Rotational Skin Stretch Feedback: A Wearable Haptic Display for Motion

Karlin Bark, Jason Wheeler, Pete Shull, Joan Savall, *Member*, *IEEE*, and Mark Cutkosky, *Member*, *IEEE*

Abstract—We present a wearable haptic feedback device that imparts rotational skin stretch to the hairy skin, along with the results of psychophysical tests to determine its resolution and accuracy for motion display. Tracking experiments with visual markers reveal the pattern of skin motion and strain imparted by the device, confirming subjective impressions that the design represents a trade-off between perception at low stimulus levels and comfort at maximum stimulus levels. In an isolated environment, users were able to discriminate between different rotational displacements of stretch within two to five degrees, depending on the reference stimulus. In a more realistic setting, subjects were able to use feedback from the device to control the positioning of a virtual object within six degrees or ± 6.5 degrees of the total range of motion. When subjects were passive and exposed to arbitrary rotations of the device, the accuracy was poorer, although it improved with training. The results suggest that wearable skin stretch devices can be an effective means of providing feedback about a user's controlled joint or limb motions for motion training and similar applications.

Index Terms—Skin stretch, skin strain, proprioception, wearable, haptics.

1 Introduction

In applications ranging from motion training and physical rehabilitation to teleoperation of a remote system, haptic feedback can provide valuable information about forces and motions, particularly when vision and audition are otherwise occupied. For example, following orthopedic surgery, a patient's gait is often different than it was presurgery. Physical therapists can observe the patient and provide oral feedback, giving instructions such as "Lift your foot a little higher." However, such statements may not clearly specify to patients how much they should move their joints. A wearable device could be used to provide patients with direct feedback regarding the speed and extent of motion of a limb or joint. In another application, a device could be strapped to an amputee's body or joint socket to indicate the movement of a prosthetic arm, reducing their dependence on vision to control the limb.

Today, the most widely used haptic technology for portable devices is vibration, as commonly found in cellphones. Vibration is easy to implement, but is best suited for transient event cues and is less effective when used continuously. It can lead to desensitization [1] and many users find the stimulus annoying after a prolonged time. In addition, sensitivity to vibrations can be reduced when people are in motion [2]. An underappreciated component of haptic sensation, particularly for applications involving portable devices, is skin stretch. Skin stretch is a known part of the normal physiological apparatus for proprioception, contributing to our sense of motion and location of our limbs [3], [4]. The motions and velocities necessary to impart skin stretch can be low, allowing for the design of compact, low-power, wearable devices. With this motivation, the work presented here has focused on skin stretch for the display of proprioceptive information, applying stretch at discrete points on a person's limbs and torso. For our applications, a device that can be strapped to a user's body is desirable as we believe the feedback is more intuitive if placed near the joint of interest (e.g., elbow or knee), where skin stretch already contributes to our proprioceptive senses. Though fingertip skin stretch devices are attractive, [5], [6], a high density of receptors is not necessary for our applications, where each device displays the motion of a single joint.

In early studies, we found that it was effective and comfortable to impart skin stretch using a pair of disks that contacted the person's arm or leg and moved in a circular pattern, producing a combination of tensile and shear strain [7]. Several variations of linear stretch were attempted, and users displayed strong directional sensitivity; however, when two contact pads moved in opposing directions, skin sensations were reported to be strongest, providing a greater perceived magnitude of stretch.

The objectives of the studies presented here are to understand what contributes to our perception of rotational skin stretch and to quantify our ability to utilize the feedback in practical applications. First, we present tests and an analysis to clarify which mechanical aspects of rotational skin stretch contribute to our perception. We then present studies to characterize psychophysical properties of rotational skin stretch, assessing the ability of users to use it either to control or to detect the position of a virtual object.

- K. Bark, P. Shull, J. Savall, and M. Cutkosky are with Stanford University, 775 S. Shoreline Blvd, #6 Mountain View, CA 94041. E-mail: kbark80@gmail.com, {pshull, jsavall, cutkosky}@stanford.edu.
- J. Wheeler is with the Sandia National Laboratories, PO Box 5800, MS 1010, Albuquerque, NM 87185-1010. E-mail: jwwheel@sandia.gov.

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2 Background

2.1 Skin Stretch Mechanoreceptors

Although much research has focused on the mechanoreceptors in the human hand, there has been less attention

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on the receptors in hairy skin and their functions. The hairy skin of the human forearm contains slowly adapting type I receptors (SAI), slowly adapting type II receptors (SAII), and three different types of fast adapting (FA) receptors including hair, field, and pacinian receptors [8]. It is emphasized that in hairy skin, both slowly and fast adapting receptors are sensitive to tangential forces and skin stretch [9], [10], [11], making skin stretch an attractive choice for tactile feedback. The traditional view is that SAI receptors are responsible for forces and pressures and SAII receptors provide information about directional skin stretch. Several investigations have found that SAII receptors are sensitive to directional movements and to specific directions of stretch, possibly contributing to our ability to discern different movements of skin [12], [13], [14]. Both SAI and SAII receptors respond to both velocity and displacement [12]; though at sustained displacements, the SAII units respond continuously while the SAI responses are more intermittent. FA receptors also play a role in skin stretch, particularly for higher velocities of movement or stretch, for which these units are more sensitive [11]. Humans have also been found to be more sensitive to tangential forces than normal forces on the hairy skin of the forearms [15].

Despite these prior studies, it is not precisely known what specific mechanical properties contribute to our perception of skin stretch in a given application. Experiments and analyses are complicated by the fact that skin is anisotropic, nonlinear, and viscoelastic [16]. While some studies have shown that stresses correlate best to mechanoreceptor activity [17], [18], others have shown that compressive strains or strain energy correlate to receptor activity [19], [20]. A primary limitation of the prior work is that few studies have been performed on human skin in vivo. As a compromise, researchers often use animal skin, such as in monkeys [20], [21], rats [17], or cats [18], for understanding receptor behavior. However, it cannot always be concluded that animal receptors react in a similar manner to human receptors [17]. The region of skin that is tested is also inconsistent, further confounding the results. What can be agreed upon is that SAI and SAII receptors respond to various types of skin stretch, and in particular, SAII units are directionally sensitive, with increased activity when stretch is along a preferred orientation or axis [17], [18], [20], [22].

