

Spatial Low Pass Filters for Pin Actuated Tactile Displays

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Abstract

A common tactile display design uses an array of mechanical pins covered by a rubber layer which acts as a spatial low pass filter. To characterize the perceptual relationship between this rubber layer and shape rendering, we conducted psychophysical experiments to examine the perception of a vertical line stimulus felt using rubber covers of varying thickness and stiffness. We found no significant change in perception for rubber thicknesses ranging from 1.5-3.0 mm and for stiffnesses ranging from 45-200 kN/m².

1. Introduction

Tactile display devices aim to realistically simulate the shape of virtual or remote objects. These devices stand to enhance teleoperation systems, which currently include only visual and force feedback. By including tactile feedback to the fingertip, the operator receives more information about the shape and spatially distributed forces in a remote environment than current systems allow. It has also been shown that spatial acuity, orientation detection, and detection of a lump by palpation are all impaired when contact forces are not spatially distributed [1]. This is important in applications such as remote medicine and minimally invasive surgery, where more informed decisions could be made with the addition of tactile feedback.

The prevailing tactile display design uses an array of pins to transmit shape or spatially distributed force information to the fingertip. Many methods have been used to actuate an array of this type, including shape memory alloy [2], pneumatics [3], voice coil actuators [4], and solenoids [5]. One important component of these pin actuated display designs is the spatial low pass filter used to make discrete pins feel like a single continuous object. For rigid mechanical pin displays, a rubber layer is commonly used as this filter. Unfortunately, it is not clear what the mechanical properties of the optimal rubber should be for use across all applications. Past research has examined the optimal rubber thickness for teletaction [6]; however, no metric

was developed to relate pin diameter and spacing to the correct rubber thickness and stiffness.

Parameters in rubber selection include the relationships among rubber type, rendering algorithm, and human perception. We chose to examine this question by attempting to render a simple vertical line that would feel the same at all lateral locations on the display. We hypothesized that there is a relationship between both the rubber thickness and stiffness and the perception of the line. More specifically, we anticipated that we could convincingly render thinner lines using stiffer and thicker rubber types. To examine these ideas, we conducted two psychophysical experiments. Experiment 1 investigates the relationship between the perception of the line width with respect to varying rubber cover thickness. Experiment 2 investigates line perception with respect to varying rubber stiffness. Both experiments attempt to discover line width threshold values for the thinnest line that can be felt as the same at all lateral points on the tactile display for each rubber type.



Figure 1. Pin actuated tactile display

2. Experiment 1: Thickness of rubber cover

2.1. Participants

A total of eight graduate and undergraduate students, ages 17-24 years, volunteered for monetary reimbursement. All subjects defined themselves as right-handed and had no known abnormalities in either hand.

2.2. Tactile display, rubber covers, and stimuli



Figure 2. The display showing a sinusoidal grating

The tactile display in the current experiment uses RC servomotors to actuate a 6x6 array of pins [7] (Figure 1). The pins are 1 mm in diameter with 2 mm on-center spacing in a square grid. They have a 2 mm height range with 0.1 mm height resolution. The mean pin stiffness of 5 kN/m is high enough that the display can be used to transmit shape information to the fingertip. Figure 2 shows the tactile display with a two-dimensional waveform stimulus.

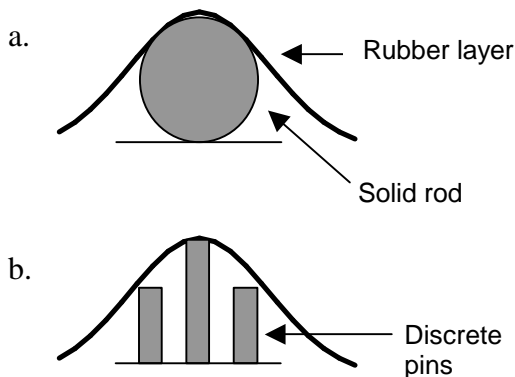


Figure 3. (a) physical object (cross-section of solid rod); (b) simulation by discrete pins

