Comparison of Skin Stretch and Vibrotactile Stimulation for Feedback of Proprioceptive Information

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Abstract

We present the results of experiments to compare vibration and skin stretch in a virtual proprioception task in which subjects used a force sensor to control the movement of a virtual arm. Pilot experiments pointed to the need to provide the arm with varying dynamics (like a real arm) and to scale the feedback from vibratory and skin stretch displays to demonstrate a clear improvement in the accuracy of movement. For the final experiments, ten subjects were first trained on the system with visual feedback and then tested with vibratory feedback, skin stretch feedback and no feedback. Both vibration and skin stretch improved the subjects' performance. For some subjects, a second no-feedback case showed improvement over the initial case, indicating learning; in other cases, the no-feedback performance deteriorated and subjects reported that they had become used to relying on feedback. Overall, skin stretch provided superior results, particularly when the virtual arm was in a low-inertia configuration and at low velocity. The results suggest that small skin-stretch devices could be worn on the body to provide useful proprioceptive information when interacting with virtual environments and in motion training for rehabilitation or sports.

Keywords: skin stretch, proprioception, vibration, sensory substitution

Index Terms: H.1.2 [Models and Principles]: User/Machine Systems—Human information processing; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 Introduction

With the proliferation of portable, wireless electronic devices, from cell phones to wearable heart-rate monitors, there has been increasing interest in the use of haptics as a communication channel to augment, or in some cases replace, visual and audio displays. Vibration is by far the most widely used haptic feedback modality in small devices, being compact, relatively low-power and easy to implement with pager motors or piezoelectric actuators. In most implementations, vibration feedback provides an "event cue," i.e., an indication that some, often exogenous, event has occurred. Recently, skin stretch has been proposed as an alternative haptic feedback mechanism [4, 21] that could be well suited to the requirements of portable or wearable devices. Skin stretch excites some slow-acting mechanoreceptors [16] and therefore does not need to be rapidly varying to elicit a response. Moreover, the applied motions are small so that the power requirements can be low.

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The work in this paper is motivated by a recognition that skin stretch is also an important component of the human proprioceptive apparatus, particularly for the distal joints [7, 5], but also at the elbow and knee. This observation suggests that skin stretch display could be useful for small, body-worn devices used in motion training for sports, physical rehabilitation or therapy, and other applications where proprioceptive information is valuable. For example, upper-limb amputees are often given myoelectrically-controlled prosthetics in which joint movements are produced when the amputee flexes muscles adjacent to the prosthesis. No position or motion feedback, other than vision, is provided to the wearer and the amputee must visually concentrate on the device to perform precise movements. Other applications where proprioceptive feedback is deficient include people with certain neurological conditions (e.g. stroke, multiple sclerosis) where afferent function is sometimes distorted or largely absent.

In recent work, the value of proprioceptive feedback has been demonstrated in force-based targeting tasks, even when visual feedback is also provided [18]. However, in other experiments proprioceptive feedback produced by a robotic device did not provide superior performance in comparison to vibrotactile feedback in a tilt estimation task [9].

We are interested in developing wearable haptic devices that can be placed on hairy skin and are capable of providing proprioceptive information. Providing haptic feedback on the hands, while attractive due to large receptor density, is not practical for prosthetics and not desirable for applications in which the hands need to be kept free and unencumbered to perform tasks.

In the following sections we describe an experiment in which we compared the ability of subjects to perform blind cursor movements without haptic feedback and with two types of feedback: skin stretch and vibration. The task is roughly analogous to asking a person to move her hand specified distances, such as 10 or 20 cm to the left or right, without looking. In the present case, subjects apply forces to a single-axis load-cell held between the fingers. The force input controls a cursor that is attached to a virtual object that, like a human or robotic arm, has position-dependent dynamics.

While there are a number of ways in which skin stretch and vibration could be used to convey information, this study focused on single actuators of comparable footprint on the skin (a few cm^2) and capable of being used continuously, varying the signal to represent position. More sophisticated approaches could be employed that utilize multiple actuators and add discrete event cues. However, in order to make as fair a comparison as possible between the modalities, we constrained the experiment to continuously varying signals with a single actuator in each case.

2 Background

2.1 Vibrotactile Stimulation

When a vibratory stimulus (either motion or force) is applied to the skin, the fast-acting mechanoreceptors (Pacinian and Meissner Corpuscles) are activated. The Pacinian corpuscles are particularly sensitive to vibrations in the range of 200-300 Hz. The afferent fibers innervating them have been shown to fire at a rate proportional to the frequency of the stimulus as opposed to other mechanoreceptors which typically code stimulus amplitude with firing rate [11].

Vibrotactile stimulation is typically provided in one of two ways in portable devices. A rotational motor with an unbalanced inertia can create a vibration stimulus that varies in both frequency and amplitude as the input voltage to the motor is varied. This is the approach commonly used in cell phones and pagers. A second approach is to use a linear actuator, such as a voice-coil or piezoelectric actuator. In this case, arbitrary waveforms can be sent to the actuator. Amplitude, frequency, waveform type and a number of other properties of the stimulus can be specified independently.

