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A Wearable Skin Stretch Device for Haptic Feedback

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Abstract

We describe a wearable haptic feedback device that imparts rotational skin stretch to provide feedback regarding movement of a virtual object. Applications for this device include feedback of motion for physical therapy or rehabilitation exercises or proprioceptive feedback for amputees. The device uses a small piezoelectric motor for a combination of low weight, moderate torques and rotation without vibrations that could interfere with the sensation of stretch. We present the results of experiments to determine the accuracy with which subjects can use feedback from the device to control the orientation of a virtual object. Most subjects were able to position the device within several degrees. In a second test, subjects were asked to identify randomly applied levels of skin stretch while they remained passive. In this case, the accuracy was poorer and subjects occasionally confused positive and negative rotations. Tests were also conducted to evaluate the effect of rotational compliance at the end effector, added to improve comfort at large displacements.

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

There is an increasing interest in small, wireless haptic displays that are portable or wearable. Possible applications of these displays include physical therapy, motion training and human interaction within virtual reality environments. One example is motion rehabilitation after orthopedic surgery. Patients must re-learn how to walk and it has been noted that in some patients, their gait pre-surgery and post-surgery are different. Physical therapists can observe the patient and provide oral feedback, giving instructions such as "Lift your foot a little higher." However, such statements do not clearly specify to patients how much they should move their joints. A wearable device that is programmed to detect and track the motion of a patient can be used at home to provide cues to guide the exercise. Another potential application for wearable haptics is tactile feedback of the motions or forces of a prosthetic arm. A device could be strapped to a users body to indicate the movement of the prosthetic arm, reducing the dependence on vision.

When considering the different methods of providing haptic feedback, the easiest and by far the most widely used technology for portable haptics is vibration, as found in cell phones, pagers etc. and incorporated into haptic vests, sleeves, and other accoutrements [3, 9]. However, vibration is best suited for transient event cues and is less effective when used for sustained stimuli. It can lead to desensitization and it can become annoying when prolonged. In addition, sensitivity to vibrations can be reduced when people are in rapid motion because the background levels of acceleration mask the vibration signals [12, 16].

In this paper we describe a wearable feedback device that works on the principle of imparting localized skin stretch. The device is designed to be mounted on a patient's arms or legs, typically near a joint, and provides feedback consisting of positive or negative rotation angles. Part of the motivation is that skin stretch is known to be part of the normal apparatus for proprioception, particularly for the distal joints but also at the elbow and knee [5], indicating that it may provide a more intuitive means of providing proprioceptive feedback associated with physical therapy, motion training, etc. Skin stretch display has the potential advantage of imparting more accurate information about the required magnitudes and directions of motion, beyond simply alerting the user as to whether a motion is correct or incorrect. Previous work has indicated skin stretch can be particularly effective at providing motion feedback [1] and that mechanoreceptors respond quickly and accurately to skin strain changes [6, 7]. In other work, skin stretch has been used for fingertip displays [4, 8, 13], however little has been done on devices that apply large strains to the hairy skin on patients' limbs.

In the following sections we present the design of the device and then describe experiments conducted to determine how well subjects can use it *actively* and *passively*. In the former case, subjects used the device to provide feedback for desired motions; in the latter case they were asked to assess the magnitudes of arbitrary amounts of skin stretch imposed on them. Previous research indicates differences in perception resulting from the different modes of touch [10], in which subjects have better accuracy with active touch. The results of these studies provide a preliminary indication of how accurately users can interpret the feedback to position an external object or interpret the position of an object passively, providing insight into which practical applications and interaction methods this feedback is best suited for.

2 Device Design

The wearable skin stretch device is designed to be attached to and provide feedback on non-glabrous skin. We envision that in future studies multiple devices could be attached at several locations including the forearm, wrist, ankle, thigh or calf. In this paper, we report on experiments with the device attached on the arm as shown in Figure 1.

The design of the portable device is based on results obtained with an earlier desktop device for which we found that it was comfortable and effective 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 [1]. We found that subjects could position a virtual object more accurately using the desktop device than with a single vibration stimulus of varying amplitude. We also found that skin stretch could provide subjects with a sense both of the range and velocity of motion and, because it rotates in two directions, it can display positive and negative values along an analog scale.

