Sensory Augmentation of Stiffness using Fingerpad Skin Stretch

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ABSTRACT

When interacting with everyday objects, we experience kinesthetic force feedback as well as various forms of cutaneous tactile feedback. Skin stretch is part of the cutaneous tactile experience that is caused by friction between the skin and the grasped object. Interacting with stiffer objects causes larger force, and results in a larger amount of skin stretch. Therefore, we hypothesize that adding artificial fingerpad skin stretch to kinesthetic force feedback will increase users' perception of stiffness. A tactile display called the Skin Stretch Stylus was designed to augment kinesthetic force feedback with skin stretch feedback. The change in users' stiffness perception due to the addition of skin stretch feedback is quantified through a two-alternative forced-choice paradigm, method of constant stimuli experiment. In this experiment, subjects compared the stiffness of virtual springs with kinesthetic force feedback augmented with skin stretch feedback versus virtual springs with only kinesthetic force feedback. Results show that the addition of skin stretch causes a significant increase in the perception of stiffness, and this effect increases with higher amount of applied skin stretch. These results indicate that skin stretch feedback could be used to augment perceived stiffness in situations where it is not possible to increase force feedback gains. Such scenarios include teleoperation systems where force feedback gains must remain low to ensure stability, and haptic devices with limited actuator force.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; J.4 [Social and Behavioral Science]: Psychology

1 INTRODUCTION

A complete haptic experience involves both kinesthetic force and cutaneous tactile stimulation. Many commercially available force feedback devices exist for the display of kinesthetic forces. However, various factors affect the maximum stiffness that can be stably rendered by these devices. These factors include encoder resolution, device inertia and damping, and haptic feedback loop rate [1]. Many haptic devices have also been developed to display cutaneous tactile information. They include vibrotactile arrays [2], cutaneous normal force feedback [3], slip display [4], and skin stretch feedback devices [5]. We proposed that skin stretch feedback be used in combination with kinesthetic force feedback. Skin stretch feedback is a promising tactile feedback modality that may be used together with kinesthetic force feedback to compensate for the limitations of force feedback devices, as well as to enhance the overall haptic interaction experience. As shown in Fig. 1, interaction with an environment using a stylus-like device causes force to act on the stylus,

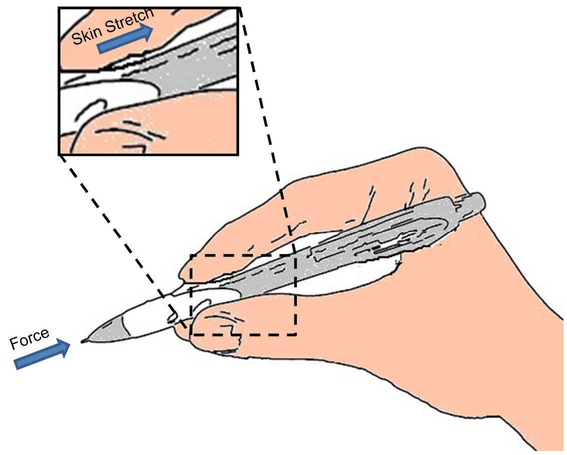

Figure 1: Hand holding a stylus. The picture illustrates that interaction with everyday objects provides us with both kinesthetic force feedback and cutaneous skin stretch feedback. The rendering of artificial skin stretch may potentially increases the perception of stiffness felt by the user.

resulting in fingerpad skin stretch due to friction between the fingerpad and the stylus. A stiffer environment causes a larger force, which results in a greater amount of fingerpad skin stretch. As with many other percepts obtained from multiple sensory modalities [6], it is likely that our sensorimotor system integrates these two information sources into a single percept of stiffness, perhaps in a statistically optimal fashion [7]. Therefore, we hypothesize that by rendering additional artificial skin stretch cues to the user, we can increase the perceived stiffness of haptically rendered surfaces without increasing the kinesthetic force. This may enable haptic device designs that render higher perceived stiffness without resorting to other forms of hardware improvement.

