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Effects of Longitudinal Skin Stretch on the Perception of Friction

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Abstract

This work focuses on the relative importance of skin stretch imposed on the fingerpad on the perception of friction. Perceptual data is presented from two separate tests. The first experiment was designed to determine the perceptual thresholds for friction based on a Karnopp friction model. In this experiment friction was rendered as purely a kinesthetic resistance via a PHANToM force feedback device. The second experiment was designed to evaluate possible changes in perceived friction magnitudes due to imposing small amounts of tangential skin stretch (0.25 - 0.75 mm) to the fingerpad in combination with force feedback (kinesthetic resistance). Results of this experiment show that even these small amounts of skin stretch increase the perceived friction. These results suggest that the addition of a simple shear plate tactile display to current haptic devices could significantly enhance the range of rendered friction since most current haptic force feedback devices have limited force capabilities.

1 Introduction

Imagine a world without friction, nothing that we do in our everyday lives would be the same. Friction allows people to walk, to grasp objects, to sit in a chair, etc. Friction is an essential ingredient of the way people perform everyday tasks. Because friction is so prevalent in everything we do, the ability of a haptic device to simulate friction is of utmost importance. Trying to manipulate an object through a haptic device without rendering friction increases the difficulty of the task and is not as realistic. In the field of haptics, friction is classically rendered as a kinesthetic resistance via a force feedback device. Typically a haptic device has an upper limit on the magnitude of friction force (or kinesthetic resistance) that can be rendered since quite often haptic devices have relatively low force capabilities. We hypothesize that the addition of skin stretch to the kinesthetic friction force will increase the perceived friction and thus increase the effective friction level that can be rendered. If this hypothesis holds true, this would greatly motivate the addition of a simple shear display to current haptic devices to help supplement limited force reflection capabilities when rendering friction. The hypothesis is verified via two perceptual experiments; the first quantifies the difference threshold of friction based solely on coulomb-like kinesthetic resistance (i.e., force feedback only), and the second experiment determines the additional effect skin stretch has on the perceived friction magnitude (i.e., tactile feedback plus force feedback). We also believe that the addition of skin stretch enhances the realism of the rendered friction.

Many friction models have been developed to describe this seemingly simple physical phenomenon. Probably the most well known model because of its simplicity is the Coulomb model which describes friction force as proportional to normal force and independent of contact area and velocity. Karnopp proposed a model to eliminate the numerical problems associated with the Coulomb model by defining a velocity threshold below which the system is said to be in the stuck or static phase and obeys classical coulomb static friction behavior [5]. If the friction force reaches a prescribed limit, the system transitions to slip phase and the friction force obeys classical coulomb kinetic friction behavior (see Fig. 2 (a)). Dahl formulated a friction model to account for the microscopic pre-sliding displacement present between two bodies which is a generalization of Coulomb friction [10]. Countless other friction models are reviewed in [8].

Some models lend themselves more easily to haptics research, while others are more complicated and have numerical issues. Hayward and Armstrong have implemented a modified Dahl model to synthesize friction with great success using a haptic device. Their modified model removes drift and oscillation problems associated with the original Dahl model [4]. Richard and Cutkosky have shown that a modified Karnopp model can be easily and accurately implemented to render kinesthetic resistance through a haptic device by incorporating a virtual spring and velocity thresholds [10]. Navhi has also successfully used a modified Karnopp model to quantify the the frictional properties of the human fingerpad [7]. The accuracy, ease of implementation, and previous success using a modified Karnopp model (implemented with a virtual spring) make it an ideal

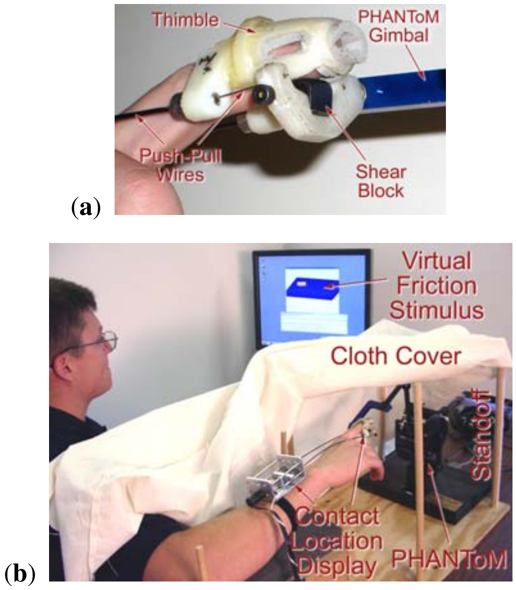

Figure 1: (a) Thimble interface of the contact location display (b) Experiment Setup

candidate for the two experiments described in this paper. Furthermore, the results of the experiments are easy to interpret because of the linear nature of the virtual spring.

