Tangential Versus Normal Displacements of Skin: Relative Effectiveness for Producing Tactile Sensations

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Abstract

We investigated the relative effectiveness of tangential versus normal displacements of skin for producing tactile sensations. Subjects adjusted the magnitude of slow tangential and oblique displacements of a flat-ended, cylindrical, 1 mm diameter probe glued to the skin in order to match the perceived intensity of a reference displacement that indented the skin normal to the surface. At both the forearm and fingerpad, subjects chose tangential displacements only 0.3 to 0.6 times as large as the reference normal displacement, indicating a significantly higher sensitivity to tangential displacement. Based on measurements of the mechanical impedance of the skin to normal and tangential displacements, these results were also expressed in terms of forces. At the forearm, subjects were more sensitive to tangential forces than normal force. However, at the fingerpad, sensitivity to tangential forces was lower than sensitivity to normal force, due to the approximately five-fold greater stiffness of the fingerpad to tangential traction. These results provide guidance for development of tactile displays: (1) When an actuator is limited primarily in terms of peak displacement (e.g., the maximum strain of a ceramic peizoelectric actuator) then tangential stimulation is a superior choice for both body sites we tested. (2) When an actuator is limited primarily in terms of peak force (e.g., the stall torque of a DC micromotor) tangential stimulation is the superior choice for the hairy skin, but normal stimulation is the better choice on the fingerpad.

1. Introduction

Tactile displays provide information to a user through the sense of touch. Initial interest in these devices focused on sensory substitution for individuals with impaired hearing [1] [2] or vision [3], [4]. Recent years have seen a surge of interest in tactile displays, motivated by applications such as telesurgery, virtual environments, and wearable computers.

Tactile displays may be broadly divided into thermal, electrocutaneous, and mechanical displays. Thermal displays are beyond the scope of this report. Electrocutaneous displays [5] [6] [7] have the advantage of simplicity, but their success has been limited by a tendency to occasionally administer painful stings, due to the relatively narrow margin (as low as 8.1 dB) between the thresholds of electrotactile detection and electrotactile pain [8]. Complicating matters, the current required to reach these thresholds varies depending on skin moisture, the thickness of the subject's epidermis, and the quality of electrical contact.

Mechanical tactile displays elicit touch sensations by deforming the surface of the skin through the application of force. Although they are more complicated than electrocutaneous displays because of moving parts, they are generally more comfortable to use. In this report we present some perceptual results relevant to the design of mechanical tactile displays.

A basic issue in the design of any mechanical tactile display is the question of how to load the skin effectively. Actuators small enough to pack in dense arrays tend to be quite limited in peak forces and peak displacements they can generate. We wondered how to direct these forces and displacements for maximum sensation. Specifically, we investigated whether it is it likely to be more advantageous to use microactuators that displace the skin surface normally (for example, [9] [10]) versus tangentially (for example, [11] [12]) when peak force or peak displacement is limited.

1.1 Prior Studies of Tangential Skin Traction

Our review of the literature did not reveal any prior studies that compare directly the perceived intensity of tangential versus normal displacements of the skin. Prior work has shown that subjects can discern the direction of

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a tangential displacement of the finger pad [13], [14], and that the perceived intensity of this stimulus increases roughly linearly with increasing tangential force [15]. Subjects' exploratory strategies when judging smooth friction [16] suggests that humans can judge the magnitude of the tangential traction on the whole fingerpad independent of the magnitude of the normal traction applied simultaneously.

The neurophysiological basis of these abilities has been investigated, revealing that SAI units in primate finger pad give sustained responses to lateral stretch of the finger pad, and that RAI receptors give transient responses during changes in the load [14]. Other neurophysiological investigations [17] have shown that sensitivity to tangential traction on the center of the finger pad is a common feature of receptors distributed throughout the distal phalanx, observed in 97% of SAI units, 82% of SAII, 76% of FAI units, and 30% of FAII units. On average, the populations of different receptor types had different preferred directions. Thus, the peripheral code for the tangential component of finger pad load may involve receptors of all types, rather than just SAII receptors with directional tuning for skin stretch [18], [19].

2. Methods

We investigated two factors that might affect subjects' perceptions of tangential displacements of the skin. First, we tested for the effects of direction, displacing the skin surface in a variety of tangential and oblique directions, in order to gage the intensity of subjects' perceptions of these stimuli compared to normal indentation, a stimulus which has been studied far more thoroughly in terms of mechanics, neurophysiology, and psychophysics (for review see [20]). Second, we tested for effects of body site. Stimuli were applied to the finger pad, where the epidermis overlying the mechanoreceptors is thick, and the forearm, where it is thinner and softer.