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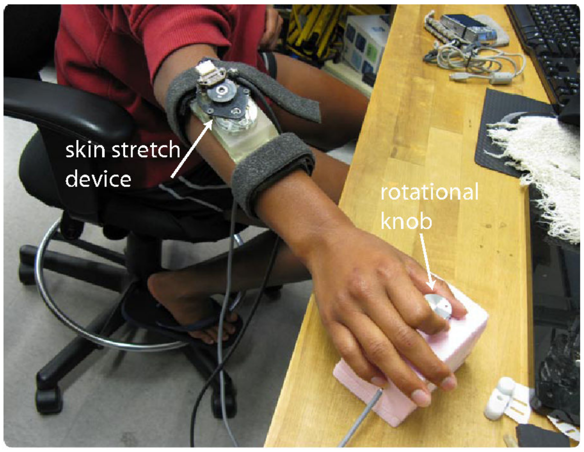


Figure 1: Wearable skin stretch device and knob used to control rotation of the device or input perceived positions.

Based on results obtained with the desktop device, initial requirements for the portable device were as follows:

- end effector positioning resolution within 1 degree (the minimum distinguishable motion for some subjects)
- operating range of ± 60 degrees.
- range of speeds of 5-200 degrees per second
- maximum torque of 0.2 Nm at maximum rotations
- very smooth motion (humans are extremely sensitive to vibrations).

2.1 Actuation

An ultrasonic piezoelectric motor (Shinsei Motors, USR30-B3) is suited to the requirements of a wearable skin stretch device. These motors use a piezoelectric ceramic element to produce small, high frequency deflections in a stator structure. The displacements are converted into unlimited rotary motion of the rotor through intermittent frictional coupling [14] . Ultrasonic piezoelectric motors produce comparatively high torques at low speeds and are not backdriveable, which reduces power consumption when holding a position against an external torque. The motors are also small, flat, and lightweight, simplifying packaging. The vibration frequencies at 50 kHz are well above the frequencies perceivable by humans, so the motion feels smooth.

The motor is coupled to the end effector through a capstan and cable drive system, which provides a 6:1 speed reduction and keeps vibrations low. The range of speeds produced at the end effector is 15–150 deg/s with a maximum torque output of 0.6 Nm. A small tensioning block is adjusted with a screw to prevent slippage between the braided steel cable and capstan.

Table 1: Wearable Skin Stretch Device Characteristics

	Design Requirements	Device Specifications
Size	small	29 x 45 x 126 mm
Max Torque	0.2 Nm	0.6 Nm
Speed Range	$\leq$ 200 deg/s	15–150 deg/s
Weight	$\leq$ 200 g	115 g
Sensor resolution	1 deg	1 deg (Hall Effect) 0.05 deg (Encoder)

2.2 End Effector

The end effector consists of two circular pads (dia. = 14 mm) spaced 26 mm apart to attach to the skin, resulting in a contact

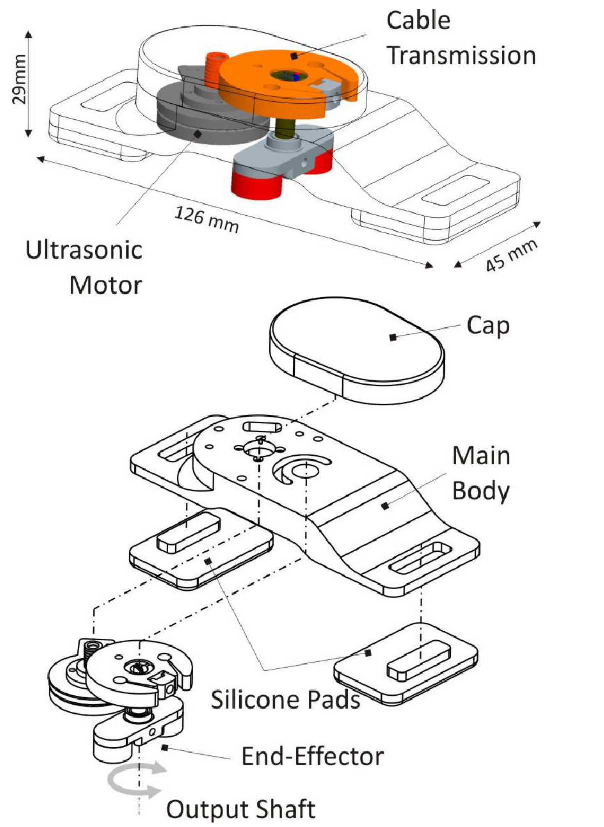


Figure 2: Wearable skin stretch device exploded view.