2.2 Sensitivity to Skin Stretch and Moving Stimuli

In addition to studies designed to understand the biological factors contributing to our sensation of skin stretch, there has been an interest in quantifying our sensitivity to skin stretch and what factors contribute to our ability to detect directions of stretch. Tactile directional sensibility can be attributed to two separate types of stimuli: stretch caused by friction-induced contact and spatial cues that vary with time [14], [23]. In other words, to detect motion on our skin, we may use the intensity of stretch through friction-based displacement, or through displacement of a moving contact and activation of a series of mechanoreceptors, referred to as spatiotemporal stimulation. In general, humans are remarkably sensitive to movements of skin and stretch induced by a contact point attached to the skin. Studies have found that on the forearm, humans can report the direction of skin stretch with movements as small as 0.13 mm, on par with visual motion detection thresholds [13]. In contrast, when using only spatiotemporal stimuli such as a low-friction air jet moving across the surface of the skin, the smallest distance of movement necessary to report the direction of the stimuli is approximately 60 times higher [14]. A drawback of lateral stretch sensitivity is that it is highly dependent on a variety of factors such as the normal force applied [24], the velocity of stretch, and varying skin stiffness [23]. In particular, as the body moves, the skin surface properties change, which has a large influence on our sensitivity. The minimum stretch necessary for a user to detect direction reliably increases significantly as the skin stiffens [23]. In addition, when stretch is applied locally to the skin, a larger field of receptors is activated [13], so that receptors located >25 mm from the contact point could signal the direction of stretch. In general, our SAI and field units are important in providing spatiotemporal cues whereas our SAII units are responsible for our encoding of the directions of lateral skin stretch [9], [17].

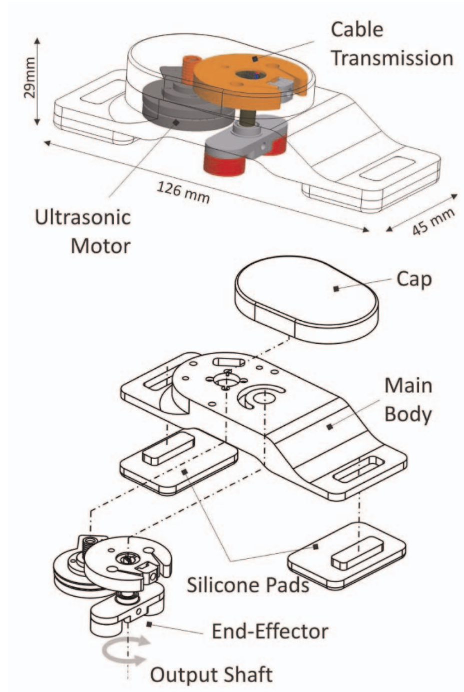


Fig. 1. Wearable skin stretch device assembly.

3 Rotational Skin Stretch

A brief description of the wearable haptic device is provided here; details can be found in [25]. The skin stretch device (Fig. 1) is designed to be attached to and provide feedback on nonglabrous skin. We envision that in future studies, multiple devices could be attached at several locations including the forearm, wrist, ankle, thigh, or calf. A double-sided skin-safe adhesive, Red-e-Tape, is used in combination with a polymer film (Skin Shield) to attach the contact pads to the user. The pads are driven by a piezoelectric motor and cable/capstan drive to avoid producing vibrations that could confound the skin stretch sensation. The transmission is not back-driveable, so power is needed only when changing the angle of rotation. Specifications are given in Table 1.

TABLE 1
Wearable Skin Stretch Device Characteristics

	Device Specifications
Size	29 x 45 x 126 mm
Contact dia.	14 mm
Contact spacing	26 mm
Max Torque	0.6 Nm
Speed Range	15-150 deg/s
Weight	115 g
Resolution	0.05 deg

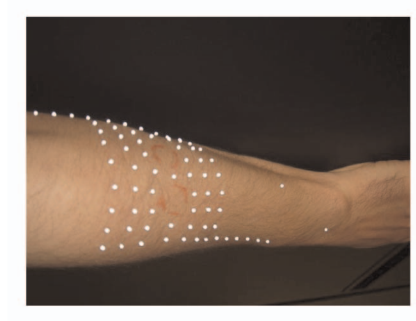
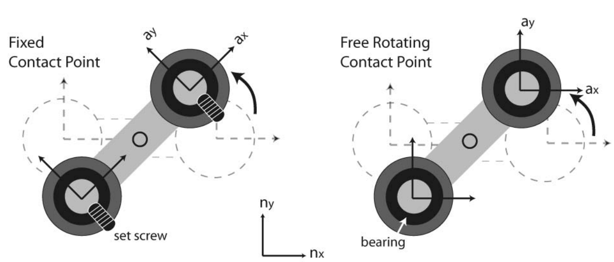


Fig. 3. Grid pattern of markers placed on arm.

Pilot studies indicated that the perceptual qualities of skin stretch are heavily influenced by the strain patterns around the end-effector. In particular, local shear strains imparted by rotation of the pads can cause a stronger sensation of intensity (Fig. 2a) but can also become uncomfortable for large rotations. A solution is to equip the pads with bearings so that they rotate freely as they track the circular arcs defined by the end-effector arms (Fig. 2b). The end-effector is designed to allow fixed or free rotating pads; a small set screw can be adjusted to prevent rotation.

4 Measuring Applied Skin Stretch

Using the approach described above, we applied skin displacements. We were interested in understanding what occurs at the skin surface when a two-point rotational stretch is applied. In the following study, we recorded the displacement, strain, and torque applied as rotational stretch was induced on an individual (female, 27). In particular, it was of interest to compare the two different end-effector configurations, with fixed and freely rotating contact pads, respectively. While these studies did not provide a rigorous characterization of skin properties, we used the observations to provide insight concerning design choices and trade-offs. The results also provide a general sense of what occurs at the skin surface as rotational stretch is applied. Results in Section 4.2 represent data from two trials, one with each type of end-effector. The device was not removed from the subject's skin between trials for consistency. A follow-up experiment was conducted with 10 different subjects at various velocities to examine if torque/displacement patterns varied between users. These results are presented in Section 4.2.4.



(a) (b)

Fig. 2. Fixed versus free end-effectors: A coordinate frame (a_x, a_y) embedded in the contact pad either rotates with (a) the end-effector arms or (b) pivots and remains aligned with a stationary reference frame (n_x, n_y).

