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Sensory Substitution via Cutaneous Skin Stretch Feedback

Samuel B. Schorr[1], Zhan Fan Quek[1], Robert Y. Romano[1], Ilana Nisky[1],
William R. Provancher[2], and Allison M. Okamura[1]

***Abstract*— Skin stretch is a novel haptic feedback method that can provide a human operator with information about the magnitude and direction of an applied force. To evaluate the potential for skin stretch feedback to be used as a sensory substitute for kinesthetic (force) feedback in robotic teleoperation systems, a study was conducted to measure the ability of users to discriminate environment stiffness using varying levels of fingerpad skin stretch instead of force feedback. A new, high-fidelity skin stretch feedback device was developed that imposes tangential fingerpad skin stretch in proportion to the intended level of force feedback. In psychophysical experiments, users received skin stretch feedback with magnitude proportional to the users' penetration depth into a virtual wall. Users' stiffness discrimination capability using skin stretch was comparable to that of using force feedback. Furthermore, larger skin stretch cues were perceived by users as portraying greater stiffness without any advance training, which indicates that skin stretch feedback would be an intuitive sensory substitute for force feedback. Thus, skin stretch feedback is a promising method for conveying kinesthetic force information in applications such as robot-assisted surgery, where high levels of force feedback may not be desirable due to stability or safety concerns.**

I. INTRODUCTION

Haptic feedback, including both kinesthetic (force) and cutaneous (skin-related) touch feedback, is an important component of many manipulation tasks. In bilateral teleoperation, in which users manipulate a haptic interface in order to control a remote robot, the display of force information to the user might be limited or impossible due to stability issues, caused by time delays or inaccuracies in robot modeling and force estimation. It has been shown that transparency and stability are directly conflicting design goals of bilateral teleoperation systems [1]. The lack of force feedback can make it difficult to perform delicate tasks, such as suturing or manipulating sensitive tissue in surgical teleoperators [2], [3]. Our goal is to convey this environmental force information to the user without the risk of feedback-induced instability.

Sensory substitution can allow users to obtain important force information from natural interactions while preserving

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[1]Samuel B. Schorr (sschorr@stanford.edu), Zhan Fan Quek, Robert Y. Romano, Ilana Nisky, and Allison M. Okamura are with the Department of Mechanical Engineering, Stanford University, CA 94305, USA

[2]William R. Provancher is with the Department of Mechanical Engineering, University of Utah, Salt Lake City, UT 84112, USA

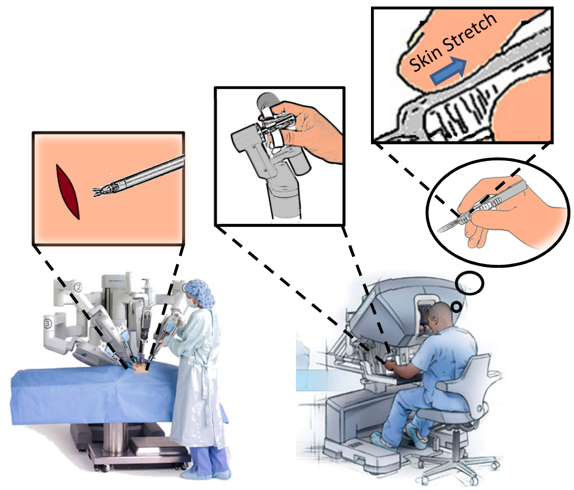

Fig. 1. Surgeon's hand holding the master manipulator. When interacting with tissue using a scalpel, the surgeon feels both the kinesthetic force as well as skin stretch on his fingerpads. Skin stretch feedback could replicate this natural cutaneous feedback in a teleoperated scenario. Images derived from photographs provided by Intuitive Surgical, Inc. (©2012).

the stability of a teleoperation system. In sensory substitution, kinesthetic force feedback is typically replaced by other feedback modalities such as visual, auditory, or vibration feedback – we propose an alternative approach. Skin stretch is a form of haptic feedback that is naturally present during daily interaction with objects. As shown in Fig. 1, when interacting with a surgical tool, any interaction force will result in a local shear force to be applied to the user's fingerpad, causing local fingerpad skin stretch. We hypothesize that skin stretch is an intuitive feedback modality to substitute for kinesthetic force feedback, and offers comparable performance to force feedback when used in a stiffness discrimination task. This paper presents the design of a new stylus-based skin stretch device that can be attached to the end of a kinesthetic haptic device, pretests to measure the intuitiveness of skin stretch feedback as a sensory substitute for force feedback, as well as a main experiment measuring users' ability to discriminate between surfaces with different stiffness using only skin stretch cues.

