An Experiment on Tracking Surface Features with the Sensation of Slip

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Abstract

This paper describes the last of three experiments that investigate relative motion between a surface and the fingertip (slip) as part of a larger program of research on "fingertip haptics." To confirm the suspicion that tangential displacement of the skin during contact contribute to the perception of feature movement, this experiment tasks subjects to follow a feature on a surface that displays the path tangent given three different factors: the first factor is the absence of tangential displacements 1) within the contact area and 2) on the whole finger pad. The second factor explores different surface speeds. Finally, we explore different rates of path curvature. A custom mechanical filter placed between the skin and the moving surface enables the selective elimination of tangential contact displacements. Thirty-three subjects completed the tracking test, showing that the absence of tangential forces from slip severely impairs performance. However, results reveal heightened performance with the filter in a "loose" configuration. The performance suggests that subjects do not use shape alone to track features, but some combination of shape and tangential forces (due to friction) together to perceive the movement of small features.

1. Introduction

Fingertip haptics intends to investigate the sensory information relayed to the brain through fingertip interaction with a surface. The tactile and kinesthetic input from the fingertip may serve more roles than one, acting as both a source of information about an object, and as a sensory cross-check for limb movement control. This experiment attempts to identify the importance of one aspect of fingertip contact, tangential skin displacement due to slip, in the greater context of surface perception. Previous experiments in fingertip haptics quantified the ability to discern speed of gross slip against the finger, and identified the relative importance of slip versus kinesthetic sensations in perceiving surface speed [9]. As a step forward, this experiment presents subjects with a feature tracking task and measures the human ability to follow a path given only tactile feedback at the fingertip.

The basic premise of this experiment is that the nature of contact during slip provides important tactile cues regarding features on the surface as well as the nature of movement of the object, and that humans take advantage of slip sensitivity when perceiving objects. Johansson and Westling conducted a similar series of experiments, but relating tactile information to grip force when performing a lifting task [4]. They find that the ability to adjust grip force appears to be independent of the surface friction characteristics. In a subsequent study, Cadoret and Smith find that it is indeed forces from friction, rather than textural information from the surface, that dictate grip force response [1]. Recent work by Edin *et al.* proposes that this reflexive response may aid in teleoperator system control when using a device that can recreate the sensation of slip on the master side [3]. Eberman and Salisbury show how difficult it is to discern surface properties solely from forces applied to the fingertip [2]. Without a qualifying context, or more information such as slip, impact, or other fingertip haptic sensations, the task of correctly identifying the complete state of contact is extremely difficult. With the knowledge from our first two experiments (how well humans can discern slip speed), this experiment investigates how the sensation of slip yields both contact information and provides subtle force information that gives humans a perception of the surface and movement of small features. The same phenomenon occurs for vertical or normal forces. However, lateral forces have received less research attention for many reasons, but primarily due to the difficulty in displaying them to the fingertip.

This experiment intends to identify which of the many fingertip sensations induced during slip contributes or inhibits the perception of the feature and its path. Finger contact sensations include (a) the kinesthetic forces from friction applied to the finger, (b) the shape of the feature on the skin, (c) the forces from surface movement that act inside the contact area between the surface and the finger, and (d) the high frequency information from the surface. The task of selectively isolating these sensations is a simple matter, having a common counterpart in everyday life. Doctors wearing surgical gloves and food service workers wearing sanitary mitts all experience some level of tactile attenuation due to the presence of the thin layer of latex or

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plastic. Shibata and Howe study the effect of glove (or membrane) thickness for both a perceptual task and a manipulation task [11]. They find that performance in both cases, as indicated in the perceptual task by detection time and by excess grip force in the manipulation task, decreases linearly with increasing thickness of the membrane. In contrast, Lee *et al.* find no significant differences in perception of shape with an experiment that varies both the thickness and the stiffness of a membrane [8]. The discrepancy between Shibata and Howe's results and Lee's results may be due to the difference in thickness ranges. Shibata and Howe study thickness ranging between 0.16 and 1.9 mm and Lee *et al.* investigate a range from 1.5 to 3.0 mm.