Some researchers have investigated the importance of tangential fingertip stretch and sliding between the finger and a surface [11, 14]. Small amounts of lateral skin stretch have been shown to provide a rich tactile sensation during exploration by several researchers. Hayward and Cruz-Hernandez have developed a haptic device that utilizes this fact, finding that movements on the order of $\pm 50\mu$m are easily detectable [2]. In addition, Biggs and Srinivasan report the fingerpad is more sensitive to tangential displacement than normal displacement [1]. Smith and Scott have also shown that shear forces on skin supply ample tactile sensations to the mechanoreceptors in human skin [12]. Salada et al. found that skin stretch played a vital role during feature tracking [11]. Additional examples of devices utilizing skin stretch/slip can be found in [13, 14].

We are investigating the relative importance of tangential skin stretch when presented in combination with coulomb-based kinesthetic resistance. Early pilot tests have shown that skin stretch does indeed play a role in the perception of friction, but this influence can be dwarfed when comparing stimuli in which the kinesthetic resistance of one stimuli is much larger than the other. Therefore, to understand the combined influence of the tactile and kinesthetic inputs, it is important to first understand the difference thresholds associated with kinesthetic resistance. Therefore, two experiments were conducted in succession to first evaluate the perceptual thresholds of friction, and then subsequently to understand how the addition of tangential skin stretch might influence the perceived friction magnitude. The remainder of the paper is organized into three sections plus conclusions. Section 2 provides a brief description of the hardware used in the experiments; Section 3 presents experiments focused on evaluating difference thresholds for coulomb-based kinesthetic resistance (force feedback only); Section 4 presents experiments with combined skin stretch and kinesthetic resistance.

2 Device Description

The hardware used for these experiments consist a SensAble Technologies PHANToM force feedback arm [6] and a contact location display apparatus. The PHANToM was used to render normal forces and kinesthetic resistance to fore-aft motions. The contact display was used to render skin stretch for the experiment presented in Section 4 and is shown in Fig. 1. The device utilizes a radiused ($\sim$1 cm) rubber-coated contact block for imparting shear and skin stretch to the user's fingerpad. The imposed skin shear (as in experiment 2) is assumed to be equal to commanded block positions, which is a reasonable assumption since there is minimal position error and backlash in the device.

The shear block is housed in a thimble that slips over and attaches to the user's finger. A servo-motor drives the block along the user's finger via two sheathed push-pull wires. The actuator is located on the user's forearm to reduce device inertia at the hand and minimize the transmission of motor vibrations to the user's fingertip receptors. The block is suspended underneath the fingerpad by the drive wires so that it does not touch the user's finger until they contact a virtual object. The display's contact element is attached to the PHANToM as depicted in Fig. 1(a). This haptic device measures the position of the block and provides reaction forces, which push the suspended element into contact with the user's finger.

To display haptic interactions with this device, a virtual object was programmed in C and C++ on a computer running RTAI Linux. A PID position feedback controller uses the display's servo-motor to adjust the position of the shear block based on detected finger motion. The bandwidth of the contact display exceeds 5 Hz for a 10 mm amplitude signal. Block positions along the finger are rendered with a maximum error of 0.21 mm for fast hand motions and an error of about 0.05 mm for the slow motions more typically used by subjects. Further details about the design and control of this device may be found in [9].

