperature sensations.

2 Tactile Communication

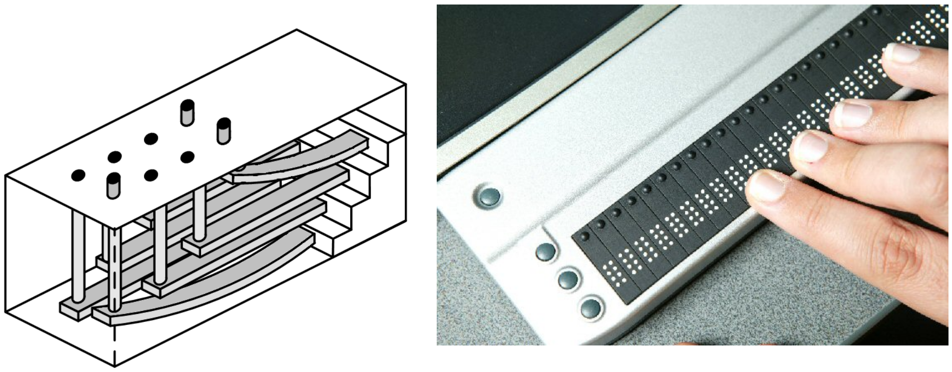
2.1 Tactile Languages

Nearly five decades ago, Geldard advocated that the sense of touch constituted a "neglected sense of communication" [32]. He noted that, while the visual and auditory systems were superior at spatial and temporal discrimination respectively, the somatosensory system was capable of both. Therefore, touch was particularly suited when hearing or sight were not available.

Others before Geldard had attempted to use touch as a communication channel. One example was Gault's Teletactor sensory substitution system that displayed the mechanical equivalent of speech sounds onto the skin by means of an electromechanical device [30]. The goal was to use the skin to "hear". This approach, unfortunately, suffered from a disregard to some inherent properties of touch. The fundamental frequencies required for proper speech comprehension precisely lie outside the range where tactile frequency discrimination is the highest; thus, the communication device and the receptive system were simply not matched.

This example illustrates how the development of an artificial tactile languages demands a set of rules that is matched to the somatosensory system's capabilities and limitations. Following this premise, Geldard and his colleagues went on to develop "Vibratese", a tactile language based on both practical considerations and on results from a set of controlled psychophysical experiments on tactile discrimination [31]. Vibratese was composed of 45 basic elements – the tactile equivalent of numerals and letters – which were the intersection of three dimensions carefully chosen for their high tactile discriminability: signal amplitude, duration, and locus of interaction. The entire English alphabet and numerals 0 to 9 could be communicated this way. Geldard et al. reported that with proper training, legibility rates of more than 60 words per minute (wpm) were possible for common prose samples – i.e., reading rates approaching three times that of expert Morse code. The early successes of Vibratese in a laboratory context exemplify how careful design based on knowledge about touch is invaluable to the development of artificial tactile communication. Unfortunately, to the best of our knowledge, Vibratese seems to have completely vanished.

Throuhout the years, Geldard's early work on the development of communication through touch has inspired various researchers, a large part of which were focusing on the development of tactile aids for deaf people from the 60's to the 80's. Tactile aids aim at substituting a defective hearing channel for tactile displays capable of communicating ambient sounds (e.g., alarm, door bell, telephone ringing) or human speech. The reader is referred to [79] for a comprehensive review of the systems that were developed in and prior to those times. Interestingly, the challenges that were identified by the community then are very similar to the ones we are faced with today



(a) (b)

Figure 1: Conventional refreshable Braille display: (a) a single Braille cell is composed of 8 dots, and (b) the entire display is made up of a linear array of cells (picture printed with permission from Pulse Data International Ltd).

when developing a tactile language – mainly, the limitations of the technology and an ongoing unsatisfactory understanding of touch (more on this later).

Noteworthy work from the 80's on tactile communication for the deaf people includes Brooks et al.'s tactile vocoder that they used to train subjects (both normal and deaf) to recognize tens of spoken common words (between 50 and 250) over training periods ranging from 24 hours to over 80 hours [12–14]. These successes can be partially explained by the use of an encoding mechanism better suited to human touch capabilities. Instead of directly transducting audio frequency energy to mechanical skin stimulation (as for Gault's Teletactor covered above), Brooks et al. made use of a multi-channel encoding scheme by which speech frequency is displayed by the location of the stimuli on the skin and speech energy is communicated by stimulus amplitude.

Another tactile language developed for sensory substitution can be found in Braille. Invented more than 175 years ago, Braille still contributes to giving the blind access to the written word. The Braille alphabet consists of a series of tactile patterns that replace the sighted's printed characters. Each character (e.g., letters, numerals, punctuation) is composed of a 2-by-3 array of raised or absent of dots that were originally embossed on paper. Nowadays, Braille is also displayed by computer peripherals, called refreshable Braille displays, that make use of an extra 4^{th} row of dots to encode new characters such as "@" (Fig. 1). Despite the growing availability of other sensory substitution technology (e.g., speech synthesis), the Braille code remains an important access medium for the visually-impaired. Its success can be explained by a combination of factors. First, its physical characteristics (dot height, dot spacing, etc.) seem optimal for tactile discrimination [58, 69]. Second, it is relatively easy to produce. In fact, with a punch and portable template it is possible to use it to take notes. This played a great role in its early success. Finally, the existence of contracted Braille (made of abbreviations and contractions) makes it possible for expert users to read faster. With proper training, expert readers can reach reading rates of 100 to 150 wpm for normal Braille – about half the speed typically reported for print reading – and up to 190 wpm with contracted Braille [58]. Unfortunately, proficiency in Braille reading can only be achieved through extended amount of training (between 4 to 24 months).