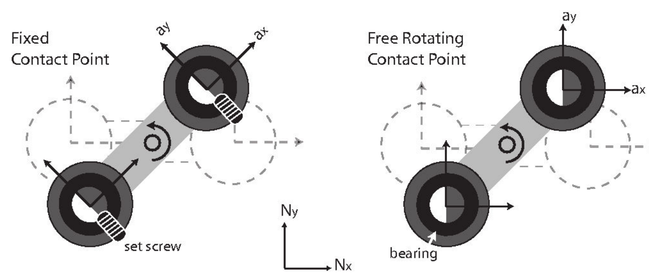


Figure 3: Fixed versus free end effectors: A coordinate frame (a_x, a_y) is embedded in the contact pad and either rotates rigidly with the end effector arms (left) or pivots and remains aligned with a stationary reference frame (right).

area of roughly 300 mm^2. The pads are large enough to adhere to the skin without excessive pressure and small enough to minimize the effects of curvature on the arm. 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.

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 but can also become uncomfortable for large rotations (Figure 3, left). A solution is to equip the pads with bearings so that they can rotate freely as they track the circular arcs defined by the end-effector arms (Figure 3, right). An end effector was designed to allow fixed or free pads, as seen in Figure 4. A small set screw is inserted into the cylinder to prevent rotation when desired. In initial tests, it appeared that with freely rotating pads, users felt more comfortable with large rotations but had more difficulty in detecting small rotations. Consequently, both configurations were tested.

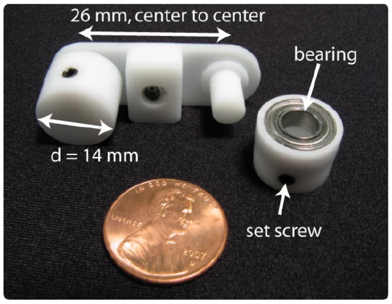


Figure 4: End effector used in experiments to switch from fix to free configuration quickly and easily.

2.3 Body

The dimensions of the body of the device are constrained by the geometry of the forearm, as we envision using the device primarily on the lower and upper arm. The overall thickness of the device is minimized to reduce inertial effects felt by the user. The length of the body is chosen such that the supporting contact surfaces are sufficiently far from the end effector so that they do not interfere significantly with the skin stretch around the end effector. The body is attached to the user using velcro straps. For comfort, soft silicone pads are placed between the contact areas of the device body and the skin. All body parts and pads are constructed using Shape Deposition Manufacturing (SDM) techniques, a rapid-prototyping method for creating multi-material robotic appendages [2].

2.4 Sensors

To keep the device compact, a hall effect sensor measures rotation of the end effector. Two miniature neodymium magnets are embedded 180 deg. apart in the center of the capstan pulley (Figure 5, left). The hall effect sensor provides an analog signal sufficient for positioning the end effector to within 1 degree of the desired orientation and is adequate for practical use. However, for the tests described in the next section, we used a standard quadrature encoder with a finer resolution of 0.015 deg/encoder tick.

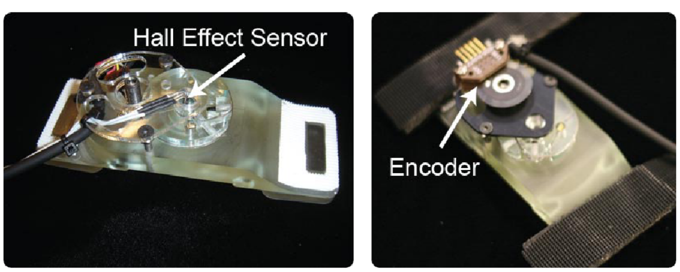


Figure 5: Wearable skin stretch device in both sensor configurations. On the left, the device is equipped with a hall effect sensor and on the right, the device is equipped with an encoder.

2.5 Control

The characteristics of the motor prevent it from rotating below a minimum speed determined by the resonant frequency of its piezoelectric elements. We used a motor driver board supplied by the manufacturer to control the motor [11]. The driver takes three inputs, two to specify the direction of motion (digital) and a third analog channel to set the speed. We used Matlab's xPC real-time toolbox with a multifunction data acquisition board to control the hardware. To avoid chattering around desired positions due to the minimum speed, a deadband in the position controller was implemented. A simple linear PI controller was used to drive the motor, which set the speed of the motor based on the position error. For the experiment described below we used a deadband of ± 0.05 degrees, a proportional gain of 0.8, an integral gain of 0.4 and a sample rate of 200 Hz. The gains are chosen to minimize tracking errors and chatter. The maximum output of the controller is limited to 3.2 V, corresponding to the maximum motor speed, as outlined in the motor driver specifications [11].