2 BACKGROUND

Humans do not have stiffness sensors, and therefore their stiffness perception comes from the integration of multiple sources of information such as force and position. Various models have been suggested for the perception of stiffness, e.g. total amount of mechanical work done (interaction force integrated over displacement) during interaction to determine the perceived stiffness felt by the user [8], regression between force and position information [9], and maximum force divided by perceived penetration into the surface [10].

A number of haptic devices and rendering methods have been used to improve the effective stiffness of haptic virtual environments. For example, the contact area spread rate model was utilized to improve the perception of compliance felt by the user during contact with a haptically rendered surface [11]. Rate hardness, the initial rate of change of force with respect to the rate of change of velocity, was shown to be important for the perception of stiffness [12] and was employed to improve the perceived rigidity of surfaces during contact. Methods that use this concept include brak-

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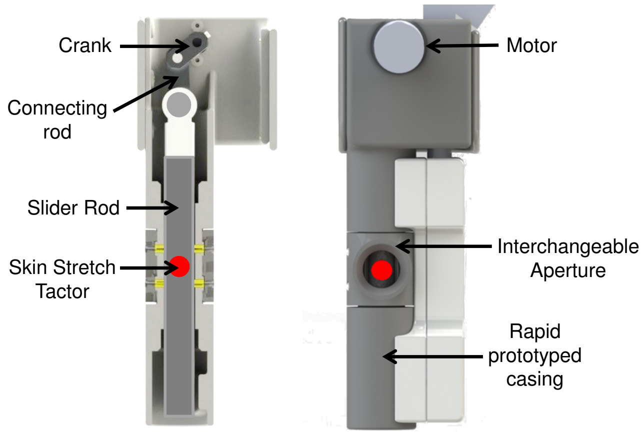


Figure 2: Cross-sectional view (left) and side view (right) of the skin stretch stylus. The device consists of a 4-bar crank-slider mechanism enclosed within a rapid prototyped plastic housing. The skin stretch tactor (red) imparts skin stretch to a user through friction between the tactor and the user's fingerpad, with the users' finger anchored on the aperture.

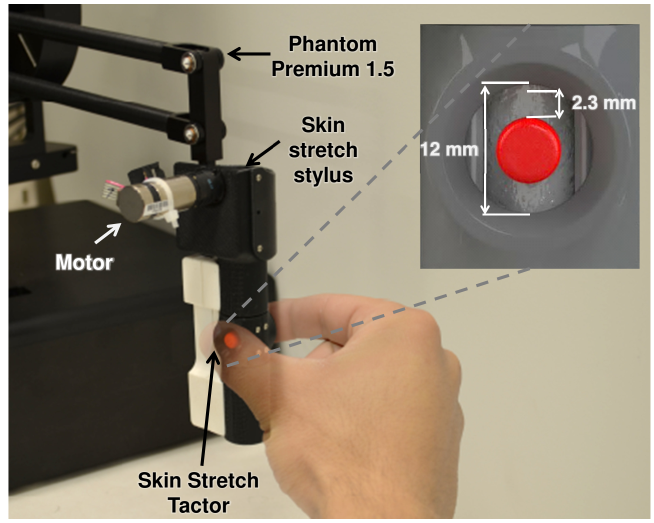


Figure 3: Skin stretch stylus attached to the end of the SensAble Phantom Premium 1.5. Subjects are instructed to hold the skin stretch stylus as shown in the figure. The distance of travel of the skin stretch tactor is software limited to ±2.3 mm in order to prevent the tactor from pinching the user's skin between the tactor and edge of the aperture.

ing pulses that are proportional to collision velocity [13], as well as impulsive forces during contact [14][15]. Similar to impulse forces, several studies display high-frequency contact information during haptic rendering to increase the realism and perceived rigidity of the contact surface [16][17].

The nervous system has been found to be capable of integrating information from several modalities into a single percept [6], and studies have also shown that humans integrate visual and haptic information in a statistically optimal fashion [7]. Many groups have studied the augmentation of haptic feedback with other modalities such as visual [18] and auditory [19] cues, with the finding that additional cues increase the perceived stiffness of the surface, albeit with different effect sizes.

