# FINGERTIP HAPTICS: A NOVEL DIRECTION IN HAPTIC DISPLAY

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## Abstract

*"Fingertip haptics" refers to the direct exploration of a virtual environment with the fingertips, rather than through an intermediate grasped object, such as a stylus or thimble. This paper describes our investigation of fingertip haptics to date, and continues to study a novel approach to rendering slip at the finger pad. We use a rotating drum to render the velocity of a surface as it passes beneath the fingertip. Our previous work resulted in a prototype device in one degree of freedom that helped test two groups of 14 subjects on their ability to sense the nature of the fingertip contact sensation (i.e., whether an actual surface or a rotating drum renders the contact sensation). The experimental results in this paper show strong justification of our mechanical approach to rendering relative velocity at the fingertip, and demonstrate fingertip sensitivity to mechanism dynamics.*

## 1 Introduction

Many dexterous tasks rely on the sophisticated information conveyed through the hands and skin by touch. Some activities depend on touch sensations only as a complement to visual or auditory information, while other activities rely solely on touch. For example, a clothing shopper might unconsciously handle a fabric at the store while also examining the patterns and color in making a decision. Alternatively, a doctor may rely completely on touch to determine the presence of cancer in tissue. In each case, fingertip exploration is crucial to identifying and understanding objects. In attempting to provide touch information through a device, most haptic interfaces require an operator to either grasp an implement (e.g., a stylus) or physically bind him or herself to a device in some way. These approaches exploit the natural psychophysical phenomenon of *distal attribution* in relating information about the object to the user. Although effective at providing touch feedback in many situations, it is apparent that holding or binding the finger to an implement or tool does not capture some of the most basic physical sensations of fingertip-to-surface interaction. The natural consequence of indirect surface interaction is evident in the work by West and Cutkosky (1997). They show that actual fingertip tracing performance exceeds both tracing with a probe and virtual tracing with a probe (even though this result is not the original intent of the work).

Key pieces of the fingertip haptics vision are under investigation or already in place in the haptic community. For example, Kontarinis and Howe (1995) show that the addition of frequency (or vibration) information to haptic feedback proves to be a major component in dexterous performance. In particular, high-frequency information, when combined with gross force feedback may in some cases be sufficient to perform a wide range of tasks (Okamura et al., 1998). Another key piece, friction during finger exploration, applies low frequency shear forces on the fingertip. Modeling these forces and fingerpad dynamics is the subject of a great deal of community effort (Pawluk and Howe, 1999), (Nahvi et al., 1998). Siira and Pai, (1996) model stochastic contributions of slip to fingerpad friction. A third key piece of fingertip haptics comes from work such as Venema and Hannaford (2000). Using a fingertip haptic device, they quantify localized surface discontinuity perception through the fingertip. Finally, as an essential piece of fingertip haptics, we believe the sensation of slip at the fingertip contains information vital to realistic surface rendering.

Gross slip and partial slip have long been topics of research relating object slip and grip force (Johansson and Westling, 1984), (Stojiljkovic and Clot, 1977). The majority of the work on slip has been at the end effector, e.g., on robotic fingers, detecting the condition. Recent work by Yamada et al. (2001) presents finite element analysis of an artificial fingertip that includes the dermal ridges and curvature of the fingertip, explicitly modeling partial slip as a means for controlling grip strength. Using a rolling element to detect slip has been a viable option for robotic manipulation. Masuda, Hasedawa and Osako proposed a roller to detect slip on robotic grippers as early as 1976 (Masuda et al., 1976). In contrast, we use a roller to *deliver* slip to the user's fingertip. Our research anticipates a significant increase in realism by including slip with other key fingertip haptic sensations. In previous work (Salada et al., 2002) and in this paper, we show that rotating a drum beneath the fingertip creates a thoroughly convincing slip sensation. This is a first step in a research program aimed at creating more sophisticated fingertip haptic devices.

