Skin Nonlinearities and their Effect on User Perception for Rotational Skin Stretch

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ABSTRACT

Given that skin is a nonlinear, anisotropic and viscoelastic material, we are interested in exploring the relationship between skin mechanical properties and skin stretch perception, for the case of rotational displacements applied to the skin on a user's limbs. Studies were conducted with 10 naive subjects first to characterize the nonlinear stiffness of the skin with respect to applied rotations and subsequently to characterize the skin viscoelastic response and hysteresis. Despite substantial subject-to-subject variability, when results are normalized by each subject's maximum torque, the torque/displacement results are fairly consistent across subjects, at low and high speeds, and can be fit with a third order polynomial. For roughly one half of the subjects, a similar nonlinearity is discernible in the perceived versus actual rotation; other subjects produced nearly linear results across the range of positive and negative rotations. Viscoelastic and hysteresis effects in the skin were also evident. However, while subjects can clearly distinguish between slow and rapid movements, the speed of the applied motion does not significantly affect their perception of rotation.

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

Skin stretch is a useful haptic feedback mechanism for conveying direction, position and velocity information. Of the devices that employ skin stretch most focus on small skin deformations. Hayward and colleagues have studied and developed haptic devices for skin stretch on the fingertips [9, 15, 20]. Others have developed haptic methods of stimulating the mechanoreceptors of the fingerpad [4, 13, 16]. Recently rotational skin stretch, providing larger deformations on the non-glaborous skin, has been realized through a benchtop device [2] and a portable, wearable device [1]. This type of skin stretch is useful for providing information, for example, about the motions of an elbow, knee or shoulder – motions that normally produce skin stretch near the joints. The possible applications for such rotational skin stretch include motion training (e.g., after surgery or a stroke) and the provision of proprioceptive feedback for operating a powered prosthetic or teleoperated device.

It has long been known that human skin is a complex organ with mechanical properties arising from multiple layers of tissue [10]. Nonlinear mechanical properties have been observed, for example, through single point rotation studies [8] and suction studies [11]. Human skin is anisotropic [12], with age-dependent stiffness, relaxation, creep and hysteresis [8, 14, 20].

In this paper we explore the relationship between skin mechanical properties and the perception of rotational skin stretch, in the context of a device that stimulates the skin by rotating two small contact patches about a common axis of rotation. The rotational skin stretch in these experiments is applied to the hairy skin on the forearm. In the following sections, we first describe the adjustable benchtop skin stretch applicator and instrumentation used to characterize skin rotational stiffness and viscoelastic effects. We then describe experiments conducted to test the torque/rotation behavior of skin on the forearm at low and high rates for rotations of up to ± 40 deg. In section 3, we present a test for comparing the perceived magnitudes of skin stretch to actual applied rotations at low (10-50 deg./s) and high (220-300 deg./s) speeds. We conclude with an analysis of the results and discussion of the implications for future work.

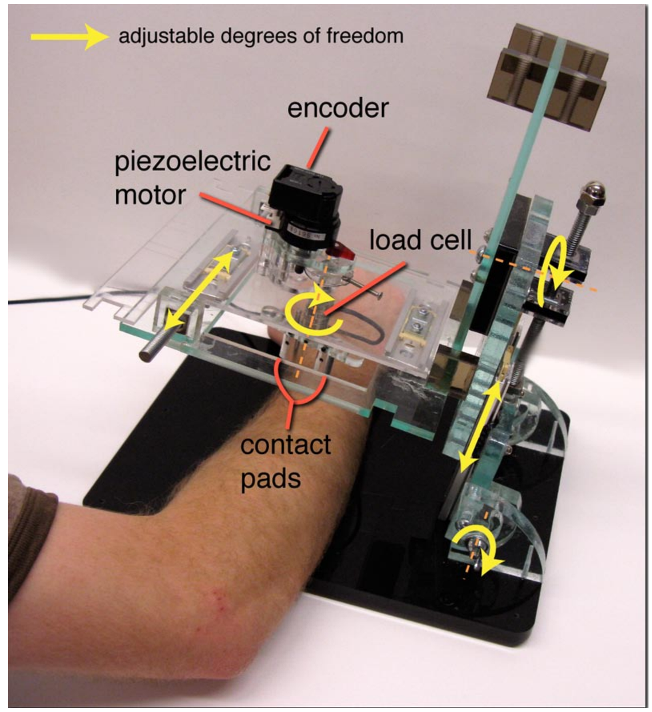

Figure 1: Benchtop rotational skin stretch device, showing adjustable degrees of freedom, motor and end effector