Skin stretch is a particularly promising approach for increasing the perceived rigidity of surfaces during haptic rendering. Unlike other feedback modalities such as vision and audition, which use different human sensory channels to augment stiffness perception, skin stretch is a haptic modality that has the potential to integrate seamlessly with kinesthetic force feedback to increase perceived stiffness. A previous study has shown that applying artificial skin stretch can increase the perception of friction during haptic rendering [20]. In this paper, we use a skin stretch stylus to explore how adding artificial cutaneous skin stretch while interacting with surfaces using a stylus-like device alters the perceived stiffness of virtual surfaces. In contrast to previous systems that provide kinesthetic feedback to the fingers through a hand-held device, e.g. [21], our device purely renders cutaneous forces through shearing by skin stretch.

3 Experiment Description

3.1 Device Design and Control

The skin stretch stylus and its control are similar to the device we developed and used in a different study [22]. We provide the design and control information for the current device here for completeness and clarity. Fig. 2 shows the cross-sectional and side views of the skin stretch stylus. The device consists of a 4-bar crank-slider mechanism enclosed in a rapid-prototyped plastic housing. Skin stretch tactors, which are the interface surfaces that impose skin stretch on the user's fingerpads, are attached to both sides of the slider. Each tactor is a rubber Lenovo Thinkpad classic dome trackpoint tactor that has a rounded surface with a sandpaper-like texture. Friction between the skin stretch tactors and the user's finger/thumb stretches the skin on the fingerpads. A conical aperture restraint surrounds the skin stretch tactor in order to prevent finger motion tangential to the stylus when the tactors move against the skin. Although prior investigation into the aperture restraint [23] has suggested a decrease in performance when using an aperture restraint compared to a thimble-type restraint, the aperture is necessary in our device to constrain the fingerpad for skin stretch, while also enabling the display of kinesthetic force feedback.

The skin stretch stylus is rigidly attached to the end of a Phantom Premium 1.5 haptic device (SensAble Technologies, Inc.). The position of the skin stretch stylus is acquired from the encoders of the Phantom Premium, and its motors apply the appropriate kinesthetic force. Movement of the skin stretch tactors provides additional artificial skin stretch stimulation.

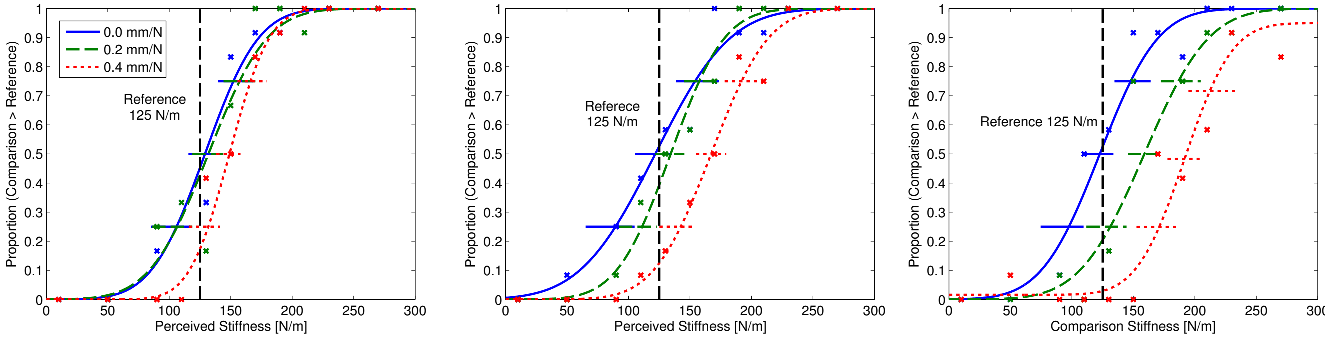
A virtual environment is rendered using the CHAI3D framework [24]. The environment consists of a flat horizontal spring-like surface with a programmable stiffness, applying vertical forces in proportion to the amount of penetration into the surface. The visual representation of the entire virtual environment is rendered with a top-down view. This allows the user to visualize the region in the Phantom Premium's workspace that the user should stay within, while preventing the user from receiving visual cues of penetration depth. The amount of kinesthetic force F_p rendered by the Phantom Premium is