II. BACKGROUND

A. Sensory Substitution

In prior work on sensory substitution, alternative modalities such as vision and audition have been used to convey

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force amplitude and direction information in teleoperated robots. While some studies related to robot-assisted surgery have shown that these alternative modalities can improve operator performance in teleoperated tasks in comparison to no haptic feedback [4], they do not always improve the performance of expert users [5], and they may be less useful in scenarios where the user is already overwhelmed with visual and auditory information.

Cutaneous feedback utilizes mechanoreceptors located within the skin. Cutaneous sensory substitution can increase task performance in some situations, such as reducing the force applied to complete a peg insertion task [6]. One form of cutaneous feedback is vibrotactile feedback, which uses vibrating actuators to induce vibration in the user's skin. Vibrotactile feedback has been studied in many different applications, including robot-assisted surgery [7], but it faces several limitations. A single vibrotactile actuator can display the magnitude or frequency of a given signal, but loses directional information. Vibrotactile arrays with multiple vibrating elements can display directional information, but at the expense of additional cost, space, and complexity.

Cutaneous normal force feedback [8], [9] is another form of feedback that has been used to substitute for force feedback in haptic rendering, in a technique called "sensory subtraction". Since natural interactions contain both kinesthetic and cutaneous elements, this feedback methodology uses a device to replicate the cutaneous effects of a real interaction, but the kinesthetic component is removed. This results in only cutaneous force applied to the skin surface in the normal direction. Our approach is similar, but takes advantage of the increased human sensitivity to shear forces, in comparison to normal forces [10].

B. Skin Stretch Feedback

Skin stretch is a promising feedback modality, in which a shear force is applied to the fingerpad of the user, similar to the skin stretch that occurs naturally during haptic interactions. An example of naturally occurring skin stretch resulting from surgical tool interaction is shown in Fig. 1. In addition to the high sensitivity of human skin to tangential skin stretch, another advantage of skin stretch feedback (particularly in comparison to vibration feedback) is that it can provide the user with directional information [11]. Skin stretch was also shown to be effective in communicating proprioceptive information [12], [13], as well as in augmentation of the perception of friction in a haptic display [14]. The richness of information content of skin stretch makes it an attractive modality for force feedback sensory substitution. This paper presents the development of a new skin stretch device designed for integration with stylus-based manipulators convey force and stiffness information. Additionally, we show that human stiffness discrimination ability using skin stretch feedback is comparable to that of kinesthetic force feedback.

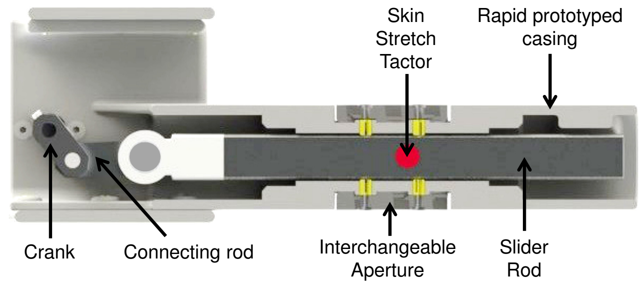


Fig. 2. Section cut of the skin stretch stylus. The device consists of a 4-bar crank-slider mechanism enclosed in a rapid prototyped casing.