Although vibration is most commonly used to provide "event cue" feedback, there have also been cases in which multiple vibrotactile stimulators are placed at various locations on the skin and patterns of activation or a sense of motion or direction can be conveyed (e.g., [28, 17]). One limitation with this approach is that the pacinian corpuscles, which dominate vibrotactile perception, have large receptive fields so that stimulators must be placed several cm apart to allow a subject to discriminate between them. In other studies, patterns of vibration pulses have been used to convey speech-type information [27]. Psychophysical experiments have also evaluated subjects' abilities to discriminate the frequency and amplitude of vibrotactile stimulations on hairy skin [22]. In these studies, the stimuli were not varied continuously but a pulse of one frequency (or amplitude) was given followed by a short pause and then another stimulus.

Murray et al. [25] provided continuously varying vibration feedback (amplitude and frequency modulated) proportional to a measured force during a telemanipulation task using voice-coil actuators on the fingertips. They found that subjects could perform the desired task better with proportional feedback than with binary feedback or no feedback. The experiment described in the following sections of this paper assesses subjects' ability to use a continuously varying vibration feedback on hairy skin to represent position information.

2.2 Skin Stretch

In comparison to vibration, skin stretch can be used to activate slow-acting (SA) as well as fast acting (FA) mechanoreceptors. Using skin stretch at low frequencies is attractive for wireless devices as it does not require much power; movements are small and velocities can be low. It has been shown in previous research that mechanoreceptors respond quickly and accurately to skin strain changes [8, 6, 26], and that humans are more sensitive to tangential forces than normal forces on the hairy skin of the forearms [3]. However, in comparison to other haptic displays, few devices utilize skin stretch. Important exceptions include the work of Hayward and colleagues [15, 30] and [10, 3, 26, 20, 8, 19, 24] who have developed fingertip displays that include skin stretch. Several investigators [20, 8, 19, 24] have also studied the mechanisms behind skin stretch. Makino [23] has developed a suction-based display that produces illusions of pressure on the skin, at least in part by producing localized skin stretch. However, non-glabrous skin stretch displays have been largely unexplored. In contrast to the previous devices, we are interested not in creating fine patterns of skin stretch at the fingertips but in applying skin stretch at discrete points on a person's limbs and torso.

In pilot experiments we determined that for applying stretch to the hairy skin on the forearms, people reported greater sensitivity when the skin stretch was applied in shear, as opposed to tensile or compressive loading. A sustained, gentle application of skin stretch in shear is easily noticeable but, unlike sustained vibration, is not annoying and does not appear to lead to desensitization.

2.3 Proprioception

Proprioception is the sense of position and movement of body segments not arising from vision [11]. A number of sensory receptors contribute to the proprioceptive sense. The muscle spindles and golgi tendon organs are sensitive to position and movement of muscles. Sensors in the joints give a sense of flexion and extension. Mechanoreceptors in the skin, including Ruffini endings and Merkel cells, also contribute to the sense of motion and position [12]. The brain integrates this afferent information to create a percept of the body segments' position and orientation. Even when vision is present, proprioceptive feedback can improve the accuracy of targeted finger movements [18].

Vibrotactile stimulation and skin stretch have been used to create illusory movements at various joints. Providing vibrotactile stimulation of about 75-100 Hz can create a sense of tendon lengthening [14]. Skin stretch near the joints also contributes to an illusory sense of motion. Collins et al. [5] found that skin stretch contributed to illusory movements at the index finger, elbow and knee and evaluated the relative magnitude of the perceived movements for various combinations of vibration and skin stretch.

For other applications (e.g. prosthetics), it may be possible to design haptic devices that create illusory movements of particular joints. However, in the present study, we were interested in what would more accurately be classified as sensory substitution. The skin shear that we apply is only loosely correlated with motion of the forearm, and the mappings of skin stretch and vibration were only intuitive in the sense that they were easy for subjects to correlate to cursor position.

3 Methods

Subjects were asked to perform cursor movements using a single-axis force sensor held between the fingers and thumb. The force sensor consisted of a load cell with two strain gauges in a half-bridge configuration. The use of a force (versus position) input minimizes the use of the subject's own proprioceptive sense. The virtual dynamics of the cursor are described in Section 3.1 below. A virtual workspace with a range of motion from 0-10 units was displayed on a computer monitor (Figures 1, 2). For each task, the cursor appeared at a starting position that was randomly chosen from (3, 5, 7) and the subject was instructed to move 2, 4 or 6 units to the right or left. Movement commands were constrained so that the desired end location was always in the range of 1-9. Subjects could not see the cursor during trials but they were given post-trial visual feedback throughout the experiment (final cursor position and desired position shown on the workspace). Subjects were instructed to attempt to move the desired number of units, stop the cursor, and press a button when they thought the virtual object was brought to a stop. Each of twelve possible combinations of starting positions and movements was repeated three times, for a total of 36 trials.

The experiment described above was performed under four feedback conditions for each subject. First, subjects were tested with no haptic feedback. They were then tested with vibrotactile and skin stretch feedback. Then they repeated the no-feedback trial to evaluate training effects over the course of the experiment. Half of the subjects did the vibrotactile feedback trial before the skin stretch and the others did them in the opposite order. Before each trial, subjects were given training with visual feedback (cursor and workspace visible) for about one minute and then given ten practice trials with post-trial vision feedback, identical to the actual trials. For the no-feedback case, this practice allowed subjects to learn the position dependent cursor-dynamics. In the feedback cases, it allowed them to learn the haptic mapping of the cursor position.

