Fingerpad Skin Stretch Increases the Perception of Virtual Friction

William R. Provancher, *Member*, *IEEE*, and Nicholas D. Sylvester

Abstract—This research focuses on the relative importance of fingerpad skin stretch on the perception of friction. It is hypothesized that the perceived magnitude of friction rendered by traditional force feedback can be increased through the addition of fingertip skin stretch. Perceptual data are presented from two separate tests performed on nine male subjects. The first experiment determines the perceptual thresholds for friction based on a modified Karnopp friction model where friction is rendered as purely a kinesthetic resistance via a PHANToM force feedback device. JNDs of 0.056-0.150 corresponding to static coefficients for friction of $\mu_s = 0.2\text{-}0.8$ were established. The second experiment evaluates possible changes in the perceived friction magnitude due to imposing small amounts of tangential skin stretch (0.25-0.75 mm) to the fingerpad in combination with force feedback (kinesthetic resistance). Our results show that even these small amounts of skin stretch lead to a statistically significant increase in perceived friction ($\mathrm{p} < 0.01$). This significant finding will enable the hapticians to more realistically and accurately render friction via a combination of kinesthetic resistance and tactile feedback.

Index Terms—Tactile display, perception and psychophysics, haptic rendering, friction, skin stretch.

1 Introduction

Grasping objects and accurately manipulating or exploring them would be quite difficult in the absence of friction. This is true whether one is trying to identify and orient a tool in his/her hand, or placing an object in a precise position and orientation. Because friction is so prevalent in everything that one does, the ability of a haptic device to simulate friction accurately is of utmost importance. Trying to manipulate or explore an object through a haptic device without rendering friction or rendering it incorrectly increases the difficulty of the task and is not as realistic [1]. Cadoret and Smith have found that when a person tries to regulate his grip force, friction appears to be more important than texture; emphasizing the importance of rendering friction in a virtual environment [2].

The ideal haptic interface would allow the user to sense the friction properties of a virtual object in the same intuitive, yet detailed way she would a real object. In a real environment, a person receives both tactile and kinesthetic sensations to make a judgment about the friction properties of an object or surface. However, in the field of haptics, friction is classically rendered as kinesthetic resistance via a force feedback device. Rendering friction as purely a kinesthetic resistance falls short of the ideal friction display—tactile feedback is also necessary. In the real world, as the fingerpad slides across a surface the skin stretches (displaces) tangentially opposite to the direction of motion. Therefore, for haptic researchers to render virtual friction in a more realistic manner, tangential skin stretch at the fingerpad should also be rendered. To implement an accurate and realistic friction model involving skin stretch and kinesthetic resistance, the interaction between kinesthetic resistance and skin stretch must be understood.

The hypothesis of this research is that the addition of skin stretch to a kinesthetic resistance force will increase the perceived friction magnitude. The authors' early pilot tests show that skin stretch does indeed play an important role in the perception of friction magnitude. However, its influence can be dwarfed when comparing stimuli where the difference in the kinesthetic resistance between them is quite large. Our approach to understanding the combined influence of the tactile and kinesthetic inputs on friction magnitude is to first establish difference thresholds associated with kinesthetic resistance (Experiment 1). We then quantify the additional effect of skin stretch in terms of these kinesthetic JNDs in Experiment 2.

Therefore, our hypothesis is tested via two perceptual experiments. The first experiment quantifies the difference thresholds for friction based solely on coulomb-like kinesthetic resistance (i.e., force feedback only). This is done to establish the human resolution (JND) to perceive kinesthetically rendered friction. The second experiment determines the added effect that skin stretch has on the perceived friction magnitude when presented in combination with kinesthetic resistance. The second experiment does this by reducing the level of kinesthetic resistance while increasing levels of skin stretch to quantify the level of skin stretch that can substitute for kinesthetic resistance. The second experiment will, therefore, quantify the effect that applied skin stretch has on perceived friction magnitude.

Typically, a haptic device has an upper limit on the magnitude of friction force (or kinesthetic resistance) that can be rendered due to motor torque limitations. If our

- W.R. Provancher is with the Department of Mechanical Engineering, University of Utah, 50 S. Central Campus Dr., 2110 Merrill Engineering Building, Salt Lake City, UT 84112-9208. E-mail: wil@mech.utah.edu.
- N.D. Sylvester is with the Department of Mechanical Engineering, University of Utah, 50 S. Central Campus Dr., 2110 Merrill Engineering Building, Salt Lake City, UT 84112-9208 and with the IM Flash Technology Corp., Lehi, UT. E-mail: nick.powderhound@gmail.com.

Manuscript received 5 Aug. 2008; revised 28 Apr. 2009; accepted 18 June 2009; published online 28 July 2009.
Recommended for acceptance by F. Barbagli.
For information on obtaining reprints of this article, please send e-mail to: toh@computer.org, and reference IEEECS Log Number TH-2008-08-0051.
Digital Object Identifier no. 10.1109/ToH.2009.34.

hypothesis that skin stretch increases perceived friction is correct, it would greatly motivate the addition of a simple tactile shear display to current haptic devices. This addition will help supplement a haptic device's limited force reflection capabilities when rendering friction. Displaying fingertip skin stretch will also yield a more realistic virtual touch interface.

2 Background

To provide context for our presented research and some of the decisions made in conducting these experiments, we now provide a brief review of the related literature.

2.1 Physical Friction Models

Friction is more complex than it seems *on the surface*; it is the result of many physical interactions which depend on contact geometry and topology, properties of the bulk and surface materials of the bodies, displacement and relative velocity of the bodies, and presence of lubrication [3]. 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. Dahl formulated a friction model to account for the microscopic presliding displacement present between two bodies which is a generalization of Coulomb friction [4]. The Bristle model attempts to incorporate contact points between two surfaces at a microscopic level [3]. There are countless other friction models, all of which capture elements of the friction phenomenon, and none of which capture all of the elements. Other friction models are reviewed by Olsson et al. [3].

2.2 Numerical Friction Models for Haptics

Some models lend themselves more easily to haptics research, while others are more complicated to implement and have numerical issues, such as the Coulomb and Bristle models. Hayward and Armstrong have developed and implemented a modified Dahl model to synthesize friction using a haptic device. Their modified model removes drift and oscillation problems associated with the original Dahl model and is easier to numerically implement [5]. An earlier, simpler approach, used in the research herein, was proposed by Karnopp [6]. 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 [6]. If the friction force reaches a prescribed limit, the system transitions to slip phase and the friction force obeys classical coulomb kinetic friction behavior. Richard and Cutkosky have shown that a modified version of the Karnopp friction model can be easily and accurately implemented to render kinesthetic resistance through a haptic device [7]. The modification to Karnopp's original model is done by incorporating a virtual spring in order to store and track the applied forces (see Fig. 2). Hence, the virtual Karnopp spring takes the place of a force sensor for determining when to transition to sliding friction. However, the virtual spring constant and the velocity threshold must be properly tuned to avoid oscillations when using the modified Karnopp model. Navhi et al. have also successfully used a modified Karnopp model to quantify the frictional properties of the human fingerpad [8]. Given the accuracy, ease of implementation, and previous success in using the "coulomb-like" modified Karnopp model (i.e., [7], [8]), we have identified it as an ideal candidate for the two experiments conducted in this paper. Furthermore, by using a modified Karnopp model, the results of our experiments are more easily interpreted because both the virtual Karnopp spring and fingerpad model used to render skin stretch are linear.

2.3 Prior Work on Fingertip Slip Display, Skin Stretch Feedback, and Force Sensitivity

Many researchers have investigated tangential fingerpad stretch and sliding between the finger and a surface. Several earlier perceptual and neurophysical studies have provided motivation for pursuing this type of feedback in designing new tactile displays. In particular, Smith and Scott have shown that shear forces applied to the skin supply ample tactile sensations to the mechanoreceptors in human skin [9]. Furthermore, Biggs and Srinivasan have shown the fingerpad to be more sensitive to tangential displacement than normal displacement [10]. As such, several research groups have recently pursued tactile display designs that utilize skin stretch and slip feedback. We briefly discuss this research below while highlighting the outcomes directly related to the use of shear and/or slip display.