3 Experiment 1: Friction Thresholds via Coulomb-Based Kinesthetic Resistance

The goal of this first experiment is to establish difference thresholds for friction based soley on kinesthetic resistance (only force feedback), reported as the just-noticeable-

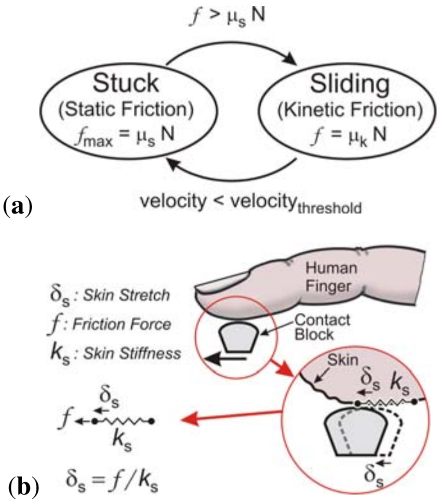

Figure 2: (a) Friction state diagram (b) Spring model of skin stretch

difference (JND). This is an important building block for understanding how one interprets friction via multiple sensory channels. Initial pilot testing to evaluate these thresholds was conducted via the method of limits to establish JND estimates. Subsequent experiments utilized the more accurate method of constant stimuli as outlined by Gescheider [3]. In these experiments, test subjects were presented with a virtual flat plate with prescribed friction levels (which correspond to static and kinetic coefficients of friction) and were instructed to explore its surface with fore-aft motions. Test subjects were trained and instructed to apply approximately 1-1.5 N of normal force, for consistency, while performing the tests. The rendered normal force stiffness was 500 N/m for virtual surfaces.

3.1 Experimental Setup and Procedure

Kinesthetic resistance was rendered by the PHANToM using a modified Karnopp friction model. The Karnopp friction model was chosen because of the ease of implementation and previous demonstrated effectiveness [7, 10]. Though unnecessary, test subjects wore the contact location display device during this experiment for consistency with the subsequent experiments that also involved rendering skin stretch with this device.

The Karnopp friction model prescribes static and dynamic friction states as shown in Fig. 2(a). In the modified version of the Karnopp model implemented herein and previously by [7, 10], during the static (stuck) phase, friction forces are accumulated by stretching a virtual "Karnopp spring." Once the friction force exceeds the static friction limit ($f_{max} = \mu_s \cdot N$), the system enters the sliding phase. During the sliding phase, rendered friction is purely a function of the normal force and coefficient of kinetic friction, $f = \mu_k \cdot N$. If, however, the velocity of the finger falls below a specified velocity threshold, this triggers a transition back to the stuck phase, where static friction prevales. Figure 2(a) provides a graphical display of the two phases and associated phase transitions. The virtual Karnopp spring stiffness and the velocity threshold were carefully tuned in order to avoid instability and oscillation between the stuck and slip phases.

User testing was automated via a simple user interface program to reduce the required interaction of the test proctor and to ensure consistency between subjects. To mask background noise, subjects wore headphones playing white noise while intermittently receiving auditory cues used to prompt subjects to probe each friction stimulus. To occlude visual cues provided by the experiment apparatus during testing, a cloth cover was placed over the test hardware as shown in Fig. 1(b). Note that this cover is pulled back in this figure to show the user's right hand and contact display solely for documentation purposes. Each test subject rested his arm on a rolling arm rest during the tests and was instructed to make gross fore-aft arm movements to explore the stimulus.

The method of limits was first used to get a rough estimate of the difference threshold (JND) at four reference static friction levels ($\mu_s = 0.2, 0.4, 0.6, 0.8$). The kinetic coefficient of friction, μ_k, for each of these friction levels was chosen to be 90% of the static coefficient based on documented friction values reported for leather on various materials (with leather deemed to be a good first-order estimate of skin). After a rough estimate of the JND at these four friction levels was obtained, we employed the method of constant stimuli with a paired-comparison forced-choice test paradigm to more accurately characterize the friction thresholds [3]. A between-subjects experiment design was employed with most test subjects typically completing tests for 2 of the 4 friction levels that were evaluated. For each reference friction level, 6 comparison stimulus values were chosen (3 higher, 3 lower than the reference). The extreme high and low values of these comparison stimuli were chosen to elicit a correct response roughly 90% of the time. A minimum of 5 people were tested at each of the four reference friction levels (Table 1), with 14 repetitions of stimulus pairs presented with a balanced presentation order randomly chosen to reduce bias. Test subjects all completed the test using their right index finger. Test subjects were males between the ages of 23 and 34, and all but two subjects were right-hand dominant.