The subject population consisted of three women and two men, all between the ages of 20 and 35, all in normal health, all right-handed. Before the experiment, each subject's informed consent was obtained and documented in accordance with the policies of the MIT Committee on Use of Human Experimental Subjects. Subjects were paid for their participation.

At the start of the experiment, a subject was seated comfortably in front of the apparatus. Depending on the trial, either the finger pad or forearm of the right hand was positioned within the workspace of a 3-axis Cartesian motion platform under PC control (Figure 1). Support for the limb depended on the body site under investigation. When the index finger pad was tested, the dorsal aspect of the distal phalanx was embedded in adhesive putty (Elmer's Tack, Columbus OH), and immobilized against the vertical face of an aluminum plate mounted on a manual linear micropositioner. When the forearm was tested, the subject rested it directly on the optical breadboard that supported the 3-axis motion platform. Lateral support for the forearm was provided at three locations: (1) at the knuckles a vertical plate prevented distal movement of the fist, (2) at the wrist two vertical posts cushioned with foam prevented pronation of the forearm, (3) at the elbow two vertical surfaces situated over the internal and external condoyles of the humerus fixed forearm movement due to abduction and rotation of the shoulder.

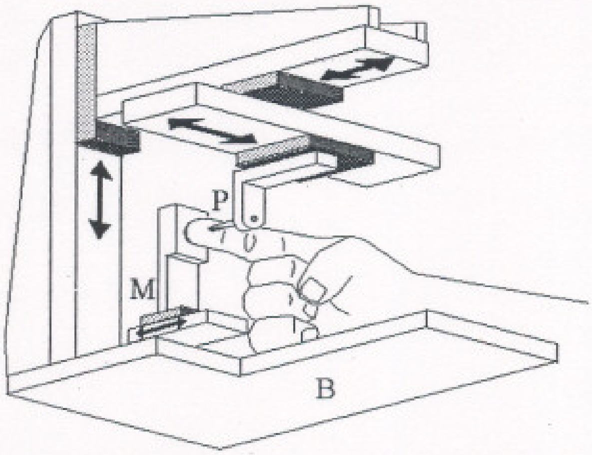

Figure 1: An illustration showing orientation of a subject's hand within the workspace of a Cartesian platform. The back of the finger and nail were embedded in putty, and attached to the vertical face of a manual linear micropositioner (M), which was used to oppose the fingertip to the probe (P) at the start of the experiment. Parts of the optical breadboard (B) have been omitted for clarity.

The motion platform was comprised of 3 orthogonal linear positioners (model 102000BN, Parker Hannifin, Harrison City PA) driven by micro stepping motors (model ZETA83-93, Parker Hannifin) to yield a nominal positioning accuracy of 12 μm on each axis. The platform carried a probe made from a stainless steel cylindrical rod ground flat on one end in order to make a circular face 1.00 mm in diameter. A thin layer of cyanoacrylate adhesive was applied to the face of the probe. It was opposed to the surface of the subject's skin and allowed to set. The probe was attached either to the center of the whorl of the right index finger pad (the preferred hand of all subjects we tested), or to the medial aspect of the forearm about 8 cm distal to internal condoyle of the humerus.

The method of adjustment was used to find points of subjective equality. Subjects were provided with a control box consisting of a one-turn rotary knob without markings, and a small push button labeled "Next." They were given a sheet with the following instructions, which they reviewed with the experimenter as part of the informed consent process, and again at the start of the experiment:

- *Press the button labeled "Next" to start a new trial.*
- *You will feel one small poke on your skin, then another, over and over again. During one poke, the computer screen will say "REF" (Reference), and during the other it will say "ADJ" (Adjustable). The "REF" pulse is always the same. The knob changes the "ADJ" pulse. Your task is to adjust the knob until the two pulses feel equally intense.*
- *When you feel like the intensity of sensation during the "REF" and "ADJ" messages matches as well as you can make it match, push the "Next" button and hold it down to get the next pair of stimuli.*
- *You can do as many practice trials as you like in order to get familiar with the task. When you feel comfortable with the task, tell the experimenter so, and then we will collect data.*
- *When we are collecting data, you will get about 30 pairs of stimuli per trial, then the machine will stop and you should take a 5-10 minute break. Most people complete one trial in about 30 minutes.*

The "Reference" stimulus was a 1.5 mm displacement of the probe straight into the surface of the skin. Depending on the trial, displacement during the "Adjustable" stimulus could be tangential, oblique, or normal with respect to the skin surface. Regardless of the direction of displacement, the orientation of the probe (Figure 1) remained constant.