$$F_p = kx_p, \tag{1}$$

where k [N/m] is the stiffness of the rendered surface and x_p[m] is the amount of penetration (in the normal direction) into the virtual object. The desired tactor movement is obtained from

$$x_t = RF_p, \tag{2}$$

where x_t [mm] is the amount of skin stretch to be artificially applied and R [mm/N] is the skin stretch-to-force ratio. The tactor position is determined by the angle of the skin stretch stylus motor; this nonlinear mapping was computed from the device kinematics. A proportional-integral-derivative (PID) position feedback controller uses data from the encoder mounted on the skin stretch motor and



(a) Subject weakly affected by skin stretch (b) Subject moderately affected by skin stretch (c) Subject strongly affected by skin stretch

Figure 4: Example psychometric curves for different skin stretch ratios for subjects weakly, moderately, and strongly affected by skin stretch. Symbols are data extracted from subject, curves are fit psychometric functions, and horizontal lines are 95% confidence intervals for estimation of 0.5 threshold value. The shift of the psychometric curve to the right of the 125 N/m reference indicates that the subject feels the combination of kinesthetic force and skin stretch feedback creates a perceptually stiffer surface.

applies motor torque to cause the tactor to reach the desired position. To determine the tracking accuracy of the skin stretch device when subjected to external loads such as the application of finger pressure on the tactor, we commanded a series of sinusoidal inputs with a user's finger pressing on the apertures and tactors of the device. The frequencies of the sinusoidal inputs range from 1 to 5 Hz, while the input amplitude varied from 0.5 mm to 1.8 mm. The maximum percentage error (controller position error and backlash error) amounted to less than 10% of the commanded amplitude, with a lower percentage error for a higher commanded amplitude. It is important to note that due to controller and backlash error, the actual amount of skin stretch provided to the user is lower than the commanded amount. This suggests that the measured effect on stiffness perception that we report in the current implementation of the skin stretch device is conservative, and may be further enhanced if the accuracy of the skin stretch device is improved.

3.2 Experiment Methods

Twelve right-hand-dominant subjects (9 males and 3 females) between the ages of 18 and 41 participated in our experiment after giving informed consent. The experiment protocol was approved by the Stanford University Institutional Review Board.

The goal of the experiment was to determine the shift in subjects' perception of stiffness when tangential skin stretch is applied to the fingerpads during the exploration of a kinesthetically rendered surface. Prior to the start of the experiment, subjects probed two physical springs with different stiffness values using a physical stylus, and were asked to determine which of the two surfaces was stiffer. They were coached if they answered incorrectly. This ensured that all subjects had a common interpretation of the concept of stiffness. Subjects were then instructed to hold the skin stretch stylus using their right hand, as shown in Fig. 3. A pilot study showed that the amount of grip force the user exerts on the aperture affects the shift in stiffness perception caused by additional skin stretch. Thus, prior to the start of the experiment, we trained the grip force of the subject to be approximately 1-2 N by asking them to press on a spring-loaded mechanism. The spring-loaded mechanism is designed such that user will grip the mechanism in a similar manner to the way they grip the aperture. Subjects underwent further training during breaks in the experiment to ensure consistent stylus grip force throughout the experiment.

To assess the effect of adding artificial skin stretch on perception of stiffness, we employed a two-alternative, forced-choice paradigm with the method of constant stimuli. We used subjects' responses to fit psychometric curves that describe their perception of stiffness as a function of the level of imposed fingerpad skin stretch. In this experiment, subjects were presented with two surfaces for each trial: a reference and a comparison. The reference surface had a kinesthetic stiffness (k) of 125 N/m and skin stretch ratios (R) of 0, 0.2, 0.4, and -0.4 mm/N. Each of the reference stimuli was compared with each of the kinesthetic-only stimuli with values of 10, 50, 90, 110, 130, 150, 170, 190, 210, 230, 270, and 310 N/m, for a total of 144 trials per skin stretch ratio. The trials were presented in balanced, predetermined, pseudo-random order, which was the same across all participants. Subjects were given as much time as they desired to interact with each surface, but were not allowed to answer which surface was stiffer until they had spent a minimum of 3 seconds interacting with each surface. The experiment consisted of a total of 576 trials, comprising 12 repetitions of the 12 comparison stiffness values for each of the 4 different skin stretch ratios. The experiment was divided into two 1.5- to 2-hour sessions of 288 trials each, completed on different days. After every 30 trials, subjects were given a 3-minute break during which they rested and underwent reinforcement training on the desired stylus grip force.