3.2 Results and Discussion

The results for each test subject and each reference friction level were computed separately to establish the JND for friction via methods outlined by Gescheider [3]. Since only a small number of repetitions were performed for each subject, there was considerable variation between the results

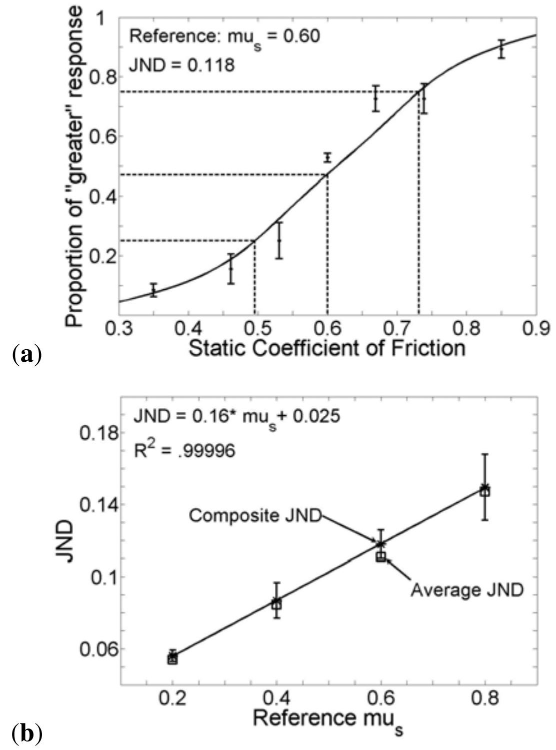

Figure 3: Experiment 1 friction JND results using the method of constant stimuli for (a) composite JND results for $\mu_s = 0.6$ and (b) friction levels $\mu_s = 0.2, 0.4, 0.6, 0.8$

for each subject. For this reason, data were also analyzed by pooling the data for all subjects for a given reference friction level and then establishing the JND with this lumped set of data. We refer to this pooled data as ‘composite’ JND results, as shown in Figs. 3(a) and 3(b). Figure 3(a) provides the composite response for a reference friction level of $\mu_s = 0.6$, with error bars indicative of the standard error. This graph shows the proportion of times subjects chose a stimulus to be the larger of the presented pair and as expected it follows a sigmoidal distribution. As shown in Fig. 3(a), the composite JND at a friction level of $\mu_s = 0.6$ was calculated to be 0.118. Plots similar to Fig. 3(a) were produced for each of the other three friction levels, all with similar characteristics.

Figure 3(b) shows the composite and average JND for each of the reference frictions levels along with a best fit line for the composite JNDs. The ‘average’ JND was established by taking the average of individually calculated JNDs, while the composite JND is a single calculated value based on pooled subject data. These results are also summarized in Table 1. As would be expected, the average JND of all subjects at each reference friction level is very close to the associated composite JND. The error bars were obtained from the standard error of the JNDs for each subject. The JNDs and corresponding Weber fractions are provided in Table 1.

Table 1: Experiment 1 friction JND results via method of constant stimuli.

Reference Friction	Composite JND	Weber Fraction	Average JND	Weber Fraction
$\mu_s = 0.2$	0.056	0.28	0.054	0.27
$\mu_s = 0.4$	0.087	0.22	0.085	0.21
$\mu_s = 0.6$	0.118	0.20	0.111	0.19
$\mu_s = 0.8$	0.150	0.19	0.147	0.18

4 Experiment 2: Perception of Friction via Skin Stretch and Kinesthetic Resistance

The second experiment was designed to study one’s perception of friction based on the addition of small amounts of tangential skin stretch to a person’s fingerpad when presented in combination with coulomb-based kinesthetic resistance. Our hypothesis is that by superimposing skin stretch with rendered kinesthetic resistance, subjects will perceive increased friction levels. Subjects were asked to judge which of two paired stimuli had the greater level of friction. The stimuli consisted of tactile inputs based on longitudinal skin stretch rendered via the contact location display combined with kinesthetic resistance rendered via a PHANToM. Subjects were made aware that there were both kinesthetic and tactile inputs in this experiment, but were not instructed on the nature of these inputs, nor how they should be interpreted. All test comparisons utilized a reference stimulus with a coefficient of friction of $\mu_s = 0.6$ that included no skin stretch component, corresponding to stimulus R_3S_0.