Ten subjects were tested (three female, seven male). Four had little or no experience with haptic devices; the other six had at least

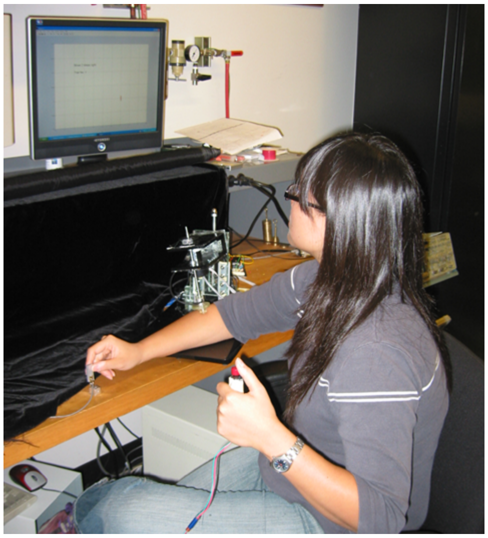

Figure 1: Subject completing the task with right arm controlling force sensor and left hand controlling button to end trial.

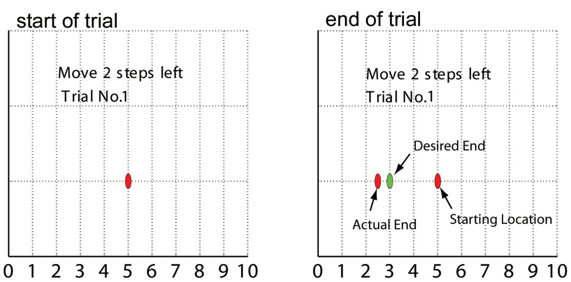

Figure 2: Example of experiment task. The left graph shows the screen presented to the subject at the start of each trial. The right graph shows the screen presented to the subject at the end of each trial, showing desired cursor position and actual position to provide post-trial feedback.

moderate experience. The experiment took about one hour to complete.

3.1 Cursor Dynamics

In pilot tests with four subjects we determined that if subjects are asked to move repeatedly to a single target, or one of a small number of targets, they often use feedback in a "pattern matching" mode. That is, they move until the vibration or skin stretch feels like it did previously when they were over the target, and then they stop. This way of using the feedback seems closer to an event-cue (event = target reached) than proprioception. Consequently, we revised the experiment to utilize varied starting locations and amounts of movement in the left or right direction, as described above.

We also discovered that the virtual object attached to the cursor should have non-trivial dynamics. If the virtual object has a fixed mass and damping, subjects quickly learn open-loop strategies such as pulsing the force applied to the sensor a certain number of times, or applying a steady force and counting "beats," to move the object a desired distance with accuracy. We hypothesize that analogous strategies do not work with human or prosthetic arms in part because the arm dynamics, and the mapping of muscle effort to movement, change continuously as a function of the arm configuration. Accordingly, we gave the cursor an inertia that varies somewhat like the endpoint inertia of a two-link robot arm whose end effector is constrained to move along a single direction in space. The endpoint inertia will be a polynomial involving sine and cosine functions of the position. A simplified approximation is a sinusoid, so that the cursor dynamics become:

$$m(x)\ddot{x} + b\dot{x} = F(t) \tag{1}$$

where b is the cursor damping, *F(t)* is the force applied to the force sensor which produces cursor motion, *x(t)*, and *m(x)* is the mass, which varies as

$$m(x) = 6 + 5sin(\frac{2\pi}{10}x) \tag{2}$$

The period of the mass variation matches the length of the visible workspace and the maximum and minimum mass are 11 and 1, respectively, with units such that a force magnitude of $F = 1$ and a mass of $m = 1$ result in an acceleration of 1 workspace unit/second^2. The damping was set to a constant value of $b = 10$. (The sinusoidal variation of the cursor mass can be seen superimposed on some of the subjects' data in Figure 12.)

A small deadband region was also added to reduce drift, such that the force applied to the cursor was related to the force from the sensor, F_j, by

$$F(s) = \begin{cases} 0 & |F_j| < 0.2 \\ F_j & |F_j| \geq 0.2 \end{cases} \tag{3}$$

Subjects removed their hands from the force sensor and the force was re-zeroed before each trial (which lasted approximately 15 seconds) to ensure that there was no drift or bias force.

Subjects were told that the behavior of the cursor was position dependent but they were not told the actual mapping. As described above, they were given time to practice moving the cursor while it was visible before the experiment.

3.2 Vibrotactile Feedback

The vibrotactile feedback in this study was provided by a C2 Tactor, from EAI Inc. This tactor consists of a linear electromagnetic actuator that produces relative motion between two moving parts, a small mass in the center of the device and a larger mass surrounding it. The tactor was placed on the arm, just below the elbow joint using a Velcro strap as shown in Figure 3. The actuator was controlled with a computer running the Mathwork's xPC Target realtime operating system through a current amplifier, controlling the actuation force. The waveform sent to the actuator can be arbitrarily specified with this approach. A frequency domain characterization of the tactor attached to the skin was performed using an accelerometer placed directly above the actuator. A mechanical resonance was found near 250 Hz, near the peak sensitivity of pacinian corpuscles.