Another example of a successful tactile communication system can be found in Tadoma, though it is much less widespread than Braille. Tadoma is a method used by a few deaf-blind to converse among each other and with those who can hear. It involves using the hands to monitor the lips movement and the vibrations from the vocal cords of the speaker by touching her or his face [72]. Tadoma experts are capable of high performance at understanding speech. By contrast, haptic displays that communicate speech artificially, such as the ones mentioned above, are still limited at delivering information and require extensive training.

One exception is the Tactuator device, designed by Tan et al., whose design goal was precisely to achieve high information transfer with a set of tactile stimuli that could be learned with minimum training [86]. The Tactuator is a haptic display capable of single-contact kinesthetic and tactile feedback to the thumb, the index finger and the middle finger. Tan et al. developed stimuli that were carefully designed for optimal discriminability. Based on results from two identification experiments, they estimated that the Tactuator was capable of achieving maximum information transmission rates of 12 bits/sec — i.e., comparable to that of Tadoma.[2]

2.2 Touch Iconography

Geldard's early efforts to develop Vibratese were partially motivated by the need to alleviate the cognitive load imposed on the visual and auditory channels by our environment. In his work, he also suggested using touch as a medium to grab a user's attention or to communicate a sense of urgency. Interestingly, his ideas are more pertinent than ever in today's modern world where we are constantly bombarded with visual and auditory information from a panoply of technological devices. In this computerized age, our attention is in constant demand. Whether we are working on our personal computer, trying to keep track of a busy schedule with a personal digital assistant (PDA) or driving a car, we are continually requested to shift our attention to information that must

[2]By considering the communication device and the human observer as connected systems, it is possible to make measurements about the amount of information that is transmitted. The amount of input information corresponds to the physical characteristics of the device's output stimuli. The amount of output information is related to what the human observer perceives. Finally, the amount of transmitted information is expressed by how many stimuli can be discriminated (i.e., the overlap between the input and output information) [59].

be attended immediately: an icon on the computer suddenly appears to signify that a new email was just received; a PDA starts ringing to indicate that there are five minutes left before the next meeting; an icon on the dashboard is flashing to inform the driver that the gas tank is almost empty! With the explosion of the number of features and functionalities that has accompanied the increasing availability of visual and auditory interfaces, the amount of communicated information and its complexity have also reached levels never attained before. *"What am I looking at?" "Where is this noise coming from?" "What does it mean?" "Is it important?" "How should I react?"* Such interruptions impair our cognitive abilities to the point where our visual and auditory systems are becoming saturated. In certain instances, the burden can grow so heavy that we are continuously distracted, leaving us unable to focus on our main activity: i.e, writing that letter on the computer, preparing for the next coming meeting or simply driving safely to destination.

For the reasons stated above, Geldard's idea of using touch as a communication channel has recently been revisited with the development of artificial tactile patterns such as haptic icons [54] and tactons [10, 11]. Haptic icons are short haptic or tactile signals rich in contextual information that are typically delivered via simple electromechanical means. These signals may have varying degrees of structural complexity. They share with their graphical and auditory counterparts the function of communicating low-level, abstract information such as the state or function of an object or the occurrence of an event. For their part, tactons are defined by Brewster and Brown as "structured, abstract messages that communicate complex concepts non-visually [to the skin]" [8, 11]. They are, therefore, quite similar to haptic icons with the difference that they result from the general philosophy behind auditory icons ("earcons") and make use of concepts typically associated with music and speech synthesis (e.g., rhythm, vibration, pitch) [75].

The sought attributes for haptic icons are not different from those of their visual or auditory counterparts. First and foremost, haptic icons should be practical, reliable, quick to identify and pleasant to the tactile sense without being too distracting. Therefore, they should be designed with consideration for context and task: they should not get in the way to the goal but should support it. In order to bring added-value to an interaction, haptic icons must be easy to learn and memorize; they must carry evocative meaning or at least convey a discernible emotional content. Finally, they should be universal and intuitive, while, at the same time, support increasing levels of abstraction as users become expert through repeated use.[3]

Recently, Maclean et al. have started applying and developing tools and methods to measure the discriminability of haptic icons in order to inform their design [17, 53, 54, 67, 87]. This research addresses questions such as: *What constitutes a meaningful artificial tactile signal? How should it be generated and delivered? What role does attention play on tactile perception? How many haptic*

[3]This process is referred to as "chunking" [15] and is well illustrated by the successes of contracted Braille with expert readers.

icons can an average user remember? Answers to these questions are starting to emerge. For instance, a recent study by Chan et al. found that seven vibrotactile icons could easily be learned in the absence of workload and with minimum training [17]. It also demonstrated how workload conditions, simulated with visual and auditory distractors, can significantly affect the time it takes for a user to detect a transition between two different icons. Taken together, these findings are of major importance to the development of haptic iconography.