3 USER STUDY

A set of user studies assessed the ability of subjects to detect the rotation of the skin stretch device. Two studies were completed, one in which the subjects were in control of the device and the task was to orient the device to match the orientation shown visually on a computer screen, and another in which subjects sat passively while the device rotated autonomously and subjects were asked to report the final orientation. The studies were repeated using both fixed and free end effectors in random order for a total of 4 data sets. The active control study was always completed prior to the passive study. Ten subjects overall (3 female, 7 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.

3.1 Methods

In all studies, the device was placed on the outer forearm as shown in Figure 1. The two contact pads were placed across the narrow width of the forearm. This location was chosen due to the relative high density of slow adapting mechanoreceptors [15].

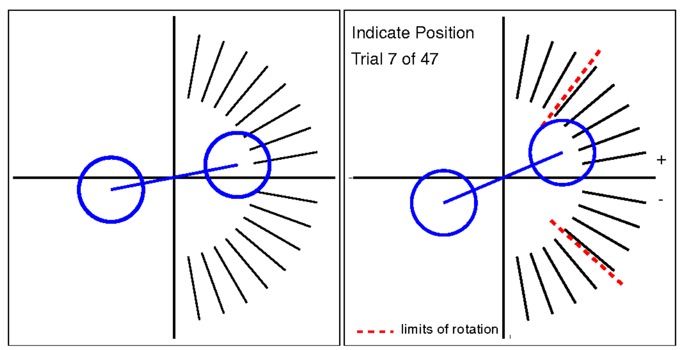
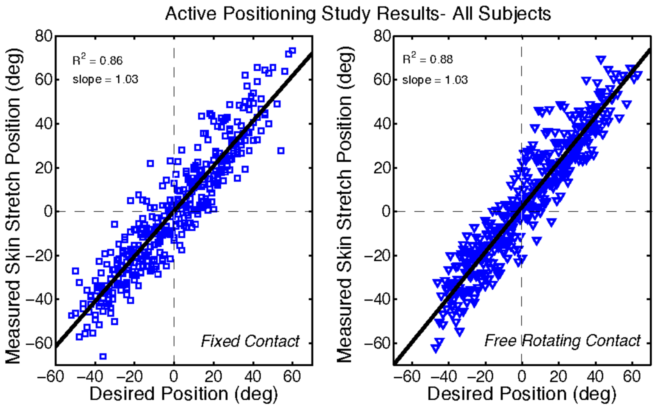


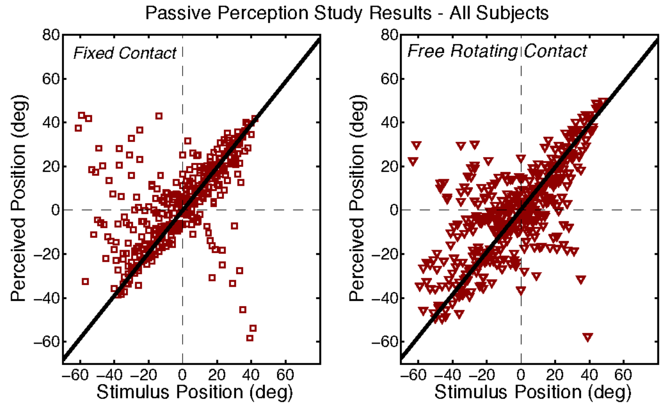
Figure 6: Display shown to subjects during trials. The left is the screen displayed during the training phase and on the right is the desired location as shown in the experiment trial. Dashed lines indicate the limits of rotation specified during the training phase.

3.1.1 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 simply a potentiometer that produced a desired position for the skin stretch end effector where 1 revolution of the knob resulted in 1.4 revolutions of the end effector. During this training period a virtual environment was also displayed on a computer screen, consisting of a dial representing the position of the skin stretch device (Figure 6). A line with two circles representing



(a) Data from all ten subjects in the active positioning task. Fixed contact pad data on the left, free rotating on the right.



(b) Data from all ten subjects in the passive perception study. Fixed contact pad data on the left, free rotating on the right.