Lederman and Klatzky perform a comprehensive suite of psychophysical experiments with the fingertip encased in a molded latex sheath [7]. They find severely impaired performance for all but vibrotactile and roughness perception due to the presence of the sheath. The present experiment extends Lederman and Klatzky's experiment in two ways. First, this experiment involves a tracking task for perception in order to better place fingertip sensations in context of surface movement. Second, this experiment selectively isolates aspects of contact not specifically explored by Lederman and Klatzky. This experiment introduces a "tangential displacement filter" using a thin but substantial membrane material (13 μm Kapton), and the lightest support structure possible (interference-fit concentric nylon rings). See Figure 1. The mechanical filter is not bound to the subject during the experiment and thus allows for three modes of interference with the task of perceiving the surface. First, the test apparatus can fix the filter between the finger and the rotating contact wheel to effectively eliminate gross forces due to friction. In another arrangement, the filter "floats" between the subject and the surface, allowing gross forces from friction to act on the finger. Finally, the filter is absent to allow all sensation. In both the fixed and the loose filter cases, however, the filter eliminates (or greatly minimizes) tangential forces that act within the contact area between the finger and the surface. Subject performance in each of the three filter conditions (absent, loose filter, and fixed filter) will identify the relative contribution fingertip contact components during tracking of the feature.

Figure 1: The Mechanical filter is made of a thin sheet of Kapton bound between two concentric rings of nylon.

Following a brief description of the testing apparatus, Section 3 describes the experimental procedure. The remaining Sections in the paper present and discuss the results of testing with human subjects.

2. Testing Apparatus

We developed a powered test device that provides active control of the spin and rotation axis of a contact wheel. For more detail on the basic test apparatus, please refer to [9]. The user places his or her hand on top of the device, palm down, with his or her index finger centered over a hole in the top plate. Beneath the hole is the wheel we use to simulate contact with a flat surface. The wheel is a 3-inch diameter Lexan® truncated sphere, resembling a plastic donut. This experiment employs a different spinning contact wheel than the first two experiments in this series. Based on the simple feature used by LaMotte and Srinivasan [5, 6], the rotating contact wheel has a small ledge around the periphery. See Figure 2. LaMotte's studies attempted to correlate mechanoreceptor response, both SA and RA types, to the slope of a half-period sinusoid when stroked across the finger pad. They found heightened RA and SA response to steeper slopes in both studies. The raised ledge feature provides a tactile shape cue on the direction of the wheel, and hence the movement of the surface. Through experimentation, we found a comfortable height for the ledge at approximately 100 μm, or the height of a thick sheet of paper.

The control system measures the speed of the wheel to ±0.6 mm/sec, and can maintain speed to less than 5% error for up to 2N normal load (finger pressure). The test apparatus also has a cam assembly that raises and lowers the drum and its servomotor with about a 2-inch stroke. The vertical stroke allows for retracting the wheel from the user's finger between experiment exposures. The drum and cam assembly then mount to a swivel plate that is also servo-controlled, thus allowing active control of the wheel's orientation about the dorsal/ventral (D/V) axis of the fingertip. The top plate turns passively with the subject's wrist and arm movements. An encoder tracks the passive movement with an effective resolution of 0.004 degrees through a traction wheel pressed against the underside of the plate. To introduce the mechanical filter between the

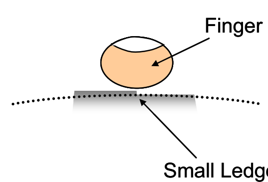

Figure 2: A small ledge runs the periphery of the rotating contact wheel, serving as the feature. The motion of the wheel as pictured is in (or out) of the page.

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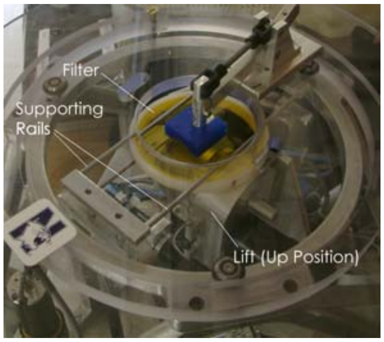

Figure 3: Supporting rails hold the filter in place between the subject's finger and the rotating contact wheel.

rotating wheel and the subject's fingertip during testing, a filter brace assembly that reaches over the rotating wheel drive assembly mounts to the D/V axis platform. Figure 3 shows the filter bracing with the filter in place. Three thin steel rods span the gap over the spinning wheel providing minimal guides for the plastic filter. As the wheel lifts into the subject's finger, the wheel picks up the filter on the way and is held in place by the subject's finger. During experimentation, a small tether attached to the brace that joins the top rods holds the filter in place over the spinning wheel. This keeps the filter in place in the event that the subject is not pressing down hard enough to hold the filter on the wheel. All subjects wear headphones to reduce acoustic cues, and place his or her hand through a curtain that comfortably obstructs the subject's view of the apparatus during the experiment.

