The Influence of Cue Presentation Velocity on Skin Stretch Perception

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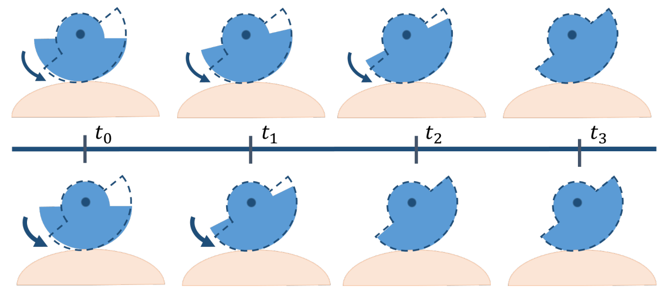
***Abstract*— Wearable haptic devices that convey skin stretch have been used in a broad range of applications, from prosthesis proprioception to language transmission. Despite their prevalence, rigorous evaluation of the perception of skin stretch cues is still ongoing. Prior studies indicate that skin stretch cue presentation velocity may impact cue perception, but we lack quantitative data regarding the impact of skin stretch velocity on cue perceptibility. It is important to understand the impact of presentation velocity to ensure the haptic cues are delivered in the most salient manner. In this paper, the Method of Constant Stimuli and Likert surveys were used to capture the just noticeable difference (JND) and participant impressions for two rotational velocities of the Rice Haptic Rocker. The velocities tested did not affect the JND; however, participants reported the faster speed was easier to discern. This study suggests skin stretch devices can be expected to maintain their perceptual performance at varying actuation speeds, meeting the requirements of a variety of applications.**

I. Introduction

Haptic feedback has become increasingly prevalent in commercial platforms such as smartphones [1], and is often used to enhance realism in gaming interfaces [1] and in medical training simulations [2]. Research has shown that wearable cutaneous haptic feedback devices can effectively convey a variety of information via touch, including kinesthetic guidance [3], [4] as well as navigational cues [5], [6], and can even facilitate communication [7]. Specific haptic cue design parameters such as actuation speed, magnitude, and mapping to an external stimulus are either driven by application requirements or chosen arbitrarily by the experimenter.

Skin stretch cues in particular have been successfully implemented in conveying proprioception [8], [9], in navigational tasks [10], and in language transmission [11]. In particular, while providing sensory feedback to users of upper limb prostheses, skin stretch actuation velocity and magnitude have been driven by the user's control input to the prosthetic hand. For example, when mapping the skin stretch cue to hand aperture, the speed and intensity of the stretch was dependent on how fast and to what extent the user opened and closed their prosthetic hand [9]. In the case of language transmission, the particular skin stretch cue parameters were dictated by the design requirement that language be transmitted quickly [11]. In other scenarios, the parameters of the stretch cue have been chosen by the experimenter independent of specific application or design guidelines [12], [13]. If skin stretch is to realize its full potential in wearable haptic applications, it is imperative that we better understand the connection between cue design choices and perceptual performance.



(a)

(b)

Fig. 1. (a) Conceptual figure showing rocker position over time with two different velocities. Varying the speed of the skin stretch haptic cue is reported to change the feeling of a given rocker position, whether the velocity affects perceptual resolution has been so far an open question. (b) The participant is seated at a lab bench in front of a monitor with headphones playing pink noise and an opaque shroud occluding their view of the wearable haptic device on their upper arm.

Several cue design parameters such as stretch velocity, normal forces, or stretch magnitude, as well as their impact on each other, have been studied to improve the effectiveness of stretch-based haptic devices and to improve understanding of human perception at various locations on the arm and hand. One study determined the just noticeable difference, or the minimum change in a stimulus required for users to perceive a difference, for a rocker device on the wrist to quantify perceptual resolution of angular positions [10]. The

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authors found a significant relationship between perceptual resolution and both normal force on the forearm and stretch magnitude. Their findings showed changes in perceptual resolution over the range of motion of the rocker device. Another study that used a thimble device actuated on the fingertip pad showed that an increase in either magnitude or velocity improved the accuracy of directional discrimination for skin stretch [14]. These studies highlight how directional discrimination is impacted by actuation velocity and how perceptual resolution is impacted by normal forces about various stretch magnitudes.