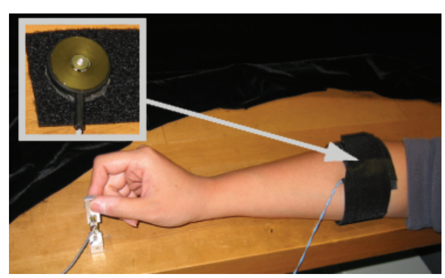

Figure 3: Vibrotactor strapped to test subject, placed on forearm below the elbow joint. The force sensor used to control cursor position is also pictured. Forces greater than 200 mN were needed to move the cursor.

Several position mappings were evaluated in pilot trials, including linear and nonlinear mappings of frequency, amplitude or both. Sine waves were used in all cases. Because of the dynamics of the actuator attached to the skin, varying the frequency also results in magnitude variations, though not linearly or even monotonically. This made a variable frequency mapping difficult to use. In addition, varying the frequency continuously results in Doppler effects when the cursor is moving rapidly, which cause the instantaneous frequency to be higher or lower depending on the direction of motion.

A pager motor was also used in pilot trials. This motor exhibited an approximately linear relationship between input voltage and magnitude and an approximately quadratic relationship between frequency and voltage input. However, the ranges of frequencies (from about 50 Hz to 175 Hz) and magnitudes that the motor was capable of producing were smaller than with the C2 Tactor.

Three subjects were tested with both the pager motor (input voltage varied as a function of cursor position) and the C2 Tactor (forcing amplitude varied as a function of cursor position at 250 Hz) and all three did better with the tactor. Based on these studies, we determined that varying the amplitude of the sine wave sent to the C2 Tactor at a constant frequency of 250 Hz provided the more effective position mapping. Pilot trials also showed that a logarithmic amplitude mapping was more effective than a linear one. This result is consistent with other findings in the literature that amplitude perception follows a logarithmic pattern [25].

The final mapping chosen obeyed the following relation:

$$A(x) = 0.5 \times 10^{0.06x} \tag{4}$$

where *A(x)* is the amplitude of the stimulus and x is the cursor position. This results in a small but perceivable stimulus level at $x = 0$ and a stimulus near the current limit of the actuator at $x = 10$ corresponding to $A(x) = 2$, which produces a peak acceleration of approximately 7.5 G as measured by an accelerometer on the tactor, in contact with skin. When the cursor moved outside the $0 \leq x \leq 10$ units workspace, the stimulus saturated at the values for 0 and 10, respectively. While more rigorous studies would be required to determine an optimal mapping of vibrotactile stimulation, this was the vibration mapping that our pilot subjects found most intuitive and performed best with.

3.3 Skin Stretch Feedback

A benchtop skin stretch device, in which the stretch pattern is induced with two contacts, was used in these experiments. The device, shown in Figure 4, allows us to vary the contact method and test different end-effector configurations to evaluate perception and ability to induce skin stretch. As indicated in the figure, the device has four manually adjustable degrees of freedom to accommodate different sizes of arms and legs while keeping the stretch applicator and the axis of rotation perpendicular to the local skin surface. A low-friction servo motor applies torques to the rotating shaft and the stretch applicator disk, inducing skin stretch primarily in shear. A six-axis force/torque sensor (ATI Nano 17) is mounted between the shaft and the stretch applicator to measure the overall forces and torques applied.

The motor is coupled to the shaft of the stretch applicator through a capstan pulley with a 1:6.83 gear ratio which provides a low friction transmission. The stretch applicator is a circular disc (d = 3.8 cm) with two smaller circular contact points (d = 0.127 cm) spaced 1.275 cm apart to attach to the skin, resulting in a contact area of roughly 2.5 cm^2. The spacing of the contact points is larger than the two point discrimination threshold for the hand and forearm, yet small enough to be used in portable devices. Early pilot tests also showed that maintaining flat contact with the skin was important in reducing the amount of slip and eliciting strong sensations. When the contact point becomes too large, it is difficult to maintain contact due to the curvature of the limbs, and when the contact point is too small, the sensations produced can be painful. The sizes of the points were chosen to provide a large enough area to adhere to the skin well, but small enough to maintain flat contact with the surface of the skin. The contact points are attached to the skin using Red-e Tape^{TM}, a strong skin-safe adhesive. Based on the results of earlier pilot tests, we determined that applying fixed rotations produced less subject-to-subject variability in the perceived skin stretch than applying fixed torques. Consequently, for these experiments, position controlled skin stretch was applied using a PID controller with feedforward components to reduce transient errors. The control is implemented using a PIC microcontroller running at approximately 800Hz. Under test conditions, the skin stretch applicator tracks commanded rotations with an accuracy of approximately ± 1 degree.

The skin stretch device was attached to the subject's arm, just below the elbow (Figure 5), in an area similar to where the vibration tactors were placed. The contact points were placed such that the line connecting them was perpendicular to the forearm.