3. Experimental Procedure

The intent of this experiment is to explore the effect of the presence of a mechanical filter on a subject's ability to track features on a moving surface. Such intent leaves quite a bit of latitude on the actual task. In other words, *any* task will suffice, as long as it is flexible for experimentation, and repeatable from subject to subject. Rather than having the subject actually move his or her arm along a path as in the previous experiment, the apparatus will recreate the sensation of moving over a surface with the subject's arm stationary. A computer controls the speed and orientation of the contact wheel to impart a "path." The experiment tasks the subject to actively turn his or her hand (along with the top plate) to orient his or her index finger parallel to the small ledge on the wheel. The path of the feature in time is set at three arbitrary values which allow for additional quantifications regarding a subject's ability to follow a moving feature. The path is a sequence of single period cosines that turn both to the left and to the right with a fixed amplitude but with three different periods. The turning of the D/V axis on the apparatus renders the path in time, while the wheel spins independently. Figure 4 shows a sample path. Twelve cosine curves (or "blocks") present the three periods in each direction (left or right) twice. To counterbalance the path, we assemble four different plans that sequence twelve cosine curves together. Four plans do not completely counterbalance the presentation, but the implementation is practical. The computer rotates through the plans, effectively randomly assigning a given plan to any given subject.

There are four experimental factors. The first factor is the presence of the filter, with three possible values (or "levels"), absent (or bare), loose, and fixed. The second

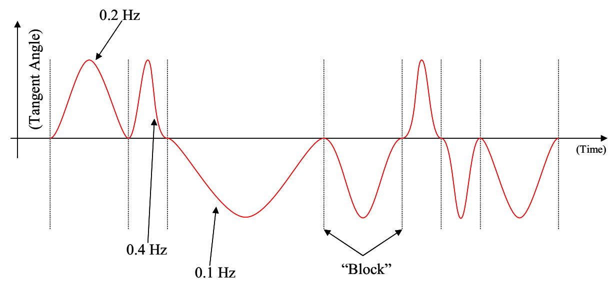

Figure 4: The path that the subjects follow is a balanced sequence of cosine curves with fixed amplitude and three different periods. The feature on the contact wheel displays the path *tangent*. We measure performance by how well the subject matches the trajectory of the path by aligning his or her wrist (as measured by the top plate) to the path tangent.

factor is the period of a turn (or cosine) in the path, which essentially represents the frequency content. There are three possible levels for the period: 10, 5, or 2.5 seconds. The third experimental factor is the speed of the surface, with four levels: 0, 50, 100, and 200 mm/sec. Finally, the fourth factor is the direction of the path. An angle of zero is straight ahead (towards the distal direction) and each turn is a full cosine period either to the left or to the right. All subjects experience all factors (there are no between-subjects factors). Subjects receive oral and written instructions prior to beginning the experiment. Each subject has the opportunity to practice while being able to see the device to become comfortable with the testing. The apparatus raises the wheel to begin a path, and lowers the wheel at the end of the path. The subject presses a button to proceed to the next path in the sequence, but only after bringing his or her hand back to the starting orientation (prompted by messages on the computer screen). Subjects "traverse" a total of four paths (one for each speed level), each lasting 70 seconds, and then rest while the experimenter changes the apparatus to accommodate the next filter configuration. The computer records each subject trajectory and actual wheel trajectory at 30 Hz.

4. Results

A total of 33 healthy subjects (three were left-handed) completed the experiment. After each subject, a small

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program calculates the absolute value of the average error in angle between the subject's finger and the wheel angle for each part, and presents the data on the computer screen. This quick-look calculation is for debriefing the subject only. Recall that each path has three basic cosine curves, each presented twice in each direction, to the left and to the right. Furthermore, the wheel speed (and thus slip speed) has four different levels, ranging from zero to 200 mm/sec. Point-wise averaging the subject's response for each cosine curve, and plotting the result versus the speed of the wheel yields twelve separate plots, with each plot containing a single "block." Figures 5, 6, and 7 show the averaged trajectory of all subjects, separated into the blocks by both speed of the contact wheel, and period of the curve for the three filter levels. Recall that the slip speed level, by row, is 0, 50, 100, 200 mm/sec from the top, and the turn period is 10, 5 and 2.5 seconds by column. There are two plots in each graph, one for left turns and another for right turns. The plots show both the angle of the wheel (the base angle) and the average subject response for comparison. Note that each plot is actually the average of two trajectories since