4.1 Methods

4.1.1 Setup

A motion capture system was used to record motions on the surface of the forearm as rotational skin stretch was applied. Four Eagle/Hawk digital cameras from Motion Analysis, Inc., were set up in a rectangular orientation to cover the workspace, recording data at 100 Hz; 1.5-mm-diameter markers were placed on the forearm in a 7×9 grid pattern, with extra markers placed to measure general displacements far from the end-effector contact points (Fig. 3). A gap in the grid pattern occurred where the contact points were placed as noted by the circles in Fig. 3. The markers were placed on the arm manually and spaced roughly 10 mm apart. The accuracy of the motion capture after setup and calibration was ± 0.2 mm. A modified skin stretch device, fixed to the ground and equipped with a long extension shaft, was used to improve the visual field of the forearm. A six-axis ATI Nano17 load cell measured the torques applied to within ± 0.06 mNm. The entire forearm rested flat on a table with the subject's palm facing down.

4.1.2 Skin Stretch Stimuli

The stimulus consisted of a sequence of rotations starting from 0 and ramping to 10, 20, and 30 degrees of rotation at a nominal speed of 80 degrees/s. Each position was held for 2 s then rotated back to zero degree before proceeding to the next position (Fig. 4). The stimulus was applied with both the fixed and free effector pads.

4.1.3 Strain Analysis

The strain at each marker location quantified how much the skin was being stretched. The average 2D normal and shear strains along the longitudinal and circumferential axes of the arm (see Fig. 5) were estimated using 2D surface strain analysis techniques [26], where strains are defined (1)-(2). Longitudinal strain is represented by ϵ_y, circumferential strain is represented by ϵ_x, and shear strain is represented by ϵ_{xy}.

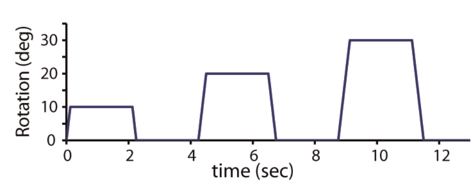


Fig. 4. Stimulus applied in stretch tests.

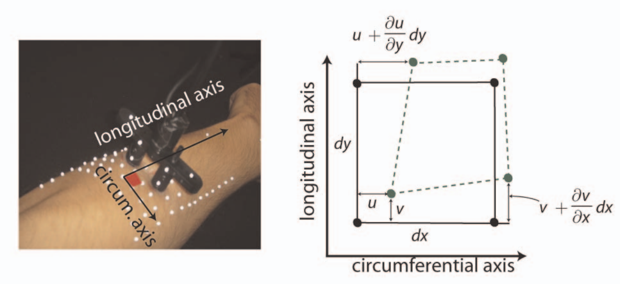


Fig. 5. Defining axes of interest for strain analysis.

At each marker location, the initial and deformed separation between the marker and each of the adjacent markers was calculated. The normal strain in the direction of each adjacent marker was estimated by comparing the initial separation of each pair of adjacent points to the deformed separation of each pair. A local orthogonal coordinate frame was defined with respect to the longitudinal and circumferential axes for each quadrant of adjacent points. Strain gage rosette equations, where θ_a, θ_b, and θ_c are defined in Fig. 6, were then used to transform these strains from extension and contraction along arbitrary axes to the normal and shear components of the local orthogonal strain tensor according to (3)-(5), where ϵ_a, ϵ_b, and ϵ_c are deformations between pairs of adjacent markers. Strain estimates from each quadrant of adjacent points were then averaged to estimate the strain at each marker.

$$\epsilon_x = \frac{\partial u}{\partial x}, \quad \epsilon_y = \frac{\partial v}{\partial y}, \tag{1}$$

$$\epsilon_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}, \tag{2}$$

$$\epsilon_a = \epsilon_x cos^2\theta_a + \epsilon_y sin^2\theta_a + \gamma_{xy} sin\theta_a cos\theta_a, \tag{3}$$

$$\epsilon_b = \epsilon_x cos^2\theta_b + \epsilon_y sin^2\theta_b + \gamma_{xy} sin\theta_b cos\theta_b, \tag{4}$$

$$\epsilon_c = \epsilon_x cos^2\theta_c + \epsilon_y sin^2\theta_c + \gamma_{xy} sin\theta_b cos\theta_c. \tag{5}$$

4.1.4 Strain Energy

The strain energy of the system is estimated using the relationship in (8) [27], where U is the total strain energy of the system. To estimate the stresses, σ_x, σ_y, and τ_{xy}, using the strains, the generalized form of Hooke's Law (6) is used. Usage of this relationship assumes skin is homogeneous, isotropic, and linearly elastic. Of course, skin is none of these things. However, this simple linear analysis is sufficient for exploring general trends arising from increasing angles of rotation, with fixed versus free end-effectors. We assume skin has a Poisson's ratio of $v = 0.5$, and a Young's Modulus, E, of 420 kPa [28].

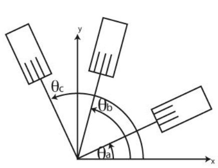


Fig. 6. Strain gage rosette configuration.

TABLE 2
Comparison of Skin Displacements (in Millimeters) for Fixed and Free Rotating End-Effectors

	Fixed End Effector			
Rotation (deg)	*Min*	*Max*	*Mean*	*Total Sum*
10	0.4	3.2	1.42	84
20	0.89	6.3	2.94	174
30	1.05	7.5	3.54	209
	Free End Effector			
Rotation (deg)	*Min*	*Max*	*Mean*	*Total Sum*
10	0.2	3.0	1.05	62
20	0.25	5.9	2.15	127
30	0.25	8.9	3.12	184

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E} & \frac{-v}{E} & 0 \\ \frac{-v}{E} & \frac{1}{E} & 0 \\ 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix}, \tag{6}$$

$$G = \frac{2}{E(1+v)}, \tag{7}$$

$$dU = \frac{1}{2}(\sigma_x \epsilon_x + \sigma_y \epsilon_y + \tau_{xy}\gamma_{xy}). \tag{8}$$

4.2 Results

4.2.1 Absolute Displacement

Analysis of the absolute displacement of each marker during skin stretch shows that a greater amount of skin is displaced when using the fixed pads. Using Motion Analysis' EvART 4.2 software, the absolute displacement of each marker relative to its starting point was calculated for the duration of the movement. For each end-effector, the maximum, minimum, and average displacement of 59 markers at various rotational positions are listed in Table 2.

While the fixed pads show higher amounts of displacement for almost all categories, the maximum displacement of a point at 30 degrees of rotation is greater with free rotating end-effectors. Larger minimum, average, and sums of displacements when using the fixed pads indicate that a larger amount of skin is being moved.