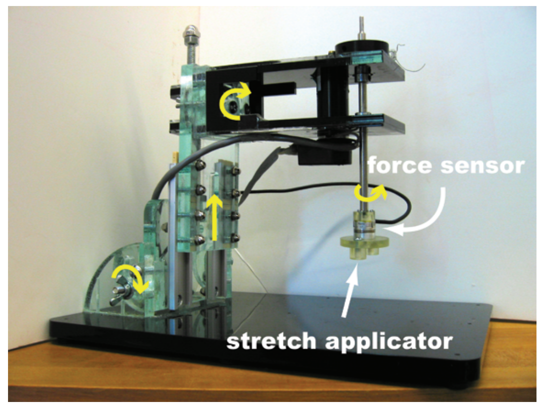

Figure 4: Skin stretch device. Arrows indicate degrees of freedom. Device is manually configured to be placed on test subject's limbs.

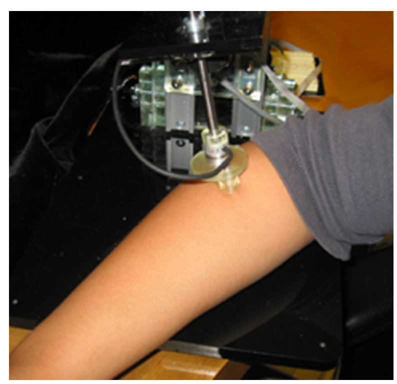

Figure 5: Skin stretch device attached to forearm below the elbow joint. Two contact points are attached using adhesive tape and rotate to apply skin stretch. Total contact area is approximately 2.5cm^2.

For these experiments, a range of ± 45 degrees of rotation was mapped to the cursor position. This range of stretch was determined to produce sufficiently large, but comfortable, magnitudes of feedback in pilot studies. To provide a rough estimate of the amount of skin stretch applied, the engineering strain of 30 points in a 5 x 8 cm space surrounding the stretch applicators was measured on one subject [2]. Rotations of 40 degrees, near the maximum rotation of stretch applied in the experiments, were found to produce absolute maximum strains of approximately 40% and root mean squared strains of approximately 25%.

One advantage of skin stretch feedback over vibration is the ability to convey direction. For these experiments, the rotation was set to 0 degrees when the cursor was in the middle of the workspace, at 5 units. The device subsequently rotated clockwise or counter-clockwise according to the direction of the cursor movement. Because there is relatively little information about perception of skin stretch applied to hairy skin, determining the optimal mapping of the cursor to magnitude of stretch is an open-ended problem. In pilot studies, a linear mapping of cursor position to degrees of skin stretch was first evaluated. Pilot subjects noted that there appeared to be a region of the cursor position surrounding $x = 5$ where it was difficult to detect rotation of the device. We hypothesize that this is due a detection threshold below which subjects do not notice skin stretch. At higher levels of stretch, the skin stiffens nonlinearly so that linear increases in displacement produce more than linear increases in stress. Thus, when skin stiffness is low, at low rotations, a greater change in rotation is required to elicit sensations; at higher angles, near the saturation limits, smaller changes in angle are detectable. To account for these effects we used a slightly nonlinear monotonic, fifth order polynomial to map cursor position to rotation. A plot of the polynomial mapping is shown in Figure 6. The slope of the polynomial is also shown, which indicates the rate of change of skin stretch with respect to changes in cursor position. The varying slope reflects the hypothesized variation in skin compliance at low and high rotations, respectively.

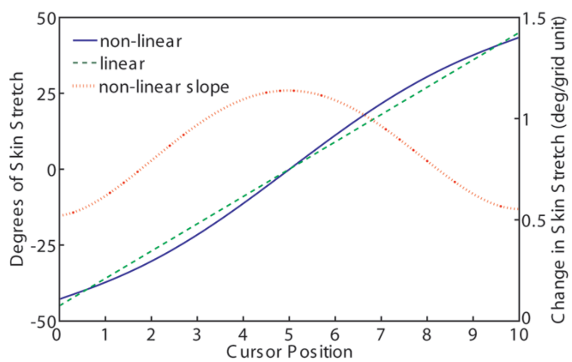

Figure 6: Skin stretch mapping relative to cursor position. Both the initial linear mapping as well as the non-linear method used are shown. Though the non-linear mapping is close to linear, at cursor locations near x=5 the increased change in stretch is great enough to overcome threshold limits to improve subject performance. The slope of the nonlinear mapping is also shown, reflecting the hypothesized variation in skin compliance.

Following the approach taken with vibration feedback, when the cursor left the region $0 \leq x \leq 10$ the skin stretch rotation was saturated at that the minimum or maximum angles (± 45 degrees). Although further testing is required to determine optimal mappings of skin stretch stimulation, the subjects in pilot tests found the slightly nonlinear mapping easy to interpret and they performed better with it than with a linear mapping.