We used a vertical line as a stimulus to eliminate complications that might be created by more complex shapes. To represent a line in three dimensions, we used a Gaussian curve to simulate a rod lying on a flat surface (Figure 3). We selected a Gaussian because it is a low frequency shape, which will reduce aliasing effects, it provides the smooth, continuous shape required to effectively simulate a rod, and it is relatively simple to render. It also has zero derivatives on the tails. The following equation defines the height of a pin, z , located at x , when the center of the Gaussian is located at x_m . The peak height of the shape is h_{max} . We define the term “line width” as the variance (σ^2) of the rendered Gaussian line.

$$z = h_{max} e^{-\frac{(x-x_m)^2}{2\sigma^2}}$$

Because of the spacing of the pins and the nature of the Gaussian algorithm, lines centered directly over a column of pins are displayed differently from lines centered directly between two pins (Figure 4). This difference is accentuated as the width of the line is decreased. Though the Gaussian curve is inherently a low frequency shape, the discrete nature of the pins introduces high frequency noise, distorting the user’s perception of the displayed shape. The rubber layer acts

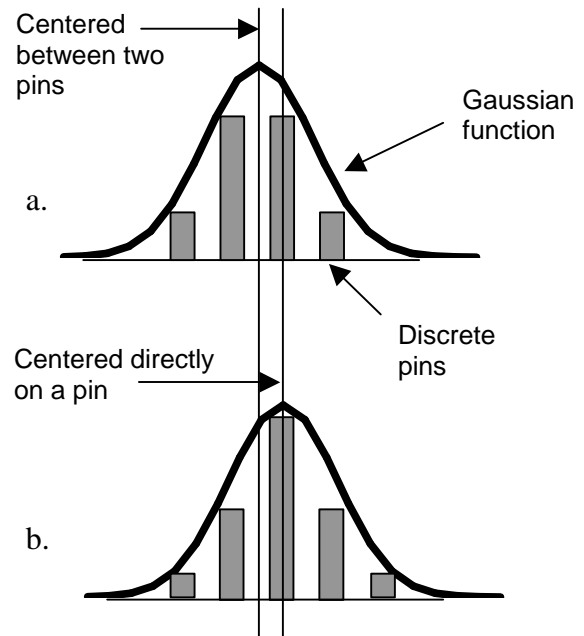


Figure 4. The same waveform is displayed differently when it is (a) centered between pins and (b) centered directly between pins

as a spatial low pass filter over the pins and eliminates some of this shape fluctuation; however, we anticipated that there is some threshold value below which the rubber layer can no longer conceal this effect. To test this idea, we simulated a rolling rod which moves back and forth across the display. At low widths, the height of the simulated rod oscillates, with its highest point at every location where it was displayed directly on a pin and its lower height where it was displayed exactly between two pins, as illustrated in Figure 4. As the width of the Gaussian increases, this effect decreases. Our goal was to find the thinnest line that would feel the same at all lateral points on the display for each of the various rubber filters provided.

We created rubber strips of varying thicknesses using a silicone mold-making rubber (HSII RTV Base and Colored Catalyst, Dow Corning). These rubber strips had thicknesses ranging from 1.5-3.0 mm in 0.5 mm increments. All had a commercially specified durometer value of 16 measured on the Shore A scale. These values were chosen based on previous research [6, 8] and our own pilot work. Fearing et al. stated that for a tactile display with 2 mm pin spacing, the best range for rubber thickness is between 2 and 3 mm; in addition, our early pilot studies showed that any thickness lower than 1.5 mm allows the user to feel individual pins.

2.3. Experimental Design

The experiment used was a two-factor, within-subject repeated measures design with rubber thickness (4 levels) and trial repetition (12 levels) as the two main factors. The four rubber thicknesses were presented in blocks, with 12 repetitions per block. The Method of Adjustment [9] was used to determine the width threshold in each trial. Subjects were presented alternating large and small widths, chosen using pilot work. There were three large and three small widths that were counterbalanced across trials so that subjects would have to adjust different amounts for each trial. The order in which the four rubber thicknesses were presented was counterbalanced across subjects.

2.4. Procedure

Participants were told that they would feel a simulation of a rod moving back and forth across the display. They were asked to adjust the width of the rod until they had created the thinnest rod whose shape remained constant at all points on the display, where shape was defined as width and height of the rod. Participants felt the display with the index finger of the left hand and controlled the width of the rod on a standard mouse with their right hand. The left mouse

button decreased the width of the line while the right button increased it. The amount of change in width was proportional to the time the mouse button was held down, with a continuous rate of 2 mm/s. A single click changed the width by approximately 0.12 mm.