4.2.2 Strains

Because a rotational as opposed to a linear motion is applied, a complex combination of compressive and tensile strains along both the longitudinal and circumferential axes is observed as the skin is stretched. A table summarizing the

TABLE 3
Range of Skin Strains at 30-Degree Rotation for Fixed and Free End-Effectors, Compared to Typical Strains Measured During Knee Bending [26]

	Rotational Skin Stretch		Normal Skin Stretch
	Fixed pads	*Free Pads*	*90 °Knee Flex*
Long. Axis	-0.64 to 0.15	-.47 to 0.22	-0.59 to 0.7
Circum. Axis	-0.13 to 0.15	-0.15 to 0.2	-0.69 to 0.99
Shear	-0.26 to 0.21	-0.31 to 0.23	-0.75 to 0.54
Principal	-0.65 to 0.19	-0.50 to 0.25	n/a

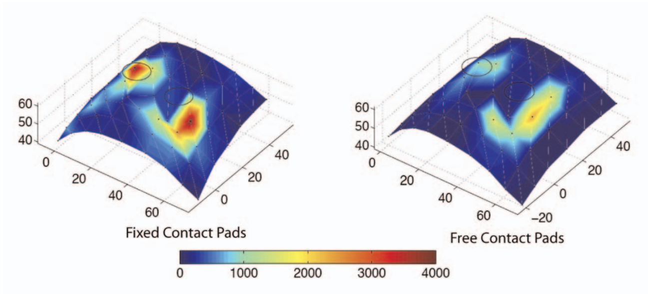


Fig. 7. Surface plot of strain energy at 10 degrees of rotation. Differences in strain energy occur at points near the contact pads (circular rings).

range of strains measured at 30 degrees of rotational skin stretch can be seen in Table 3. To provide context for these measurements, skin strains estimated during 90 degrees of knee flexion using a similar analytical method are presented as well [26]. In general, strains occurring with rotational skin stretch are similar to or less than strains measured for normal joint motion, although compression strains along the longitudinal axis with the fixed pads are an exception. Comparisons between the strains estimated for the fixed and free pads show minor differences.

4.2.3 Strain Energy

It has been suggested that some mechanoreceptor activity correlates best with strain energy density [19], [20], a scalar measure of local strain that is independent of direction. The differences between the two cases are more clearly seen in the surface plots of the local strain energy for a small rotation in Fig. 7. Here, it is observed that the strain energy at points located near the contact pads differs more than at points further away. These results correlate with our observations that users may be able to distinguish small rotations with greater accuracy using the fixed end-effectors.

4.2.4 Torques

Another useful measure is the torque required to produce a given rotational displacement about an axis normal to the skin surface. The required torque varies from subject to subject, depending on age, skin stiffness, placement of end-effectors, etc. In general, the torque required with fixed end-effectors was approximately twice as high as for free end-effectors over a range of typical angles (Fig. 8).

To examine the variation in torque/displacement properties between users and to determine if changes in velocity had an effect on skin properties, a separate test using the fixed end-effectors was conducted on 10 subjects (Ages 24-32, seven male, three female). All participants volunteered, giving written consent prior to the study and

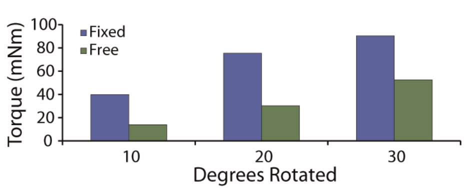


Fig. 8. Maximum torque measured as a function of displacement with fixed and free end-effectors.

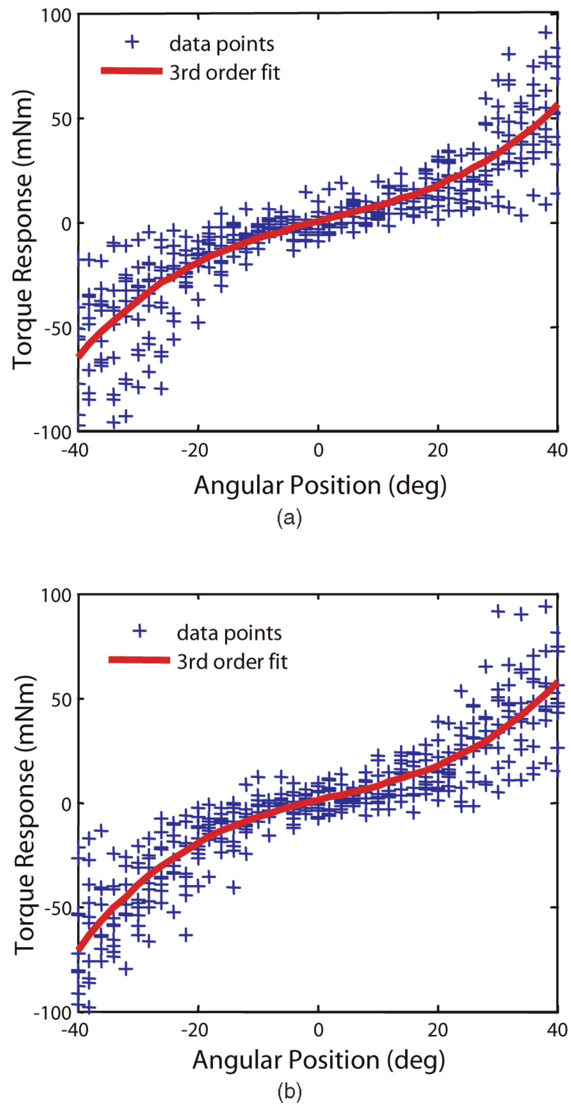


Fig. 9. Torque/displacement response from 10 subjects for (a) slow (10-50 degrees/s) and (b) fast (220-300 degrees/s) movements.

experiment protocols followed the guidelines set by the Stanford Research Compliance Office (IRB Protocol 13172). The skin stretch device moved to 41 different rotation angles from - 0 degrees to 40 degrees spaced two degrees apart in a random order for two different sets of tests at velocities randomly chosen from [10, 20, 30, 40, or 50 degrees/s] for low velocities and [220, 240, 260, 280 or 300 degrees/s] for high velocities.

Fig. 9 depicts the compiled data for 10 subjects. Torque response is shown for all subjects in the low- and high-velocity tests. A third order polynomial is fit to the data. The slow and fast movement results are similar, suggesting that for the speeds of interest, the effective stiffness is not strongly velocity dependent.

5 Perception

To characterize skin stretch, it is not only important to understand the mechanical behavior of skin, but also to quantify a user's perception of the feedback being applied.