4 Results

The data collected from the experiments were analyzed to determine the effectiveness of providing haptic feedback in blind movement tasks. The main parameters of interest were the absolute and relative error (absolute error divided by desired movement length) in final cursor position and the instantaneous velocity of the cursor at the end of each trial. Force data from the load cell and the skin stretch device were also recorded, though not presented here. A one-way analysis of variance (ANOVA) comparison of means was conducted to determine if the means in position error were significantly different across the various feedback methods: no feedback (NF1), vibration (V), skin stretch (SS), and the final no feedback case (NF2). The ANOVA method used was a post hoc analysis conducted using the Tukey-HSD tests [13]. In cases where equal variance could not be assumed or if samples sizes were very unequal, Games-Howell post-hoc tests were implemented. The effects of varying step sizes and the starting/ending positions of the cursor were also studied. The data were grouped into several subcategories to identify patterns and trends.

Error bars on the plots below indicate plus one standard deviation. Standard deviations were generally quite large relative to the means. This is largely due to the fact that the difficulty of the task caused standard deviations within subjects to be similar in magnitude to inter-subject standard deviations (such that normalization does not significantly decrease standard deviations). The task was designed to be comparably difficult to moving a real arm a specified distance without looking, which we expect would also result in relatively large variances. However, with 36 trials for each subject, for each feedback condition, p-values were generally small whenever the averages were noticeably different. Quantitative results across all subjects as well as anecdotal observations of the most interesting cases are presented in the following sections.

4.1 Cursor Position

4.1.1 Overall Error

As anticipated, the addition of haptic feedback improved movement accuracy significantly. As seen in Figures 7 and 8, the relative and absolute position errors decreased with vibration and skin stretch feedback. Overall, in both absolute and relative error analysis, skin stretch produced significantly smaller error values ($p < 0.01$) when compared to all other cases, including vibration. The standard deviation of the errors was also lower with skin stretch than the other cases. Vibration feedback also appeared to result in lower position errors as compared to receiving no feedback. However, upon further inspection, relative errors with vibration feedback are only significantly less ($p < 0.005$) as compared to first no-feedback case, NF1. When compared to the second no feedback case (NF2), position errors were not significantly lower. When individual subject data were compared, seven of ten had the lowest absolute error with skin stretch feedback, one with vibration, and two in the second no feedback trial.

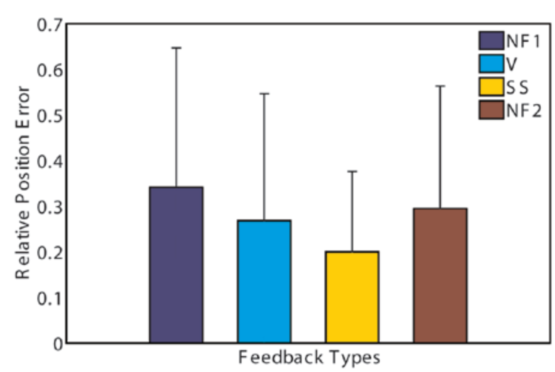

Figure 7: Average relative position errors for ten subjects. Error bars are plus one standard deviation. Both skin stretch and vibration result in significantly smaller relative errors ($p < 0.005$) than no feedback 1, and skin stretch provides significantly smaller errors ($p < 0.005$) compared to all other feedback modes.

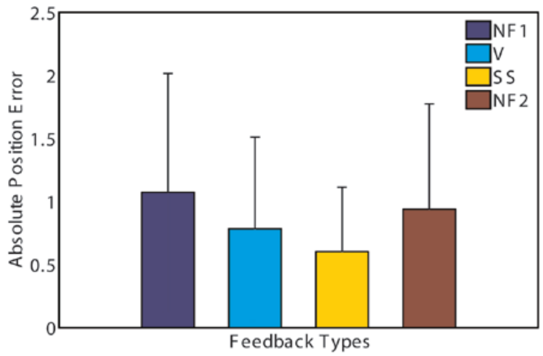

Figure 8: Average absolute position errors for ten subjects. Similar to relative error, both skin stretch and vibration result in significantly smaller absolute errors ($p < 0.05$) than both no feedback cases, and skin stretch provides significantly smaller errors compared to all other feedback modes ($p < 0.01$).

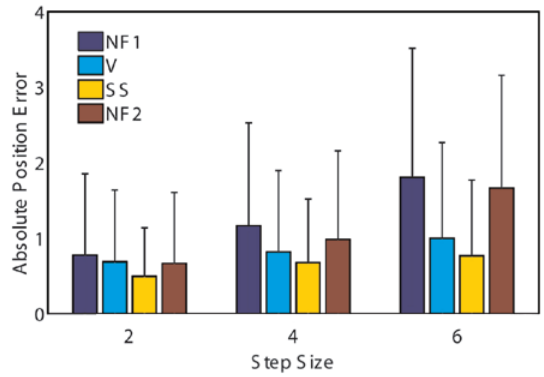

Figure 9: Average absolute position errors relative to step size. As expected, absolute errors tend to increase with increasing step sizes across all feedback modes. Both skin stretch and vibration feedback result in smaller errors at each step size, with skin stretch performing best, though not significantly.

Overall, subjects had significantly less error in the second no feedback case than the first, indicating that some improvement was taking place over the course of the experiment due to practice. However, this trend was not consistent across all subjects. Some did worse the second time and reported that they had become somewhat dependent on the feedback and had difficulty moving accurately when it was removed. We also performed a linear regression on the relative position errors across the 36 trials for each feedback case to see if significant improvement was occurring over the course of the trials. No significant trends were found in any of the feedback cases.