4.1 Experimental Setup and Procedure

This experimental setup mirrors the experimental design and user interface described for our first experiment, including 14 repetitions per stimulus pair (refer to Section 3.1). In this second experiment, however, subjects also received tactile stimulation in the form of longitudinal skin stretch to the fingerpad of their right index finger, rendered via the contact location display (Fig. 1(a)). Skin stretch was assumed equal to the commanded position of the tactile display’s contact block (see Section 2). The levels of skin stretch (denoted as $S_0 - S_4$) and kinesthetic resistance (denoted as $R_1 - R_4$) that were used in this second experiment are provided in Table 2. The reference stimulus for each comparison is denoted as R_3S_0 with a coefficient of friction $\mu_s = 0.6$ and no skin stretch, respectively. Comparison friction levels, R_4 and R_2, were chosen to be one JND above and below the reference level, R_3. R_1 was chosen to be one JND be-

Table 2: Experiment 2 test matrix

R1S0	R1S1	R1S2	R1S3	R1S4
R2S0	R2S1	R2S2	R2S3	R2S4
R3S0*	R3S1	R3S2	R3S3	R3S4
R4S0	R4S1	R4S2	R4S3	

* Reference

Reference Friction Level	Max Stretch Level
R1: $\mu_s = 0.38$ $\mu_k = 0.34$	S0: 0 mm
R2: $\mu_s = 0.48$ $\mu_k = 0.43$	S1: 0.25 mm
R3: $\mu_s = 0.60$ $\mu_k = 0.54$	S2: 0.40 mm
R4: $\mu_s = 0.72$ $\mu_k = 0.65$	S3: 0.55 mm
	S4: 0.75 mm

low R_2. The levels of skin stretch, S_i, were chosen somewhat arbitrarily, and though smaller levels of skin stretch were intended in the design of this experiment, 0.25 mm was the smallest nonzero stretch level that could reliably be rendered due to torque and controller limitations of the test apparatus. Subjects were instructed to select which of the paired stimuli exhibited greater friction based on the resistive kinesthetic force and the tactile input.

As suggested in Fig. 2(b), skin stretch was implemented based on a simple spring model of human fingerpad skin. In general the skin stiffness could be represented with a nonlinear spring model; however, for simplicity we have implemented a linear spring model for these experiments. As suggested in Fig. 2(b), the imposed skin stretch is directly proportional to friction force that was calculated by the Karnopp friction model and inversely proportional to the modeled skin stiffness. The spring stiffness for each trial was selected in order to render a desired skin stretch based on the assumption of a 1.5 N normal force. Before testing began, subjects were instructed to provide a normal force of 1-1.5 N and were trained on how this felt. To implement the desired level of skin stretch for each stimulus, the rendered skin stiffness was scaled by the coefficient of friction to achieve iso-skin stretch levels corresponding to 0, 0.25, 0.40, 0.55, and 0.75 mm for each of the skin stretch levels $S_0 - S_4$, respectively, across all friction levels, R_i (see Table 2). In order to ensure that only skin stretch and no slip occurred during testing, an estimate of the coefficient of friction between skin and the rubber-coated contact block was measured to be $\mu_s \simeq 1.0$ using a JR3 force sensor (model no. 67M25A-U562) and levels of skin stretch were chosen to stay within static friction limits.

4.2 Results and Discussion

Figure 4(a) shows typical results for one subject. This subject maintained an average normal force around 1-1.5 N; this behavior was typical among all subjects. Since the skin stretch calculations were based on an assumed normal force of 1.5 N and small variations in applied normal force occurred, the actual maximum rendered skin stretch for each trial also varied in proportion to this variation. Further details concerning the interpretation of the psychophysical data are discussed below in the context of the composite results shown in Fig. 4 (b).