Further investigation is needed to complete our understanding of skin stretch as a mechanism for haptic feedback, specifically the influence of cue presentation velocity on perceptual resolution, as shown in Fig. 1a. Participant feedback from some of our previous studies suggests the velocity of skin stretch actuation may play a role in the perception of the haptic cue. In one experiment, rocker position was mapped to position of a cursor on a computer screen, which subjects controlled using the keyboard [15]. The protocol used random cursor increment sizes, between one and six degrees of rocker movement per key press. Subjects reported that varying the speed at which they pressed the keyboard produced different sensations during the task, especially for small increments. In another study with the multi-sensory MISSIVE device [11], pilot participants reported an inability to distinguish direction of skin stretch when presentation speed was high. Both cases suggest that the presentation velocity of the cue has an effect on an individual's ability to correctly perceive the cue. This has been observed in other studies as well, including an application of palm skin stretch, where stretch velocity had a significant effect on the intensity perceived by the user [16]. The authors observed that increased cue presentation speed resulted in a perceived increase in stretch magnitude. Together, these studies and observations suggest that the velocity of skin stretch significantly impacts the user's perception of the cue, in either magnitude or direction; however, the effect on perceptual resolution has not been studied. In this paper, we compare just noticeable differences of stretch intensity at two distinct skin stretch cue presentation velocities to determine if there is an impact on perceptual resolution.

II. Methods

We conducted a psychophysical study with accompanying surveys to compare the perception of skin stretch cues delivered at different velocities. The just noticeable difference (JND) was calculated using the Method of Constant Stimuli [17] for a given stretch magnitude at two distinct rotational velocities. A previous study [16] found that at higher speeds, participants perceived higher magnitudes of stretch. Therefore, we hypothesize that at higher stretch velocities observers will find the cue easier to perceive, resulting in a smaller JND among participants.

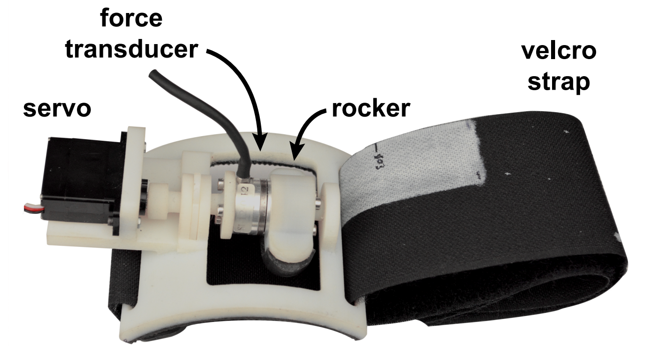


Fig. 2. The Rice Haptic Rocker consists of a semicircular rubber, frictional interface, where rotational motion creates a skin stretch cue to the user. A servomotor is used for position control, and a force transducer is used to measure interaction forces.

A. Participants

Ten able-bodied participants (age 23.5 $\pm$ 2.46 (21-29), 4 female, 2 left-handed) participated in the experiment. No participant reported any significant physical or cognitive disabilities that could hinder perception of tactile stretch on the upper arm and affect participation in the study. All participants provided written informed consent, and the procedures outlined in this paper were in accordance with the policies of the Institutional Review Board of Rice University (IRB-FY2016-231).

B. Experimental Test Bed

The Rice Haptic Rocker is a haptic skin stretch device with silicone frictional contact with the skin. The rocker rotation induces a stretch sensation, and has been tested in several configurations. In this study, the rocker was mounted longitudinally, and actuated on the upper arm with a wearable frame [18], [9]. A servomotor actuated the rocker to produce the desired rotation for the desired stretch cue magnitude. The device was modified from [18] to include a six-axis force transducer (ATI Nano17) in series with the rocker, similar to [15] (see Fig. 2).

C. Just Noticeable Difference

For each sensory stimulus, there is an inherent subconscious response to the event, in our case tactile sensations. The stimulus must increase or decrease by some relative amount for an individual to confidently identify a change. The primary method of quantifying perceptual resolution is through the just noticeable difference (JND) [17].