2 ROTATIONAL SKIN STRETCH APPARATUS

Figure 1 depicts the benchtop skin stretch device. This device is designed as a research tool to test rotational skin stretch, which it effects by moving two small circular contact pads about a common point of rotation. Each contact pad has a diameter of 1.21 cm, creating a total contact area of 2.3 cm^2. The contact pads are spaced 1.33 cm apart and are mounted to an end-effector that rotates on a shaft perpendicular to the arm surface. The contact area was chosen to be large enough to adhere to the skin without excessive slipping, but

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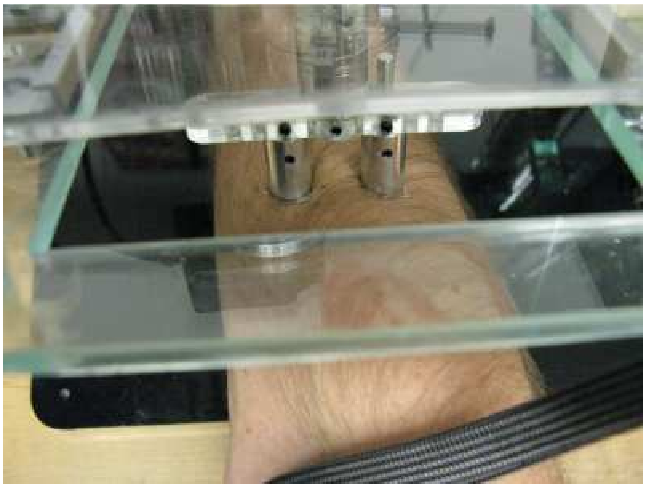

Figure 2: Skin stretch 0° rotation - Unstretched

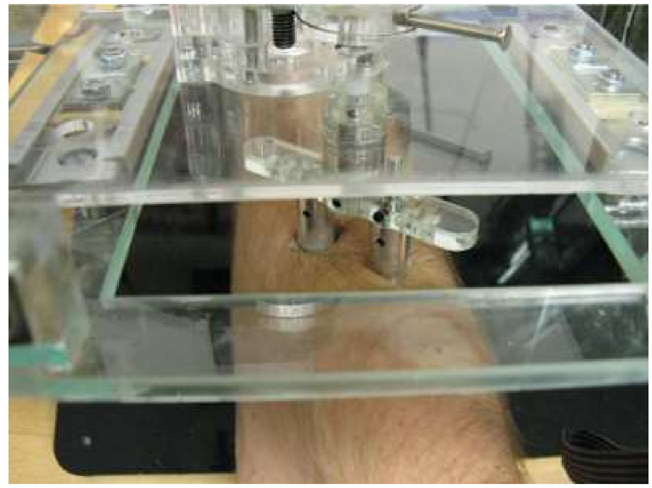

Figure 3: Skin Stretch 40° rotation - Stretched

small enough to maintain an approximately constant gentle pressure, despite the curvature of the forearm. The contact pads are attached to the skin using a double-sided Red-e-Tape™ and adhesive polymer Skin Shield™.

As the device rotates, it deforms the skin primarily in shear, tangential to the surface, and produces strains to which mechanoreceptors respond quickly and accurately [3, 7, 6]. Although the device in these studies is used on the forearm, it could be applied to other parts of the arms or legs, or to the torso.

The benchtop skin stretch applicator (Fig. 1) is adapted from a similar device used in a previous study [2]. The frame has three manually adjustable degrees of freedom in order to position the contact pads on limbs of different sizes and shapes while keeping the common axis of rotation aligned with the local normal vector to the surface.