III. Skin Stretch Stylus Design and Control

A. Skin Stretch Stylus Design

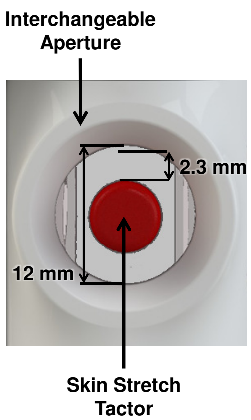
We implemented a stylus-based skin stretch device to replicate the skin stretch naturally present when interacting with manual tools. A cross-section of the device is shown in Fig. 2. The device consists of a 4-bar crank-slider mechanism with a 7 mm diameter Lenovo Thinkpad classic dome trackpoint tactor attached to the slider. This tactor is the moving contact element between the stylus and skin. The crank arm is powered by a 16 mm geared DC motor. The entire 4-bar mechanism is enclosed in a plastic cylindrical housing that constrains the movement of the slider. A conical aperture with a 12 mm inner diameter is used to restrain finger motion tangential to the stylus when the tactor moves against the skin, and to anchor the user's grip on the stylus. Friction between the moving tactor and the skin surface ensures that tactor motion is translated into fingerpad skin stretch. While human movement of a system with dynamics can cause natural skin stretch due to forces between the tool and finger, the grounding of the skin surrounded by the aperture allows isolation of the skin from unintended fingerpad skin stretch. This type of aperture restraint was used by Gleeson et al. in the design of a skin stretch actuator for implementation in different applications [15].

B. Skin Stretch Stylus Control

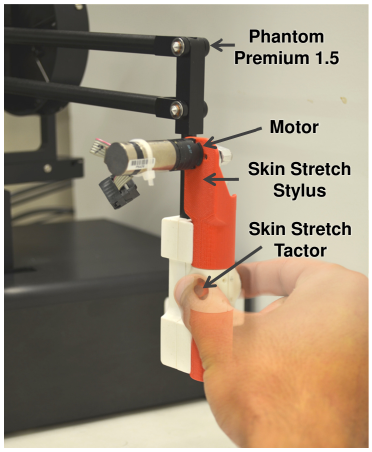
The skin stretch stylus is attached to the last actuated link of a SensAble Phantom Premium 1.5 device as shown in Fig. 3(b). The Phantom Premium is used to track the location of the skin stretch stylus, while the stylus is used to render skin stretch.

A virtual environment was rendered in C/C++ using the CHAI3D framework. The virtual environment consists of a horizontal plane with a varied virtual stiffness. Instead of rendering the force to be displayed by the Phantom, we calculated a proportional amount of skin stretch and applied it using the skin stretch stylus. We used the following algorithm to determine the amount of skin stretch to be rendered to the user. First, the force that would be applied when pressing vertically into the surface is calculated by

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



(a)



(b)

Fig. 3. (a) Range of travel of the tactor is limited to 2.3 mm. (b) Skin stretch device attached to the end of a SensAble Phantom Premium haptic device. Subjects were instructed to hold the device as shown, with the thumb and index finger each in contact with both the aperture and skin stretch tactor.

where F_p is the calculated virtual force orthogonal to the plane, k is the virtual stiffness, and x_p is the amount of orthogonal penetration into the virtual plane. The skin stretch tactor movement is then calculated by multiplying the virtual force and the skin stretch ratio,

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

where x_t is the desired tactor position and R is the skin stretch ratio. A proportional-integral-derivative (PID) controller uses the encoder values from the skin stretch stylus' motor and adjusts the motor joint angle to the desired position. The end point location of the tactor is determined through a nonlinear crank-slider kinematic mapping.

The range of motion of the tactor was limited in software to ± 2.3 mm from its center position, to prevent the tactor motion from reaching a hardware limit within the aperture. The static backlash of the skin stretch device was measured by moving the tactor through its entire range of motion while under load from a human finger and while under no load. The largest backlash observed was 0.038 mm. In addition, the tracking performance of the tactor was evaluated using a sinusoidal command input with a frequency ranging from 1 Hz to 5 Hz, which was the range of input interaction frequency we observed in our subjects. The total tactor position error based on backlash and controller tracking error was found to be less than 10% of the tactor range of motion. The backlash and tracking error would cause the tactor to move less than the position commanded by the controller, so the results obtained using this apparatus are conservative in terms of the perceptual effect for a given commanded tactor movement.