3.3 Data Analysis

To assess the effect of the addition of artificial skin stretch on perception of stiffness, we used subjects' responses to calculate the Point of Subjective Equality (PSE), the point at which subjects, judged the reference to be equal to the comparison. For our experiment, the PSE represents the stiffness-only stimuli that is perceptually equivalent to the reference stimuli (kinesthetic force feedback combined with skin stretch). We fit psychometric curves to the subjects' responses using the psignifit toolbox version 2.5.6 [25], and extracted the PSE at the point where the fit function crosses the 0.5 value. We calculated confidence intervals using the accelerated and bias-corrected bootstrap method described in [26].

Statistical analysis was performed using MATLAB anovan, ttest, and custom-written functions. To statistically test the effect of the skin stretch ratio on perceived level of stiffness, we used repeated-measures one-way ANOVA [27][28]. We used the Greenhouse-Geisser correction to adjust for the degrees of freedom in the repeated-measures ANOVA (due to homogeneity assumption) [27], and the p-values calculated using this adjustment are referred to as p_{adj}. We performed multiple post-hoc comparisons to test the statistical significance of contrasts between different skin stretch ratios, and used Bonfferoni correction for family-wise error. Statistical significance was determined at the 0.05 level.

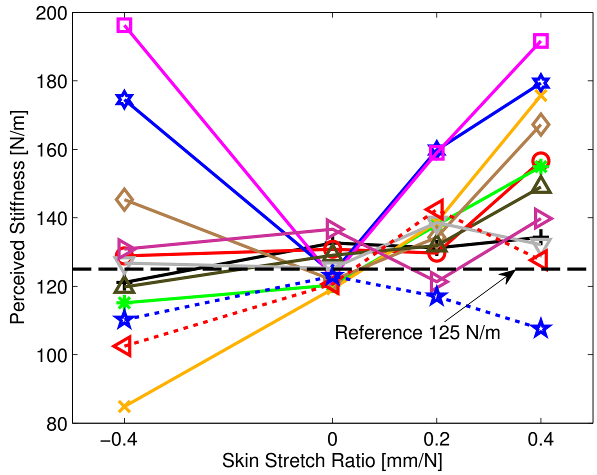


Figure 5: Individual trends for stiffness perception for all 12 subjects. Symbols are connected with lines for visualization of the stiffness perception trend for individual subjects. The dashed, black horizontal line is the kinesthetic reference stiffness in all conditions.

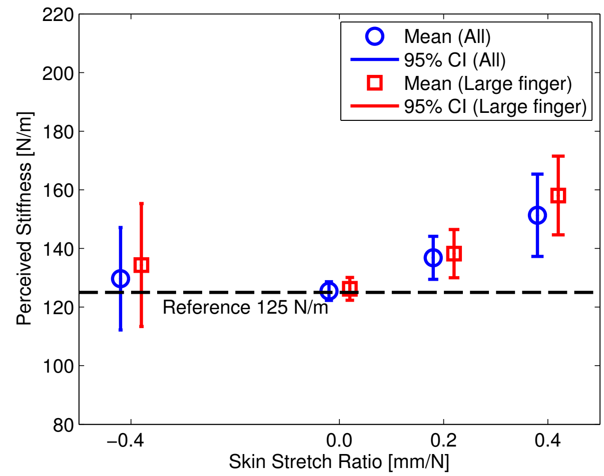


Figure 6: Mean and 95% confidence intervals for the perceived stiffness for skin stretch ratios of -0.4, 0.0, 0.2, and 0.4 mm/N for all subjects and larger finger subjects. There is a significant increase in the mean perceived stiffness for all subjects when skin stretch is being applied.