For these experiments, the device was equipped with a new motor and controller. The motor is an ultrasonic motor (Shinsei Motors, USR30-B3) adapted from a wearable version of the skin stretch device [1]. With a piezoelectric element oscillating at 50kHz [17], it produces no perceivable vibrations. The motor drives the end-effector and contact pads via a cable/capstan transmission with a 5:1 speed ratio. The maximum end-effector torque is 0.5 Nm and the range of available speeds is approximately 10-300 deg./s clockwise or anticlockwise.

Skin forces and torques are sensed through a small 6-axis load cell (ATI Nano 17), which is mounted between the drive shaft and end-effector. Motions are measured using a 500 line quadrature encoder. The encoder is mounted to the motor shaft and has a resolution of 0.036 deg/encoder tick.

System control is achieved using a simple proportional controller implemented using the Matlab™ xPC real-time toolbox, running at 1 kHz. Commanded positions are achieved with a tracking accuracy of 0.25 deg over the range of speeds used in these studies.

3 Skin Properties and Perception Tests

3.1 Mechanical property tests

A user study was conducted to measure mechanical skin properties and to determine whether a correlation exists between nonlinear skin properties and user perception. Ten subjects (seven male, three female) ages 24-32 years old voluntarily participated in this user study, which was preapproved by Stanford's Institutional Review Board. None of the subjects had previous experience using a skin stretch device.

All of the subjects participated in the perception study and basic skin properties testing while five of the ten subjects also participated in additional extensive skin properties testing. The experiment lasted approximately 60 minutes for those performing additional extensive testing, and it lasted about 30 minutes for those performing only basic testing. The two contact pads of the skin stretch apparatus were placed across the forearm roughly two-thirds the distance from the wrist to the elbow (Figs. 2). This location was chosen because of the relatively high density of slow acting mechanoreceptors [18].

Before testing started, subjects were instructed to place their right arm flat on the base of the rotational skin stretch device. After the device was attached to the skin of the forearm, subjects were instructed to keep their right arm as still as possible during testing. To begin testing, two sets of sine waves of 30° amplitude and 0.5 Hz frequency were applied to the subject's arm. Each set of sine waves lasted 5 cycles. This basic skin properties testing was intended to investigate skin non-linearities, relaxation, and hysteresis during continuous dynamic actuation. It also served to give subjects a brief introduction to the feeling of skin stretch before perception testing.

Subjects next performed the perception phase of testing. During this phase the rotational skin stretch device moved to 41 different rotation angles from -40° to 40° spaced 2° apart in a random order for two different stages of tests. The range of angles was chosen to maximize the range of skin stretch magnitudes without causing discomfort to users. During the first stage of testing, the device moved slowly between positions, at velocities randomly chosen from the set of (10, 20, 30, 40, or 50 deg/s). During the second stage, the velocities were randomly chosen from (220, 240, 260, 280 or 300 deg/s). The two different sets of speeds were used to examine whether user perceptions change for slow versus fast movements.

After moving to each new position a text box appeared and the subject entered a perceived position associated with that angle. After the subject entered the value, the skin stretch device moved to the next point. Users were instructed to enter perceived position values based on their own open scale in any units of their choosing. To avoid having subjects forget the sign associated with twist direction, each text box displayed the sign and subjects were only required to record the amplitude of their perceived position. It was also noted to subjects that at the zero position the displayed sign is meaningless. The perception testing was designed to investigate