4.1.2 Error by Step Size

Because vibration and skin stretch are very different modes of tactile feedback, we were interested to see if one feedback mode was better suited for certain applications and to identify where each provided the most improvement. The position errors were sorted into various subcategories according to step size (the number of units the test subject was asked to move the cursor), and the desired ending position of the cursor. At first glance, when sorting the data by step size, it is clear that the addition of haptic feedback provides benefits over no feedback at each step magnitude (Figure 9). As expected, the absolute error increases as the desired step size increases, for all feedback modes. When no feedback is provided, the relative errors do not change significantly as a function of step size (Figure 10). However, for the two feedback modes, relative error decreases significantly ($p < 1 \cdot 10^{-6}$) as step size increases from 2 to 6. This trend indicates that subjects seem to be getting a sense of absolute position when haptic feedback is provided. If a true sense of position were provided, we would expect to see uniform absolute errors at all step sizes, such that relative errors decrease for larger step sizes.

4.2 Final Velocity

4.2.1 Overall Velocity

The cursor velocity was also calculated through differentiation (forward difference method) of the recorded cursor position throughout the experiment. No additional data filtering was needed since the cursor dynamics effectively act as a low-pass filter. The instantaneous velocity of the cursor when the subject pressed the button (i.e., when the subject believed the cursor had been brought to a stop) was determined for each trial. Overall, the final velocities with skin stretch feedback were significantly lower than in any other mode (Figure 11, with p-values less than $1 \cdot 10^{-9}$). Although

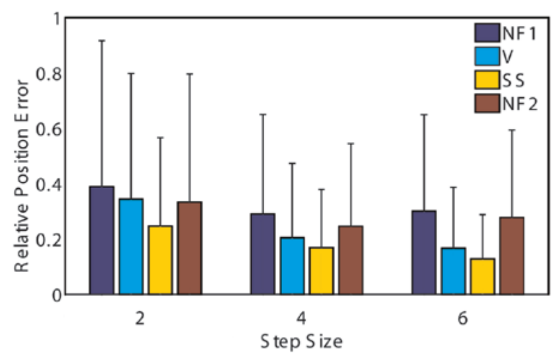

Figure 10: Average relative position errors by step size. The general trend is that relative errors decrease with increasing step sizes with feedback. At large step sizes (6), subjects perform significantly better ($p < 0.002$) with feedback than without, though there is no significant difference between skin stretch and vibration. In addition, relative error decreases significantly ($p < 1 \cdot 10^{-6}$) as step size increases from 2 to 6 when feedback is provided

it appears that the average cursor velocity increased with vibration feedback and at the end of the experiment with the second no feedback case, when examining individual subject data, only 2 of the 10 subjects had significantly higher velocities for those two feedback modes.

It appears that the subjects were only able to easily detect velocity when skin stretch feedback was provided. However, we also note that the average velocities at which the subjects moved the cursor were lower with skin stretch than in the vibration or no feedback modes. It appears that because skin stretch provided a better qualitative sense of velocity, subjects moved more slowly in this case. In the other cases, there was little sense of cursor velocity and no motivation to limit speed.

4.2.2 Velocity by Cursor End Position

A point of interest when examining the final velocities is the correlation with cursor position and inertia. As the cursor inertia increases, while damping remains constant, more effort is required to bring the cursor to a stop. In all feedback methods, the average ending velocity of the cursor relative to the desired ending position

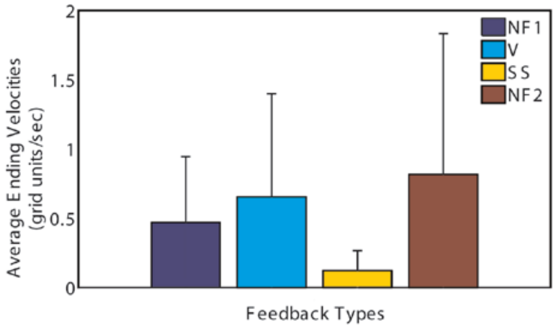

Figure 11: Overall average ending velocities. Skin stretch is far superior to all other feedback modes in maintaining low end velocities ($p < 1 \cdot 10^{-9}$).

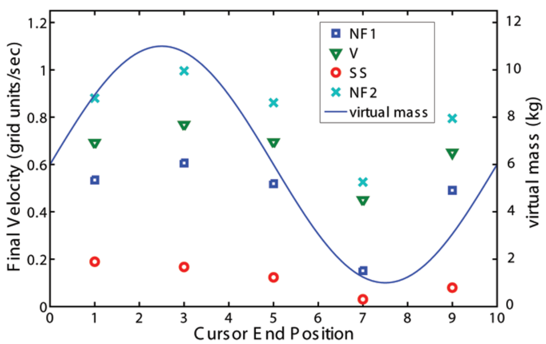

Figure 12: Average ending velocities with respect to desired ending cursor position. Skin stretch velocities remain significantly lower (p<0.003) than all other feedback modes. Average ending velocities from each feedback mode follow the sinusoidal characteristics of the varying inertial properties of the cursor with respect to cursor position.

closely matches the pattern of the inertial changes (Figure 12). A cursor position of 7 corresponds to a low cursor inertia, and correspondingly, the measured ending velocities of the cursor are lowest at that location. This suggests that subjects were indeed experiencing the challenges of controlling the varying cursor dynamics. However, the errors are consistently lower with skin stretch (p<0.003), and the variation with cursor position is generally lower than with other feedback modes.