Rotation of the knob caused a linear change in the magnitude of the "Adjustable" stimulus over a range from 0 to 2 mm. Once a given "Adjustable" stimulus had begun, rotation of the knob had no effect until the stimulus was completed. This insured that the displacement plateau was flat during every trial.

In order to minimize tactile cues during the dynamic part of the stimulus, the velocity of the motion platform was changed smoothly (Figure 2), with constant acceleration during the first half the ramp and constant deceleration during the second half calculated to achieve the desired displacement in one second. After each ramp, the displacement was held for one second, and then released over one second. The stimuli were applied repeatedly, with one second between presentations, until subjects pressed a button indicating that they had matched the perceived intensity of the two stimuli.

The computer monitor was used to remind subjects which stimulus was which, since preliminary trials showed that after they had brought the magnitude of the adjustable stimulus near its final value and were making small adjustments, they sometimes lost track of which stimulus they were adjusting. Most subjects consulted the monitor for the first few trials, then performed the remaining trials with their eyes closed to aid concentration, turning to the monitor only when they lost track of which stimulus was adjustable. The monitor displayed either the letters "REF" during the reference stimulus, or "ADJ" during the adjustable stimulus.

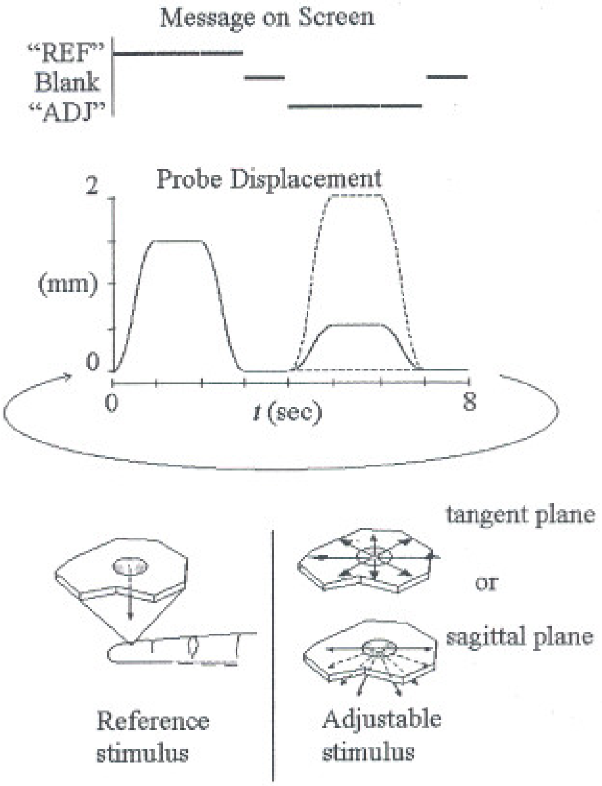

Figure 2: Messages on a computer monitor in the subject's view (**top**), gave them an indication of the timing of stimuli (**middle**). The reference stimulus (**REF**) depressed the skin in contact with the probe by 1.5 mm. The contact area is indicated by gray circles of 1 mm diameter (**bottom**) drawn in perspective around a right index finger. The direction of the adjustable displacement either lay in a plane tangent to the skin surface (one of eight directions, **bottom right**), or in the sagittal plane (one of 8 directions, **bottom right**), or repeated the reference stimulus (**bottom left**). Using a knob, subjects could control the magnitude of the adjustable stimulus (**ADJ**) over 0-2 mm range (**middle row, second pulse, dashes**), in order to match the perceived intensity of the two stimuli. Presentation of the stimuli was repeated until the subject indicated a match by pressing a button.

The 1.5 mm displacement was selected in preliminary experiments as the smallest signal on the forearm with which subjects could work confidently. Based on prior measurements [21] of perception of indentations on hand

and forearm to normal indentations at a similar frequency (1 Hz), the 1.5 mm reference pulse was above detection threshold at the forearm by about 15 dB re: 1μm peak. At the fingerpad, the reference pulse was above detection threshold by about 30 dB re: 1μm peak.

Measurements were gathered in 4 sets (2 sites × 2 planes). The site was either forearm or finger pad. The stimulation was either in the tangent plane to the skin or in the sagittal plane. In each trial subjects tried to match the reference stimulus to itself (as a control) or to one of eight experimental directions. Each of these directions was tested 3 times, for a total of 27 measurements (8 experimental directions + 1 control direction) × 3 repetitions per direction per set. Presentation order within each set was random without replacement. Order of the sets was randomized. Subjects completed data collection over one day (all 4 sets) or two days (2 sets per day). The data (5 subjects × 2 sites × 2 planes × 9 directions × 3 repetitions = 540 measurements) were analyzed offline using a scientific computing package (MATLAB™).