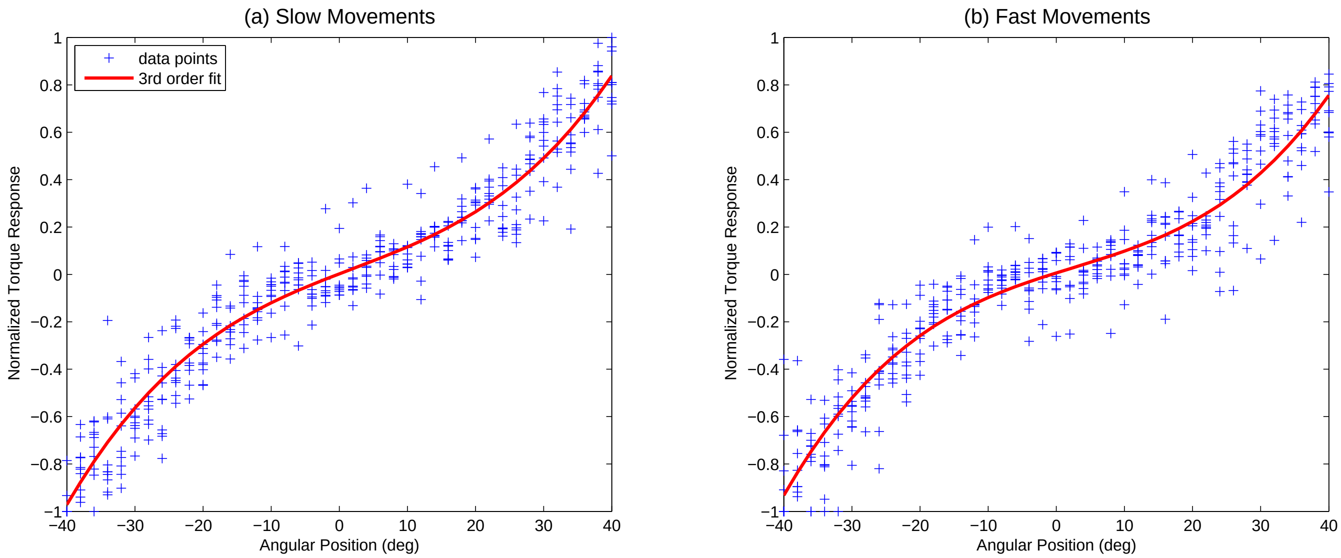

Figure 4: Nonlinear skin response using normalized data from all subjects for slow (10-50 deg/s) and fast (220-300 deg/s) movements.

the relationship between perceived position and actual position and between perceived position and torque.

Five of the ten subjects performed additional skin property testing. During this phase, which occurred after perception testing, a series of position ramp inputs was applied to the user. The ramps cycled back and forth between $\pm 30^\circ$, stopping at each peak for 10 seconds. When moving the ramp speed was set at 5 deg/sec. This testing was performed to investigate additional mechanical skin properties including relaxation and hysteresis for move-and-stop motions.

Data were collected during testing for subsequent analysis of skin stretch properties and user perception. Force/torque, position, and timing data were gathered and used to quantify mechanical skin properties while force/torque, position, speed and perception input provided a means of analyzing user perception.

4 Results

4.1 Skin Properties

Results from the skin properties / perception study provide several useful insights about human mechanical skin properties relating to two-point rotational skin stretch. We highlight and detail three of these properties: nonlinearity, relaxation and hysteresis.

4.1.1 Nonlinearity

Figure 4 depicts the compiled data for all subjects. For each subject, the torque response was normalized by the absolute maximum torque magnitude recorded for the same subject. A 3rd order polynomial is fit to the data for the case of slow movements (10-50 deg/s) and fast movements (220-300 deg/s). For small angles of ± 15 deg. or less, the torque/displacement relationship is approximately linear but at angles of ± 25 deg. and larger the skin stiffens noticeably. The slow and fast movement plots are also quite similar, suggesting that for the speeds of interest, the effective stiffness is not strongly velocity dependent. However, as seen in the next section, there are significant relaxation and hysteresis effects for intermittent motions.

4.1.2 Relaxation

Results from relaxation skin properties testing are shown in Table 1. Two separate modes of relaxation were investigated and a decaying

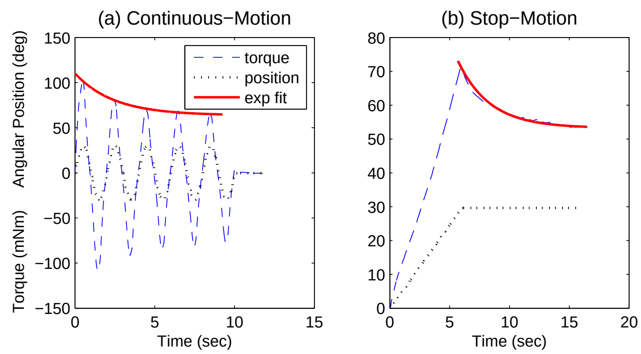

Figure 5: Relaxation plots from typical subjects. (a) 30° Amplitude, 0.5 Hz Sine Wave (5 cycles), (b) 30° Amplitude, 5 deg/sec Ramp (1^{st} Ramp).