Hayward's research group is one of the first groups to exploit the use of lateral skin stretch to provide tactile feedback [11]. They show that small amounts of lateral skin stretch from an array of tactors can provide rich tactile sensations during exploration. Hayward and Cruz-Hernandez present a haptic device utilizing this type of feedback and find that movements on the order of $\pm 50\ \mu\mathrm{m}$ are easily detectable [11]. A similar device, developed by Fritschi et al., is capable of presenting both lateral skin stretch with their pin array, as well as, normal pin motion [12], [13]. While the above devices do apply skin stretch, the stimulation is applied locally, at several different points on the fingerpad using small pins ($\sim 1\ \mathrm{mm}$ diameter each). The net tactile feedback from these devices is provided via the procession of multiple pins moving in sequence. In contrast, and more pertinent to the present study, a number of other researchers have looked at applying a more uniform shear stimulus over the entire fingerpad.

Like the authors' compact tactile display, Webster et al. and Tsagarakis et al. have made compact fingertip-mountable tactile displays that have been used to improve task performance in virtual environments. Webster et al. constructed a compact slip display that resembles a powered mouse ball that can be mounted to the end of a PHANToM [14]. They show a reduction of task interaction forces with the addition of slip feedback when moving a virtual object into a specified orientation. Tsagarakis et al. have also built a compact slip display using two separate rollers placed at the tip of the finger [15]. The two rollers are oriented at 45 degrees relative to the finger's length. They show that by controlling the relative speed of each roller they can communicate multiple perceptible speeds and orientations of slip.

A larger version of the slip display developed by Webster et al. is presented by Fritschi et al. [16]. The Fritschi display has been integrated with a 10-DOF, hyper-redundant robotic arm for conducting experiments with combined kinesthetic and tactile feedback. Their preliminary experiments show an increase in the perceived realism of virtual surfaces with the addition of submillimeter amounts of skin stretch. Their result agrees with what we have observed in our experiments presented herein.

Hayward and Yi have used shear feedback based on an object's height gradient in order to create the illusion of an out-of-plane bump [17]. This research was actually conducted on a kinesthetic display; however, since the user interacted with their device by placing his/her fingertip on a flat disk, their device induces skin stretch in a manner quite similar to the research presented herein.

Salada et al. used a rotating drum that applied a specific slip orientation and slip rate to the fingertip [18]. Their test subjects track the orientation of the slip display under various conditions that allow or prevent various levels of skin stretch and slip to occur. Their test results show a significant reduction in the users' orientation tracking performance when fingertip skin stretch was prevented. Salada eliminates skin stretch in his experiments through the use of a membrane-like spatial filter between the rotating drum and the user's finger. Salada's findings on the importance of skin stretch is in agreement with several prior studies. These prior studies show that people have greater sensitivity to applied skin stretch than to sliding an object on their fingertip when judging the direction of tactile stimuli [19], [20]. Salada's results are also the reason that the studies herein focus on the contribution of skin stretch to the perception of friction rather than on sliding.

Taking a cue from Salada's results, both Winfield et al. and Biet et al. have pursued tactile display designs where the working principle is to change the effective coefficient of friction of the interaction surface [21], [22]. This is done through the development of an air bearing "squeeze film" between the user's finger and the device. Hence, these researchers are indirectly invoking skin stretch on the user's fingerpad. However, this display type must rely on the user's finger motion to apply skin stretch. To address this shortcoming, Chubb et al. [23] evolved the system presented by Winfield et al. to modulate both the coefficient of friction and position of the device's contact surface. Chubb et al. apply in-plane oscillations to their device's friction pad while actively varying this pad's friction level to create shear forces that are perceptible to the user as a sustained vibration. This permits their device to apply shear forces and skin stretch somewhat independently from the user's finger motions. Also based on Salada's results, Gleason et al. used shear feedback on the fingertip to communicate direction cues that are useful for navigation [24].

3 Device Description

The hardware used for these experiments consists of a SensAble Technologies PHANToM Premium 1.0 force feedback arm [25] and a contact location display apparatus

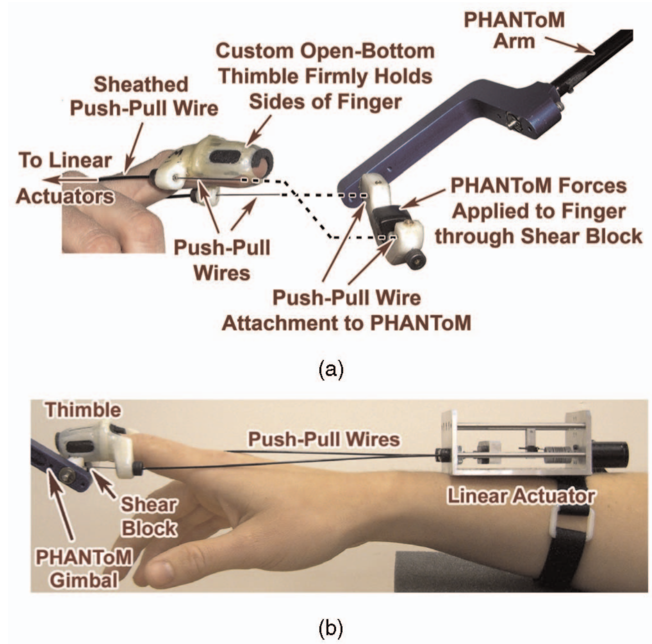


Fig. 1. (a) The shear block of the contact location display device directly attaches to the PHANToM at its gimbal. The push-pull wires are inserted into holes in the shear block carrier through holes as indicated by the dashed lines and held in place via setscrews. The shear block is suspended beneath the open-bottom thimble until it is desired to render that contact has occurred. To render contact, the push-pull wires are deflected transversely by forces applied by the PHANToM normal to the fingerpad. These forces push the shear block into contact with the user's finger. (b) Assembled contact location display device.

[26]. The PHANToM was used to render normal forces and kinesthetic resistance (fore-aft friction forces) for both experiments. Normal force was implemented in software through a virtual spring with a stiffness of 500 N/m. Finger motions were tracked via the PHANToM and the corresponding motions were displayed visually using OpenGL on a computer screen. The rotation of the PHANToM's base joint was neither controlled nor tracked, subjects were simply instructed to try not to rotate the base left/right (although if they did, there would not be any significant effects). The standard 3-DOF PHANToM gimbal was not used for these experiments. It was replaced by a 1-DOF gimbal with the shear block attached as displayed in Fig. 1. Gimbal rotations were not measured and subjects were instructed not to twist (roll) or tilt (pitch) their finger to the best of their ability. Small variations in finger angle do not affect how the haptic stimulus is rendered.

A contact location display device as shown in Fig. 1 was used to render skin stretch for Experiment 2. The device utilizes a radiused ($\sim$1 cm) rubber-coated wood block for imparting shear and skin stretch to the user's fingerpad. The shear block is housed in a cradle that is directly attached to the PHANToM gimbal as depicted in Fig. 1. The subject's finger is held in a custom open-bottom thimble that is located above the contact block. A servomotor drives the block along the length of the user's fingerpad via two sheathed 0.61 mm diameter steel push-pull wires to impose skin stretch.