IV. EXPERIMENTAL METHODS

A total of 12 subjects participated in the experiment, which consisted of two short pre-tests and a main experiment. The purpose of the main experiment was to determine the ability of subjects to discriminate between virtual surfaces of different stiffness using skin stretch feedback. The purpose of the preetests was to determine subjects' untrained responses to skin stretch stimuli. Nine of the subjects were male and three were female. All subjects gave informed consent, and the protocol was approved by the Stanford University Institutional Review Board. The skin stretch device was attached to the end of the SensAble Phantom Premium haptic device, and subjects were instructed to hold the skin stretch device with their thumb and index fingers covering the aperature and tactor as shown in Fig. 3(b). In each stage of the experiment, users were asked to explore two different virtual surfaces and determine which was stiffer under a two-alternative, forced-choice paradigm, which forces a decision between the reference and comparison stimuli. During these comparisons, users were provided with a computer display that indicated the stylus and virtual surface positions. This visual feedback was removed once the user made contact with the surface in order to prevent any effect of vision on the perception of the surface stiffness. We first performed two pre-tests without any specific instructions as to how to interpret the skin stretch stimuli. After the pre-tests, the subjects were instructed to interpret higher amounts of skin stretch relative to their hand motions as an indication of higher stiffness before proceeding to the main discrimination experiment.

A. Pre-test 1: Natural Intepretation of Skin Stretch Only Cues

The first pre-test was designed to determine whether subjects uniformly interpreted greater skin stretch as representative of greater stiffness, without any training. Subjects were presented with pairs of skin stretch stimuli and asked which stimulus represented a stiffer object. Subjects were evaluated on how they interpreted the relation between skin stretch and stiffness using a short protocol that employed the method of constant stimuli. First, subjects were told how to hold the stylus and were also given explanation of the haptic scenario which was rendered to them. Then, subjects were presented with pairs of skin stretch cues containing a reference and comparison stimulus. The reference skin stretch stimulus was based on a kinesthetic stiffness (k) of 125 N/m with a skin stretch ratio (R) of 0.6 mm/N, while comparison stimuli were based on the stiffness values of 50, 75, 100, 150, 175, and 200 N/m, with a skin stretch ratio of 0.6 mm/N. Kinesthetic stiffness was *not* rendered in this experiment. Rather, the skin stretch was rendered in proportion to the hypothetical stiffness using the skin stretch ratio. A total of 30 trials were completed, consisting of 5 repetitions for each of the 6 comparison skin stretch gain values.

B. Pre-test 2: Interpretation of Skin Stretch as Stiffness

The second pre-test was performed to determine whether there was a kinesthetic stiffness that could be considered subjectively equal to the reference skin stretch only stimulus. In this test, we compared how subjects responded when asked to compare a kinesthetic stiffness and a skin stretch only stimuli. In the entire study, this was the *only* test for which actual kinesthetic feedback was applied. Subjects were presented with a reference skin stretch stimulus based on a kinesthetic stiffness (k) of 62.5 N/m with a skin stretch ratio (R) of 0.6 mm/N and a comparison stimulus with actual kinesthetic stiffness values (k) of 0, 10, 20, 30, 40, 50, and 60 N/m. A total of 35 trials were completed, consisting of 5 repetitions for each of the 7 kinesthetic comparison values.

C. Main Experiment: Stiffness Discrimination Sensitivity Using Skin Stretch Feedback

After completing the pre-tests, subjects underwent training on the interpretation of skin stretch cues. In this training, subjects were first presented with two physical spring surfaces and were told to use a pen-based stylus to press on the two surfaces while noticing the effect on their fingerpads. The experimentor then explained that interacting with a stiffer spring with the stylus would cause more tangential fingerpad skin stretch than interacting with a spring of lower stiffness. Then, to familiarize the user with the skin stretch cues from our skin stretch stylus, they were presented with two kinesthetically rendered walls of low (50 N/m) and high (150 N/m) stiffness. Subjects were next presented with two skin stretch stimuli that were based on walls of stiffness (k) equal to 50 and 150 N/m, respectively, with R of 0.8 mm/N. They were told that the larger skin stretch stimulus represented a larger stiffness than the smaller skin stretch stimulus, in the same way that the 150 N/m kinesthetic stiffness was larger than the 50 N/m stiffness. This ensured that all subjects were interpreting greater skin stretch as representative of greater stiffness during the main experiment.