3 Encoding of Tactile Information in Humans

From the time the skin is stimulated (e.g., by a pointy object) to the resulting perception (e.g., a localized prickly sensation), a variety of complex mechanical, perceptual and cognitive phenomena take place. At first, skin undergoes deformation that is projected to diverse mechanoreceptors underneath the surface. Next, these receptors encode and transmit the stimulus to the central nervous system where it is integrated and relayed to increasingly higher levels of brain processing for interpretation. Psychological factors, such as attention and emotion also play an important role in the perceived sensation. Designing for meaningful tactile communication should be guided by a broad and integrated knowledge of how tactile information is encoded, transmitted, and processed at various stages of a tactile interaction.

3.1 Mechanical Stimulation

A good understanding of the different modes of mechanical stimulation afforded by the skin sets the ground for a wide range of skin interactions; the skin can be tapped, vibrated, stretched, compressed, indented, and more. While not unique among all the perceptual systems in its property to convert external mechanical energy to internal neural impulses – the eardrum also carries out a similar function – the somatosensory system is the only one that offers such a wide surface for interaction. Skin is the largest organ in the body and covers almost 2 m^2 in an average adult. Therefore, in addition to the basic engineering attributes that are typically considered for the coding of artificial perceptual information (e.g., amplitude, frequency, duration, resolution and signal waveform), an extra dimensionality can be found in varying the locus of interaction [31, 94]) (e.g., by stimulating different regions of the torso).

Figure 2: Mechanoreceptors of the glabrous skin (drawing adapted from [1]).

3.2 Skin Anatomy and Neurophysiology

Microneurographic studies in humans and monkeys have revealed the presence of four types of skin mechanoreceptor afferents in the glabrous skin (Fig. 2). These are characterized by the size of their receptive field (type I for small and well-defined borders and type II for large and poorly-defined borders) and their adaptation rate to a stimulus (Slowly Adapting [SA] and Rapidly Adapting [RA]). Collected evidence indicates that Merkel cells (SA-I), which innervate the fingertip skin at 100 units/cm^2 in humans, are mainly responsible for the detection and identification of spatial patterns such as Braille dots and sharp edges [44, 45, 70]. Meissner corpuscles (RA-I), which are even more densely packed in the human finger (150 units/cm^2), are thought to be only, but highly, sensitive to dynamic skin deformation over a wide and uniform receptive field. Unlike Merkel cells, Meissner corpuscles poorly resolve spatial information but rather account for the detection and the neural encoding of skin motion. They detect low frequency vibrations and are responsible for signaling rapid state changes used for the accurate control of grip forces in prehension. Pacinian corpuscles (RA-II) are extremely sensitive to the smallest skin motion (in nanometers) and are mostly responsible for the perception of high frequency stimuli with peak responses between 200-300 Hz [44]. Therefore, they probably account for the remote perception of an object via a tool. Finally, the role of the Ruffini endings is still widely unknown, a puzzle that is accentuated by the fact that Ruffini endings have never been found, neither in the glabrous skin of monkeys, nor in the human fingerpad skin [62, 63, 65].

Knowledge about the neural mechanisms that govern the peripheral encoding of tactile information is also limited. Phillips and Johnson listed four candidates for coding texture [71]: *spatial* codes, *temporal* codes, *spatiotemporal* codes and codes based on *intensity*. The results of psychophysical and neurophysiological experiments allowed them to confirm that SA-I units are most likely to resolve spatial detail [45, 102]. Smith et al. believe that both spatial and temporal codes are used to encode roughness [81]. Results from a roughness discrimination experiment with lubrication suggest that the rate of variation in tangential stroking force is important in the subjective determination of roughness. This finding is consistent with the presence of a temporal encoding mechanism. Nevertheless, Smith et al. also noted that any roughness estimation requires a minimum surface contact between the skin and the texture, an observation that supports spatial coding. Models of tactile information transmission, such as the ones above, are typically based on variations in mechanoreceptor firing rates. However, more recently, Johansson and Birznieks have put forward the idea that complex skin spatial events might be coded by the sequence in which different afferents initially discharge [43]. In any case, the encoding of tactile information can only be explained by the spatial response of a population of SA-I mechanoreceptors [49].

3.3 Skin Biomechanics

Results from a recent in vivo study of the skin under local tangential deformation indicate strong non-linear skin properties such as hysterisis and creep [100]. Different research groups have tried to develop models for the biomechanics of the skin to infer the resulting mechanistic behavior of the various mechanoreceptors located underneath the skin. One prominent model was put forward by van Doren who compared it to measured data obtained through a psychophysical experiment on tactile sensitivities [92]. The best match between his modeled and measured sensitivities was for predicted sensitivities based on *normal strain* at the mechanoreceptor levels. This is similar to Phillips and Johnson's finding of a model that is based on *maximum compressive strain* and that predicted spatial discharge-rate profiles measured in one type of afferents (SA-I) [70]. Others have suggested that *strain energy density* might be a better candidate for the encoding of shape, at least for SA-I receptors during static tactile sensing [82]. Despite the successes in matching models to psychophysical data, it should be stressed that biomechanical models of the skin make use of idealistic assumptions such as a linear visco-elastic, homogeneous, incompressible skin medium. In reality, skin is composed of different layers and elements (e.g., ridges, epidermis, dermis, papillae) that display a variety of complex biomechanical characteristics