The actuator of the contact location display is located on the user's forearm to reduce device inertia at the fingertip and to minimize the transmission of motor vibrations to the

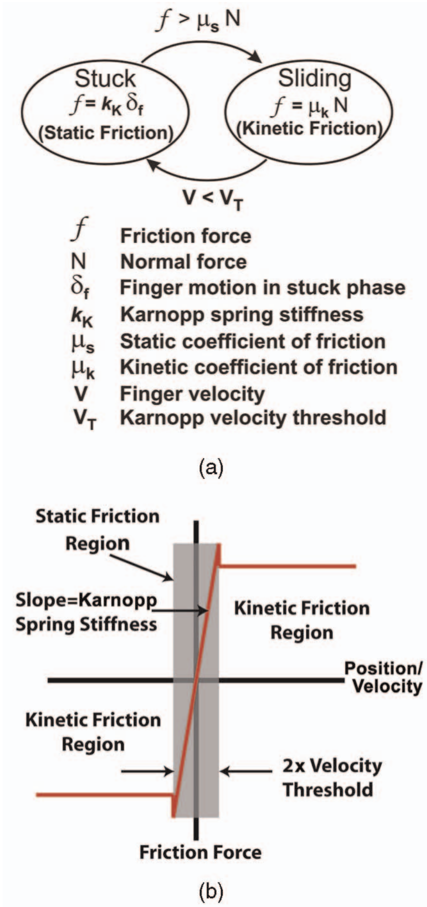


Fig. 2. (a) Karnopp friction model state diagram and (b) associated force motion graph. Below a specific velocity threshold the system is considered stuck and friction force is based on stretching a virtual "Karnopp" spring. Once the maximum static friction force has been reached, the system transitions to sliding. During sliding, kinetic friction is a function of the normal force and coefficient of friction.

user's fingertip mechanoreceptors. The shear block is suspended underneath the fingerpad by the drive wires so that it does not touch the user's finger until it is desired to render contact with the virtual environment. The bandwidth of the contact location display device exceeds 5 Hz for a 10 mm amplitude signal. Shear block positions along the finger are rendered with a maximum error of 0.21 mm for fast hand motions and an error of approximately 0.05 mm for slower motions more typically used by our test subjects.

The shear block (shown in Fig. 1a and schematically in Fig. 6) was dip coated with rubber (Performix brand Plasti Dip) to prevent it from sliding on the finger when applying skin stretch. The static coefficient of friction between this rubber coating and a fingerpad was experimentally measured to be $\mu_s \approx 1.0$, using a JR3 force sensor (model no. 67M25A-U562). The shear block's coefficient of friction conservatively exceeds the requirements to prevent slip in Experiment 2. Because of the reasonably high accuracy of rendered shear block motions and the high coefficient of friction of the shear block's rubber coating, the rendered skin stretch in these experiments is assumed to be equal to that of the commanded shear block motions.

To display haptic interactions with this device, a virtual surface was programmed in C and C++ on a computer running RTAI 3.1 on Red Hat 9 Linux. A 1 kHz PID position feedback controller uses the display's servomotor to adjust the position of the shear block based on detected finger motion. Further details about the design and control of this device can be found in [26].

4 Experiment 1: Friction Thresholds via Karnopp Friction-Based Kinesthetic Resistance

The goal of this first experiment is to establish difference thresholds for friction based solely on kinesthetic resistance (force feedback), reported as the just noticeable difference or JND. This is an important building block for understanding how a person interprets friction via multiple sensory channels.

4.1 Experiment 1 Details

4.1.1 Karnopp Friction Model Implementation

Kinesthetic resistance was rendered by a PHANToM force feedback device using a modified Karnopp friction model. The Karnopp friction model was chosen because of the ease of implementation and previously demonstrated effectiveness in rendering coulomb-like friction without numerical difficulties [8], [7]. Though unnecessary for Experiment 1, test subjects wore the contact location display device during this experiment to maintain consistency with Experiment 2 where the subjects did wear the device. However, during Experiment 1, the rubber-coated shear block was removed from the contact location display.

The Karnopp friction model prescribes static and dynamic friction states as shown in Fig. 2 [6]. In the modified version of the Karnopp model implemented herein, friction forces during the static (stuck) phase are calculated by stretching a virtual "Karnopp spring" of stiffness k_K. Once the friction force exceeds the static friction limit ($f_{max} = \mu_s \cdot N$), the system enters the sliding phase. The "Karnopp spring" was held at a constant stiffness of 1.5 N/mm throughout this experiment. This stiffness value approximates the stiffness of human fingerpad skin [27], such that skin stretch would be applied in a "natural" manner. That is, the stretch of Karnopp spring approximates the skin stretch that is naturally experienced when sliding one's finger over a surface. Furthermore, by keeping the Karnopp spring constant fixed at 1.5 N/mm, higher coefficients of friction allow the test subject to move his finger farther before transitioning to sliding phase. This is consistent with real world friction behavior during tactile exploration. It should also be noted that when friction is being rendered, a reversal of finger direction will first unstretch in the Karnopp spring before force/stretch is built up to oppose the new direction of travel. This is also consistent with observations of fingerpad deformations when reversing directions.

During the sliding phase, rendered friction is purely a function of the normal force and coefficient of kinetic friction. The friction forces are still rendered via a Karnopp spring, but with the lower force threshold ($f = \mu_k \cdot N$). If, however, the velocity of the finger falls below a specified

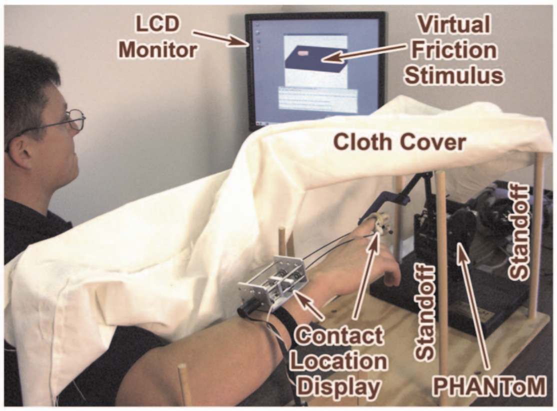


Fig. 3. Experimental setup for both experiments. The subject's arm and hand were covered with a cloth to occlude any visual clues provided by the hardware. The cloth is pulled back in this image for clarity.

velocity threshold, the system transitions back to the stuck phase, where static friction prevails. Upon transition back to static friction, the Karnopp spring forces are allowed to again grow until the static threshold is exceeded ($f_{max} = \mu_s \cdot N$). Fig. 2a provides a graphical display of the two phases and associated phase transitions. The virtual Karnopp spring stiffness and the velocity threshold are empirically tuned in order to avoid instability and oscillation between the stuck and slip phases. The velocity threshold is set to 12.5 mm/s.

4.1.2 Experimental Setup and Methods

The basic experimental setup is illustrated in Fig. 3. User testing is automated via a simple user interface program. This is done to reduce the required interaction of the experimenter and to ensure consistency between subjects. To occlude visual cues provided by the experiment apparatus, a cloth cover is placed over the test hardware as shown in Fig. 3. The only visual prompt presented to the subject is the virtual object and finger, and the user interface program. Subjects wear headphones that play white noise and deliver intermittent audio cues about the experiment. Each test subject rests his arm on a rolling armrest during the tests and is instructed to make gross fore-aft arm movements to explore each stimulus.

In our experiments, test subjects are presented with a flat virtual surface with prescribed friction levels. Test subjects are trained and instructed to apply approximately 1-1.5 N of normal force, for consistency, while exploring virtual friction stimuli. The rendered normal force stiffness is 500 N/m for virtual surfaces.

In contrast to many experiments with haptic devices where stimuli are applied to the subject's finger, the subject "experienced" our friction stimuli through active exploration. For expediency, prescribed time periods are allotted for exploring each stimulus. It is found that subjects often needed more time to judge the stimuli at the beginning of each experiment, though there is a very fast learning curve. They are also able to judge the second of two paired stimuli almost immediately. For this reason, we included two adaptations in the design of our automated test interface.