The main experiment employed a forced-choice paradigm using the method of constant stimuli [16], in which subjects attempted to distinguish between virtual objects of varying stiffness using only skin stretch stimuli. During this main experiment, *no* kinesthetic force was applied. Rather, the amount of skin stretch applied to the user was determined based on a hypothetical stiffness and a designated skin stretch ratio. There were 3 blocks in the experiment, one each using a skin stretch ratio, R, of 0.4, 0.6, or 0.8 mm/N. The order in which subjects carried out the 3 blocks was randomized. Subjects were presented with two objects, the reference surface with a constant stiffness of 125 N/m, and a comparison surface with stiffness of 25, 50, 75, 100, 115, 135, 150, 175, 200, or 225 N/m. The surfaces were presented in balanced, predetermined, pseudo-random order. Subjects were allowed to interact with each surface for as long as they desired, but were not allowed to progress until they had spent at least 3 seconds on the surface. After probing the two surfaces, subjects chose which surface was stiffer. A total of 160 trials were completed, comprising of 16 repetitions of the 10 comparison stiffness values.

D. Data Analysis

We used the Psignifit toolbox version 2.5.6 [17] to fit psychometric curves to the data of the subjects for each of the skin stretch ratios, and calculated confidence intervals

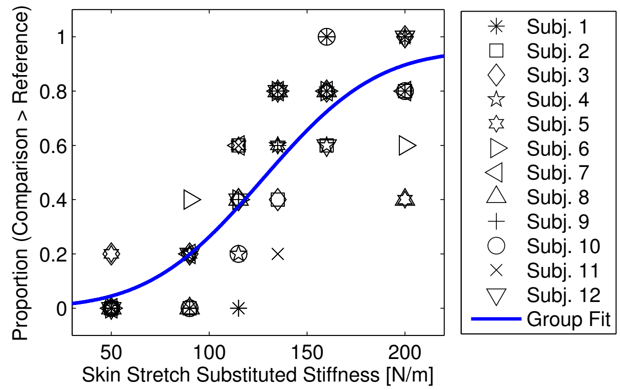


Fig. 4. Participants' untrained response to skin stretch feedback from pre-test 1. No kinesthetic stimulus was applied during these trials. Skin Stretch Substituted Stiffness is the stiffness presented via equivalent skin stretch with a 0.6 mm/N skin stretch ratio. Individual points represent the proportion answered by each subject. A psychometric curve is plotted using the combined data of the participants. The individual data and the psychometric curve indicate that subjects perceived higher skin stretch to represent higher stiffness.

of the stimated parameters using the accelerated and bias-corrected method. After fitting the psychometric curve, the 0.5 threshold value is used to determine the point of subjective equality (PSE) of each subject. This is the point at which the subject would say the comparison is stiffer than the reference 50% of the time. The 0.75 and 0.25 threshold values are used to calculate the Just Noticeable Difference (JND) for each subject.

The Weber fraction (WF) for each subject is then calculated as

$$WF = \frac{JND}{k_{ref}} \times 100. \tag{3}$$

The WF determines the subjects' ability to discriminate between different stimulus in proportion to the reference stimulus. For the main experiment, a balanced one-sided ANOVA test was performed on the WF data using four groups, consisting of kinesthetic feedback and the three skin stretch feedback ratios.

V. EXPERIMENTAL RESULTS

A. Pre-test 1: Natural Interpretation of Skin Stretch

Fig. 4 shows the result of each participant's response to pre-test 1, together with a psychometric curve fit for the combined data of all subjects. All subjects interpreted greater skin stretch to indicate greater stiffness with no training on interpretation of the cues.