In preliminary experiments, subjects' data were examined for effects of fatigue or practice. No statistically significant effects were observed. In interviews, subjects indicated that they found the task straightforward. This perception was mirrored in their desire to try relatively few (typically 3-10) practice stimuli before beginning data collection.

Draping the motion platform with a black cloth that occluded subjects' view of the apparatus minimized visual cues. Auditory cues were minimized by white noise played through headphones. Skin temperature was not measured directly or controlled. However, room temperature was maintained by a climate control system set to 69°F.

3. Results

Figure 3 shows the displacements of the skin chosen to match the intensity of the reference stimulus (a normal displacement of 1.5 mm), on the finger pad and forearm. Although there was typically anisotropy in the response of individual subjects (e.g. Figure 3, S2 top view), on average (Figure 3, AVG) subjects showed comparable sensitivity to different tangential displacements, regardless of whether the direction was proximal, distal, radial, ulnar, or intermediate between these directions. Subject's perceptions of displacements in the sagittal plane (Figure 3, side views) showed considerable anisotropy. In general, the more tangential the direction, the smaller the displacement required for the subject to perceive the same intensity. Although individual variations are apparent, on average (bottom) the right and left halves of these curves were comparable, again indicating that subjects did not show a markedly different sensitivity for distal versus proximal displacements.

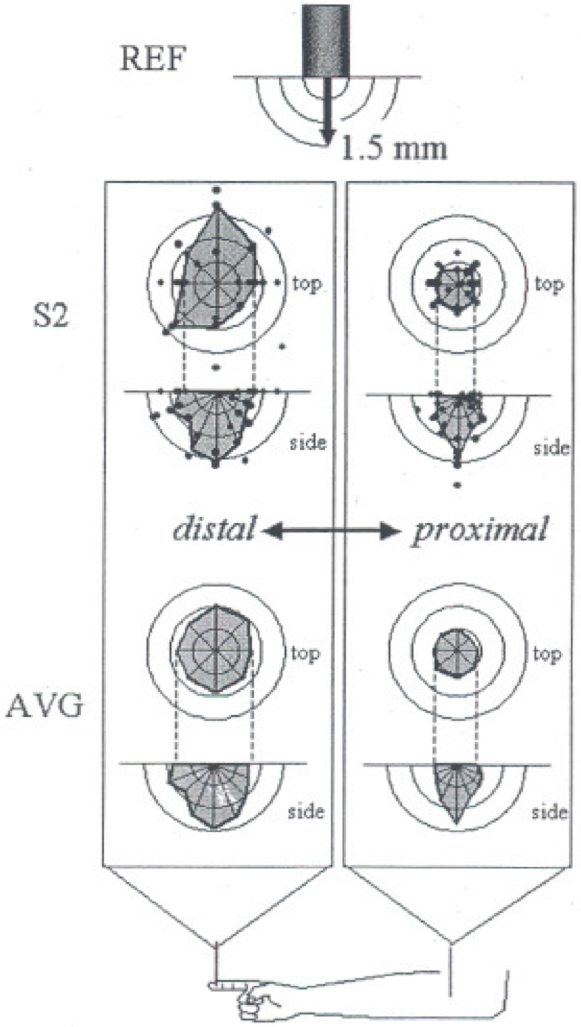

Figure 3: The control stimulus (**REF**) was a 1.5 mm normal displacement of a probe (top, **gray cylinder on surface of skin**) 1.0 mm in diameter. Points of subjective equality are shown for skin displacements in various directions on fingerpad (**left column**) and hairy skin of the forearm (**right column**). Raw data (**points**) from one subject (**S2**) demonstrates the typical scatter observed in repeated measurements. The perimeters of the filled polygons join the median response for each of the 8 tangential directions (**views labeled "top"**) and 8 sagittal directions (**views lableld "side"**) tested for each subject at each site. Plots at bottom, averaged over five subjects (**AVG**) showed no statistically significant difference in subjects' responses to displacements in different tangential directions. Tests of sagittal skin displacements (**views labeled "side"**) illustrate the transition between perception of normal displacements and tangential displacements.