The literature concerning a human's ability to distinguish different levels of hairy skin stretch is not extensive but includes several publications by Norrsell and Olausson [9], [13], [14], [23], [24]. Skin stretch perception and sensitivity can be dependent on the location of stretch, the size of the contact point that induces the stretch, the normal force applied, the method of attaching the stretch applicator, and the number of contact points. In addition, most studies with skin stretch involve only a single contact point that moves linearly [13], [14] or twists [28], [29], producing different sensations than the two-point rotation stretch studied in these experiments.

To understand our ability to interpret rotational skin stretch feedback, a simple psychophysical study was completed to estimate the difference thresholds and observe how perception of skin stretch changed as the rate of stretch and the magnitude of stretch varied. The ability of users to use skin stretch feedback in a more practical setting was studied in a separate series of perception tests.

5.1 Difference Thresholds

From prior observations, the velocity of skin stretch seemed to play a role in perception. Pilot studies indicated that subjects could easily detect changes in stimuli (sensing motion), yet felt no difference in stimulus magnitude. Also, the ability to discriminate between stimuli appeared to change as the amount of rotation varied. Users appeared to be more sensitive to changes in stimuli at higher degrees of rotation. Experiments to determine the effects of these two main factors, angular velocity of stretch (degree/s) and magnitude of stretch (degree), on the ability to perceive rotational position were completed.

5.1.1 Methods

Participants. Twelve subjects (Ages 23-49, four female, eight male) participated in this experiment. Four of the subjects were familiar with rotational skin stretch, while the remaining eight subjects had never used the skin stretch device. All participants volunteered, giving written consent prior to the study and experiment protocols followed the guidelines set by the Stanford Research Compliance Office (IRB Protocol 13172).

Stimulus. Two reference positions (10 and 30 degrees) and two reference velocities (20 and 80 degrees/s) were studied for a total of four conditions.

Many types of haptic feedback (e.g., vibration) can be started and stopped on demand and controlled with varying amplitudes and waveforms. However, skin stretch has the ability to convey a sense of velocity and static position with a single stimulus. In addition, it is not possible to create a step input of position; there is necessarily a velocity component. When discriminating between different stimuli, there are a variety of factors the subject can utilize to determine the difference. For example, when applying skin stretch at constant speed, it is possible for participants to use their sense of timing to determine which of the two stimuli is larger. To eliminate the ability of subjects to use timing, the duration of all three stimuli presented during each trial was constant. Therefore, as the comparison stimulus increases, the velocity of rotation increases accordingly. In practical applications, one might use the sense of velocity to interpret the stimulus. Therefore, subjects were allowed to use their sense of velocity for these tests. However, when asked after the experiment if they had detected any differences in velocities, none of subjects reported noticing any.

Experiment details. The subjects were instructed to place their right forearm flat on a table with their palm facing down. Subjects were also equipped with headphones to mute noises from the device and were asked to close their eyes or turn their heads to avoid receiving visual cues. Using the fixed end-effector configuration, the device was then attached to the subject's arm. The two contact pads were placed across the narrow width of the forearm. This location was chosen due to the relatively high density of slow-adapting mechanoreceptors [8].

A three-interval, one-up three-down adaptive procedure was used to estimate difference thresholds of rotational skin stretch [30]. This method has been used previously for force discrimination [31] and is an efficient method of estimating difference thresholds.

At the beginning of each trial, the subject was presented with three stimuli. Two were the reference positions while the third comparison stimulus was greater than the reference. The stimuli were presented in random order and the subject was asked to indicate which of the three was the comparison. When a subject correctly indicated the comparison stimulus three times in a row, the magnitude of the comparison was decreased. If a subject incorrectly identified the stimulus, the magnitude was increased. The comparison stimulus increment was larger in early trials to help reach convergence faster and, subsequently, was reduced. The experiment was complete after a total of 15 reversals, where a reversal was any point at which the comparison stimulus changed from decreasing to increasing or vice versa. Only the last 12 reversals were used for data analysis.

To reduce bias, sessions of varying conditions are typically interleaved. However, in these studies, when interleaving the reference positions, the time taken to complete the experiment increased beyond 60 minutes. Data from pilot subjects indicated that concentration was difficult to maintain over a period of time greater than 30 minutes. Data also showed obvious signs of fatigue and portions of increasing comparison stimulus levels, affecting the analysis. To ensure that fatigue would not be an issue, each condition was run separately. This resulted in four separate sessions each consisting of 60 to 100 trials, lasting between 20 and 30 minutes. Only a single session was recorded per day and the experiment was conducted over four days.

Data analysis. For each subject and for each of the four conditions, the peak and valley pairs occurring at a reversal were recorded. These peaks and valleys were grouped and averaged to estimate the difference threshold. The last six pairs were used in the data analysis. This resulted in six samples per subject, per condition. These six samples were averaged to determine an average difference threshold (0.794 point on the psychometric curve) for each individual [31]. Repeated measures analysis of variance (ANOVA) with pairwise comparisons was performed to analyze the effects of both velocity of skin stretch (20 and 80 degrees/s) and reference position (10 and 30 degrees) on a subject's ability to discriminate between rotations of stretch.

TABLE 4
Difference Thresholds with Standard Error for 12 Subjects

	Rotational Velocity		
Reference Position	*20 deg/s*	*80 deg/s*	*Average*
10 deg	0.23 ±0.03	0.18 ±0.01	0.21 ±0.03
30 deg	0.13 ±0.01	0.12 ±0.01	0.13 ±0.01

As the reference stimulus level increases, the Weber Fraction decreases.

5.1.2 Results

The magnitude of the reference stimulus had a significant main effect on the difference threshold with a modest effect size ($F = 21.979$, $p = 0.001$, $\eta_P{}^2 = 0.665$). Perhaps surprisingly, no significant main effects were found due to velocity ($F = 2.955$, $p = 0.114$, $\eta_P{}^2 = 0.221$). This result also confirmed our decision to keep the total duration of the stimulus constant while varying the velocity, as the changes in velocity likely had no effect on subject's ability to discriminate between rotations. The difference threshold is presented as a Weber Fraction (WF), $\Delta Deg/Deg_{ref}$, where ΔDeg is the difference between the threshold and reference stimulus and Deg_{ref} is the reference stimulus. On average, at a reference of 10 degrees, the discrimination threshold was 2.1 degrees, while at a reference of 30 degrees, the discrimination threshold was significantly higher at 3.9 degrees, resulting in WFs of 0.21 and 0.13, respectively. WFs for each of the four conditions are specified in Table 4.