4 Experiment Results

Example psychometric curves fit to the responses of subjects who were weakly, moderately, and strongly affected by skin stretch are depicted in Fig. 4. For subject in Fig. 4(a), there is a small effect for 0.2 mm/N skin stretch ratio, with a slight shift to the right for 0.4 mm/N skin stretch ratio. The subjects in Fig. 4(b) and Fig. 4(c) registered a greater shift in the PSE when larger skin stretch is rendered. Fig. 5 depicts the PSE values of all subjects. Six out of twelve subjects show a positive shift in perceived stiffness that increased with increasing skin stretch ratio. However, there is a large intra-subject variability in perception for the negative skin stretch ratio of -0.4 mm/N. Therefore, we did not include the negative skin stretch ratio of -0.4 mm/N results in our statistical analysis.

Fig. 6 shows the mean and the 95% confidence interval for the estimated mean of the perceived stiffness of the reference stimuli for all subjects. When averaged across all subjects, we found a statistically significant increase in the mean PSE when artificial skin stretch is applied to the subject's fingerpads ($p = 0.001$), and that the effect increases as larger skin stretch is applied using a higher skin stretch ratio. The results of repeated measures one-way ANOVA together with post-hoc comparisons between different skin stretch ratio groups are presented in Table 1.

A detailed examination of Fig. 5 reveals that some of the subjects showed relatively small perceptual effects (shown with dashed lines in Fig. 5). A possible explanation for such a lack of perceptual effect could be the size of the subjects' fingerpads. The shift in perceived stiffness for a skin stretch ratio of 0.4 mm/N as a function of the measured user finger size is shown in Fig. 7. There is a statistically significant positive correlation between the size of the fingerpad and the shift in stiffness perception ($R = 0.76$, $p = 0.0045$). We believe that the subjects with very small fingerpads did not properly experience the effects of skin stretch because their fingers were too small to hold on securely to the device's apertures. In that case, the fingers would move with the the skin stretch tactors, preventing tactor motion from imposing additional skin stretch. These subjects therefore experienced a fundamentally different experiment due to the lack of finger restraint from apertures that were not properly sized for their fingers. Based on this result, we repeated the statistical analysis excluding subjects with index finger width less than 14 mm (small finger group, $n = 2$, '$\times$' symbols and dashed lines in Fig 5). This was based on the device aperture size of 12 mm and a 1 mm overlap between finger and device at each side of the aperture. The results for the group of subjects with large fingers ($n = 10$) are depicted in Fig. 6 (squares) and on the right side of Table 1, and are qualitatively similar but more pronounced than the results of all subjects taken together.

Fig. 8 and 9 shows the mean and standard deviations of the interaction force experienced by the subjects during the experiment. The results indicate that the varying level of skin stretch does not affect the way subjects interact with the virtual surfaces.

5 Discussion

The experimental results show that rendering skin stretch in the direction of applied force increases the stiffness perceived by most users. However, as shown in Fig. 5, the magnitude of the perception

	All subjects			Large finger subjects		
Group Analysis	$F_{2,22}$	p	p_{adj}	$F_{2,18}$	p	p_{adj}
ANOVA	9.54	0.0010	0.0041	14.9	$1.53*10^{-4}$	0.0013
Post-hoc analysis	Size of effect [N/m]	t_{22}	p	Size of effect[N/m]	t_{18}	p
$\mu_{0.2} > \mu_{0.0}$	11.33	2.70	0.0065	12.01	2.88	0.0050
$\mu_{0.4} > \mu_{0.2}$	14.52	3.46	0.0011	19.84	4.76	$7.86*10^{-5}$
$\mu_{0.4} > \mu_{0.0}$	25.84	6.16	$1.67*10^{-6}$	31.85	7.64	$2.35*10^{-7}$

Table 1: Results for the repeated measures one-way ANOVA, together with the post-hoc analysis with the appropriate Bonfferoni correction, for all subjects and large finger subjects. There is statistically significant difference between the mean PSE values across all three comparisons when considering all subjects and when considering only large finger subjects.