Before beginning the experiment, participants were shown animations of a rod moving across a flat horizontal plane, similar to Figure 3(a), contrasted with animations of an oscillating rod. They then felt examples of both cases using the display and were given time to gain familiarity with the interface.

Participants were given no time limits to complete the task, although they were told that normal times were about 30-75 seconds per trial. Participants adjusted the display until they felt confident and pressed a button to move on to the next trial. Average trial time was approximately 45 seconds. The speed of the moving line ranged from 1.2-1.8 mm/s and was counterbalanced across trials. These speeds were all slow enough to prevent temporal aliasing. Pilot studies had indicated that performance was not affected by such differences in speed. Participants received no visual feedback during the experiment; to eliminate audio cues, they wore earplugs and headphones playing noise in the frequency range of sounds made by the tactile display.

2.5. Results

A two-factor, within-subject ANOVA was performed on the subject-selected line widths. The factors were rubber thickness (4 levels) and repetition (12 levels). The main effect of rubber thickness was not statistically significant, ($F(3, 21) = 0.86, p > .05$). The mean line width values with corresponding standard errors were 3.20 (0.47), 3.66 (1.10), 3.56 (0.55), and 3.50 mm (0.62) for rubber thicknesses of 1.5, 2.0, 2.5, and 3.0 mm, respectively (Figure 5).

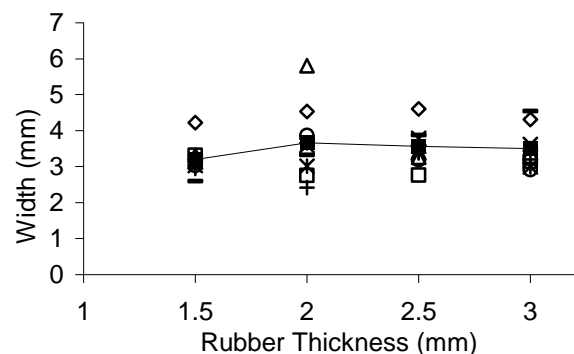


Figure 5. Experiment 1: Mean line width (mm) as a function of rubber thickness for each subject. Symbols indicate individual subjects; means are connected by the line.

The main effect of repetition was found to be statistically significant, ($F(11, 77) = 2.35, p < .02$). A trend analysis was conducted on the repetition effects. Neither the linear nor quadratic trends were significant ($F(1, 7) = 1.87, p > 0.2$ and $F(1, 7) = 0.002, p > 0.9$, respectively). Although the cubic effect was statistically significant ($F(1, 7) = 11.29, p < .02$), the trend was not particularly informative for current purposes.

The interaction between rubber thickness and repetitions was not significant ($F(33, 231) = 0.97, p > 0.5$).

3. Experiment 2: Stiffness of rubber cover

3.1. Participants

A total of eight participants was drawn from the same subject pool as used in Experiment 1.

3.2. Apparatus, Experimental Design, and Procedure

The tactile display and stimulus were the same as in Experiment 1. The four rubber cover types used in Experiment 2 were 1.5 mm thick Neoprene strips, with commercially specified durometer values of 10, 20, 30, and 40 measured on the Shore A scale. The choice of these values was based on the result of pilot work and commercial availability.

Table 1. Commercially specified durometer and experimentally calculated modulus values for the different rubbers

Durometer (Shore A)	Modulus (kN/m ²)
10	65.1
16 (silicone)	46.4
20	66.9
30	83.0
40	210.4

Although we chose the rubber types based on their commercial properties, in order to accurately characterize the rubbers, we calculated the modulus of each rubber type using elongation tests (Table 1). Note that the calculated modulus of the silicone rubber is

actually lower than the modulus of the softest neoprene rubber.

The experimental design and procedure were both the same as those of Experiment 1.

3.3. Results

A two-factor ANOVA was performed on the subject-elected line widths, with factors being stiffness (4 levels) and repetition (12 levels). Although there appears to be a slight upward trend, indicating that the width participants chose increased as the stiffness of the rubber increased, the trend is not significant ($F(3, 21) = 2.36, p > .1$). The mean values with corresponding standard errors were 3.97 (0.88), 3.98 (1.26), 4.17 (1.09), and 4.67 mm (1.41) for rubbers of increasing modulus (Figure 6). Included in Figure 6 is a reference value indicating the relation of the 1.5 mm RTV rubber to the four Neoprene rubbers. This point is consistent with the upward trend displayed by the four Neoprene rubber types; however, since this data was obtained from a different group of subjects, no statistical analysis or conclusions can be drawn from it.