exponential of the form

$$exp_{fit}(t) = (a_i - a_f)e^{-\alpha t} + a_f \qquad (1)$$

was fit to each. In this case, a_i is the starting amplitude, a_f is the ending amplitude and α is the decay rate. For the continuous motion sine waves, (1) was fit through the positive torque amplitudes of each successive cycle. For the 30° amplitude ramp-stop motions, (1) was fit to the torque values corresponding to the first ramp from the point when motion stopped until just before motion began again. Figure 5 shows an example for two typical test subjects.

Table 1 shows that the exponential curves fit well with continuous motion data as shown by high R^2 values. The notable exception is the continuous-motion data for subject 5 which did not correspond to a good exponential fit. For this subject, the successive sine amplitudes were almost unchanging making it difficult to fit an exponential curve. Results from the five subjects who performed extended testing through the stop-motion ramps also showed high correlation to exponential curve fits.

Table 1: Relaxation results, exponential curve fits of the form: $(a_i - a_f)e^{-\alpha t} + a_f$

	Continuous-Motion Relaxation								Stop-Motion Relaxation			
	Sine Wave Series #1 (30° Amp, 0.5 Hz)				*Sine Wave Series #2 (30° Amp, 0.5 Hz)*				*Ramp (30° Amp, 5 deg/sec)*			
Subject	a_i	a_f	α	R^2	a_i	a_f	α	R^2	a_i	a_f	α	R^2
1	109.99	86.75	0.25	∼1.00	91.06	77.37	0.29	0.99	70.97	53.27	0.38	0.99
2	61.03	44.75	0.28	0.99	51.08	43.68	0.27	∼1.00	19.67	10.51	0.09	0.94
3	86.37	62.21	0.39	∼1.00	68.90	52.20	0.16	0.98	36.66	28.85	0.22	0.77
4	73.41	56.39	0.50	0.98	63.79	54.00	0.31	0.99	35.52	28.86	0.35	0.98
5	62.24	61.58	-0.10	0.41	71.04	56.87	0.03	0.25	17.61	14.36	0.32	0.96
6	110.36	63.74	0.41	∼1.00	54.70	35.31	0.36	0.98	X	X	X	X
7	54.88	50.25	0.31	0.84	42.06	35.55	0.46	0.98	X	X	X	X
8	98.93	74.32	0.46	∼1.00	72.88	69.31	0.29	0.78	X	X	X	X
9	90.66	51.61	0.42	0.99	55.53	48.32	0.48	0.96	X	X	X	X
10	65.38	45.23	0.29	0.97	47.49	35.85	0.23	0.96	X	X	X	X

4.1.3 Hysteresis

Hysteresis information was gathered for continuous position input and ramp input. Figure 6 shows the hysteresis response from two typical subjects. In both cases the starting point is at zero torque and zero angular position, but after movement begins, that point is not reached again as movement progresses around the hysteresis curve. The area inside the hysteresis band represents lost energy. It is clear from the plot that more energy will be lost if the position is halted at the end points than if motion is continuous.

For the sine wave input (Figure 6(a)) the ends of the hysteresis curve come to a sharp point. This point is changing, sinking a little closer to zero torque with each cycle over several cycles. This is the continuous-motion relaxation. In contrast, the ends of the ramp-stop input (Figure 6(b)) are flat indicating a relaxation of torque without motion, which is stop-motion relaxation.