Biggs and Srinivasan have compared tangential deformation to indentation of the skin [7]. They used a basic continuum mechanics model to predict the strain energy density at mechanoreceptors level, for both the hairy skin of the forearm and the glabrous skin of the fingertip. In a complementary experiment, subjects were asked to adjust the magnitude of a skin tangential force so that it was perceived at the same intensity than a reference force applied normally to the skin. Interestingly, the predictions from the model roughly matched data from the psychophysical experiment: results showed a higher sensitivity to normal forces than tangential forces at the fingerpad, and the opposite at the forearm. Based on these findings, Biggs and Srinivasan questioned the effectiveness of making use of tangential displacement of the skin for tactile displays. They concluded that, despite their interesting properties, fingertip tactile displays exhibiting tangential skin stimulation would suffer from serious drawbacks such as the inherent larger stiffness of the skin to tangential stimulation.

3.4 Psychology of Touch

Simple psychophysical experiments have unambiguously demonstrated the great subtleties and capabilities of the tactile system. Mechanoreceptors are capable of both detecting very fine tactile features [83] and conveying crucial kinesthetic information, such as finger joint position [27] or contact forces to the brain [36]. Similarly, the importance of skin tangential forces for object manipulation has long been demonstrated [64, 81]. It is well known that to prevent slips when holding an object, normal forces to the grip surface are applied in reaction to variations in the tangential forces sensed at the skin level.

One debate that persists, however, is about the perceptual and physiological differences between active and passive touch. Active touch refers to the exploratory action of touching, whereas passive touch describes a stimulation of the skin brought about by some outside agent [35]. On one side, a few experiments tend to support the superiority of active touch over passive touch (e.g., [39]). On the other, concerns have been raised on whether these experiments did really constitute a fair comparison because they neglected to provide equivalent information in both modes [73]. Vega-Bermudez et al. found no significant difference in performance between the passive and active tasks of recognizing tactile letters, which suggests that the sensory neural mechanisms underlying both exploration modes are identical [96]. Surprisingly, contrary evidence suggests there does exist a phenomenon known as "gating" by which the transmission of tactile inputs to the primary somatosensory cortex is decreased during active exploration. Chapman notes that the effects of gating during active touch are likely compensated by other mechanisms that can enhance performance, such as attention and hand movement [18]. This could explain why a superiority of passive touch is rarely reported in the literature (see [55] for a unusual exception).

Various space and time interactions among tactile stimuli, and their effects on perception, are commonly reported (refer to [33, 78] for overviews of the most important ones):

- *Masking* is a phenomenon by which the performance at identifying a target stimulus is decreased by the prior or subsequent presentation of a masker stimulus [19, 23–25]. To reduce the undesirable effects of temporal masking, Craig suggests increasing the interval between two successive stimuli. On the other hand, he also notes that this can only result in lower rates of tactile communication since masking is related to the time interval between the onsets of the target and masker. Similarly, increasing the spatial distance between the masker and the target, such as displaying them on two different fingers, will likely decrease the effects of masking; however, it will also introduce undesired outcomes due to the extra attentional load imposed by having to concentrate on both stimulation sites simultaneously.

- Vibrotactile *adaptation*, or the tendency for sensitivity to decline with prior exposure to a vibratory stimulation above threshold, is yet another example of tactile interaction. Adaptation is clearly reported by a handful of psychophysical experiments that either found an increase of the sensitivity threshold or a decrease of the perceived intensity following the exposure to a conditioning vibrotactile stimulus [5, 97, 98]. Fortunately, the effect is not permanent and proper time gaps between the conditioning stimulus and the target can avoid it all together. Accumulated evidence suggests that neural adaptation takes place both at the mechanoreceptors level (i.e., expressed by a decrease in firing rates), and at higher perceptual levels [5].

- Vibrotactile *enhancement* is well-reported time interaction with an effect that is opposite to that of adaptation [34, 97]. It is expressed by an increase in the magnitude estimation of a vibrotactile target stimulus following the presentation of a conditioning stimulus with significantly higher magnitude.

- The tactile equivalent of visual *change blindness* has also been recently observed with vibrotactile stimuli [28, 29]. Change blindness is manifested by the failure to detect change in a tactile pattern that is presented repeatedly in-between interstimulus.

Interactions between stimuli have important implications for the future design and implementation of tactile displays, but they are not utterly drawbacks to the conception of an artificial tactile language. Some researchers have suggested taking advantage of well-known tactile phenomena to compensate for the technological limitations of tactile displays. Technological constraints make it difficult to pack miniature actuators in a tactile display densely enough to match the fingertip's spatial resolution. To this effect, it was suggested that the *saltation effect* (or "rabbit" effect) be used to convey the sensation of motion in between actuators of a tactile display with limited actuator resolution [33, 85]. The "rabbit" effect is the sensation that a stimulus is progressively "jumping" between two stimulation points. It is generated by delivering a series of successive taps, first at the departure point and then at the arrival point. The resulting illusion of smooth motion between the two points is strong and convincing but requires that the stimuli be delivered with tight temporal control.