The main effect of repetition was statistically significant ($F(11, 77) = 3.55, p < .001$). A trend analysis on these results indicated that neither the linear nor quadratic trends were significant ($F(1, 7) = 0.86, p > 0.3$ and $F(1, 7) = 2.19, p > 0.15$, respectively). The cubic effect was significant ($F(1,7) = 10.10, p < .02$) but not informative for current purposes.

The interaction between rubber stiffness and repetitions was statistically significant ($F(33, 231) = 1.62, p < .05$). Regardless of stiffness level, the mean line width tended to decrease from Trial 1 to Trial 2, after which point it remained fairly constant until Trial 11, with one exception. The mean line width for the stiffest rubber (40A) tended to increase fairly linearly from Trial 6 through Trial 11. Mean line width decreased from Trial 11 to Trial 12, regardless of rubber stiffness. We note that the large number of degrees of freedom may have been primarily responsible for the marginal significance of this complex interaction. We therefore believe it is reasonable to refrain from discussing it further.

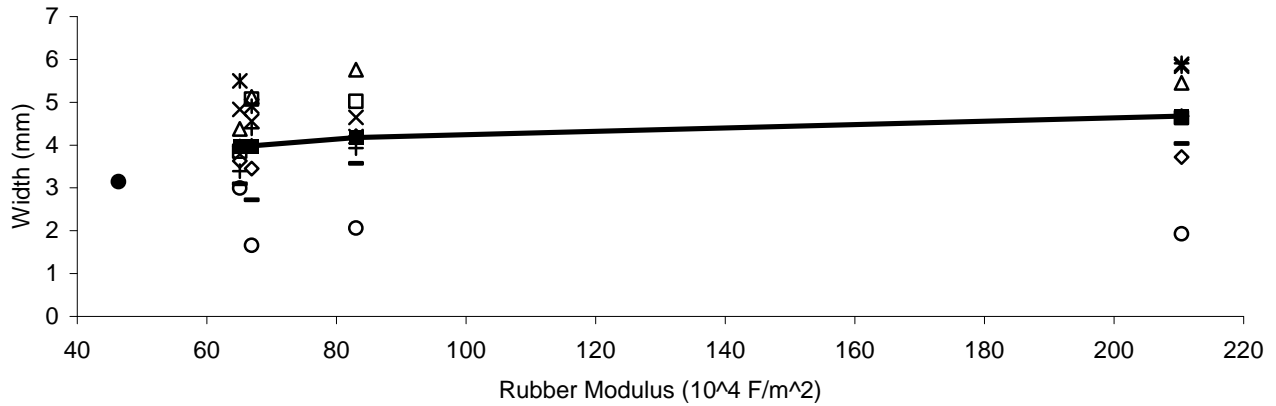


Figure 6. Experiment 2: Mean line width (mm) as a function of rubber modulus for each subject. Symbols indicate individual subjects; means are connected by the line. A reference point for the mean threshold value of the silicone rubber is shown on the far left of the graph.

4. Force Measurements

To examine the relationship between threshold value and the force applied to the tactile display, we ran two additional small studies with the last two subjects from both Experiments 1 and 2. The experiments were conducted with the same procedure as before with one addition: a small digital scale was placed beneath the display to measure the forces applied during the experiment at a rate of 5Hz.

Participants in the force measurement experiment study pressed down on the display with forces ranging from about 2-4 N (Figure 7). A finger resting on the display without applying pressure created a force of about 1-1.5 N. There were no obvious trends relative to force with respect to either rubber thickness or stiffness.

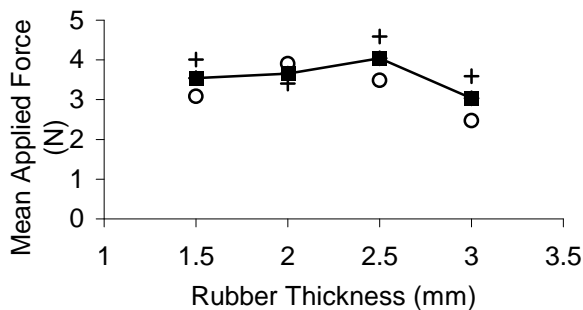


Figure 7. Example of force data: Mean applied force as a function of rubber thickness for each subject

The only apparent result was that all participants, in both experiments, tended to use more force for each subsequent block (Figure 8).