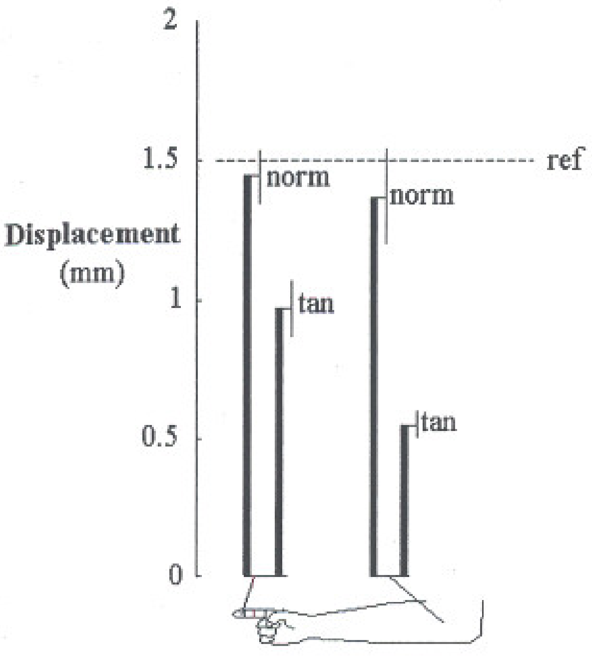

Figure 4: Mean displacement chosen to match the reference signal (**ref**, a 1.5 mm normal indentation) at two locations, (forearm and fingerpad), and in two directions (normal and tangential). At both body sites, subjects matched the reference signal with a normal indentation (**norm**) of comparable magnitude, indicating that they could do the task correctly. Significantly smaller tangential displacements (**tan**) were sufficient to match the perceived intensity of the reference signal at both body sites (at forearm $z(178)=13.89$, $p<0.005$, at pad $z(178)=9.85$, $p<0.005$). At the forearm, subjects chose significantly smaller tangential displacements ($z(298)=11.5$, $p<0.005$) than they did at the finger pad. Error bars indicate the 99% confidence interval of each mean.

Displacements (Figure 4) were expressed as forces (Figure 5) based on measurements of mechanical impedance of the skin to normal and tangential displacement at the fingerpad (normal: 0.09 mN/µm, tangential: 0.53 mN/µm) and forearm (normal: 0.03 mN/µm, tangential: 0.04 mN/µm) [22]. Although the average tangential displacements of the fingerpad were smaller (Figure 4), the average forces were larger, based on these impedances. To match the normal stimulus on the fingerpad (125 ± 40 mN) required average tangential forces approximately 4-fold larger (509 mN). However, on the forearm, subjects required tangential forces (23 mN) only about half as large as the normal stimulus (44 mN).

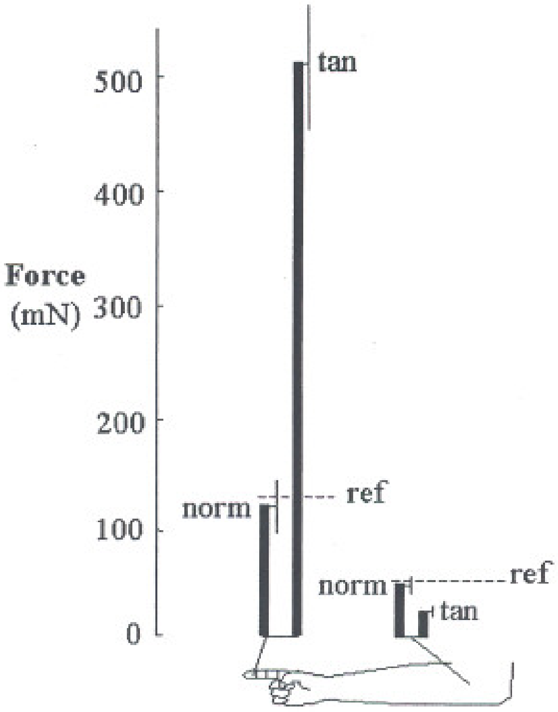

Figure 5: Mean forces chosen to match the reference signal (**ref**, a 1.5 mm normal indentation) at two locations, (arm and finger pad), and in two directions (normal and tangential). At both body sites, subjects matched the reference signal (**ref**) with a normal indentation (**norm**) of comparable force and displacement. At the fingerpad, significantly larger tangential forces (**tan**) were required in order to match the perceived intensity of the reference signal. At the forearm, significantly smaller tangential forces were sufficient. Error bars indicate the 99% confidence interval of each mean.

4. Discussion

We asked subjects to adjust the magnitudes of tangential and oblique displacements of a probe glued to the skin so that these stimuli felt as intense as a reference stimulus, a 1.5 mm displacement normal to the skin surface (Figure 2). Subjects matched the normal displacement with significantly smaller tangential displacements (Figures 2, 3), indicating that they were relatively more sensitive to tangential displacements. The effect was significantly larger at the forearm than the finger pad (Figure 4).