4 Distributed Tactile Displays

Numerous research groups around the world have tackled the problem of building useful and cost-effective tactile displays that allow for rich tactile communication. The challenge is not a trivial one. Simplified tactile displays already play a role in tactile communication, as seen by the widespread use of vibrating hand-held devices (e.g., cell phones and PDAs). These devices rely on a single actuator (e.g., on/off eccentric rotating motor, voice coil[4]); consequently, their expressive capabilities remain limited. Rich tactile communication, on the other hand, requires *distributed* displays comprising high-density arrays of high-performance miniature actuators. There is no alternative to reproducing the complex patterns of skin deformation that occur at the fingertip when we touch an object (e.g., [52]). This situation is analogous to visual signal communication. While simple abstract communication can be achieved with a single light source, e.g. a flashing light to signal Morse code, a larger amount of information can be transmitted with a two dimensional array of pixels (i.e., a field). Given the current state of the technology and the scale of the actuation mechanisms, packing a high density of individually controlled actuators on a small surface remains a challenge. By comparison, screen technology is much more mature.

4.1 State of the Art

Most attempts to date at building distributed tactile displays have focused on devices that stimulate the fingertip because of its high tactile acuity.[5] Some have considered other regions (e.g., the tongue and mouth [3, 89], the back [2], the torso [76, 95], the thighs [21]). Generally, distributed tactile displays operate by indenting the skin with arrays of pins that raise out of a surface in order to create a discrete representation of a texture or a small-scale shape [50, 68, 93]. Other techniques make use of actuators that vibrate [16, 40, 84], that heat up [41], that blow pressured air [1], that change shape when submitted to an electric or magnetic field [6, 90], that create small currents through the skin [47, 48], and the list goes on, see Fig. 3. Among the most employed actuator technologies, we find shape memory alloys (SMA), piezoelectric ceramics, motors, pneumatic valves, Peltier elements, rheological fluids, pistons, electrodes, and others.

A number of technologies and modes of interaction have been prototyped, each combination yielding its own set of properties (The reader is referred to table 1 of the appendix for a summary of the advantages and drawbacks of each technology). Unfortunately, none of the proposed designs seems to be satisfying. To our knowledge, most of the distributed tactile displays built to this day

[4]See Audiological Engineering Corp. Tactaid^{TM} – www.tactaid.com.

[5]The lips and tongue are more sensitive to tactile stimuli than the fingertip but, by far, they do not have its spatial resolution. These organs are awkward to use, impractical or even inappropriate in most situations.

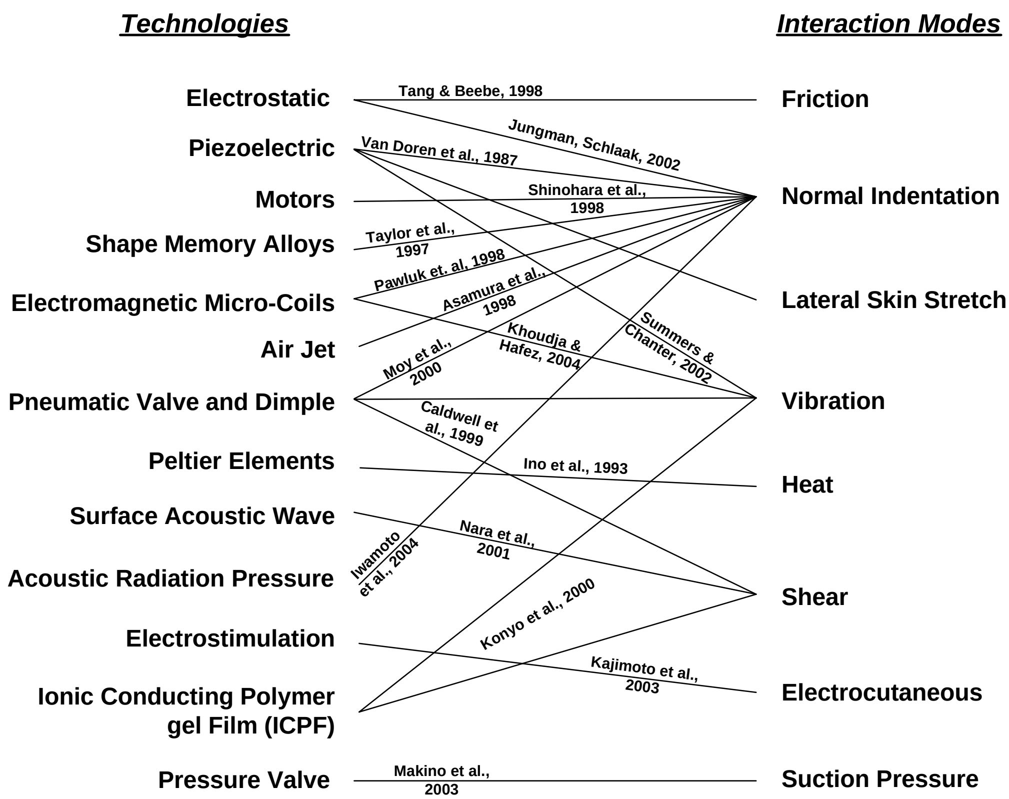


Figure 3: Examples of combinations of modes of interaction and actuator technologies for the design of tactile displays.

fail to convey meaningful tactile information and to be practical at the same time. The devices are too bulky or do not provide enough force to deform the skin. They are often constrained to a low bandwidth or are simply limited to a small number of actuators with low-spatial density. Lastly, they require constant maintenance or are too complex to operate most of the time.