## 2 Work to Date

Our initial work on fingertip haptics established the validity of rendering slip at the fingertip with a rotating drum by analyzing subject response a question on surface recognition (Salada et al., 2002). We continue the analysis here by examining the second, comparative question also presented to subjects during the same test to establish the degree of perception in a relative sense. In particular, even though subjects were not able to significantly discriminate between a fixed surface and the rotating drum with the fingertip, we investigate if they could perceive a change between the two surfaces. Before analyzing the comparative question in the experiment, this work discusses the experimental setup and explains the method of measuring perception.

## 2.1 Experimental Setup

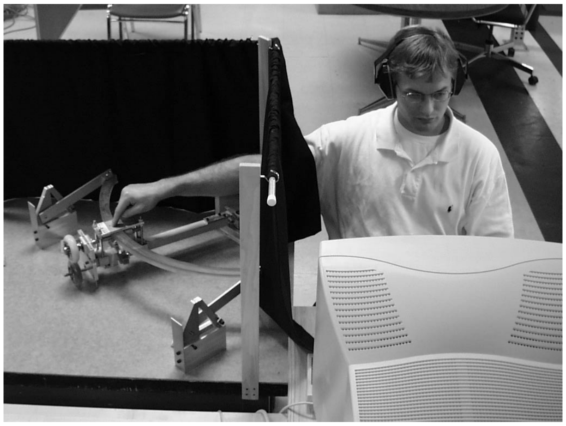
Figure 1: Subject in Test Apparatus During Testing

We postulate that the sensation of sliding one's finger along an actual surface is nearly indistinguishable from the sensation felt by rotating a drum beneath the finger during the same movement. In the summer of 2001, we constructed a device to test this hypothesis that allowed us to quickly swap between a fixed, flat surface and a rotating drum as presented to the finger through an aperture. The rotating drum surface delivers the same velocity as the fixed, flat surface through mechanical linkage during user movement. We isolated human test subjects from visual and acoustic cues and posed a set of questions about the one-dimensional surface they felt through a pair of circular apertures.


Figure 2: Surface Training Unit

A photo of the test apparatus with a subject during testing is in Figure 1. We tested a total of 28 subjects, separated equally into "knowledgeable" and "naïve" groups. We acquainted the knowledgeable subjects with the test apparatus, revealing that in some cases a fixed, flat plastic surface would be beneath the fingertip aperture, and in other cases a rotating drum with the same surface finish would be beneath the aperture. The naïve subjects were not informed of the two different ways of rendering the sensation of a surface, but were trained on the sensation of touching a plastic surface through an aperture prior to testing with a "training unit." (See Figure 2.) In testing either group, the subjects placed their finger on the aperture and moved back and forth, feeling the either the drum or the fixed, flat surface slip beneath their fingertip. We list some key apparatus dimensions in Table 1.

| | |
|---|---|
| Diameter of Rotating Drum: | 5.84 cm |
| Radius of Movement Arc: | 38.74 cm |
| Big/Small Aperture Diameters: | 1.27/0.953 cm |

Table 1, Key Apparatus Dimensions

We asked subjects to explore the "surface" through the aperture 8 times during a Session (we label each opportunity an "exposure"). We posed two questions each exposure, one "absolute," and the other "comparative." For the knowledgeable subjects, the absolute question asked which surface they felt, the flat surface or the rotating drum. We asked the naïve subjects a much more general absolute question, "Do you feel a surface or not?" The absolute question attempted to quantify the basic effectiveness of the illusion of a surface. As a follow-up question for each exposure, participants in both groups received the same second question:

Question #2:

This surface isn't anything like the last surface.
Can't say one way or the other.
This surface is identical to the last surface.
<--(1)---------------(2)---------------(3)---------------(4)---------------(5)-->

Figure 3: Comparative Question for Each Exposure

Of course, this follow-up question is not given after the first exposure since no comparison is available, for a total of seven comparisons per subject per Session. Just as with the absolute question, we opted for a five-point scale response rather than a forced-choice comparison to allow for an evaluation of confidence. The comparative question serves two purposes. In the event that a subject could perceive the difference between the drum and the flat surface, but had simply guessed incorrectly, the relative question would reveal accurate perception even though the absolute question may have indicated otherwise. Asking the second question also reduces participant boredom in the event they are frustrated by the lack of ability to discern anything changing. A more complete description of the experimental apparatus and set up is in Salada et al. (2002).