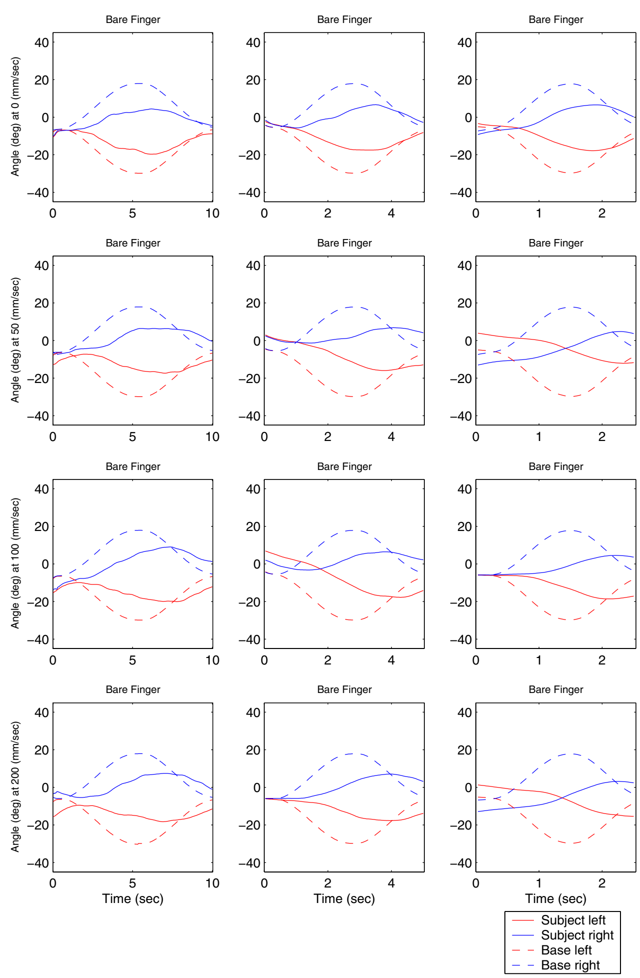

Figure 5: Bare finger subject response separated into slip speed (row) and turn period (column),*i.e.*, by block.

subjects experience each condition twice in a path. The surface feature, a small ledge, steps "down" from right to left with respect to the forward direction (down along the negative A/P axis). Likewise, the surface feature (ledge) steps up for left turns.

5. Analysis

Initial observations from the separated trajectories reveal a surprising ability of subjects to track the path with the loose filter. There are many ways to measure performance, and a simple average angle error does not capture some salient aspect of tracking performance that is readily visually apparent. We settle on using a trajectory measuring technique introduced by Shadmehr and Mussa-Ivaldi in [10] for analysis. Their metric calculates a correlation coefficient between two vector fields, *U* and *V*, as

$$\rho(U,V) = \frac{Cov(U,V)}{\sigma(U)\sigma(V)}, \quad where\ \sigma(\cdot) = \sqrt{\|\cdot - \varepsilon(\cdot)\|},$$

and ε is the expected value of the vector. Figure 12 shows averaged results with the correlation coefficient on the *tangent* of the trajectories, where *U* is the actual wheel tangent and *V* is the subject's averaged tangent line trajectory. Using the tangent line trajectory instead of the trajectory minimizes any error due to subjects having a bias in how each may align the feature to his or her wrist during the experiment. Performing a univariate ANOVA with the tangent of the trajectory shows that all main effects are significant. Furthermore, nearly all interaction effects are significant. In the trajectory correlation measurements there is a sharp drop in tracking performance for the shortest turn period for the bare finger and fixed filter conditions. This behavior is not present with the loose filter. The metric shows that increasing slip speed detracts from tracking performance of the feature. Mauchly's test for sphericity shows significance for the main effect of turn period ($p = 0.021$) and the following interactions not involving turn period: filter by speed ($p = 0.013$) and filter by speed by direction ($p = 0.020$). Therefore, we use the Huynh-Feldt epsilon correction when examining all effects involving turn period and the two interactions listed. For the correlation coefficient on the derivative trajectories, all four main effects are significant: filter ($p = 0.000$, $\eta^2 = 0.827$), turn period ($p = 0.000$, $\eta^2 = 0.454$), speed ($p = 0.000$, $\eta^2 = 0.274$) and direction ($p = 0.0016$, $\eta^2 = 0.269$). Significant interactions include filter by turn period ($p = 0.000$, $\eta^2 = .569$), filter by speed ($p = 0.000$, $\eta^2 = .386$), and turn period by speed ($p = 0.0007$, $\eta^2 = 0.116$). Two three-way interactions are significant: filter by turn period by speed ($p = 0.003$, $\eta^2 = 0.076$) and filter by turn period by direction ($p = 0.030$, $\eta^2 = 0.086$).