Figure 7: Overall data from both studies.

the contact pads is shown to make the display intuitive, correlating the virtual environment with the device end effector. The subjects were instructed to move accross 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 phase though subjects typically spent only 1-2 minutes to complete this exercise. At the end of the trial, the maximum positions in each direction were recorded and corresponding lines were placed on the 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.

3.1.2 Active Positioning Study

The purpose of this study was to determine how well subjects could position the skin stretch end effector to a desired rotation. 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...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 lines indicating the subject's specified range of motion were also displayed on the screen to provide the subjects with a reference (Figure 6). 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 1 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. A push-button switch was used to confirm the subjects' inputs.

3.1.3 Passive Perception Study

The second study is 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 rotation 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 and 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 with the knob and confirmed the final position input by pressing a button.

3.2 Results

3.2.1 Active Positioning Study

Figure 7(a) shows the desired orientation versus the measured end effector orientation for all ten subjects, for both the 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 is a linear trend to the results 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.

Overall, subjects were able to map the skin stretch feedback linearly to the desired position using both end effector designs. The average residual for all ten 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 is no statistical difference in overall performance (residual or scatter) between the fixed and free end effectors across the ten subjects. The results of this study indicate that the accuracy with which subjects could position a virtual arm is approximately $\pm 6.5\%$ of the their total range of motion when considering both end effector designs. The range of rotation varied between subjects and between end effector configurations, though there was no indication that one end effector design resulted in larger ranges of motion. However, when asked to indicate which of the two designs they preferred, seven of the ten subjects stated they preferred the free rotating contact pads due to the increased comfort. Two stated that there was no difference and only one subject preferred the fixed configuration. Though it was hypothesized that subjects would have an increased range of motion using the free end effectors, the change in end effector design did not have a significant effect for most subjects. Of the ten subjects, six had a larger range of motion using the free end effector, three had a smaller range and one had an equal range. Linear regression slopes and R^2 values for individual subjects are presented in Table 2. Slopes greater than 1 indicate subjects were moving beyond the range of motion set in the training phase.

3.2.2 Passive Perception Study

Figure 7(b) shows the actual end effector orientation versus the reported end effector orientation for all ten subjects, for both the fixed and free end effector configurations. 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 nearly as well as in the active positioning study. Of the ten 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 Figure 8.

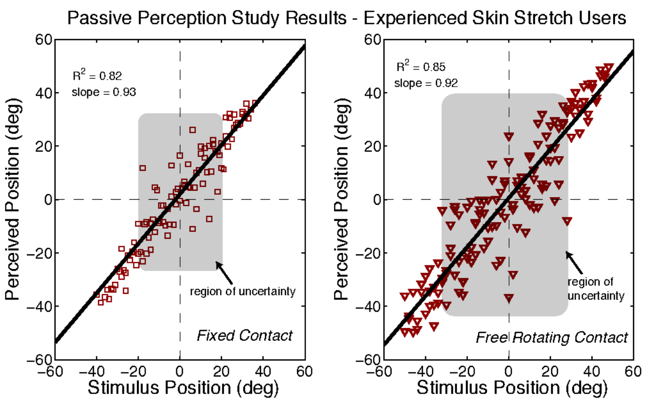


Figure 8: Scatter plot of actual end effector position vs. perceived position with regression line for three experienced subjects. Data with the fixed contact are on the left, free rotating on the right

It is clear that subjects with prior experience using skin stretch feedback performed much better than subjects naive to the feedback. It can be inferred that with proper training and time, subjects can learn to use the feedback for an open loop task, when subjects receive information passively. However, the average residuals of the 3 experienced subjects differed between the two end effector designs, ± 5.5 deg with the fixed end effector and ± 8.1 deg for the free rotating contact. In fact, overall, subjects reported that they felt less confident in reporting the perceived position using the free end effector, particularly in regions of stretch near zero degrees. Looking at the data there does appear to be a region of uncertainty surrounding zero degrees, in which the residuals are larger suggesting that subjects, on occasion, had difficulty perceiving the stimulus level in comparison to the outer limits of the stretch range. Qualitatively, if we estimate the region of uncertainty to be approximately between -20 and 20 degrees for the fixed end effector, there is indeed a difference between the average residuals within the region and outside (the region is marked in Figure 8). The average residual within the region of uncertainty is ± 6.4 deg while the average outside the region is ± 3.0 deg. Similarly for the free end effectors, we can estimate the region of uncertainty to be between -30 and 30 degrees, where the average residual is ± 9.6 deg and ± 5.6 deg otherwise. In both cases, there is a region of uncertainty in which subjects are less accurate (though this effect is magnified with the free end effector) increasing the average residual.