The test interface initially gives subjects seven seconds to probe the first stimulus and six seconds for the second stimulus. These times are decreased for the first three comparisons, settling to five and three seconds for the first and second stimuli, respectively. A one second pause is implemented between the first and second stimuli, during which subjects are instructed not to move their finger. The time blocks are indicated to the test subjects by playing tones through their headphones.

TABLE 1
Experiment 1 Comparison Stimuli for Friction Levels, $\mu_s = 0.2, 0.4, 0.6, 0.8$

Reference Friction	Comparison Stimuli (μ_s)					
$\mu_s = 0.2$	0.02	0.08	0.14	0.26	0.32	0.38
$\mu_s = 0.4$	0.20	0.27	0.33	0.47	0.53	0.60
$\mu_s = 0.6$	0.35	0.46	0.53	0.67	0.74	0.85
$\mu_s = 0.8$	0.49	0.65	0.72	0.88	0.95	1.11

The method of limits is first used to get a rough estimate of the difference threshold (JND) at four reference static friction levels ($\mu_s = 0.2, 0.4, 0.6, 0.8$). After establishing rough estimates of the JND at these four friction levels, we employ the method of constant stimuli with a paired-comparison, forced-choice test paradigm to more accurately characterize the friction thresholds [28]. The rough JND estimates are used to help select comparison stimuli for the method of constant stimuli experiments.

For each reference friction level, six comparison stimulus values were chosen (three higher than the reference and three lower than). Comparison stimulus values for each reference stimulus are shown in Table 1. The extreme high and low values of the comparison stimuli are chosen through initial testing to elicit a correct response roughly 90 percent of the time. The kinetic coefficient of friction, μ_k, for each of these friction levels is chosen to be 90 percent 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).

Nine test subjects participated in this experiment. A minimum of five people were tested at each of the four reference friction levels (Table 2), with 14 repetitions of each stimulus pair. Subjects were asked to report which of the two presented stimuli had a greater amount of friction. The presentation of stimulus pairs for each reference level is balanced and presented in a randomized order to reduce bias and habituation. Subjects wear headphones playing white noise (plus the time-block tones) to mask any background noise. Subjects enter their responses by entering a 1 or 2, plus the enter key, using the number pad of a computer keyboard. Most test subjects typically completed tests for two of the four friction levels. The test at each reference level takes approximately 30 minutes to complete. Test subjects complete the test using their right index finger, and all but two subjects were right-hand dominant. All test subjects were males between the ages of 23 and 34. Finger velocity data and normal force data were collected during each of the tests.

4.2 Results and Discussion

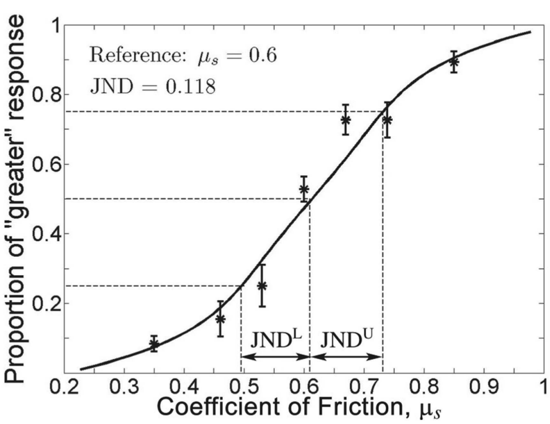
The results for each test subject and each reference friction level are computed separately to establish the JND for friction rendered purely as kinesthetic resistance via

TABLE 2
Experiment 1 Kinesthetic Friction JND Results via Method of Constant Stimuli

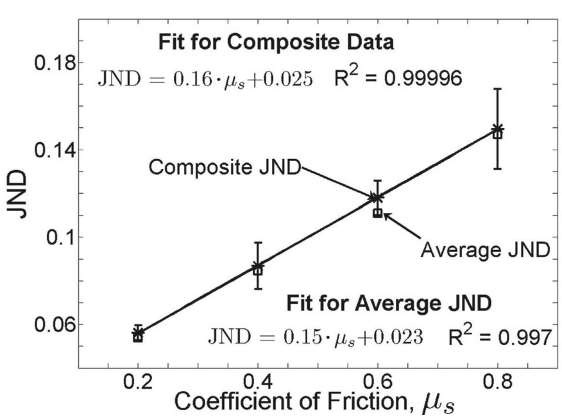
Reference Friction	Composite JND	Composite JND %	Average JND	Standard Error	Average JND %
$\mu_s = 0.2$	0.056	0.28	0.054	0.0034	0.27
$\mu_s = 0.4$	0.087	0.22	0.085	0.011	0.21
$\mu_s = 0.6$	0.118	0.20	0.111	0.0080	0.19
$\mu_s = 0.8$	0.150	0.19	0.147	0.018	0.18

The composite JNDs were found by pooling the data for all subjects for a given reference friction level and establishing the JND on this lumped set of data. The average JND was calculated by finding individual JNDs and then averaging them together.

methods outlined by Gescheider [28]. These methods entailed converting the recorded proportions to z-scores, establishing a linear fit to the data points, solving for the upper and lower JNDs, and then converting the fit line back to the equivalent proportions to plot the sigmoid as shown in Fig. 4a. Since only a small number of repetitions were performed for each subject, there was noticeable variation between their results. For this reason, data for all subjects for a given friction level were pooled and analyzed to establish the JND. We refer to this pooled data as "composite" JND results, as shown in Fig. 4. Fig. 4a provides the composite response for a reference friction level of $\mu_s = 0.6$, with error bars indicating the standard error. This graph shows the proportion of times subjects chose a stimulus' friction magnitude to be larger than the reference. As expected, the data follow a sigmoidal distribution. The dashed lines mark the 25 percent and 75 percent proportions corresponding to the points where the upper and lower JNDs were calculated. As shown in Fig. 4a, the composite JND at a reference friction level of $\mu_s = 0.6$ was calculated to be 0.118. Plots similar to Fig. 4a were produced for each of the other three friction levels, all with similar characteristics (see [29]).



(a)



(b)

Fig. 4. Experiment 1 kinesthetic friction JND results using the method of constant stimuli. (a) Composite JND results from all subjects for $\mu_s = 0.6$. (b) Composite and average JND results for friction levels $\mu_s = 0.2, 0.4, 0.6, 0.8$. Error bars indicate the standard error of the average JND data.

Fig. 4b shows the composite and average JND for each of the reference friction levels along with a best fit line for the composite JNDs. The "average" JNDs were established by taking the average of individual subject JNDs, while the composite JND is a single calculated value based on pooled subject data. These results are also summarized in Table 2. As would be expected, the average JND of all subjects at each reference friction level is very close to the associated composite JND. This supports the assumption that if each subject had completed more repetitions, his JND would approach that of the composite data. The trend line fit to the composite data indicates an extremely good correlation. This trend line allows us to predict the JND for arbitrary static friction levels between 0.2 and 0.8, and will be utilized in Experiment 2. The error bars were obtained from the standard error of the JNDs for each subject. The error bars shown in Fig. 4b tend to get larger for higher coefficients of friction. This is an expected trend since many human perception abilities follow this type of behavior of scaling with stimulus magnitude [28].