For the reasons stated above, distributed tactile displays have seldom made it to the commercial market. An exception is the Optacon, a 1970s commercial sensory aid for the blind manufactured by Telesensory Corporation. The Optacon was composed of a 24-by-6 array of vibrating pins on which users would lay down their left index fingertip in order to read printed material [9,22]. Each pin of the array could be made to vibrate at a fixed frequency (around 230 Hz) or kept idle by the device's control system. The system also included a camera to allow the real-time conversion of optical information into an equivalent vibrotactile pattern. Typically, visually-impaired users would scan printed text with the camera probe in their right hand and feel the resulting tactile image under their left fingertip. Reading required dozens of hours of practice, but the device was embraced enthusiastically by a large part of the blind community. With proper training, reading rates could reach 50-100 wpm. Unfortunately, manufacturing of the Optacon was eventually discontinued because it was not commercially viable.

5 Conclusion

In 1960, Geldard noted that "almost any certain fact about somesthetic functioning is likely to prove valuable [to the development of tactile means for communication]" [32]. Unfortunately, as illustrated in section 3, the exact fundamental mechanisms governing the sense of tactile touch remain open for debate. This reality makes it difficult to infer practical considerations for the design of tactile stimuli and tactile displays. Designing an optimal tactile display requires a precise knowledge of the somatosensory system, which in turn, is one of the aspects we are trying to study with the device. Hence, we are caught in a vicious circle. Nevertheless, observations and insights collected from both the touch literature and personal experience at building tactile displays for the past few years should still guide our efforts.

Touch can be an effective means for communication. This is demonstrated by the long lasting successes of Braille (and to some extent Tadoma). Over the years, Braille has proved invaluable to the blind community. Unfortunately, the years of training that are required to master Braille make it a language that can't be accessible to everyone. Undoubtedly, there is room and potential for other means of artificial tactile communication that do not require as much training and that can appeal to the mass. As noted by Geldard when he was developing the Vibratese system: "coding to letters and numerals is really a quite pedestrian way of getting meaning into tactile patterns" [32]. This suggests that the design of an artificial tactile language should be inspired by the wide diversity of rich tactile interactions that we experience with the world on a daily basis. To this effect, some researchers have started the study and development of a universal iconography for touch that aims, among other things, at alleviating the current cognitive load imposed by modern technology.

Good design for tactile interaction should be guided by a minimum understanding of touch. This starts by recognizing the dual nature of skin, which is both intricate and subtle. Skin is a highly non-linear medium that acts as a filter between the stimulus and the mechanoreceptors.

While the exact roles and functions of the different skin mechanoreceptors remain unclear, some is known about the psychology of touch; for instance, the effects of some complex interactions between tactile stimuli presented successively have been identified (e.g., masking, adaptation). These phenomena can significantly impair the performance of tactile communication if they are not well understood or are simply ignored. Conversely, they can also be exploited to compensate for some limitations of the technology. Therefore, knowledge about the limits and capabilities of the somatosensory system should go hand in hand with the design of tactile displays.

Rich and natural tactile communication that go beyond single-point stimulation can only come from tactile displays that are capable of distributed interaction. Over the years numerous designs and technologies have been prototyped and some show potential but to this day none has succeeded at being both useful and practical. Failure to date can be partially explained by the technological challenge of having to pack a high number of fragile electromechanical actuators onto a small surface the size of a fingerpad.

Overcoming the limitations of actuator technology will not be sufficient to guarantee the achievement of a an artificial tactile language that is both usable and practical. Future work on artificial tactile feedback will also have to address the challenge of matching the tactile interactions to the tasks they are trying augment. The work involved is an exciting example of fundamental perceptual science combined with applied engineering and careful HCI design.