Though individual subject data indicated that subject-to-subject variation was high, the general pattern of decreasing Weber fractions with increasing stimulus intensity held true for 10 of the 12 subjects. Subjects also tended to report that they felt less sensitive to the stimulus at lower rotations.

5.2 Absolute Positioning

To determine the feasibility of using the device in applications, subjects were asked to use the skin stretch rotation to convey information about the position and motion of an external object. As an example application, one might present the distance of the nearest car behind a driver, assuming vision is either obstructed or devoted elsewhere. Or, as mentioned previously, subjects could use skin stretch feedback to position a robotic arm or a prosthetic device. We conducted two experiments to determine how well subjects could use the feedback *actively* and *passively*. In the former case, subjects used the device to provide feedback concerning voluntary motions; in the latter case, they were asked to assess the magnitudes of arbitrary amounts of skin stretch imposed on them. The distinction is motivated by previous research that indicates differences in perception resulting from the different modes of touch [32], in which subjects have better accuracy with active touch.

The tests were repeated using both fixed and free end-effectors in random order for a total of four data sets. The active control study was always completed prior to the passive study. Ten subjects overall (three female, seven male) were tested, and all subjects completed both studies. Ages ranged from 22 to 37, with a mean age of 27.5. The studies were approved by Stanford's Institutional Review Board (IRB Protocol 13172).

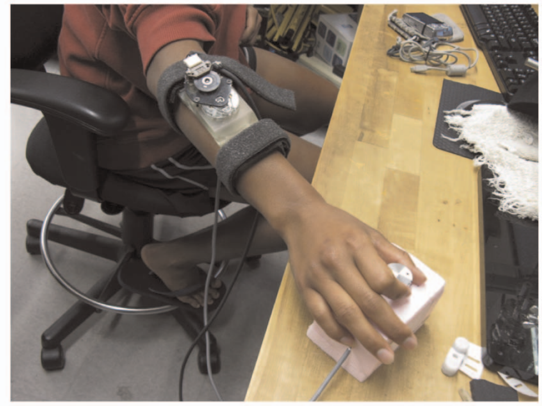


Fig. 10. Wearable skin stretch device and knob used to control rotation of the device or input-perceived positions.

5.2.1 Methods

In all studies, the wearable skin stretch device was placed on the outer forearm, as shown in Fig. 10. In contrast to the previous studies, the subject's forearm was not constrained to rest on a table and, instead, was positioned however the subject desired, either resting on the table or hanging in free space. In an attempt to simulate a more practical scenario, subjects were not given headphones to block ambient noise and were simply instructed to avoid glancing at the device to report the perceived position.

Training. A training procedure was first performed to determine the appropriate range of skin stretch rotations for each subject and to allow them to become accustomed to the feedback. After the device was placed on the subject's forearm, they were given the opportunity to control the motion of the skin stretch device using a small knob. The knob was a potentiometer that produced a desired position for the skin stretch end-effector where one revolution of the knob resulted in 1.4 revolutions of the end-effector. During this training period, a graphical display was presented, consisting of a line with two circles representing the contact pads to show the rotation of the device (Fig. 11). The subjects were instructed to move across the workspace at various speeds and to move the device to the maximum comfortable rotations in both positive and negative directions. Subjects were given as much time as they desired in this training

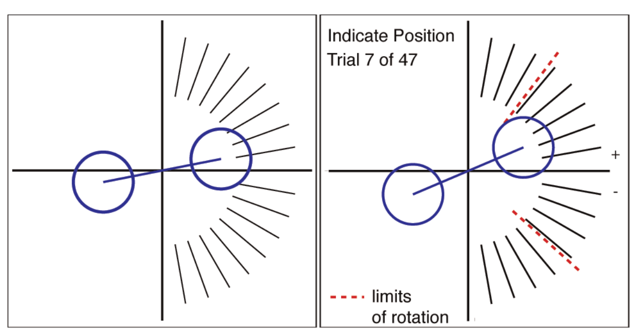


Fig. 11. Display shown to subjects during trials. Left is the screen displayed during the training phase (showing the actual location); right is the desired location shown in the experiment. Dashed lines indicate the limits of rotation established during training.

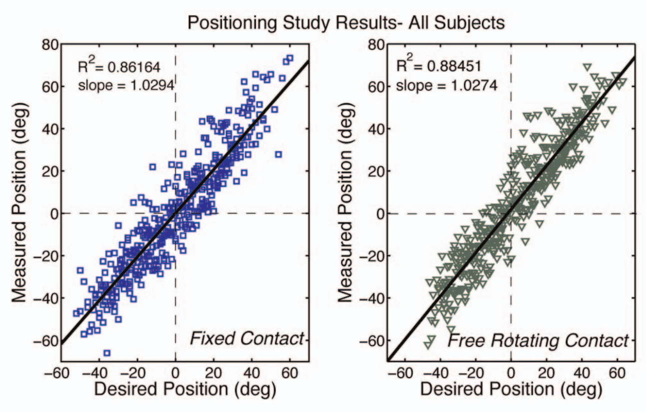


Fig. 12. Data from all 10 subjects in the positioning task.

TABLE 5
Active Task Residuals and Regression Results for Individual Subjects

	Fixed End Effector			Free End Effector		
Subject	*Residual avg (deg)*	*Slope*	R^2	*Residual avg (deg)*	*Slope*	R^2
1	5.4	0.85	0.86	4.2	1.16	0.94
2	5.4	0.94	0.94	7.2	1.1	0.87
3	5.6	0.72	0.81	2.6	0.77	0.96
4	5.6	0.93	0.91	3.7	1.15	0.96
5	3.5	0.93	0.97	4.3	0.79	0.96
6	4.7	0.89	0.92	4.9	1.03	0.94
7	3.1	0.81	0.89	1.4	1.49	0.93
8	8.3	0.98	0.89	7.7	0.98	0.89
9	4.5	1.23	0.94	5.0	1.12	0.94
10	5.7	1.31	0.93	4.8	0.96	0.90

phase, although they typically spent only 1-2 minutes with the device. At the end of the trial, the maximum positions in each direction were recorded and corresponding dashed lines were placed on the graphics screen in subsequent trials so that responses were constrained to fall in this range. This training procedure was completed each time the end-effector configuration changed.