# 3 Considering Question #2

We were careful to maintain a balance in the number of exposures to each surface and aperture combinations during a Session (there are a total of four combinations, two "surfaces" with two differently sized apertures). However, to eliminate any presentation order bias, a random algorithm created the presentation order, unique to each participant. Unfortunately, this did not allow us to perfectly balance all of the possible exposure presentation orders (4 total).[1] Table 2 shows the number of transitions from one combination to the next for all twenty-eight participants, separated by group. The analysis of the comparison data is subject to some statistical critique in the event the number of data points falls below 12 (a conventionally accepted minimum number of measurements for statistical analysis). Only one class of transitions falls below this rule of thumb in our experiment: transitions where neither the surface nor the aperture changed between exposures numbers only 10 and 6 in Session Two for the knowledgeable and naïve groups respectively. We note where this lack of data affects the analysis below, and are careful to draw conclusions from the results.

| | *Surface Change, Aperture Change* | *Surface Change, Aperture Same* | *Surface Same, Aperture Change* | *Surface Same, Aperture Same* |
|---|---|---|---|---|
| Knowledgeable Subjects, Session One | 30 | 19 | 32 | 17 |
| Naive Subjects, Session One | 27 | 28 | 30 | 13 |
| Knowledgeable Subjects, Session Two | 30 | 29 | 29 | 10 |
| Naïve Subjects, Session Two | 32 | 33 | 27 | 6 |

Table 2: Surface Comparison Counts

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[1] For simplicity, we do not consider the comparison order. Including order would yield a total of 16 possibilities and completely deplete any statistical degrees of freedom.

# 4 Results

An effective way to display the results is to present a histogram of responses. Unlike the analysis of the absolute question, we measure perception by taking the unsigned difference between the response and the expected response for a given exposure to compute a score difference. For example, if indeed the surface changed from the flat, fixed surface to the rotating drum between exposures, the expected (extreme) response would be close to 1. (Refer to Figure 3.) We calculate a score difference as the absolute value of one, minus the response. In the event that the surface did not change, we calculate the score difference as five, minus the response. When the score difference is low (with a minimum of zero), the response is very perceptive. A higher score difference, closer to 2, indicates an admitted inability to perceive a surface change. A score greater than 2 indicates a false perception of the surface changing. Figure 4 illustrates the general shape of the response histograms for four different scenarios: The idealized histograms show high perception, low perception, false perception, and total guessing.

Figure 5 shows the normalized score difference histograms for each group of subjects for both Sessions for each type of comparison. The four comparison types include the situation where nothing changed as a control group (Figures 5g and 5h). Furthermore, we display both Session One and Session Two side-by-side for an initial impression of learning trends or fatigue.

An interesting feature to note in nearly all of the response histograms is a marked dip at the score difference of two. Recall that a score difference of two indicates that the subject responded with a number 3, or “Can’t Say One Way or the Other.” (See Figure 3.) It appears that on average, subjects were more inclined to be wrong about their perception than admit to being unable to tell a difference. This effect is the natural result of a comparative question that is not completely forced-choice. (Such a question would only have two responses, e.g., “drum or flat.”) However, the benefit of using a multiple point scale is that we have greater access to confidence levels in subject response. For example, if a histogram has the general shape of accurate perception, yet with low histogram frequencies at a score difference of zero (as in Figure 5b), we conclude that subject perception was accurate with low confidence.

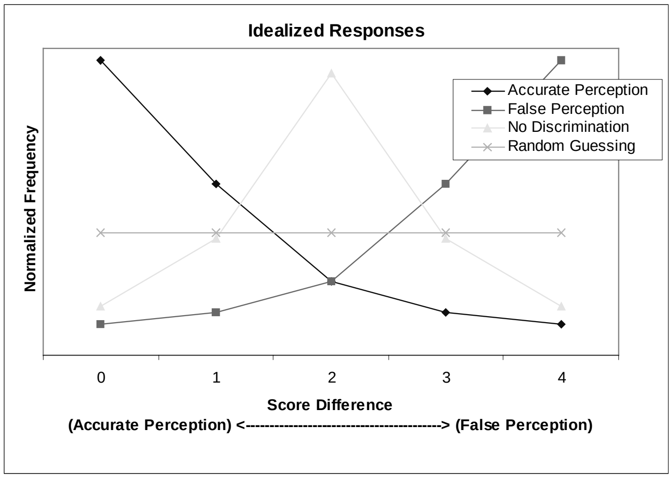

Figure 4: Idealized Response Histograms

Another clear pattern in the data is frequency peaks at a score difference of 3. Excepting Figure 5c,