Table 2: 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

4 DISCUSSION

A new, wearable haptic device has been developed to provide users with skin stretch feedback. The relatively compact size and low weight of the device allow for unencumbered user movement and integration into a practical environment. Experiments have shown that the device is effective in closed-loop tasks where the feedback is correlated to user movements or 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. Examples of this type of use are display of kinesthetic or proprioceptive feedback of an arm such as a prosthetic device for an amputee, or motion training applications. Not surprisingly, when the feedback is not correlated to user input, it becomes comparatively difficult to interpret, though results indicate that with sufficient training, users are able to learn to use the device in a passive setting.

When in control of the device, subjects are able to use their own pre-determined methods to reach the desired position. Skin stretch feedback provides a complex combination of velocity, timing, and static force sense which subjects can use to map to a desired position. It is interesting to note that in the active positioning task, there are no direction error outliers as subjects trust that if they command the device to move in one direction, it will in fact, move in that direction. 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.

In evaluating end effector design, experimental and qualitative observations indicate that there are benefits and drawbacks to both fixed and free pads. Performance with both designs was similar in the active studies, though more subjects qualitatively preferred using the freely rotating contact pads due to the increased comfort. In the passive studies, accuracy was measured for experienced users and it was determined that performance decreased using the free end effectors, resulting in larger residuals overall. In addition, the region of uncertainty near zero was found to be greater using the free end effectors compared to the fixed for the passive perception task with higher residuals. No such effect was identified in the active positioning study as subjects could use a variety of strategies to determine the position of the device.

We believe that the free end effector design reduces the shear strains applied near the contact pad, providing greater comfort but at the cost of reducing perceptual resolution. A hybrid design may provide the best combination of comfort at high rotations and increased resolution, with lower residuals, at low rotations in the region of uncertainty. The new design (Figures 9 and 10) incorporates a compliant mechanism that produces the desired effect. Each contact pad has two opposed torsional springs, with a preload. For small angles of the device, the pads move as if they are fixed rigidly to the arms. However, as the torque at each pad increases, it overcomes the torsional preload so that the the pads start to rotate, approximating the case of freely rotating pads (Figure 9). Studies to incorporate the hybrid design and test the device in a more practical setting are underway.

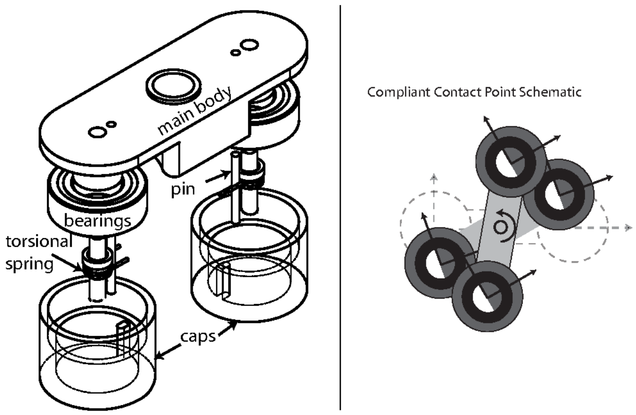


Figure 9: Hybrid end effector with torsional springs CAD (left) with schematic to describe achieved motion of contact points (right).

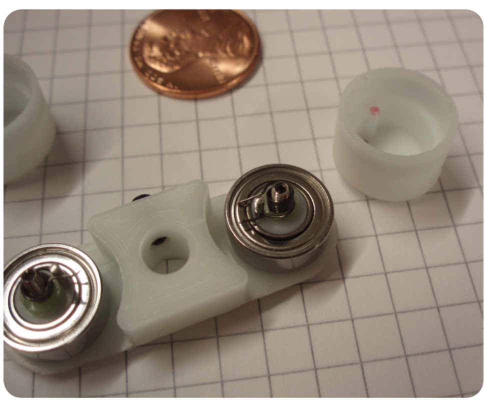


Figure 10: Hybrid end effector with torsional springs.

In summary, the foregoing results indicate 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 the introduction, in which an afferent/efferent command loop exists so that users receive skin stretch feedback in response to motor commands. Experiments to evaluate the effectiveness of skin stretch for these applications are underway.

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