Normal force data and velocity data were gathered throughout the entire test for each subject. Normal force data were recorded every millisecond of each stimulus and then averaged. Fig. 5a shows the average normal force for each stimulus with the trial number referring to a single paired comparison. Although there is much variation in normal force from one paired comparison to the next, the two lines tend to follow each other suggesting that subjects applied about the same normal force for both of the stimuli in a single comparison. It is imperative that subjects exert about the same normal force between paired comparisons since the kinetic friction is a function of normal force. The lower plot in Fig. 5a shows the standard deviation of normal force calculated from the data collected every millisecond for each trial. The standard deviation shows that subjects generally maintained a fairly constant normal force while exploring each stimulus. The ability of the subject to maintain a reasonably constant normal force in the presence of changing friction forces agrees with the

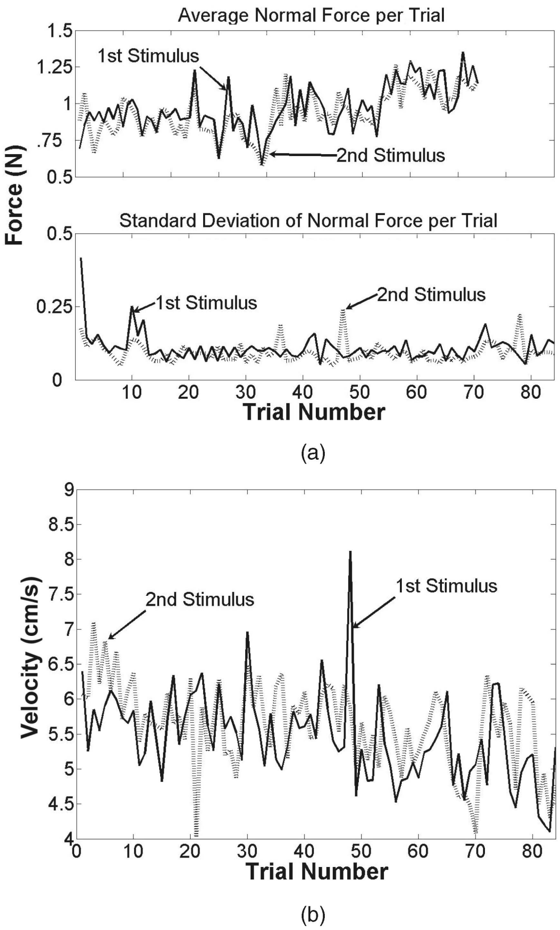


Fig. 5. Experiment 1. (a) Typical average normal force and associated standard deviation per stimulus for reference $\mu_s = 0.6$. (b) Typical average absolute value of velocity per stimulus for reference $\mu_s = 0.6$.

research performed by Smith and Scott [9]. All subjects followed these same trends and all subjects generally exerted between 1 and 1.5 N; the average normal force across all subjects was 1.31 N with a standard deviation of 0.21 N. On average, subjects pressed slightly harder for the second stimulus ($\overline{x} = 0.06$ N, $\sigma = 0.069$ N). This represents only a 4.5 percent difference in applied normal force between stimuli. As this change is below the reported 7 percent JND for discriminating force levels, this is not considered to have a significant effect [30]. Nonetheless, even if this difference in applied normal force was significant, its effect would be mitigated by the balanced experiment design for stimulus presentation.

Typical finger velocity data are shown in Fig. 5b. The absolute value of instantaneous finger velocity was recorded every millisecond and then averaged at the end of every stimulus. The standard deviation of finger velocity was also calculated; however, this has very little meaning since subjects were instructed to make fore-aft motions with their arm and therefore the standard deviation was large. Subjects were not instructed on how fast to move their finger; however, most subjects utilized finger motions between 4 and 7 cm/s. The average velocity across all subjects for exploring the stimuli was 5.29 cm/s. The maximum and minimum average velocity for a single subject was 7.96 and 2.30 cm/s, respectively. Subjects generally employed about the same finger velocity for both stimuli of a paired comparison, with an average difference between paired stimuli of only 1.6 mm/s (with a standard deviation, $\sigma = 3.4$ mm/s). However, the exact velocity is not critical in judging friction magnitude as modeled. This is due to the nature of mode switching in the Karnopp friction model between static and dynamic modes. Our test subject's finger motions generally exceeded our model's chosen velocity threshold, v_T (12.5 mm/s). Therefore, subjects experienced "kinetic" (sliding) friction for a majority of time in each trial.

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

The second experiment was designed to study the perception of friction based on the addition of a small amount of tangential skin stretch to one's fingerpad when presented in combination with coulomb-like kinesthetic resistance. Our hypothesis is that by superimposing skin stretch with rendered kinesthetic resistance, subjects will perceive an increased friction magnitude. Subjects were asked to judge which of two paired stimuli had a greater friction magnitude. The stimuli consisted of tactile inputs based on longitudinal skin stretch applied using the contact location display combined with kinesthetic resistance rendered via a PHANToM. Skin stretch was applied via a rubber-coated shear block, which had been removed from the contact location display when conducting Experiment 1.

The influence of skin stretch was quantified by comparing friction stimuli of lesser kinesthetic resistance with skin stretch to a reference stimulus of greater kinesthetic resistance and no skin stretch (stimulus R_3S_0 in Table 3). The reference stimulus had a coefficient of friction of

TABLE 3
Experiment 2 Test Matrix

R_1S_0	R_1S_1	R_1S_2	R_1S_3	R_1S_4
R_2S_0	R_2S_1	R_2S_2	R_2S_3	R_2S_4
R_3S_0*	R_3S_1	R_3S_2	R_3S_3	R_3S_4

* Reference Stimulus

Reference Friction Level	Max Stretch Level
R_1: $\mu_s = 0.38$ $\mu_k = 0.34$	S_0: 0 mm
R_2: $\mu_s = 0.48$ $\mu_k = 0.43$	S_1: 0.25 mm
R_3: $\mu_s = 0.60$ $\mu_k = 0.54$	S_2: 0.40 mm
	S_3: 0.55 mm
	S_4: 0.75 mm

R_i and S_j represent kinesthetic resistance levels and skin stretch levels, respectively. The reference stimulus for each paired comparison was R_3S_0 (marked with a *), which corresponds to a static coefficient of friction of $\mu_s = 0.60$ and no skin stretch. Actual kinesthetic resistance and skin stretch values are also given.

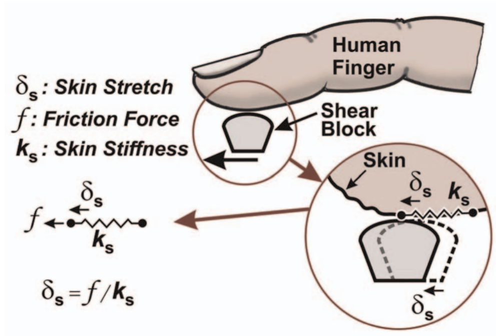


Fig. 6. Spring model of skin stretch used in Experiment 2. The skin is assigned a stiffness and the deflection of the spring (i.e., position of the shear block) is controlled by detected finger motions.

$\mu_s = 0.6$. The comparison stimuli with lesser kinesthetic friction levels were chosen to be 1 and 2 JNDs below that of the reference stimulus based on results from Experiment 1. This allows the effect of added skin stretch to be quantified in terms of the equivalent amount of kinesthetic resistance. This equivalency is measured as the point of subjective equality (PSE) in our cross-modal friction perception experiment. Hence, we are effectively creating a cross-modal JND for applied skin stretch when used with kinesthetic friction display. Comparison stimuli with an equal amount of kinesthetic resistance as the reference ($\mu_s = 0.6$) were also tested in order to show the pure effect of skin stretch without the confounding effect of a lesser resistance level. Further details are provided below and in Sylvester's Master's thesis [29].

5.1 Experiment 2 Details

5.1.1 Skin Stretch Model Implementation

As suggested in Fig. 6, skin stretch was implemented based on a simple spring model of human fingerpad skin. In general, the skin stiffness could be represented by a nonlinear spring model; however, for simplicity we have implemented a linear spring model for these experiments. As suggested in Fig. 6, the imposed skin stretch is directly proportional to the friction force calculated by the Karnopp friction model (see Section 4.1.1) and inversely proportional to the modeled skin stiffness. Therefore, as a subject moves his finger forward, the friction force would build up in the Karnopp spring, and skin stretch is applied in proportion to this friction force ($\delta_s = f/k_s$). The spring stiffness for each trial was selected to render a desired skin stretch based on the assumption of a 1.5 N normal force. Rendering a specific skin stretch level also required the virtual skin stiffness to be scaled by each stimulus' coefficient of friction ($k_s = \mu_s \cdot N/\delta_s$).