To examine the statistical differences, Table 1 shows the estimated marginal means of the correlation coefficient

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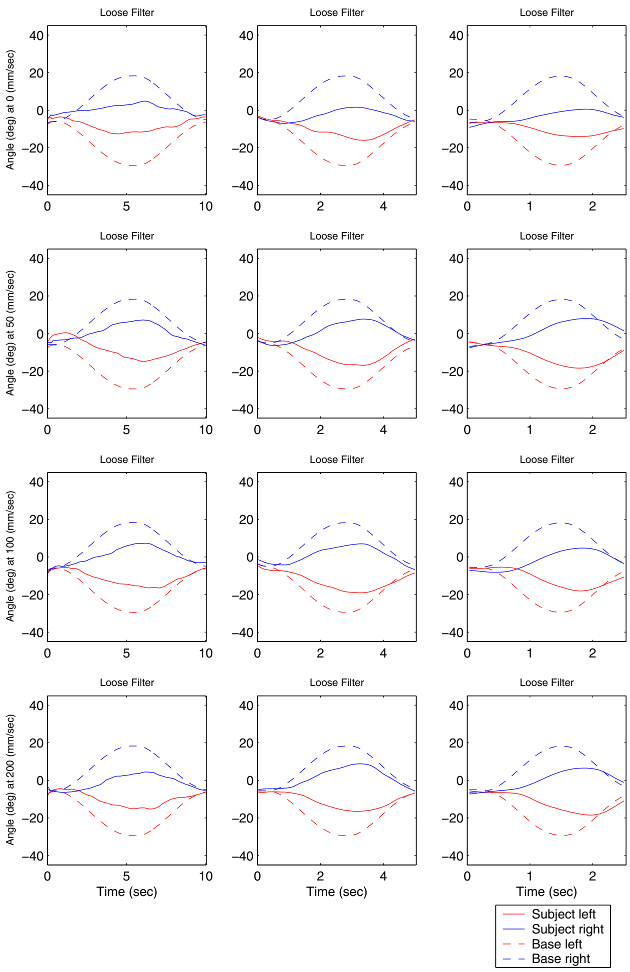

Figure 7: Loose Filter subject response by block.

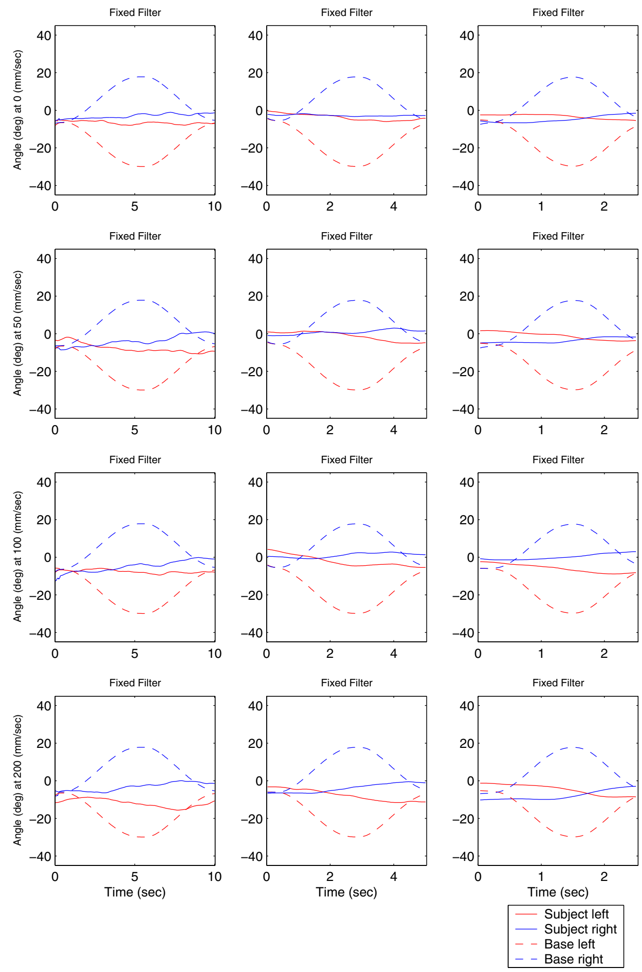

Figure 6: Fixed filter subject response by block.