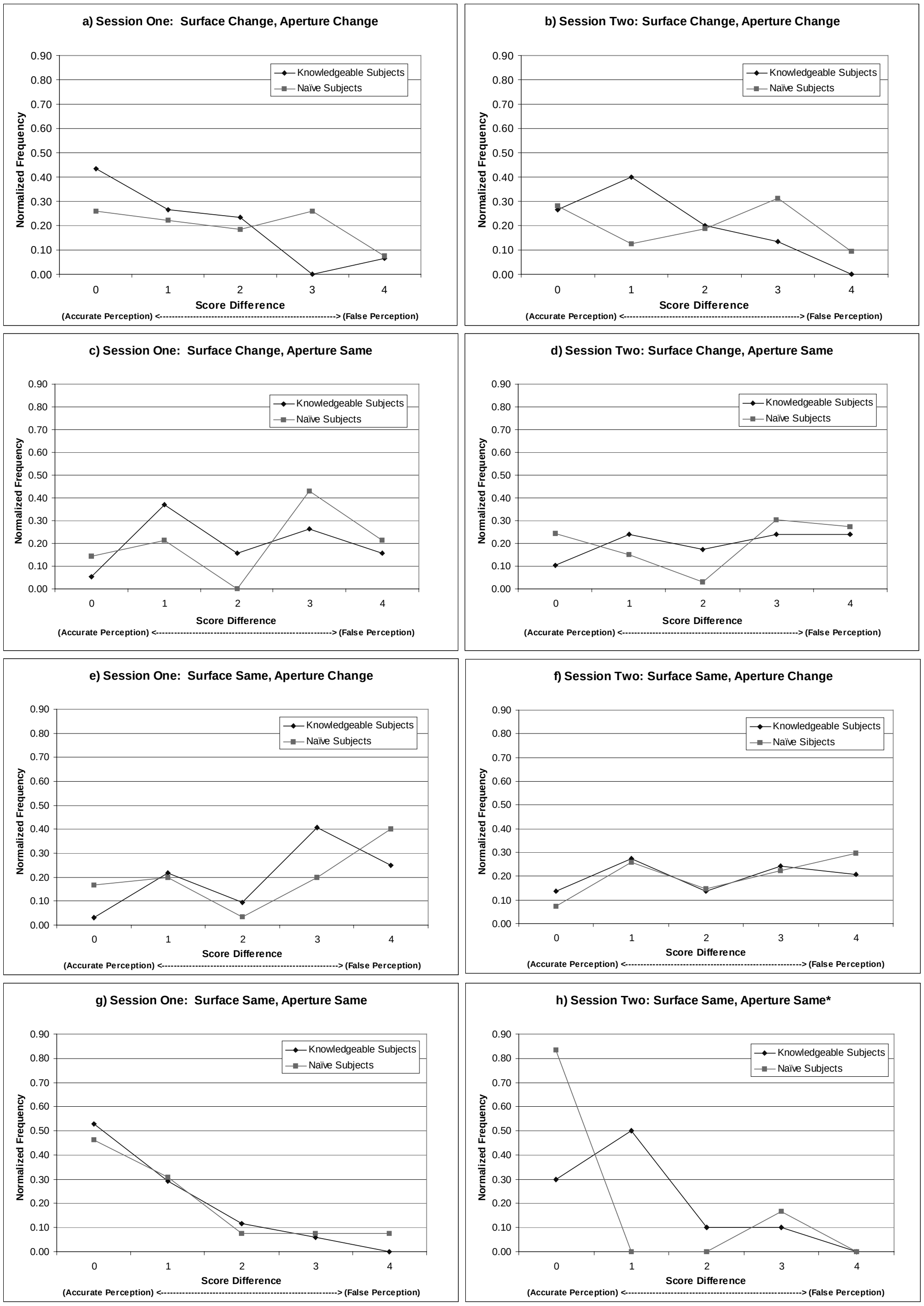

Figure 5: Raw Score Difference Histograms

*An asterisk indicates low statistical degrees of freedom.