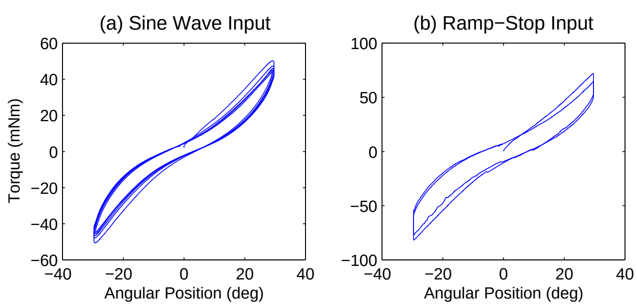

Figure 6: Hysteresis plots from typical subjects. (a) 30° Amplitude, 0.5 Hz Sine Wave (5 cycles), (b) 30° Amplitude, 5 deg/sec Ramp (2 cycles).

4.2 Perception

For each subject, a 3rd order and a 1st order polynomial regression were fit to the actual position versus perceived position scatter plots.

$$y\_fit^1 = \alpha_0 + \alpha_1 x \quad (2)$$

$$y\_fit^3 = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3 \quad (3)$$

To determine whether users perceived absolute positions in a nonlinear fashion, the difference in sum squared errors (SSE) between the nonlinear y_fit^3 and linear y_fit^1 regression fits was used [5]:

$$F = \frac{[SSE(y\_fit^1) - SSE(y\_fit^3)]/(p+1-k)}{SSE(y\_fit^3)/(n-p-1)} \quad (4)$$

where $p+1$ was the number of parameters in the 3rd order model, k was the number of parameters in the 1st order model and n was the total number of data points. In this case $p+1 = 4$, $k = 2$ and $n = 41$. Since a higher order model will alway follow the data better than a lower order model, the F value gives an indication of how much better the 3rd order model fits than the 1st order model.

The null hypothesis H_o is that the linear and nonlinear fits are equally good, and the alternative hypothesis H_a is that the nonlinear fit is significantly different. Equation (4) follows an F-distribution, and thus an F table can be used to determine significance.

Table 2 shows the results of the perception study for each subject through the p-value significance levels of the nonlinear regression fits. Five of the ten subjects perceived position nonlinearly at the $p < 0.05$ significance level. Subjects 1 and 3 perceived position nonlinearly for both slow and fast movements, while Subject 6 perceived nonlinearly for only fast movements and Subjects 7 and 8 for only slow movements. Other subjects did not perceive movements nonlinearly.

Figure 7 depicts an individual subject's model fitting. For slow movements, the subject's perceived position followed a distinct nonlinear pattern, and thus the 3rd order model fit much better than the 1st order model as seen in Figure 7(a),(b). Conversely, for fast movements the linear and nonlinear model fits were almost identical resulting in no significant difference in the error of fitting (Figure 7(c),(d)).

5 Discussion

As seen in the presented results, five of the ten subjects displayed nonlinear perception on at least one of the fast and slow movement perception tests. This indicates that the nonlinear skin properties may play a role in user perception of rotational skin stretch. In particular, subjects may be using torque related to skin strain to determine the absolute position of the skin stretch device. In some cases the subject's perceived position response to actual skin stretch displacement follows a similar pattern to the skin's torque response (for example, we can compare Figure 7(a) and Figure 4). Other subjects did not perceive rotational skin stretch nonlinearly and thus may be less affected by nonlinear skin properties.

We have observed in previous studies that experienced skin stretch users are able to linearize perceived position with actual position very well. During training, users likely develop an internal model of the skin's dynamic response and use that model to linearize. Because in this study none of the subjects had any previous experience using rotational skin stretch, it may be that additional training would eventually allow all subjects to linearize perceived position with actual position.

Another observation is that even though human skin distinctly

Table 2: Perception Results: P-Values for Nonlinear Perception Fit of Actual Position vs. Perceived Position (**bold** indicates significance of $p < 0.05$)

P-values of Nonlinear Fit

Subject	*Slow Movements*	*Fast Movements*
1	**0.040**	**1.9e-4**
2	0.17	0.49
3	**1.6e-3**	**0.049**
4	0.14	0.11
5	0.48	0.65
6	0.15	**0.037**
7	**0.021**	0.059
8	**7.7e-7**	0.86
9	0.93	0.12
10	0.30	0.39

shows nonlinear behavior over the $\pm 40^\circ$ range of angular positions tested in this study, approximating it as linear over a smaller angular range (e.g. $\pm 20^\circ$) may be sufficiently accurate for practical purposes. However, a reduction in the range of motion is accompanied by a reduction in the resolution of the display, which is generally undesirable.