Test subjects experience a typical sequence of events for this implementation of friction and skin stretch. Once making contact with the virtual object, an anchor point for the virtual Karnopp spring is set. As the subject moves his finger forward, friction force is built up in the virtual Karnopp spring in a linear fashion as a function of finger position (see Fig. 2b). Skin stretch is then applied in the direction opposite to the finger motion and in proportion to the calculated (static) friction force ($\delta_s = f/k_s$). The force and skin stretch continues to increase in magnitude as the subject moves his finger forward until the static friction limit is exceeded ($f_{max} = \mu_s \cdot N$), at which point the friction model transitions to sliding mode. This transition results in an instantaneous reduction in friction force and skin stretch, corresponding to the kinetic coefficient of friction ($f_{sliding} = \mu_k \cdot N$). This also results in the anchor point of the Karnopp spring being reset.

If the subject's finger velocity exceeds the implemented velocity threshold, v_T (12 mm/s), then the subject continues to experience resistance and skin stretch that is in proportion to his normal force and μ_k. Hence, the anchor point of the Karnopp spring is also dragged along (and behind) the subject's virtual finger while in kinetic friction mode. If, however, his finger speed is less than v_T then the Karnopp model switches back to static mode, and the anchor point of the Karnopp spring again becomes fixed. Friction forces once again change linearly as a function of finger position in static mode. Also note that the magnitude of friction forces and skin stretch are preserved on the transition from kinetic to static friction.

5.1.2 Experimental Setup and Methods

Skin stretch was assumed equal to the commanded position of the tactile display's shear block (see Section 3). The levels of skin stretch (denoted as S_0-S_4) and kinesthetic resistance (denoted as R_1-R_3) that were used in this second experiment are provided in Table 3. 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_2 and R_1, were chosen to be one and two JNDs below the reference level, R_3, respectively. These JNDs were based on the composite data experimental findings from Experiment 1 that are presented in Fig. 4 and Table 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. Skin stretch levels were limited to 0.75 mm to further prevent the shear block from sliding and not stretching the skin as predicted by the commanded shear block motion. In pilot testing, subjects indicated a drop in perceived friction level when sliding occurred, so the authors were careful to avoid this.

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. This was done across all friction levels, R_i (see Table 3). Note, however, that for the skin stretch to feel most realistic both the Karnopp spring and modeled skin spring stiffness must be chosen to match the stiffness of a human fingerpad (e.g., using guidance from [27]).

The experimental setup for Experiment 2 mirrors the experimental design and user interface described for our first experiment, including a balanced and randomized set of stimulus pairs presented 14 times each. As in Experiment 1, white noise was played through headphones and tones were

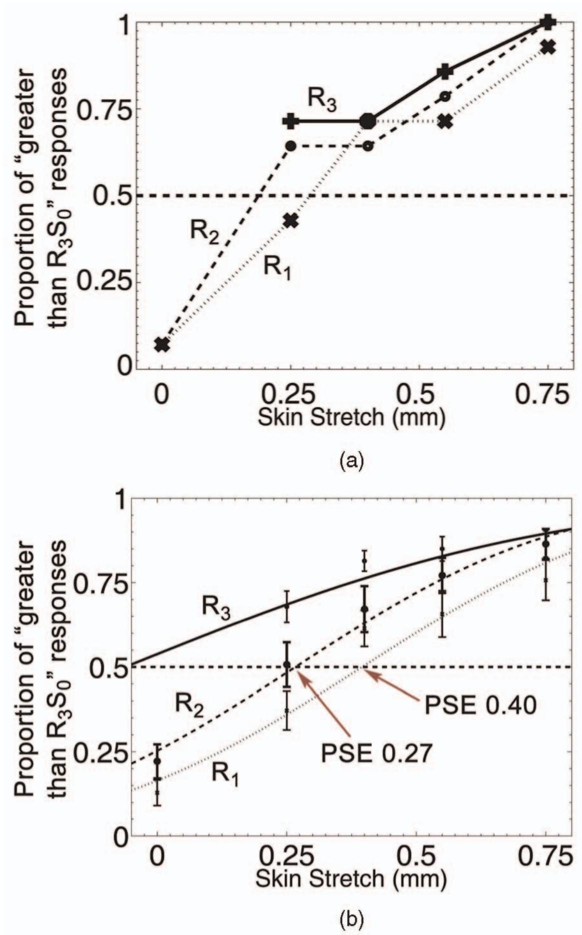


Fig. 7. Results for Experiment 2: skin stretch superimposed with kinesthetic resistance. (a) Responses to combined skin stretch and kinesthetic resistance for a typical subject. (b) Composite test results for combined skin stretch and kinesthetic resistance from all subjects. Error bars indicate the standard error based on combining individuals' data.

utilized to delineate stimulus exploration time blocks (refer to Section 4.1.2). In this second experiment, however, subjects also received tactile stimulation in the form of longitudinal skin stretch to the fingerpad, rendered via the contact location display (Fig. 1). As with Experiment 1, subjects were again asked to report which of the two presented stimuli had a greater amount of friction. Nine test subjects completed all of the test conditions. All test subjects were males between the ages of 23 and 34 and completed the experiment with their right index finger. All but two subjects were right-hand dominant.

5.2 Results and Discussion

Results for Experiment 2 are shown in Fig. 7. Fig. 7a shows typical results for one subject. Subjects responses for each resistance level, R_1-R_3, are shown. Each stimulus R_iS_j was compared to the reference R_3S_0. Lines with differing characteristics are drawn between points for each resistance level to improve readability. The data show that the perceived friction for all three resistance levels increases as additional skin stretch is experienced. Further details concerning the interpretation of the psychophysical data are discussed below in the context of the composite results.

The responses from all subjects were analyzed individually and then combined to consider their composite response. The composite results are shown in Fig. 7b. Each of the sigmoidal curves in Fig. 7b were fit to data by methods documented in [28], as described in Section 4.2. These curves correspond to kinesthetic friction levels R_1-R_3 and represent psychometric functions relating each of the comparison stimuli to that of the reference stimulus, R_3S_0. Kinesthetic resistance levels, R_2 and R_1 were chosen to be 1 and 2 JNDs below the reference level, R_3. 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-like kinesthetic resistance (R_3), and shows the pronounced influence of skin stretch. The psychometric curves corresponding to R_1 and R_2 show the cross-modal effect of how varying the skin stretch level is interpreted when the friction level ($R_{1,2}$) is different than the reference friction level (R_3). Again increased skin stretch has a strong effect on perceived friction magnitude.

The upward trend for all friction levels (R_1-R_3) suggests that skin stretch has a significant effect on the subject's perception of friction. In particular, curve R_2, which is 1 JND below R_3, shows a PSE, corresponding to a skin stretch of 0.27 mm, based on the sigmoidal curve fit. Thus, the data suggest that the addition of 0.27 mm of skin stretch would be interpreted by subjects as equivalent to a resistance that was 1 JND greater in magnitude without skin stretch. Similarly, the curve corresponding to R_1 therefore suggests that the addition of 0.40 mm of skin stretch would be perceived as equivalent to a coulomb-like kinesthetic resistance 2 JNDs greater in magnitude.

Further statistical comparisons were also made with the data reported in Fig. 7b. First, a direct test for significance was made on each curve. For each resistance level R_1-R_3, each of the skin stretch stimuli (R_iS_{1-4}) was compared to the respective stimulus resistance level with zero skin stretch (R_iS_0). This comparison was done using a t-test of dependent means and the error rate was controlled using the Bonferroni correction ($\alpha = 0.05$/number of nonorthogonal comparisons). For all three curves, the addition of skin stretch resulted in a statistically significant increase in perceived friction ($p < 0.003$).