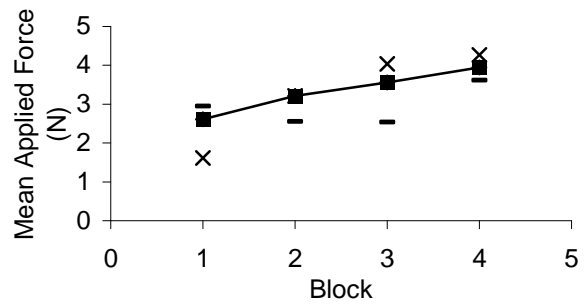


Figure 8. Example of order effects: Mean applied force as a function of block order for each subject

5. Discussion

Our goals were to examine the human perception of vertical lines displayed by a tactile feedback device to the fingertip and to choose the most appropriate rubber filter to be used when displaying this type of stimulus. Because of the nature of the display and the Gaussian rendering algorithm we employed, lines centered in different lateral locations on the display are displayed differently. Our experiments were designed to find the smallest width of a vertical line that would feel the same when represented at any location on the display. We hypothesized that this threshold width would change with varying thickness or stiffness of the rubber filter layer, and more specifically, that thinner or softer rubbers would require a larger threshold value.

Unexpectedly, the psychophysical data reveal that small changes in thickness do not affect the line width threshold. Rubber stiffness has no effect either, unless the RTV sample from Experiment 1 is included; however, even then, the magnitude of the upward trend

is very slight (Figure 6). Such an outcome is not only surprising because the results failed to show the trend that we had hypothesized, but also because the conclusion that increases in stiffness require an increase in threshold is somewhat counterintuitive. We assumed that a stiffer rubber would make it more difficult to feel slight fluctuations in the shape of the moving rod. However, one can consider putting an extremely stiff material on top of the display, for example, a thin piece of metal. It would then become much easier to feel small height oscillations, and, thus, a higher threshold is required.

This trend is still very slight, and mean values for both experiments were all similar. One possibility is that the thicknesses and stiffnesses tested each spanned a range that was simply too narrow to elicit any perceptual differences. However, the ranges were chosen on the basis of results from previous research [6, 8] and from our own pilot studies. We would therefore argue that testing values outside of these ranges would be inappropriate for our goal, which was to generate results that are useful for practical design.

Another concern was that the discretization of the adjustable line width responses may not have been precise enough for the current task. Consider the consequences if participants could only adjust the line width with a response precision that was lower than the participants' abilities to differentiate the stimulus. The participants would likely select similar line widths as only a small number of appropriate responses would be available. However, a single, quick mouse click creates a difference of only 0.12 mm in width, a change that was indiscernible to all participants. We conclude that the response precision was appropriate for the experiment.

Alternatively, threshold values may have been similar because participants changed the force they applied in order to achieve the same stimulus levels with the different rubber types. To do so, they may have applied more force when the rubber layer was thicker or stiffer. Our small force measurement studies examined this idea, but no relationships between force and either rubber thickness or stiffness were observed. However, it was observed that subjects tended to use more force with each subsequent block of trials. This result suggests that participants may have experienced adaptation or fatigue effects over successive blocks of trials. Additional force measurement experiments are necessary to explore this effect further and to potentially discover relationships between applied force and rubber type.

The current experiments have specific relevance to pin actuated tactile displays, where aliasing in rendering will always be an issue. Our future work will be directed towards the question of how to create the most appropriate rendering algorithms for this type of display and stimulus. We believe that this area needs to be

approached from a perceptual standpoint in which rendering algorithms must be verified by perceptual experiments. Future work will include determining the tactile resolution for perceiving line orientation and developing an algorithm based on those results.

Differences in rubber thickness and stiffness do not significantly change the threshold for feeling a line as the same at all lateral points on the tactile display. These results suggest that those who wish to design a tactile display in the future need not worry about what type of rubber they choose as a low pass spatial filter, provided it falls within appropriate stiffness and thickness ranges evaluated in the current study.

6. References

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