The magnitude of speed of movement did not have a significant effect on either skin properties or perception testing for the range of motions and speeds of interest. Testing with Slow Movements and testing with Fast Movements produced results that were virtually identical for skin properties and did not affect user perception results with the exception Subject 8. Before running the skin response / perception study, it was thought that there would be distinct observable differences in the results of the Slow and Fast phases of perception testing. However, the results do not bear this out.

More generally, the results of the skin stretch properties reported here align with the results of previous work on skin properties. The result of a nonlinear relationship between twist angle and skin torque matches with the results of different studies that have tested rotational skin properties using other methods [8, 11]. Similar trends in time-dependent relaxation and hysteresis were observed in linear skin stretch testing on the fingertip [19].

Moving forward we would like to develop a mathematical model of the skin based on these general skin property trends. This model would be designed to relate angular skin stretch positions to skin torque and ultimately user perception. Such a model would need to account for nonlinearities, relaxation and hysteresis as well as other properties we have not yet investigated, such as creep. The model would contain general parameters whose specific values would be subject dependent but easy to determine with a short period of calibration.

Additionally, we intend to investigate the effect of skin stretch training on user perception. Pilot studies showed that users were able to linearize perceived position with actual position very well. This was particularly the case when users were allowed to watch the device move while feeling the twisting sensation on their arm simultaneously. It would be interesting to know whether this result will generalize to a larger population of users.

Using a verified model, whether linear or more complex, will help extend the use of rotational skin stretch to applications such as rehabilitation for recovery of motor skills, proprioception for neurally-controlled prosthetic limbs and motion training for athletics or physical therapy.

6 Conclusion

In conclusion, in this paper we presented biomechanical properties of the non-glaborous skin on the human forearm and demonstrated

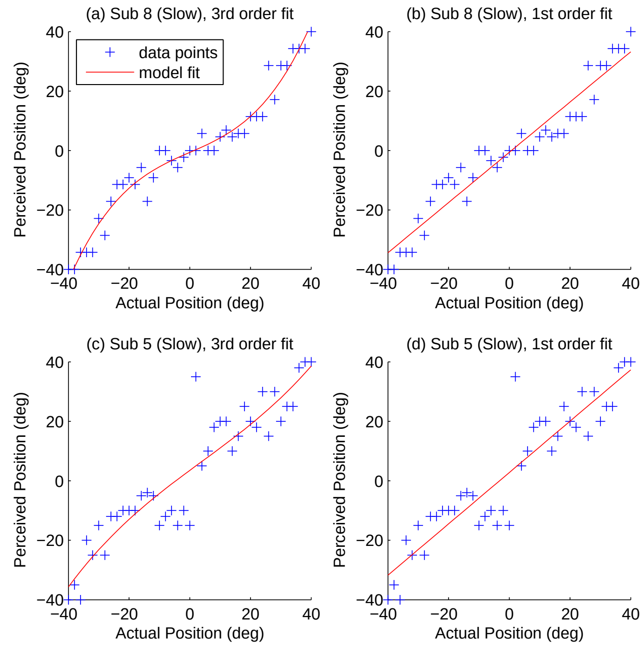

Figure 7: Example perception results for two subjects. Subjects recorded perceived values on a self-selected open scale which were then normalized to -40/40 deg. The perception of Subject 8 during slow movements followed a distinctly nonlinear path (a), (b), while the perception results for Subject 5 for slow movements did not display this nonlinear trend (c),(d).

how nonlinearities can affect human perception during rotational skin stretch. Experimental results showed that half of the subjects tested perceived rotational skin stretch displacements in a nonlinear manner resembling nonlinear trends seen in skin properties of the forearm. We hope to build on these results in order to extend rotational skin stretch to previously unreached applications.

7 Acknowledgments

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