A test for linear correlation was also performed for all resistance level curves, R_1-R_3. In all cases, the perceived friction was found to increase with increasing skin stretch. For resistance levels R_1 and R_2, the correlation was found to be statistically significant ($p < 0.01$). However, the correlation found for the R_3 data points was not statistically significant ($p = 0.097$).

At this point, it is appropriate to return to the manner in which friction stimuli were rendered in order to more carefully reflect upon the above results. While the above results show the significance of skin stretch, there are several important factors in these experiments that require further explanation in order to ensure the proper interpretation. Each of these factors are listed and discussed below.

1. *Influence of kinetic friction*: When test subjects explored the virtual friction stimuli, they often moved their finger fore/aft with sufficient distance and speed to transition from static to kinetic friction

(see Section 4.2). Hence, subjects then experience proportionately smaller skin stretch during the kinetic phase of exploration. This is dictated by the kinetic coefficient of friction, μ_k, which was set 10 percent below the associated static friction coefficient, μ_s. However, since this drop in friction reflects true friction behavior, this isn't considered a confounding effect in interpreting the presented results. But, this did result in a 10 percent drop below the prescribed skin stretch levels in Table 3.

2. *Influence of applied normal force*: When skin stretch was applied, it was rendered in a manner that would provide the desired skin stretch when a subject applied exactly 1.5 N of normal force (based on the static coefficient of friction). As described earlier, scaling of the applied skin stretch with applied normal force was done to prevent slipping of the contact block. However, the average normal force applied by each test subject was typically less than 1.5 N ($\overline{x} = 1.31$ N, $\sigma = 0.21$ N). Based on these computed normal force values, it is clear that, on average, less than the intended amount of skin stretch was applied and experienced by subjects in our experiments. This means that values of skin stretch lower than reported in Fig. 7 are in fact causing a significant increase in perceived friction. For example, if subjects experiencing stimulus R_2S_1 applied 1 N of normal force rather than 1.5 N, that ~ 0.167 mm of skin stretch would have been rendered instead of 0.25 mm. This effect is additive to the 10 percent reduction in skin stretch due to factor 1 above. Hence, the PSE for resistance R_2 is likely less than the reported 0.27 mm. The reduction in applied skin stretch due to lower applied normal forces does not invalidate our results; rather, it means that our reported results are conservative. Even less than a quarter of a millimeter of skin stretch can have a profound effect on how people perceive friction.
3. *Influence of inherent friction of the PHANToM*: The PHANToM device has inherent friction and inertial drag, which causes resistance to movement that the users in our study can surely feel. Measurements of this inherent drag were made using an Omega LCEB-5 5-pound single axis load cell, accurate to ± 0.03 percent. The PHANToM was moved in the horizontal plane using motions that approximated the speed at which subjects explored friction stimuli (~ 5 cm/s). Approximately, 0.2-0.3 N of resistance was measured, though forces were higher if a reversal in direction was quite brisk, due to increased inertial forces. This drag force will have been superimposed on our commanded friction forces, which in particular may have affected the JND results at the lower friction levels from Experiment 1. It is also possible that these drag forces also influenced the results of Experiment 2. However, 0.2 N of drag is relatively small compared to the nominal 0.9 N friction forces experienced in Experiment 2. Nonetheless, this drag resistance will have increased the actual kinesthetic resistance that was experienced by subjects and if this resistance had been compensated for, one would expect proportionately smaller JNDs in Experiment 1, and hence a lower PSE in Experiment 2 (since thresholds generally scale with the stimulus magnitude).
4. *Influence of fit and compliance between the finger and thimble*: As these experiments were conducted using a family of custom designed, foam-lined thimbles, care was taken to ensure a good fit with each user's fingertip. However, it is possible that the compliance of the foam lining resulted in a small amount of relative motion between the user's fingerpad and the shear block. This compliance was quite small compared to the smallest skin stretch levels ($S_1 = 0.25$ mm). Furthermore, the results for the kinesthetic resistance JNDs from Experiment 1, where the shear block was removed, very nearly agrees with the results reported for the data point at R_2S_0, which lies near 0.25. Hence, the presence of a small amount of skin stretch in the S_0 cases appears not to have had a significant effect. Furthermore, from the authors' prior experience (e.g., [26]) subjects tend to rapidly adapt to the feeling of the thimble against the sides, tip, and top of their finger and are able to focus their attention on stimuli presented on their fingerpad. Therefore, the fit and compliance of the thimble interface are not considered to be significant influences in these experiments.
5. *Influence of the experimenters' instructions*: The shear block was not present on the contact location display when conducting Experiment 1. As a consequence of using many of the same subjects in both experiments, most of the subjects noticed the addition of the shear block in Experiment 2. They also noticed that the shear block moved on their fingerpad when they interacted with our sample stimulus before they began Experiment 2. When asked, we did acknowledge that the movement of the shear block was a possible part of a stimulus. However, rather than providing further interpretation of the block movement, we simply repeated the experiment instructions; that the subjects were to judge which of two presented stimuli had the greatest magnitude of friction. While we do not believe that our comment about the presence and/or movement of the block affected the results of our experiment, we acknowledge that it may have unintentionally introduced experimental bias.

We do not believe that factors 4 and 5 above had significant effects on our experimental results. Furthermore, factors 1-3 above would all suggest that our results as reported are conservative. Therefore, the effect of skin stretch is not only significant, but it is also likely that even smaller stretch levels will have a significant effect on a person's perception of friction.

6 Conclusions

In this paper, the authors evaluated difference thresholds for Karnopp friction-based kinesthetic resistance, rendered via a PHANToM robotic arm. This experiment yielded difference thresholds with percent changes that ranged from 0.28 to 0.19 across friction levels, $\mu_s = 0.2$-0.8, respectively. This experiment was conducted in support of our hypothesis that the addition of skin stretch to kinesthetic resistance forces will increase the perceived friction magnitude. Our hypothesis is strongly supported by the results of second experiment. In this experiment, the authors found that a small amount of skin stretch (0.27 mm) superimposed on kinesthetic resistance can have a significant effect on perceived friction. Furthermore, the addition of skin stretch was found to lead to an increase in perceived friction at all resistance levels R_i ($p < 0.01$).

These results suggest that the addition of a simple shear tactile display to current haptic devices could significantly enhance the realism and range of friction rendered with these systems without requiring larger motors on the haptic display. Our test subjects also stated that the presence of skin stretch enhanced the realism of the friction sensation, which is in agreement with other researchers' findings [16], [14]. More importantly for the authors' research group, the most profound result of this work has been that such small amounts of skin stretch are so easily detected. Our research group has begun to use the small shear stimuli to communicate direction cues via skin stretch applied at the fingertip [24].

Future experiments could expand this study to consider a broader range of friction levels to investigate whether the reported influence of skin stretch holds constant across a range of resistance levels. The influence of slip in combination with skin stretch and kinesthetic resistance could also be considered, though our pilot studies show slip to decrease perceived friction levels. We have already begun developing new hardware to faithfully render smaller levels of skin stretch, as well as, stretch in the lateral direction (see [24]). Future work could also implement more complex models for friction (e.g., [5]) and skin stiffness (e.g., as measured in [27]).

Acknowledgments

The authors gratefully acknowledge the advice and guidance of Dr. Roberta Klatzky in their many discussions during the course of this research. The authors also thank Suresh Sainath for his initial programming efforts and Brian Gleeson for help with statistical computations.

References

[1] A. Frisoli, M. Bergamasco, S. Wu, and E. Ruffaldi, "Evaluation of Multipoint Contact Interfaces in Haptic Perception of Shapes," *Multi-Point Interaction with Real and Virtual Objects, Springer Tracts in Advanced Robotics*, vol. 18, pp. 177-188, Springer, 2005.