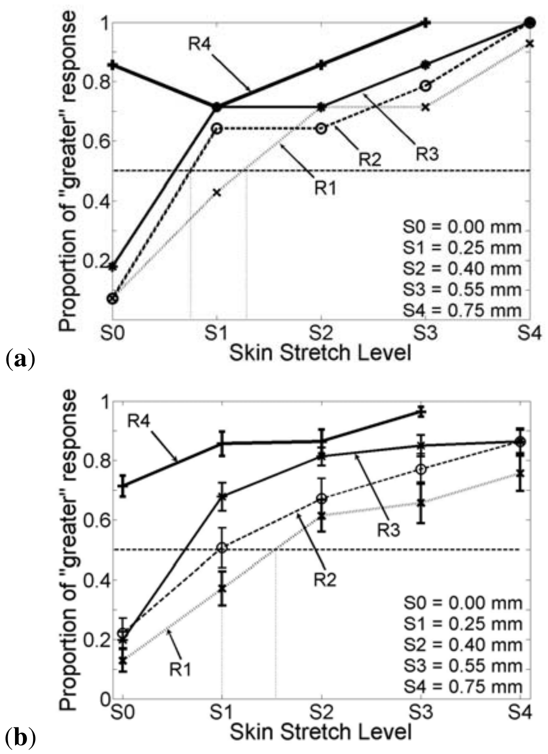

Figure 4: Experiment 2 skin stretch superimposed on kinesthetic resistance (a) Plot of typical responses to combined skin stretch and kinesthetic resistance of 1 subject. (b) Plot of composite test results for combined skin stretch and kinesthetic friction from all subjects.

The responses from all subjects were analyzed individually and then combined to also consider their composite response. The composite results are shown in Fig. 4 (b). Each of the curves in Fig. 4 (b) correspond to friction levels $R_1 - R_4$ and represent psychometric functions relating each of the comparison stimuli to that of the reference stimulus, R_3S_0. Kinesthetic resistance levels, R_4 and R_2, are 1 JND above and below the reference level, R_3. R_1 is 1 JND below R_2. The curve related to friction level R_3 represents the pure influence of skin stretch ($S_1 - S_4$) superimposed on a constant level of coulomb-based kinesthetic resistance (R_3), and shows the pronounced influence of skin stretch. As expected for the R_3 curve, the point associated with R_3S_0 lies well below 0.50 meaning that all comparison stimuli ($R_3S_1 - R_3S_4$) with non-zero skin stretch were interpretted as having greater levels of friction than the reference R_3S_0. The psychometric curves corresponding to R_1, R_2, and R_4 show the cross-modal effects of how varying the skin stretch levels are interpreted when the friction levels ($R_{1,2,4}$) are different than the reference friction level (R_3). Again there is a pronounced effect of increased skin stretch on perceived friction levels.

The upward trend for all friction levels ($R_1 - R_4$) suggests that skin stretch has a significant affect on the subject's perception of friction. In particular, curve R_2 shows a point of subjective equality (PSE) which lies very near S_1, corresponding to a skin stretch of 0.24 mm. This data suggests that the addition of 0.24 mm of skin stretch in combination with lower friction levels would be interpreted identically by subjects as a resistance level that was 1 JND greater in magnitude without skin stretch. The curve corresponding to R_1 therefore suggests that the addition of 0.33 mm of skin stretch would be interpreted interchangibly with a coulomb-based kinesthetic resistance level 2 JNDs greater in magnitude. Therefore, low levels of friction rendered via force feedback can indeed be augmented with addition of small amounts of skin stretch.

5 Conclusions

In this paper we evaluated difference thresholds for coulomb-based kinesthetic resistance rendered via a PHANToM robotic arm that show a Weber ratio ranging from 0.28 to 0.19 across friction levels, $\mu_s = 0.2 - 0.8$, respectively. Further, in our second experiment we show the pronounced effect that a small amount of skin stretch (0.24 mm) superimposed with friction can have on one's perception of friction. These results suggest that the addition the addition of a simple shear plate tactile display to current haptic devices could significantly enhance the sensation and range of friction rendered with these systems without requiring larger motors in the haptic display. This means that the typical small range of friction that can be rendered with the common haptic devices could be greatly augmented by the superposition of a small amount of skin stretch. It should also be noted that subjects said that the presence of skin stretch enhanced the realism of the friction sensation. Future work will consider expanding this study to consider a broader range of friction levels and will also consider the influence of slip in combination with skin stretch and kinesthetic resistance. We will also consider implementing more complex models for friction (e.g., [4]) and skin stiffness.

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