Active positioning study. Using the range of motion set by the subject in the training phase, a data set of desired locations spanning the range in increments of 2 degrees was determined (e.g., a range of -37 to 43 degrees results in a data set of $-37, -35, -33 \ldots 43$). Because the data set was dependent on each individual subject's range of motion, the number of trials varied from subject to subject. The desired locations were randomized and displayed visually to the subject. Red dashed lines indicating the subject's specified range of motion were also displayed (Fig. 11). The subjects were asked to move the skin stretch device to match the position shown on the screen. As in the training phase, subjects were able to control the device using the knob; however, the gains were changed such that one revolution of the potentiometer resulted in 0.23 revolutions of the skin stretch device. This gain was chosen so that participants would not be able to simply use the proprioceptive sense in their fingers from the training phase to position the device. Subjects pressed a push-button switch to confirm their inputs.

Passive perception study. The second study was a perception experiment in which subjects no longer had control of the skin stretch device. In these trials, the device was moved from one quasi-random orientation to another at a random velocity and subjects were then asked to report the perceived orientation. Similar to the positioning study, the data set of commanded end-effector orientations spanned the range of rotations set by the user, in increments of 2 degrees. The device moved from one position to the next at a speed chosen randomly from [20, 40, 60, 80, 100] degrees per second. No visual feedback was provided. The subjects were asked to report the perceived orientation of the end-effector by rotating the virtual end-effector on the screen, using the potentiometer knob and confirming their final position by pressing a push-button switch.

5.2.2 Results

Active positioning study. Fig. 12 shows the desired orientation versus the measured end-effector orientation for all 10 subjects, for both fixed and free end-effector configurations. A linear regression on the data is also shown as a measure of how well subjects could use the skin stretch feedback to correlate to end-effector position. For both configurations, there was a linear trend with fairly uniform scatter ($R^2 = 0.86$ fixed, $R^2 = 0.88$ free). A total of 393 trials were completed using the fixed end-effector, and 407 trials for the free end-effector.

The average residual for all 10 subjects using the fixed end-effector was 5.2 degrees with a standard deviation of 1.4 degrees, and 4.8 degrees with a standard deviation of 2.1 degrees using the free end-effector. There was no significant difference in overall performance (residual or scatter) between the fixed and free end-effectors across the subjects. The results of this study indicate that the accuracy with which subjects can position a virtual arm is approximately ± 6.5 percent of their total range of motion. The range of rotation varied between subjects and end-effector configurations, though there was no indication that one design resulted in consistently larger ranges. Of the 10 subjects, six had a larger range of motion using the free end-effector, three had a smaller range, and one had an equal range. However, when asked to indicate which of the two designs they preferred, seven of the 10 subjects stated they preferred the free rotating contact pads due to the increased comfort. Two stated that there was no difference and one subject preferred the fixed configuration. Linear regression slopes and R^2 values for individual subjects are presented in Table 5. Slopes greater than 1 indicate that subjects were moving beyond the range of motion set in the training phase.

Passive perception study. Fig. 13 shows the actual versus reported end-effector orientation for all 10 subjects, for fixed and free end-effectors. A weighted linear regression on the data is also shown. A total of 361 trials for the fixed end-effector and 376 trials for the free end-effector are represented in the plots. It is clear that subjects performed poorly in comparison to the positioning study. Specifically, subjects occasionally had trouble distinguishing which direction the skin stretch device was rotating. Data points located in quadrants II and IV represent trials in which a direction error likely occurred.

Though most subjects performed comparatively poorly in this task, it was observed that a few subjects performed

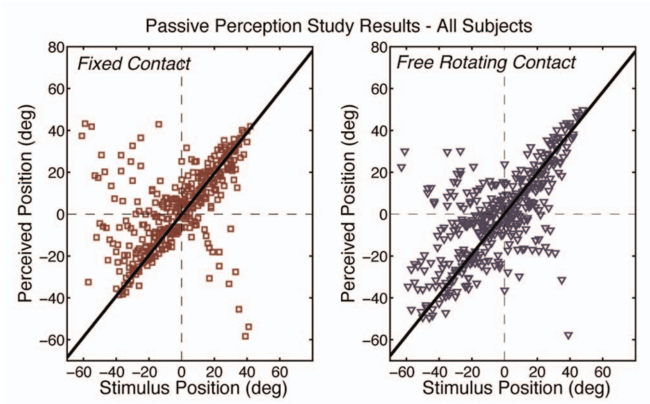


Fig. 13. Data from all 10 subjects in the perception study, with fixed and free rotating end-effectors.

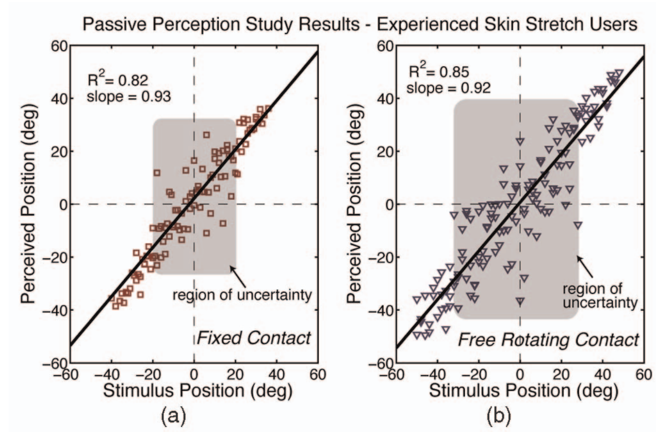


Fig. 14. Scatter plot of actual end-effector position versus perceived position with regression line for three experienced subjects. (a) Data with the fixed contacts. (b) Free rotating.

nearly as well as in the active positioning study. Of the 10 subjects tested, three had prior experience with skin stretch feedback. The data from these subjects were grouped together and the results can be seen in Fig. 14.

It is clear that subjects with prior experience using skin stretch feedback performed much better than subjects naive to the feedback. This suggests that with with adequate training, subjects can learn to use the feedback for an open-loop task, in which they receive information passively. The average residuals of the three experienced subjects differed between the two end-effector designs: ± 5.5 degrees with the fixed end-effector pads and ± 8.1 degrees for the free rotating pads. Overall, subjects reported that they felt less confident in determining the position using the free end-effector, particularly for small rotations. Looking at the data, there appears to be a region of uncertainty surrounding zero degrees, in which the residuals are larger. For example, if we consider the range between ± 20 degrees, for the fixed end-effector, the average residuals are ± 6.4 degrees, whereas they are ± 3.0 degrees outside of this range. For the free end-effectors, we estimate the region of uncertainty as ± 30 degrees, with average residuals of ± 9.6 degrees within this region and ± 5.6 degrees otherwise.