B. Pre-test 2: Interpretation of Skin Stretch as Stiffness

There were two types of responses to this pre-test. For three subjects, a skin stretch stimulus was never considered to be stiffer than a kinesthetic stimulus. That is, regardless of how low the kinesthetically rendered stiffness was, the subjects never responded that the skin stretch stimulus was stiffer than the kinesthetic comparison stimuli. However, nine of the subjects responded that for certain values, the skin stretch reference was stiffer than the kinesthetic comparisons. The point of subjective equality for this 2^{nd} group of subjects

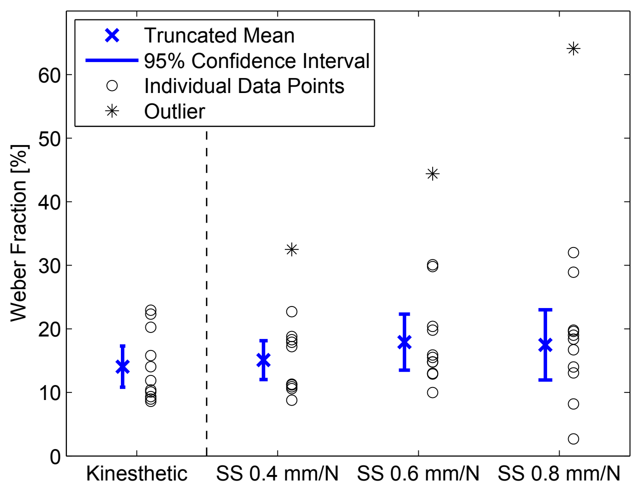


Fig. 5. Truncated mean Weber fractions for kinesthetic and skin stretch (SS) feedback with R = 0.4, 0.6, and 0.8 mm/N skin stretch ratios together with 95% confidence intervals. The outlier's Weber fraction was excluded from the calculation of the truncated mean as it was greater than two standard deviations away from the mean.

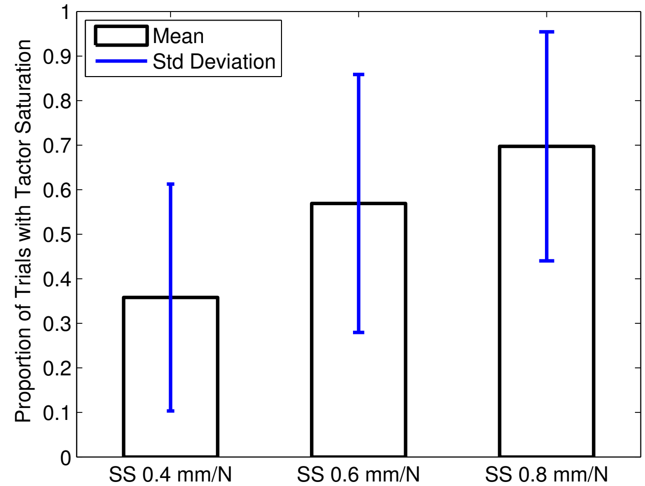


Fig. 6. Proportion of trials under each experiment block for which the skin stretch device reached saturation on rendered skin stretch stimuli. The proportion of trials for which skin stretch saturated increased with increased skin stretch ratio.

was a kinesthetic stiffness ranging from 9 to 40 N/m. One subject interpreted the skin stretch stimulus as stiffer than all kinesthetically rendered stiffnesses.

C. Main Experiment: Stiffness Discrimination Sensitivity Using Skin Stretch Feedback

The average Weber Fraction (WF) for skin stretch stimuli across all subjects was calculated for each skin stretch ratio. Fig. 5 shows the truncated (without outlier data) mean WF with 95% confidence intervals for our subjects using skin stretch feedback with 0.4, 0.6, and 0.8 mm/N skin stretch ratios. A data point was considered an outlier if it fell greater than two standard deviations away from the mean. The truncated mean Weber fractions for the different skin stretch ratios were 15.1%, 17.9%, and 17.5%, respectively. Fig. 5 also shows the mean WF for kinesthetic force feedback of 14.1% using a Phantom Premium to render force feedback with our device attached (determined from a different study [18]). A 1-way ANOVA analysis did not reveal a statistically significant effect of stiffness presentation modality (kinesthetic, and the different SS ratios) on the WF ($F_{3,40}$ = 0.93 and p = 0.44).

Although subjects were instructed to interact with the skin stretch device through a prescribed range of motion, their range of motion was not constrained; they were free to move the device into the virtual surface as much as desired. However, the tactor movement was software limited to $\pm$2.3 mm. Thus, beyond a certain penetration depth, the movement saturates and the tactor stops moving. Past this point, additional penetration into the surface does not result in additional skin stretch.