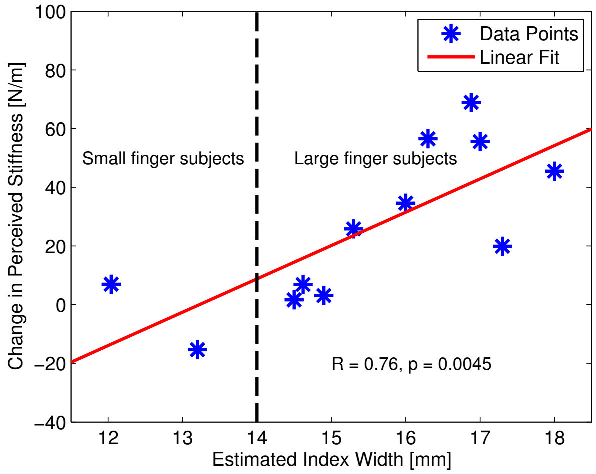


Figure 7: Correlation between the estimated size of the subjects' fingertip and the shift in stiffness perception for a skin stretch ratio of 0.4 mm/N. There is a statistically significant positive correlation between subjects fingerpad size and shift in stiffness perception.

shift varies across subjects. This may be due to different subjects having different skin mechanical properties and different sensitivity to skin stretch. Therefore, the same amount of skin stretch applied will result in a different increase in perceived stiffness by each subject.

The high variability in the perceived stiffness for the negative skin stretch ratio of -0.4 mm/N indicates that subjects have different interpretations of the skin stretch stimulus. This may be because imposing skin stretch in the direction opposite to the applied force is not consistent with skin stretch that occurs during natural interactions. Several subjects perceived the negative skin stretch cue as an indication of deeper penetration into the surface, resulting in a lower perceived stiffness, while other subjects perceived the negative skin stretch cue as a larger force acting on the stylus and hence a higher perceived stiffness. These results indicate that it would not be possible to consistently *decrease* a user's perception of stiffness by rendering skin stretch in a direction opposite to the direction of applied kinesthetic force.

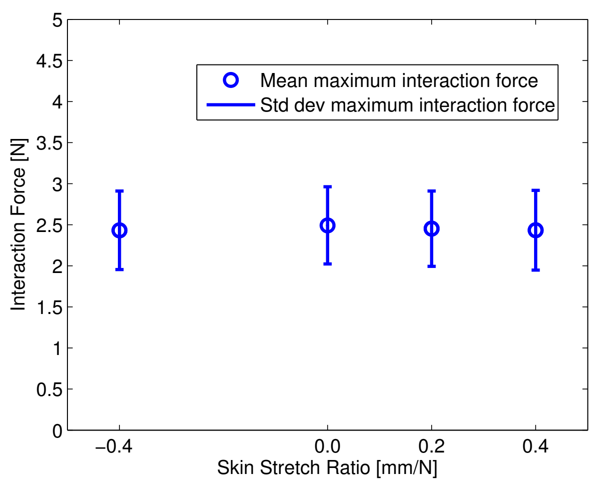


Figure 8: Mean and standard deviation of the maximum interaction force experienced by the subjects during the experiment. The results show similar maximum interaction forces, indicating that subjects interact with the 4 different virtual surfaces in a similar manner.

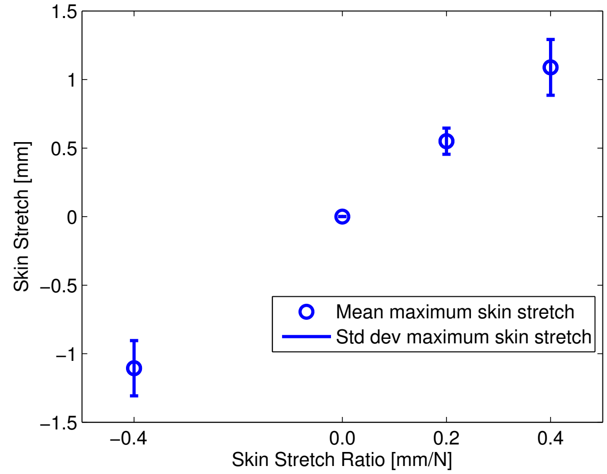


Figure 9: Mean and standard deviation of the maximum skin stretch experienced by the subject during the experiment. The results indicate that subjects experience varying levels of skin stretch for each of the 4 virtual surfaces with different skin stretch ratios.