6 Discussion

A wearable device has been developed that utilizes skin stretch on the hairy skin for haptic feedback. The two-point rotational stretch described in this paper provides a useful range and resolution of perceived feedback, and the relatively compact size and low weight of the device allow for user movement and integration into a practical environment.

We have shown that the rotational motion produces proportional displacements, amounts of strain, torques, and strain energy to provide a stimulus with a useful range of perceivable values. The final device design represents a trade-off between providing a large (typically ± 45 degrees) range of comfortable rotations and ease of perceiving small rotations. In pilot tests, we observed that an end-effector with freely spinning pads sometimes provided a larger range of comfortable rotations; however, fixed pads provided more noticeable stretch at small rotations. For one individual in which the differences in stretch were measured, there was, on average, 0.3 mm reduction in displacements with the free rotating pads. Given that humans are capable of sensing skin pulls of distances 0.13-0.3 mm [13], the difference between fixed and free rotating pads could be expected to influence users' perception of skin stretch. However, in most of the latter perception experiments, the differences were not significant. The exception was for the case of experienced subjects responding to arbitrarily imposed rotations, particularly for small rotations. At higher rotations, the two designs produce nearly identical results though the free end-effectors were sometimes more comfortable. Therefore, a provision that is being incorporated into the next design is to use preloaded torsion springs on the end-effector pads such that the pads rotate rigidly with the arm at small angles but rotate less at high angles, as the springs deflect. Additional future design changes will be to make the device lighter, more compact, and more flexible so that it can be mounted more easily on various parts of the body. These changes should also reduce extra tactile cues that can arise in some applications when muscles or tendons move beneath the device. (Depending on the application, such additional cues could be useful or undesirable.)

A unique attribute of skin stretch feedback is that it can provide a sense of static position and motion with a single stimulus, though the ability of users to perceive different velocities of stretch is still unknown. Although a display designed to move across the surface of the skin could also provide a sense of motion, skin stretch provides a sense of intensity due to the increasing strain with higher rotations. If necessary, users can use the steady position of the skin stretch for static information, as evidenced by the difference threshold tests. Interestingly, though users had qualitatively noted that faster rotations increased their perceived intensity of the stimulus, the changes in velocity of stretch had no significant effect on their ability to distinguish between different positions.

In the perception tests, higher Weber fractions at smaller reference stimuli were observed, following observed psychophysical trends for other stimuli such as vibration [33], [34], [35]. We caution that the results of the perception tests do not provide a full-scale resolution of rotational skin stretch. We do not expect subjects to be able to perceive differences of 2 degrees of rotation in practical applications. The tests were completed in an isolated environment and only tested subjects' ability to distinguish comparison stimuli that were greater than a given reference. To prevent fatigue, each set of conditions only tested one reference stimulus and subjects could easily learn and memorize the reference. In a more practical setting, the stimulus will be constantly changing, reducing subjects' ability to discriminate. The experiment provided a best case resolution of skin stretch and showed that our perception is not constant relative to the intensity of stretch.

In a more practical setting, when in control of a device, subjects are able to use their own predetermined methods of integrating position, velocity, force sense, and timing to reach a desired position. We note that in the active positioning task, there were no direction error outliers as subjects trusted that if they commanded the device to move in one direction, it would do so. However, when subjects are not in control of the device and stimuli are presented passively, their perception of the direction of movement degrades, and they report that they require a higher level of concentration. A region of reduced certainty around zero degree of rotation was observed, with correspondingly larger errors. In this case, the design with fixed end-effector pads is preferred as it allowed experienced users to reduce their errors. Studies should be completed to analyze how well users can interpret skin stretch feedback in more realistic environments when the body is in motion and contracting surrounding muscle and skin. In addition, we note that the subjects in all studies presented here were healthy, with average physical fitness and ages of 22-49. Because skin properties change with age and fitness, it would be beneficial to widen the subject pool to examine whether these variables have an effect on users' ability to utilize skin stretch feedback.

In summary, the foregoing studies illustrate that while rotational skin stretch feedback may be employed passively for long-term applications in which users have significant time to become accustomed to the feedback and learn to utilize it, it is best suited for tasks such as those listed in Section 1, in which an afferent/efferent command loop exists so that users receive skin stretch feedback in response to motor commands. Minimal training is required for subjects to map the feedback linearly to movement of an external object, indicating the device could easily be used in applications to control movement or position. Applications in which the control channel is unpredictable or noisy (e.g., myoelectric controlled systems), are likely to be ones for which skin stretch will provide significant benefit.

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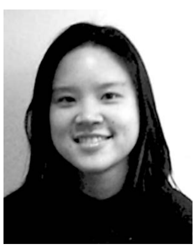

Karlin Bark received the BS degree in mechanical engineering from the University of Michigan, Ann Arbor, in 2003, the MS degree in mechanical engineering from Stanford University in 2005 with a focus on design and controls, and the PhD degree in mechanical engineering from Stanford University in 2009. Her research interests include haptics, human-factor-based design, and robotics.

Jason Wheeler received the BS degree from Brigham Young University, the MS degree from Massachusetts Institute of Technology, and the PhD degree in mechanical engineering from Stanford University in 2009. He is a senior member of the technical staff of the Intelligent Systems and Robotics Center at Sandia National Laboratories. His research interests include medical and rehabilitation robotics as well as biomechanics and sensorimotor mechanisms.

Pete Shull received the BS degree in both mechanical engineering and computer engineering in 2005 from LeTourneau University and the MS degree in 2008 from Stanford University with focus on robotics and controls. He is currently working toward the PhD degree in mechanical engineering at Stanford University. His current research involves wearable real-time multimodal feedback for gait retraining. His research interests include robotics, controls, and haptics development for medical applications.

Joan Savall is currently a senior scientist at Howard Hughes Medical Institute (HHMI) and a consulting assistant professor in the Mechanical Engineering Department at Stanford University. He was an assistant professor at the University of Navarra and a senior researcher at CEIT, Spain. His main focus is on combining mechanics, optics, and electronics into robotic systems and medical devices. He designed and built numerous haptic devices and medical instruments and is the inventor of multiple appliances patented by several institutions. He is a member of the IEEE.

Mark Cutkosky is currently a professor at the Center for Design Research, Department of Mechanical Engineering. He has graduated 30 PhD students and published extensively in robotics. He has consulted with various companies on robotics and human/computer interaction devices and holds several patents on related technologies. His current research interests include robotic manipulation and tactile sensing, mechatronic systems design, and the design and fabrication of biologically inspired robots. He is a member of the IEEE.