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Appendix

Type	Actuator	Mechanism	Nb. Act.	Interaction	Interesting Properties	Drawbacks	Ref.
Electrostatic	Capacitor with Polyimide (PI) insulator	Capacitor formed of the conducting fluids in the fingertip acting as the first plate and external electrodes acting as the other plate. A voltage induced across the capacitor creates attraction between the skin surface and the external electrode surface.	49	Friction	- Reproduction of shear forces at thesurface of the skin - Active touch device (sliding of finger)	- Large voltage (200-600 V) - Complex fabrication process of the PI layer - Fixed operating freq. (100 Hz) - Sensitive to humidity of skin	[88]
	Capacitor with polymeric elastic dielectric	Stimulator tip mounted on a stack of capacitors with polymeric elastic dielectrics. When a control voltage is applied across the capacitors, the dielectric material contracts and the position of the stimulator tip is set.	No proto.	Normal indentation	- Low cost, lightweight and flexible material - Potential for large strain (up to a few mm)	- Large operating voltage (100-1000 V) - Little current knowledge of the material properties and manufacturing process	[46]
Rheological Fluid	Electro-rheological (ER) fluid	ER fluid cell resisting the motion of the fingertip. The ER fluid changes from a liquid state to a solid state when exposed to an electric field. Altering the ER fluids state induces horizontal and vertical reactive forces during finger scanning.	25	Resistance to finger motion	- Low energy consumption - Simple mechanical design - Active touch	- Problems, such as liquid accumulation, related to the use of an ER fluid - Tradeoff between the resolution of the array and the force of the response (due to the hazard of having large control voltages close to each other)	[90]
	Magneto-rheological (MR) fluid	MR fluid placed in a Plexiglas box surrounded by solenoids. Inducing a current in a solenoid creates a magnetic field that changes the fluid to a near-solid in the vicinity of the solenoid.	16	Shape Softness	- Active exploration from the user - Both a kinesthetic device and a tactile device	- Low actuator spatial resolution - Need to wear latex glove - Large power dissipation (overheating)	[6]
Electromechanical	Piezoelectric	Bending bimorph carrying an L-shaped wire acting as the skin contactor.	100	Vibration	- Large working bandwidth (20-400 Hz) - Large spatial resolution of actuators (1/mm^2)	- Large control voltage (85 V) - Complexity of manufacturing	[84]
		Piezoelectric ceramic plates are assembled next to each other in a staggered pattern to form a 1D array of contactors.	88	Normal indentation	- Large bandwidth (0-1000 Hz) - Simple design - Controllable actuator amplitude	- Limited to displaying tactile signals in a single dimension - Mechanical coupling between the actuator plates - Weak maximum displacements of the actuators (11 m)	[93]
		Mechanically amplified piezoelectric actuator driving a vibratory pin.	50	Vibration	- Controllable actuator amplitude (5-57 m) - Simple circuitry	- Fixed operating frequency (250 Hz) - Limited to simple sensations of vibration	[40]
		Vertical movement of a contactor induced by a pair of piezoelectric levers.	48 (4000 virtual)	Normal indentation	- Vertical movement of up to 0.7mm - The device is mounted on a sliding apparatus that permits the exploration of a large surface area without the need for an extensive number of actuators	- Small spatial resolution - Large control voltage (200 V) coming out of a power supply card - Low bandwidth (20 Hz)	[57]

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Type	Actuator	Mechanism	Nb. Act.	Interaction	Interesting Properties	Drawbacks	Ref.
		Skin contactors glued on a membrane that is deformed by a matrix of piezoelectric actuators.	64 (112 contactors)	Laterotactile	- Large spatial resolution of contactors - Portability of device (e.g., can be put on a computer mouse) - New mode of interaction (lateral stretch)	- Limited actuator displacement and force - Large control voltage (±200 V) - Indirect control of the positions of the contactors	[38]
		Array of piezoelectric benders that are vertically mounted.	64	Vibrolaterotactile	- Early example of tangential mechanical deformation of the skin - Designed to fit the palm of the hand - Capable of 63 levels of intensity	- Fixed output frequency (250 Hz) - Large spatial actuator resolution (8 mm centers)	[20]
	Motor	RC servomotor slightly rotating a lever arm on which a skin contactor is fixed. The small rotation of the lever arm results in a vertical motion of the contactor. A sheet of rubber covers all the contactors to create a spatial low pass filter.	36	Normal indentation	- Large vertical displacement (up to 2 mm) - Poor actuators spatial resolution (2 mm) compensated by a rubber sheet acting as a spatial low-pass filter - A mouse attached to the display permits active exploration	- Complex control system - Fairly big and cumbersome device - Low bandwidth (25 Hz)	[99]
	Motor	2 DOF mechanism consisting of servomotors that pull and push laterally on metal pins in contact with the fingertip skin.	4	Lateral stretch	- The pins/contactors have 2 DOF - Considerable displacement and force exhibited by the pins/contactors	- Fairly complex and large mechanical structure - Limited to 4 actuators	[26]
	Motor	Miniature DC motors that remotely pull on spring-loaded pins through a transmission pulley system made of nylon tendons. The tactile interaction occurs at the fingertip, but the actuators are located on the user's wrist.	16	Normal indentation	- Portable fingertip display - Low mass - Large displacement (25 mm)	- Low bandwidth (in the tens of Hz) - Friction in the transmission system	[77]
	Motor	The rotation of a step motor is transformed into vertical movement of a skin contactor by using a lead-screw mechanism.	4096	Normal indentation	- Large contactor force - Large contactor displacement (up to a few mm) - Considerable surface area (200 mm x 170 mm) and large number of actuators	- Very slow refresh rate (15 s) - Limited to display shape (i.e., no texture) because of high contactor spatial resolution (3 mm) - Complex and expensive control system	[80]
	SMA	A shape memory alloy (SMA) wire pulls a lever that lifts a skin contactor. The contactor indents the fingertip skin.	24	Normal indentation	- Large vertical extension of the contactors - Large contact force	- Hysteretic behavior of the SMA material - Low control bandwidth (10 Hz) - Large power dissipation	[50]
	SMA	Vertical pin fixed to the middle of a SMA wire like an arrow is mounted on the wire of a bow. Controlling the length of the SMA wire with an electric current moves the pin up and down. A latex rubber membrane acting as a seal is laid on top of the pins.	Line of 10	Normal indentation	- Interesting bandwidth for a SMA device (30 Hz) - Low strain of the SMA material amplified by an ingenious mechanical arrangement	- Hysteretic properties of the SMA material - Complex cooling system - Uses a line of skin contactors instead of a matrix distribution (as a consequence, the line edges are felt)	[101]