for all factors. The most evident trend is the heightened performance with the loose filter. Furthermore, the stationary slip speed (0 mm/sec) results in higher performance as compared to all other slip speeds when evaluating performance with the trajectory derivative correlation coefficient. Considering the factor of the filter, nearly all cases show that subjects performed better with the loose filter configuration than the bare finger condition. However, two of the three statistically significant contrasts with the large turn period show that the bare finger performed best. In all cases, both the bare finger and the loose filter performance are significantly better than with the fixed filter. Subjects were not able to track the fastest period with the bare finger or with the fixed filter. Since subjects could not readily track any of the turns well with the fixed filter, the bare finger versus loose filter difference for the fastest period most likely accounts for the filter by turn period interaction. For the loose filter, a considerable number of the medium and small turn performance contrasts are significantly better compared to the large turn performance. The most significant contrasts involving speed are between the "no slip" condition and any of the other conditions. The difference in performance between the zero speed and non-zero speed slip condition occurs almost exclusively with the bare finger filter arrangement.

6. Discussion

Of the four fingertip cues under investigation in this experiment (introduced at the end of Section 1), the fixed filter eliminates skin stretch from movement (cue *c*) (presumably within the contact area) and forces from friction (cue *a*). Poor subject performance with the fixed filter reveals how essential these cues are to the tracking task. It is important to note which fingertip sensations *are* present with the fixed filter in place. The two remaining fingertip cues are shape cues (*b*), and normal (as opposed to tangential) vibrotactile information (*d*). Even with the enlarged shape cues due to the low-pass mechanical filtering, subject performance in tracking is marginal. In sharp contrast to the fixed filter performance, subjects' ability to track the feature movement increases with the loose filter configuration. This result is unexpected and reveals a key relationship between the four fingertip cues. Since masking skin stretch (cue *c*) produces a heightened tracking ability, fingertip sensitivity to skin stretch must *inhibit* or change the relative information level from the friction forces (cue *a*) against the finger. When the fixed filter is in place, the only cues available are from shape (*b*) and vibration (*d*). With the loose filter configuration, the "signal to noise" ratio between skin stretch (*c*) and force from friction (*a*) increases, yielding heightened tracking performance. The heightened performance with the stationary wheel is another clue to the sensitivity to skin stretch. This reveals that there are at least two modes of skin stretch present. The first is skin stretch due to the forward motion of the surface, and a second is stretch due to the twisting about the D/V axis. The general drop in performance with the non-zero slip speeds reveals a complex and possibly inhibitory relationship between these two sensations. A small but important result is the better performance of the bare finger over the loose filter for the large turn period. This suggests that at slow speeds, the twisting skin stretch plays an important role that the loose filter masks. The relationship quickly shifts in favor of masking skin stretch for faster turn periods, as the loose filter performance exceeds bare finger performance.

7. Conclusions

Thirty three subjects performed a feature tracking task with three different fingertip contact conditions. Subjects performed best when a thin membrane interfered with the contact while still allowing forces from friction to pass through. The results show that tangential forces are extremely important to fingertip sensitivity and essential to tracking movement. A surprising conclusion is that the importance of tangential forces may center on the relationship between two kinds of fingertip cues, forces from friction and skin stretch. Acting in the tangential direction, subject performance increases when the relative contribution between friction forces and skin stretch widens (in favor of friction forces). Contrary to the conventional approach of pin array tactile displays, this experiment reveals that shape and vibration information alone is not sufficient for tactile tracking of a raised, moving feature.

Table 1: Marginal Means by Factor

Factor: FILTER

Bare	Loose	Fixed	Sig.
0.219	0.476		0.0000
0.219		-0.016	0.0000
	0.476	-0.016	0.0000

Factor: TURN PERIOD

Large	Medium	Small	Sig.
0.224	0.297		0.0000
0.224		0.158	0.0124
	0.297	0.158	0.0000

Factor: SPEED

0	50	100	200	Sig.
0.303	0.212			0.0050
0.303		0.193		0.0000
0.303			0.198	0.0012
	0.212	0.193		0.8731
	0.212		0.198	0.9795
		0.193	0.198	0.9999

Factor: DIRECTION

Left	Right	Sig.
0.247	0.206	0.0017

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