5 Discussion

The results of the present study indicate that skin stretch may be an effective method for providing proprioceptive feedback in wearable displays. The fact that skin stretch was superior to vibration for the prescribed task is likely due to at least two factors. First, preliminary psychophysical experiments indicate that the effective analog resolution of skin stretch on the hairy skin is higher than the resolution with vibration amplitude [1]. This may be part of the reason that vibrotactile stimulation is still used predominantly for providing "event cues" rather than proportional feedback. Additional studies are ongoing to quantify this result. Second, as discussed previously, skin stretch is an important part of the proprioceptive sense and provides a more intuitive mapping for position information. In addition, the fact that skin stretch gives a realistic sense of velocity in addition to position, could provide benefits for many applications.

Vibrotactile stimulation was also found to provide some improvement in movement accuracy though not significantly compared to the second no feedback trial, indicating that perhaps in some cases additional experience and training with the cursor dynamics may be nearly as effective as vibration. The present study did not fully assess the effects of training on movement accuracy. Because subjects were given post-trial vision feedback throughout the experiment, some improvement over time was expected. In fact, most subjects had lower errors in the second no feedback trial than the first but no significant improvement was found across the 36 trials for a given feedback case. All subjects were given uniform training in this study. To fully assess learning effects, a future study should be done where the training method is a controlled variable.

While vibrotactile stimulation was found to be less effective than skin stretch in this study, it remains an attractive choice for wearable haptic applications due to its size and power characteristics. In the present study, the amplitude of the vibration was continuously varied according to cursor position as this was found to be the most effective continuous mapping. However, other strategies could be employed where discrete changes in amplitude or frequency occur at specific intervals. This would require the subject to "count" to some extent to perform movements and the inherent resolution of the feedback channel would be limited. In any case, when vibration is used, it is desirable only to turn on the stimulation when a movement is being made as many subjects reported that continuous vibration was annoying. In addition, neural adaptation causes desensitization over time. Multiple vibration stimulators could also convey a sense of motion if they are appropriately sequenced [29]. However the stimulators must be spaced relatively far apart due to the large receptive fields of the deep pacinian corpuscles. Because skin stretch activates primarily superficial, slow acting receptors, it is less susceptible to these issues. A constant stimulation is not annoying and can be effectively ignored if desired. If multiple actuators are used, they can be spaced quite close together without interference. One more advantage of skin stretch is the ability to convey positive or negative direction without the use of multiple stimulators. In our experiments, there was a clear advantage to skin stretch feedback due to the greater range of possible stimuli, as the simulator rotated from negative to positive angles.

Although these initial studies indicate there are unexplored benefits to using skin stretch for tactile feedback, there are a few practical issues that must be addressed when attempting to implement skin stretch in a wearable device. Particularly if the skin contact area is relatively small, as with the device used in this study, care must be taken so that the device does not slip against the skin. How well the device works is highly dependent on the where it is placed on the skin and on the subject. The device tends to slip more if there is a lot of hair on the skin or in areas where skin curvature is high. Though the Red-E-Tape was found to adhere adequately to the skin, it is assumed that some amount of slip occurred throughout the skin stretch trials. The varying stiffness of skin on different parts of the body, as well as subject-to-subject variation of skin properties, present significant design and control challenges. Some individual calibration may be required when the device is attached. Because skin stiffness properties also depend on the configuration of the body or limbs, the perceived magnitude of stretch also appears to change. In early pilot experiments, we attempted to place the skin stretch applicator near the elbow joint to provide something closer to an illusory sense of joint movement. However, we observed that as the trials progressed, subjects would move and bend their elbows slightly to re-adjust their seating configuration. This resulted in varying the skin stretch near the joint and hence, the perceived skin stretch mappings. To minimize these effects, we opted to apply the skin stretch in a more stable location slightly further from the elbow joint where the mounting was less affected by small joint movements. This resulted in a modality closer to sensory substitution. In our experiments, we simply asked our subjects to refrain from moving their arms when completing the task and did not restrain the forearm. Also, while most subjects qualitatively preferred skin stretch to vibration, one of them reported that it was uncomfortable, particularly in the areas of high rotation. This subject had lower error with vibration than skin stretch.

We are currently developing small, wearable skin stretch devices that provide stimulation in various ways. Concepts that have larger skin contact areas, and do not tend to slip, are being evaluated for comparison with the skin-rotation method applied in this paper. Future experiments will assess the psychophysical qualities of skin stretch with different devices and skin locations. Also, we will study using multiple actuators and more sophisticated mappings, including multimodal feedback, to convey proprioceptive information. Ultimately, we anticipate that skin stretch will be most useful as a complement to vibration, providing relatively low-frequency proportional feedback for activities that involve controlled movement.

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