Fig. 6 shows the proportion of total trials for which the tactor travel saturated during subjects' interaction with the device. This proportion increases with skin stretch ratio, as higher skin stretch ratios result in larger tactor movements for the same hand motions and penetration depth. Despite the increased incidence of tactor motion saturation, perception performance did not deteriorate.

VI. DISCUSSION

A. Pre-tests 1 and 2: Intuitiveness of Interpretation of Skin Stretch Feedback

When naturally interacting with an environment using a stylus, a stiffer surface exerts greater force on the stylus, which correspondingly results in a larger amount of local fingerpad skin stretch. Our first pre-test shows that all subjects interpreted greater skin stretch feedback as an indication of higher stiffness with no initial training, indicating the intuitiveness of associating a higher stiffness with greater amount of skin stretch. This intuitive interpretation of skin stretch stimuli means that users might require less time for training than other sensory substitution methods, and that a feedback mechanism naturally present in real life haptic interaction could result in lower cognitive load than other sensory substitution methods.

In the second pre-test, subjects directly compared skin stretch and kinesthetic stimuli. Nine of the subjects found the skin stretch stimulus to be subjectively equal to a positive kinesthetic stiffness. This further indicates the natural interpretation of skin stretch stimuli as an indication of stiffness.

B. Main Experiment: Weber Fraction of Skin Stretch Stimuli

The WF for kinesthetic stimuli with our experimental setup was 14.1% [18], which lies within the WF range for kinesthetic stiffness reported in the literature, e.g. [19], [20], [21]. There was no significant difference in the WF for kinesthetic and skin stretch stimuli. We also expect the skin stretch WF to improve with training: this experiment was the first time the subjects had used skin stretch to discriminate between different surfaces. With more training, it is possible that their ability to discriminate between surfaces of different stiffness using skin stretch would improve. Prior research has shown that for a profession in which stiffness discrimination is important, increased experience correlated with improved discrimination ability [22]. Humans have daily experience judging stiffness through a comprehensive haptic experience that resembles the kinesthetic condition. Gaining more experience with skin stretch feedback could improve discrimination ability in a similar manner.

Software limits dictated a maximum of ± 2.3 mm of skin stretch, which resulted in a 2-4 cm workspace within the surface, depending on the skin stretch ratio. The proportion of total trials for which the tactor travel saturated during subjects' interactions with the virtual surface increased with skin stretch ratio and the effective workspace decreased. Despite the decrease in workspace, our results show that the discrimination ability at each skin stretch ratio was relatively similar. This indicates that users were not using the terminal skin stretch magnitude to differentiate between the surfaces, since the terminal magnitude for all saturated trials was 2.3 mm. It can be inferred from this result that subjects may be using skin stretch rate information to discriminate between stiffnesses.

VII. CONCLUSIONS AND FUTURE WORK

A cutaneous haptic feedback device rendering skin stretch feedback to the user was developed and used to compare the ability of users to discriminate surface stiffness using skin stretch stimuli versus kinesthetic force feedback. This study shows that users are able to discriminate stiffness with similar fidelity when using skin stretch cues in comparison to kinesthetic feedback, as the WF for skin stretch feedback was not significantly different from the WF for kinesthetic feedback. It is expected that the ability for users to discriminate stiffness using skin stretch cues will improve through training and usage.

This work shows that skin stretch feedback can be provided easily through a small position-controlled device integrated with an off-the-shelf kinesthetic haptic device. Existing teleoperation systems could therefore incorporate skin stretch feedback via an add-on attachment to the master manipulator. Skin stretch feedback is intuitive, and the use of this modality to differentiate surfaces of different stiffness has shown performance comparable to force feedback. Together with the ability to convey directional information, skin stretch feedback is a promising candidate to substitute for force feedback in teleoperation systems. We plan to implement a multi-DOF skin stretch feedback device in a surgical teleoperation scenario. Mock surgical tasks, such as tissue palpation and suture knot tying, will be performed with the skin stretch feedback device in order to evaluate the effectiveness of skin stretch feedback as a sensory substitution method for force feedback in surgical teleoperation.

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