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TYPE	ACTUATOR	MECHANISM	NB. ACT.	INTERACTION	INTERESTING PROPERTIES	DRAWBACKS	REF.
		SMA NiTi wire attached to a sprung pin in contact with the skin. An electric current induced in the SMA, makes it contract and pulls the pin down.	64	Normal indentation	- Fairly large controllable strains of the SMA wires (up to 5% - 5 mm)	- Low operating frequency (1-3 Hz) - Large heat generation	[91]
	Coil	Small electromagnetic actuators with micro-coils actuate flexible membranes at a specific frequency (also Peltier elements)	64	Vibration Heat	- Low cost fabrication technology - Relatively high density matrix (2 mm interspace) - High temporal resolution - Coupling between thermal feedback and vibrotactile interactions	- Low static force - Limited to vibrational and thermal interactions (i.e., no direct stimulation of slowly adapting skin mechanoreceptors)	[4]
		Two fixed coils and a moving magnet suspended by two helical springs act as a motor controlling the displacement of a long stainless steel probe.	400	Normal indentation	- Large contact force (up to a few Newtons) - Large displacement of the actuators (up to 25 mm) - Good actuator resolution	- Very large control system - Very complex and expensive device	[68]
Air Jet	Piston	Air jet produced by controlling the pressure through a tube with a piston.	1	Normal indentation (by air jet)	- Stimulation of superficial receptors creating a sensation ("bug creeping under the skin") not reproducible with other TDs - No direct mechanical contact with the skin	- Impossibility to get a high-resolution array due to the size of the jet actuators	[1]
Thermal	Peltier Element	Peltier Element	1	Heat	- Very simple - Capable of simulating real sensations of the quality of materials under passive touch	- Only one single actuator - Incapable of presenting dynamic information such as pressure or strain	[41]
Pneumatic	Pneumatic valve & dimple	Array of pressurized silicone tubing. By changing the pressure in the chambers, the displacement of vertical contactors in the tubes is controlled.	25	Normal indentation	- Constant contact with the finger - No leakage and no pin friction - Controllable pin displacement (up to 0.7 mm) - Highly portable	- Very low bandwidth (5 Hz) - Low spatial resolution (actuators are 25 mm apart) - Undesired operating vibration resulting from the PWM control signal	[60]
		Pneumatic inflow controlling the pressure and vibration of stainless steel pins. Pneumatic muscle generating lateral forces to simulate friction.	16	Normal indentation Vibration Shear	- Compact and integrated package capable of three different types of stimulations - Large normal force (2 N) and displacement (35 mm) - Large vibratory bandwidth (20-300 Hz)	- Complex system - Few contact pins with fairly high spacing separation (175 mm)	[16]
Electrocutaneous	Electrostimulation	Visual images are captured by an optical sensor mounted on the display before being translated into electrical tactile stimulation on the fingertip.	16	Electric current felt as: 1- vague pressure 2- acute vibration	- Can generate 2 distinct sensations (vague pressure and acute vibration) - Mounted on a force sensor to regulate the sensation magnitude and decrease discomfort - Sensor directly mounted on tactile display	- Given the technology, fairly low spatial resolution (actuators are at least 2 mm apart)	[48]
		Active electrode becomes electrically connected to ground through the fingertip when the user touches it. The current passing through the finger creates a tactile sensation of vibration and pressure.	49	Electric current	- Simple method - Possibility of large tactile resolution - Flexibility (e.g., can be put in a glove)	- Can cause pain - Adaptation to the stimulus occurs very quickly	[47]

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Type	Actuator	Mechanism	Nb. Act.	Interaction	Interesting Properties	Drawbacks	Ref.
Others	Pressure Valve	Drawing air from a suction hole contacting with the palm creates the illusion that the skin is pushed by a "muddler".	20	Suction pressure	- No interference between neighboring stimulators - Two kinds of basic patterns of stimulation (large holes and small holes)	- Very low spatial resolution (only appropriate for the palm of the hand) - Need for regulation of air pressure	[56]
	Surface Acoustic Wave	Burst of surface acoustic waves (SAWs) are used to modulate the amount of surface friction applied to a slider on which the user's finger rests. This allows the control of the shear stress applied on the finger's skin by the slider while moving. The SAWs are created by interdigital transducers.	n/a	Shear stress	- Original and unexplored method	- Not a direct-contact tactile display	[61]
	PZT transducer (producing ultrasound)	Elastic gel is covered with an ultrasound reflector and is radiated with ultrasound. The net effect is one of induced pressure on the fingertip lying on the reflector.	10 and 30	Acoustic radiation pressure Vibration	- High spatial resolution (1 mm) - High refresh rate - Free from contact problems	- Bulky system - Weak continuous pressure force	[42]
	Ionic Conducting Polymer gel Film (ICPF)	ICPF cilium-shaped actuator submerged in water. Applying an electric field between the surfaces of the actuator makes it bend.	10	Vibration (at high freq.) Shear (at low freq.) Brushing	- The softness of the ICPF material allows for very delicate touching - Low driving voltage (under 15 V) - Fairly high frequency operation (up to more than 100 Hz)	- ICPF actuators require to be submerged in water in order to bend - Low actuator resolution	[51]

Table 1: State-of-the-art distributed tactile displays for the fingertip (updated from [66])