nearly all of the peaks occur when the aperture changed. This leads us to suspect that the aperture change causes a false perception of the surface change, and may be a confounding factor. Even though it is an interesting effect by itself, the false perception effect is not what we hoped to accomplish by introducing two aperture sizes. The raw data for question two (and for question one), and a copy of the first paper addressing this experiment may be found electronically at lims.mech.northwestern.edu/projects/fingertip.

# 5 Analysis

To investigate causal relationships in the data, we first perform simple two-tailed t-test with the following null and alternative hypotheses:

$H_0$: Mean Score Difference = 2
$H_A$: Mean Score Difference either < 2, or > 2

In other words, were the subjects in each group able to perceive when the surface and aperture or any combination thereof changed? Once again, recall that a score difference of 2 indicates an admitted inability to perceive a change in the surface. Mean score differences below two show high perception, while mean scores of 2 or greater show either inability to sense a change, or false perception. Score differences at or above 2 confirm our hypothesis that there is no perceptual difference between a rotating drum and a fixed, flat surface. The results of the t-test are in Table 3.

| | *Surface Change, Aperture Change* | *Surface Change, Aperture Same* | *Surface Same, Aperture Change* | *Surface Same, Aperture Same* |
|---|---|---|---|---|
| Knowledgeable Subjects, Session One | p=0.000,<br>t=-4.785, df=29 | P=0.716,<br>T=0.369, df=18 | p=0.005,<br>t=2.985, df=31 | p=0.000,<br>t=-5.803, df=16 |
| Naive Subjects, Session One | p=0.204,<br>t=-1.302, df=26 | P=0.194,<br>T=1.331, df=27 | p=0.119,<br>t=1.606, df=29 | p=0.016,<br>t=-2.793, df=12 |
| Knowledgeable Subjects, Session Two | p=0.000,<br>t=-4.397, df=29 | P=0.248,<br>T=1.092, df=28 | p=0.693,<br>t=0.399, df=28 | p=0.008,<br>t=-3.354, df=9 |
| Naïve Subjects, Session Two | p=0.455,<br>t=-0.757, df=31 | p=0.451,<br>t=0.763, df=32 | p=0.133,<br>t=1.550, df=26 | p=0.030,<br>t=-3.000, df=5 |

Table 3: T-test Results

As mentioned before, the small degrees of freedom in the last class (Surface Same, Aperture Same), casts some concern on the strength of the significance. Since we are interested in a general impression of perception, we evaluate the above tests at the 85% confidence level (softer than the conventional 95%), which yields the set of conclusions in Table 4.

| | *Surface Change, Aperture Change* | *Surface Change, Aperture Same* | *Surface Same, Aperture Change* | *Surface Same, Aperture Same* |
|---|---|---|---|---|
| Knowledgeable Subjects, Session One | < 2 | = 2 | > 2 | < 2 |
| Naive Subjects, Session One | = 2 | = 2 | > 2 | < 2 |
| Knowledgeable Subjects, Session Two | < 2 | = 2 | = 2 | < 2 |
| Naïve Subjects, Session Two | = 2 | = 2 | > 2 | < 2 |

Table 4: Conclusions from Analysis

The highlighted entries in Table 4 show accurate perception, score differences less than 2. The control group of Surface Same, Aperture Same confirms that subjects were indeed truthfully reporting what they felt. (However, the strength of this validation should be lessened somewhat by the small degrees of freedom in this class of comparisons.) A strong confirmation of our perceptual illusion is in the second column of Table 4. When the surface changed and the aperture did not, none of the subject groups accurately perceived the change. Essentially, there was no perceptive difference between the rotating drum and the fixed, flat surface.