When these data were expressed in terms of forces, a slightly different picture emerged. At the forearm, subjects still showed higher sensitivity to tangential stimuli, selecting tangential forces only about half as large as the reference normal force. However, at the fingerpad subjects required tangential forces about four-fold larger than the reference normal force, due to the high impedance of the fingerpad to tangential stimuli.

4.1 Limitations of the Data

A concern in designing this experiment was the possibility of forward masking of the adjustable stimulus by the reference stimulus. This concern was addressed in two ways. First, presentations of the reference and adjustable stimuli were cyclic. After a few evenly spaced cycles, there was no impression of which stimulus came first. Also, the separation of the two stimuli (1 second) was long enough to fall outside the roughly ± 300 ms range in which significant forward and backward masking has been observed in presentations of vibrotactile patterns [23].

The data (Figure 4 and 5) indicate that these measures successfully controlled for effects of masking. When subjects matched the "Reference" stimulus with another normal displacement there was no statistically significant difference (Figure 4 and 5, dashed lines). However, the mean normal displacements of these control trials were slightly less than the "Reference" at both body sites, which suggests that there may have been a small systematic bias in the experiment. Our data cannot address the source of this bias. We speculate that it may have been due to the fact that a control trial typically followed an experimental trial. Since subjects were relatively more sensitive to the experimental oblique and tangential stimuli, they would have left the rotary input knob at a low-magnitude setting at the end of a given experimental trial. It seems possible that this low-magnitude starting position for the subsequent control trial might have biased responses toward lower magnitudes, perhaps causing a small bias in the control trials in Figures 4 and 5.

Another concern was the portion of the stimulus during which the probe was moving to or away from the displacement plateau. In order to achieve displacement plateaus of various magnitudes, we had to change either the velocity or duration of these ramps. Neither choice is guaranteed to be psychophysically neutral. Changes in velocity of the stimulus have been reported to alter subjects' perceptions of tactile intensity [24]. Likewise, changes in duration of the stimulus have been shown to alter subject's perceptions of skin displacement [25]. Ultimately we chose to keep the duration constant and alter the velocity of the ramp, because this enabled us to eliminate any timing cues that might have allowed our subjects to discern magnitude.

The effect of translating the stimulus across the receptive fields of many mechanoreceptors was also a concern. Prior studies have demonstrated that the response of mechanoreceptors and the perception of subjects is enhanced when a stimulus (the normal load applied by the bristles of a camel's hair brush) slides across the skin [26-28], traversing the receptive fields of many mechanoreceptors. We limited this effect as much as possible by keeping the total displacement small (less than the diameter of a typical mechanoreceptor field), keeping the peak velocity low (less than the 3 mm/s) and by holding the probe still for one third of the stimulus period.

Another choice in designing the experiment was the shape and orientation of the probe. We selected a flat-ended rigid cylinder, held at a constant orientation (Figure 1). This stimulus concentrates stress at the edges of the contact area during both normal and tangential displacement [29]. It seems possible that a hemispherical probe, which tends to develop a more uniform distribution of stress in a medium, might give different results. We chose a flat-ended stimulus for our experiments because it is a common configuration for tactile displays, for example [12], and is comparable to stimuli used in other psychophysical experiments [21].

A final issue was our decision to ask subjects about intensity of the sensation rather than about displacement of the skin or force. Estimates of displacement have been found to be less affected by velocity than are estimates of intensity [25]. Ultimately, we chose to ask subjects about their perceptions of intensity because of our interest in tactile displays.

4.2 Implications for Tactile Displays

The development of tactile displays that actively modulate tangential traction on the skin, for example, [30] and [31], has been motivated by studies demonstrating the functional importance of this stimulus for maintenance of grasp [32], and perception of texture [14]. Results of the present study suggest that tangential loads also offer some advantages in terms of eliciting tactile sensation with a minimum of skin displacement.

This advantage is particularly relevant for tactile displays that use ceramic piezoelectric transducers that are capable of producing high forces but only small displacements. A current tactile display of this type [12] demonstrates that very small lateral displacements (~0.05 mm) of finger pad skin elicit enough tactile sensation to give users an impression of skin contact with a sharp edge. It remains to be seen whether tangential traction will become a common stimulus modality for general-purpose tactile displays.