[2] G. Cadoret and A.M. Smith, "Friction, Not Texture, Dictates Grip Forces Used during Object Manipulation," *J. Neurophysiology*, vol. 75, no. 5, pp. 1963-1969, 1996.

[3] H. Olsson, K.J. Astrom, C.C. de Wit, M. Gafvert, and P. Lischinsky, "Friction Models and Friction Compensation," *Eur. J. Control (UK)*, vol. 4, no. 3, pp. 176-195, 1998.

[4] P.R. Dahl, "Solid Friction Damping of Mechanical Vibrations," *Am. Inst. of Aeronautics and Astronautics J.*, vol. 14, pp. 1675-1682, 1976.

[5] V. Hayward and B. Armstrong, "A New Computational Model of Friction Applied to Haptic Rendering," *Experimental Robotics VI*, pp. 403-412, Springer, 2000.

[6] D. Karnopp, "Computer Simulation of Stick-Slip Friction in Mechanical Dynamic Systems," *Trans. ASME J. Dynamic Systems, Measurement and Control*, vol. 107, no. 1, pp. 100-103, 1985.

[7] C. Richard and M.R. Cutkosky, "Friction Modeling and Display in Haptic Applications Involving User Performance," *Proc. IEEE Int'l Conf. Robotics and Automation (ICRA)*, vol. 1, pp. 605-611, 2002.

[8] A. Nahvi, J. Hollerbach, R. Freier, and D. Nelson, "Display of Friction in Virtual Environments Based on Human Finger Pad Characteristics," *Proc. 1998 ASME Int'l Congress and Exposition*, vol. 64, pp. 179-184, 1998.

[9] A.M. Smith and S.H. Scott, "Subjective Scaling of Smooth Surface Friction," *J. Neurophysiology*, vol. 75, no. 5, pp. 1957-1962, May 1996.

[10] J. Biggs and M.A. Srinivasan, "Tangential versus Normal Displacements of Skin: Relative Effectiveness for Producing Tactile Sensations," *Proc. 10th Haptics Symp.*, pp. 121-128, 2002.

[11] V. Hayward and M. Cruz-Hernandez, "Tactile Display Device Using Distributed Lateral Skin Stretch," *Proc. Eighth Haptics Symp.*, pp. 1309-1314, 2000.

[12] M. Fritschi, K. Drewing, R. Zopf, M. Ernst, and M. Buss, "Construction and Psychophysical Evaluation of a Novel Tactile Shear Force Display," *Proc. 13th IEEE Int'l Workshop Robot and Human Interactive Comm. (RO-MAN '04)*, Sept. 2004.

[13] K. Drewing, M. Fritschi, R. Zopf, M. Ernst, and M. Buss, "First Evaluation of a Novel Tactile Display Exerting Shear Force via Lateral Displacement," *ACM Trans. Applied Perception*, vol. 2, no. 2, pp. 118-131, 2005.

[14] R.J. Webster, T.E. Murphy, L.N. Verner, and A.M. Okamura, "A Novel Two-Dimensional Tactile Slip Display: Design, Kinematics and Perceptual Experiments," *ACM Trans. Applied Perception*, vol. 2, no. 2 pp. 150-165, 2005.

[15] N. Tsagarakis, T. Horne, and D. Caldwell, "Slip Aestheasis: A Portable 2d Slip/Skin Stretch Display for the Fingertip," *Proc. First World Haptics Conf.*, pp. 214-219, 2005.

[16] M. Fritschi, M. Ernst, and M. Buss, "Integration of Kinesthetic and Tactile Display—A Modular Design Concept," *Proc. 2006 Euro-Haptics Conf.*, 2006.

[17] V. Hayward and D. Yi, "Change of Height: An Approach to the Haptic Display of Shape and Texture without Surface Normal," *Experimental Robotics VIII, Springer Tracts in Advanced Robotics 5*, Siciliano, B. and Dario, P., eds., pp. 177-188, Springer Verlag, 2003.

[18] M. Salada, J.E. Colgate, P. Vishton, and E. Frankel, "An Experiment on Tracking Surface Features with the Sensation of Slip," *Proc. First World Haptics Conf.*, pp. 132-137, 2005.

[19] U. Norrsell and H. Olausson, "Human, Tactile, Directional Sensibility and Its Peripheral Origins," *Acta Physiologica Scandinavica*, vol. 144, no. 2, pp. 155-161, 1992.

[20] W. Gould, C.J. Vierck Jr., and M. Luck, "Cues Supporting Recognition of the Orientation or Direction of Movement of Tactile Stimuli," *Proc. Second Int'l Symp. Skin Senses*, pp. 63-78, Mar. 1979.

[21] L. Winfield, J. Glassmire, E. Colgate, and M. Peshkin, "Tpad: Tactile Pattern Display through Variable Friction Reduction," *Proc. Second World Haptics Conf.*, Mar. 2007.

[22] M. Biet, G. Casiez, F. Giraud, and B. Lemaire-Semail, "Discrimination of Virtual Square Gratings by Dynamic Touch on Friction Based Tactile Displays," *Proc. Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2008 (Haptics '08)*, pp. 41-48, Mar. 2008.

[23] E.C. Chubb, J.E. Colgate, and M.A. Pehskin, "Shiverpad: A Device Capable of Controlling the Shear Force on a Bare Finger," *Proc. 2009 World Haptics Conf.*, pp. 18-23, Mar. 2009.

[24] B. Gleeson, S. Horschel, and W. Provancher, "Communication of Direction through Lateral Skin Stretch at the Fingertip," *Proc. 2009 World Haptics Conf.*, pp. 172-177, Mar. 2009.

[25] T.H. Massie and J.K. Salisbury, "The Phantom Haptic Interface: A Device for Probing Virtual Objects," *Proc. ASME Winter Meeting, Haptics Symp.*, Nov. 1994.

[26] W. Provancher, M. Cutkosky, K. Kuchenbecker, and G. Niemeyer, "Contact Location Display for Haptic Perception of Curvature and Object Motion," *Int'l J. Robotics Research*, vol. 24, no. 9, pp. 691-702, 2005.

[27] J. Wang and V. Hayward, "In Vivo Biomechanics of the Fingerpad Skin under Local Tangential Traction," *J. Biomechanics*, vol. 40, no. 4, pp. 851-860, Mar. 2007.

[28] G.A. Gescheider, *Psychophysics: The Fundamentals.* Lawrence Erlbaum Assoc., Inc., 1997.

[29] N. Sylvester, "Friction Perception and Tactile Feedback," master's thesis, mechanical eng., Univ. of Utah, 2008.
[30] S.J. Biggs and M.A. Srinivasan, "Haptic Interfaces," *Handbook of Virtual Environments: Design, Implementation, and Applications,* K. Stanney, ed., chapter 5, pp. 93-115, Lawrence Erlbaum Assoc., 2002.

William R. Provancher received the BS degree in mechanical engineering and the MS degree in materials science and engineering from the University of Michigan. He received the PhD degree from the Department of Mechanical Engineering at Stanford University in the area of haptics and tactile sensing and feedback. His postdoctoral research involved investigating and designing bio-inspired climbing robots, focusing on creating foot designs for climbing vertical surfaces with compliantly supported spines. He is currently an assistant professor in the Department of Mechanical Engineering at the University of Utah. He teaches courses in the areas of mechanical design and mechatronics. His active areas of research include haptics, tactile sensing and feedback, and the design of novel climbing robots. Details of his research and related publications can be found at his homepage: http://www.mech.utah.edu/wil/. He is a member of the IEEE.

Nicholas D. Sylvester received the BS degree in mechanical engineering from Brigham Young University and the MS degree in mechanical engineering from the University of Utah. His MS thesis focused on the added effect that fingertip skin stretch can have on a person's perception of friction. He is currently a manufacturing engineer at the IM Flash Technology Corp. in Lehi, Utah.