Another striking result of the analysis is the inordinate number of false perceptions when the surface did not change, but the aperture did (third column, Table 4). Clearly, the different aperture sizes confounded subjects, as suspected above. Rather than gaining insight on how aperture size affects perceived fingertip sensations, changing apertures during a session simply caused confusion. We consider the aperture issue and its significance in the Conclusions below.

The first column shows the perceptiveness of the knowledgeable subjects, and the apparent inability for naïve subjects to perceive simultaneous changes in the surface and the aperture size. This suggests the basic effectiveness of the illusion of a surface is intact when users are not aware of the mechanism. The absolute question analysis in Salada et al. (2002) shows that knowledgeable subjects were able to correctly identify the underlying surface when the small aperture was in place. Since it appears that the aperture change (or lack of change) affects both knowledgeable and naïve groups nearly equally, we conclude that the perceptiveness revealed in this analysis and in the previous paper is due to some other aspect of the mechanism, and not due to the confounding factor of the aperture change.

# 6 Further Analysis

The second approach to analyzing the data is to investigate any significant mean score differences from the first session to the second session, and between the two groups. Initial, visual inspection of the histogram plots indicates some differences that may provide new information. As mentioned before, we expect to reveal trends in learning and/or fatigue with such data available.

We conducted paired sample t-tests between Session One and Session Two, and also conducted paired-sample t-tests between the two groups, knowledgeable and naïve, within a Session. Much to our surprise, neither set of tests revealed significant changes in mean performance with two exceptions. On the Surface Same, Aperture Same transition, performance significantly improved ($p=0.096$) for the knowledgeable group from Session One to Session Two, and the mean performance was significantly better in the knowledgeable than the naïve groups for the second session ($p=0.010$) for the Surface Change, Aperture Change transition. Rather than reading too much from these results, we note that the low statistical degrees of freedom in the second Session for the Surface Same, Aperture Same, and recall the conclusion about device dynamics for the Surface Change, Aperture Change. Since each exception closely relates to known issues, we do not pursue the results further.

# 7 Conclusions

Analysis of the comparative question reveals two significant results. First, we validate the hypothesis that there is no perceptual difference between the rotating drum and the fixed, flat surface beneath the fingertip. Second, we reveal a significant sensitivity to changing aperture sizes that was not expected.

The confounding effect of the apertures does not mean that studying such a relationship is not worthwhile. The relationship between contact area (as limited by an aperture) and perception of the surface is already the subject of our next test. We now understand the importance of presenting aperture size changes much less frequently than changing surface properties in future experiments. Perhaps, using only one aperture size per Session is the most appropriate approach.

Since the confounding aperture would equally affect both naïve and knowledgeable subjects, and we observe that it does not, we conclude that the unexpected results in Salada et al. (2002) are indeed the result of subjects sensing other aspects of the device. Namely, we suspect that subjects were sensitive to the slosh at the start and end of a movement, or device dynamics. This ability to perceive such dynamic effects was thought not to be significant enough to accommodate during this test. A more elaborate test apparatus is necessary to compensate for such affects.

# 8 Future Work

The most exciting aspect of fingertip haptics is the ability to pursue the relationship between rendering haptic sensations with fingertip devices as opposed to rendering the same with traditional haptic devices (that impart mostly kinesthetic, non-tactile, feedback). Perhaps there are significant new relationships between fingertip sensations and gross finger movement like the shape and lateral force relationship revealed by (Robles De La Torre and Hayward, 2000). We intend to pursue the same, taking advantage not only of the added sensory input capabilities of our novel approach, but also exploiting the sensitivity (or for that matter, insensitivity) of the fingertip to slip sensations.

An interesting possibility for an advanced version of a fingertip apparatus with a rotating element is the opportunity to control the texture on the cylinder with a technology capable of imprinting new patterns on the surface in real time. Furthermore, with a modification to the housing that supports the cylinder, the cylinder itself may be drawn away from the fingertip to render softer surfaces or no surface contact at all as the user departs from the virtual object. The potential for rendering complicated tactile sensations with respect to finger movement is high. Instead of attempting to stimulate the somatic nerves independently, or trying to substitute one tactile sensation for another, we essentially recreate the surface, and all of its complex interaction with the skin along with the finger as it explores a path on the object.

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