There are some practical limitations on the use of tangential displacements for tactile displays. First is the relatively high impedance of the fingerpad to tangential displacements – about 5-fold higher than impedance for normal displacement [22]. If a given stimulator design employs actuators that tend to be force-limited (e.g., DC motors) rather than displacement limited (e.g. piezoelectric ceramics), tangential tractions are not as good a choice as normal tractions for stimulating the fingertip. However, when stimulating non-ridged skin (e.g., for a body-wearable display), tangential tractions retain their advantage even when a given actuator is force-limited.

Another drawback of tangential stimulation is slip. Unless the display is glued to the skin, a preload of sufficient normal force is required to prevent relative motion. However, our experience suggests that this preload can be made acceptably small. In preliminary experiments we used a probe tipped with 600-grit sandpaper to insure a high coefficient of friction between the actuator and the skin. The pre-indentation into the finger pad (0.25 mm) required to prevent visible slip during the tangential displacements our subjects selected (typically about 0.7 mm) was comfortable for a 30 minute experiment, suggesting that this arrangement would work for a tactile display. In our final experiments we chose to glue the probe only so that the contribution of tangential displacements to tactile perception could be studied independent of normal displacement.

A third limitation of tangential tractions for tactile displays is that they provide only two of the three components of surface traction applied to skin during ordinary contact with objects. Thus, although a tangential displacement can be adjusted to create a sensation of intensity comparable to that of a normal displacement, other features of the traction and percept will not match. This mismatch was evident in the reports of two of our subjects who asked after the experiment whether "the probe sometimes went sideways." Their ability to detect the difference between the normal and tangential loads of equal subjective intensity was expected. Previous investigations have shown that subjects can discern the direction of finger pad stretch due to tangential displacement of a smooth plate [14].

Although it is probably impossible to simulate perfectly the sensation of a three-dimensional traction using a two-dimensional array of tangential actuators [12], a good approximation may be within reach. Developing rendering algorithms for this purpose is an interesting direction for future work.

5. References

[1] J. Wiesner, N. Wiener, and L. Levine, "Some Problems in Sensory Prosynthesis," *Science*, vol. 110, pp. 512, 1949.

[2] F. A. Saunders, "Electrocutaneous Displays," presented at Conference on vibrotactile communication, Austin, Texas, 1974.

[3] J. C. Bliss, M. H. Katcher, C. H. Rogers, and R. P. Shepard, "Optical-to-Tactile Image Conversion for the Blind," *IEEE Transactions on Man-Machine Systems*, vol. MMS-11, pp. 58-64, 1969.

[4] B. W. White, F. A. Saunders, L. Scadden, P. Bach-Y-Rita, and C. C. Collins, "Seeing with the skin," *Perception & Psychophysics*, vol. 7, pp. 23-27, 1970.

[5] K. A. Kaczmarek, J. G. Webster, P. Bach-y-Rita, and W. J. Tompkins, "Electrotactile and vibrotactile displays for sensory substitution systems," *IEEE Transactions on Biomedical Engineering*, vol. 38, pp. 1-16, 1991.

[6] P. Bach-y-Rita, K. A. Kaczmarek, M. E. Tyler, and M. Garcia-Lara, "Form perception with a 49-point electrotactile stimulus array on the tongue: A technical note," *Journal of Rehabilitation Research and Development*, vol. 35, pp. 427-430, 1998.

[7] H. Kajimoto, N. Kawakami, T. Maeda, and S. Tachi, "Tactile feeling display using functional electrical stimulation," presented at 9th International Conference on Artificial Reality and Telexistence, Tokyo, 1999.

[8] I. R. Summers, P. R. Dixon, P. G. Cooper, D. A. Gratton, B. H. Brown, and J. C. Stevens, " Vibrotactile and electrotactile perception of time-varying pulse trains," *Journal of the Acoustical Society of America*, vol. 95, pp. 1548-1558, 1994.

[9] G. Moy, C. Wagner, and R. S. Fearing, "A compliant tactile display for teletaction," presented at IEEE International Conference on Robotics and Automation (ICRA 2000), San Francisco, CA, USA, 2000.

[10] D. T. V. Pawluk, C. P. van Buskirk, J. H. Killebrew, S. S. Hsiao, and K. O. Johnson, "Control and pattern specification for a high density tactile array," presented at IMECE98, Anaheim CA, 1998.

[11] R. Ghodssi, D. J. Beebe, V. White, and D. D. Denton, "Development of a Tangential Tactor Using a LIGA/MEMS Linear Microactuator Technology," presented at 7th Symposium on Micro-Mechanical Systems at the ASME Winter Annual Meeting, Atlanta, GA, 1996.

[12] V. Hayward and J. M. Cruz-Hernandez, "Tactile display device using distributed lateral skin stretch," presented at International Mechanical Engineering Congress & Exposition, Orlando Florida, 2000.