Our results indicate that there is a relationship between the fingerpad size of the user and the amount of increase in perceived stiffness when skin stretch is applied. This result is inconsistent with a previous study [23] that showed that aperture size does not significantly change the perceptual effect that skin stretch has on the user. However, our study is different in the manner in which subjects interacted with the skin stretch stylus. In [23], a user's wrist and fingertip rests on a rigid aluminum plate extending out from an arm rest device, and skin stretch is rendered through the movement of the tactor. As there is no movement of the arm rest, a user's hand and finger are therefore firmly grounded to the rigid aluminum plate and the device is able to render skin stretch to the fingerpad through relative movement of the tactor. In our device, users must hold on to the aperture firmly so that both kinesthetic force and skin stretch can be rendered. Users with small fingertips might not have been able to ground their fingertips on the aperture, and their fingerpads may have "floated" on the moving skin stretch tactor instead. This will result in a loss of rendered skin stretch, resulting in little to no perceptual effect. The index finger width of 14 mm used in our analysis as the cutoff size for indicating "large fingers" is also close to the aperture size of 12 mm, providing evidence for the effect mentioned above. This result suggests that further investigation of the effect of aperture size on the perceptual effect of skin stretch should be conducted for cases where the user is also grasping the device through the aperture interface, especially for cases in which a users' fingerpad width is close to the aperture size. This will lead to practical guidelines for the ratio between finger size and device aperture size for optimal grounding of fingerpad.

Unlike other methods of sensory augmentation using vision and auditory feedback, skin stretch is a form of cutaneous feedback, which is part of natural human haptic interaction. Therefore, it may be more intuitive and easier for users to integrate kinesthetic with skin stretch feedback, compared with vision and auditory feedback.

6 Conclusions and Future Work

We developed a cutaneous haptic feedback device that renders skin stretch to the user, and used it to show that inducing artificial skin stretch leads to an increase in the perceived stiffness of kinesthetically rendered surfaces. In addition, we show that higher skin stretch ratio with respect to the kinesthetic force corresponds to larger increase in perceived stiffness. For skin stretch that is applied opposite to the direction of the kinesthetic force, there is also a change in perceived stiffness, but the direction of the shift in perception is inconsistent among subjects.

These results indicate that we can render increased stiffness perception to the user without increasing the kinesthetic force rendered by the device. Therefore, in kinesthetic force display devices for which the display of force information is limited by actuator saturation, additional stiffness sensation can be provided through the addition of a skin stretch device attached to the end of the kinesthetic display. In scenarios in which the stiffness of the haptic feedback has to be limited due to stability concerns (e.g. in bilateral teleoperation), providing additional skin stretch feedback could allow the user to perceive higher stiffness without compromising stabiliy, since the skin stretch feedback uses an alternative information channel that does not interfere with the kinesthetic force display of the teleoperation system. The results of the current paper, taken together with a companion study that explored discrimination of stiffness using solely skin stretch feedback [22], suggest that skin stretch feedback is a promising candidate to be used as sensory augmentation and sensory substitution for teleoperation systems.

We are currently investigating the perceptual effect on stiffness estimation that skin stretch has when a different amount of kinesthetic stiffness is rendered to the user, as well as the maximum amount of skin stretch that results in an increase in perceived stiffness. In future studies, it will also be interesting to determine the effect of the directionality of the skin stretch stimulus with respect to the force feedback and the overall perceptual performance. This will provide an indication of how the skin stretch augmentation method can be applied to the design of a universal feedback device with 3 DOF force feedback. In addition, it would also be interesting to explore the underlying neural mechanisms behind the perceptual shift that we report in the current paper. Such an investigation would improve our understanding of how various forms of information are integrated to give rise to the perception of stiffness.

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