[13] W. R. Gould, C. J. Vierck Jr., and M. M. Luck, "Cues supporting recognition of the orientation or direction of movement of tactile stimuli," in *Sesory Functions of the Skin in Humans*, D. R. Kenshalo, Ed. New York: Plenum, 1979.

[14] M. A. Srinivasan, J. M. Whitehouse, and R. H. LaMotte, "Tactile detection of slip: Surface microgeometry and

peripheral neural codes," *Journal of Neurophysiology*, vol. 63, pp. 1323-1332, 1990.

[15] M. Pare, H. Carnahan, and A. M. Smith, "Magnitude estimation of tangential force applied to the fingerpad," *Experimental Brain Research*, vol. in press, 2001.

[16] A. M. Smith and S. H. Scott, "Subjective scaling of smooth surface friction," *Journal of Neurophysiology*, vol. 75, pp. 1957-1962, 1996.

[17] I. Birznieks, P. Jenmalm, A. W. Goodwin, and R. S. Johansson, "Directional encoding of fingertip force by human tactile afferents," *Acta Physiologica Scandinavica*, vol. 167, pp. A24, 1999.

[18] A. B. Vallbo and R. S. Johansson, "The tactile sensory innervation of the glabrous skin of the human hand," in *Active Touch*, G. Gordon, Ed. New York: Pergamon Press, 1978, pp. 29-54.

[19] B. E. Edin and N. Johansson, "Skin strain patterns provide kinaesthetic information to the human central nervous system," *Journal of Physiology*, vol. 487.1, pp. 243-251, 1995.

[20] C. E. Sherrick and R. W. Cholewiak, "Cutaneous Sensitivity," in *Handbook of Human Perception and Human Performance*, vol. I, K. R. Boff, L. Kaufman, and J. P. Thomas, Eds. New York: John Wiley and Sons, 1986, pp. 12-1 - 12-57.

[21] J. C. Makous, G. A. Gescheider, and S. J. Bolanowski, "The effects of static indentation on vibrotactile threshold," *Journal of the Acoustical Society of America*, vol. 99, pp. 3149-3153, 1996.

[22] T. T. Diller, *Frequency Response of Human Skin in Vivo to Mechanical Stimulation*. Master of Science, Mechanical Engineering, Massachusetts Institute of Technology, 2001.

[23] J. C. Craig, "Tactile pattern perception and its perturbations," *Journal of the Acoustical Society of America*, vol. 77, pp. 238-246, 1985.

[24] J. D. Greenspan, D. R. Kenshalo, and R. Henderson, "The Influence of Skin Indentation on Threshold and Suprathreshold Tactile Sensations," *Somatosensory and Motor Research*, vol. 1, pp. 379-393, 1984.

[25] P. R. Burgess, J. Mei, R. P. Tuckett, K. W. Horch, C. M. Ballinger, and D. A. Poulos, "The neural signal for skin indentation depth I. Changing Indentations," *The Journal of Neuroscience*, vol. 3, pp. 1572-1585, 1983.

[26] J. Greenspan, "Influence of velocity and direction of surface-parallel cutaneous stimuli on responses of mechanoreceptors in feline hairy skin," *The Journal of Neurophysiology*, vol. 68, pp. 876-889, 1992.

[27] B. B. Edin, G. K. Essick, M. Trulsson, and K. A. Olsson, "Receptor encoding of moving tactile stimuli in humans. I. Temporal pattern of discharge of individual low-threshold mechanoreceptors," *The Journal of Neuroscience*, vol. 15, pp. 830-847, 1995.

[28] G. K. Essick and B. B. Edin, "Receptor encoding of moving tactile stimuli in humans. II. The mean response of individual low-threshold mechanoreceptors to motion across the receptive field," *The Journal of Neuroscience*, vol. 15, pp. 848-864, 1995.

[29] K. L. Johnson, *Contact Mechanics*. Cambridge: Cambridge University Press, 1985.

[30] B. B. Edin, R. Howe, G. Westling, and M. Cutkosky, "A physiological method for relaying frictional information to a human teleoperator," *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 23, 1993.

[31] D. G. Caldwell, N. Tsagarakis, and C. Giesler, "An integrated tactile/shear feedback array for stimulation of finger mechanoreceptor," presented at IEEE International Conference on Robotics and Automation, Detroit, 1999.

[32] G. Westling and R. S. Johansson, "Responses in glabrous skin mechanoreceptors during precision grip in humans," *Experimental Brain Research*, vol. 66, pp. 128 - 140, 1987.