For a given reference stimulus, there is a distribution about it describing the proportion of instances its difference from similar stimuli are recognized. Above a certain increase, the observer will always recognize a comparison as larger than the reference. Similarly, below a certain decrease a comparison will never be perceived as larger than the reference [17]. The resulting behavior typically mimics a cumulative normal distribution function, as shown in Fig. 3. The value

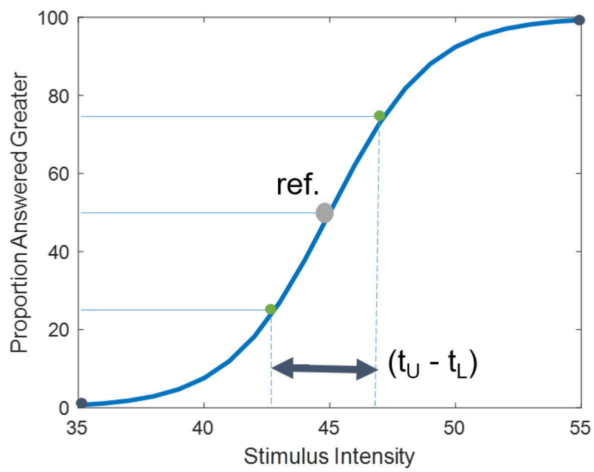


Fig. 3. The psychometric curve captures the uncertainty present in identifying the difference between a reference value and a range of comparison values. The just noticeable difference (JND) is used to define the perceptual resolution about the reference value, defined as half of the difference between the stimulus values corresponding to a seventy-five (t_U) and twenty-five (t_L) percent proportion of responses than they are greater than the reference stimulus.

perceived as greater than the reference fifty percent of the time should be equal to the reference itself. The upper, t_U, and lower, t_L, thresholds are defined as the stimuli that are perceived as greater than the reference seventy-five percent and twenty-five of the time. The JND is then defined by:

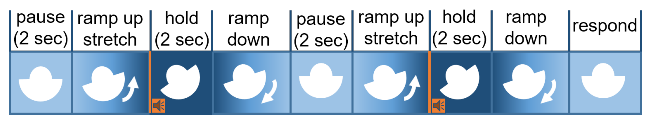
$$JND = \frac{(t_U - t_L)}{2} \quad (1)$$

In other words, the JND represents the amount of change in a stimulus necessary for a twenty-five percent increase (or decrease) in how often it is perceived as greater than the reference value. For haptic devices such as the Rice Haptic Rocker, it is important to determine the JND for the mode of haptic feedback to effectively map cues to the external information we seek to convey to a user.

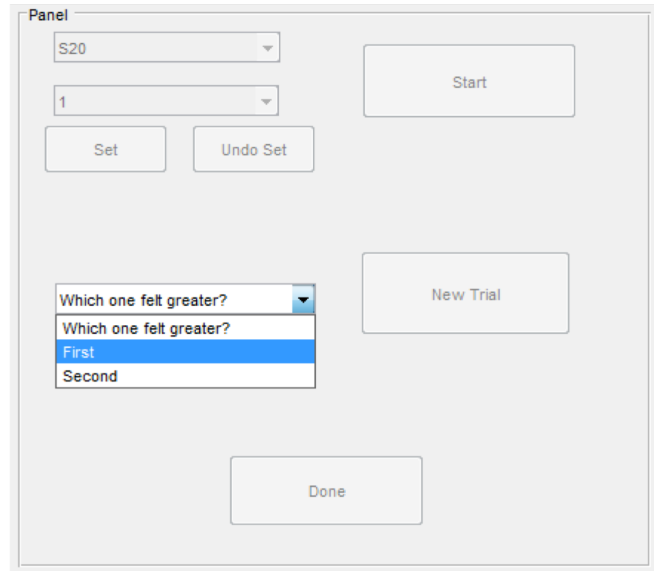
D. Protocol

Participants were seated in front of a computer with the device fixed to their upper arm with a Velcro strap. The tightness was dependent on the participant's comfort but was sufficient enough to prevent slipping while the rocker was in motion. The location of the frame was marked on the participant's arm to limit variability of placement across experimental blocks. Similarly, the strap was marked to mitigate the variability in tightness between blocks. After the device was secured on the participant's arm, a black curtain was drawn between the participant and their arm to prevent any visual cues during the experiment, and headphones played pink noise eliminating possible auditory cues from the actuation of the servomotor, as shown in Fig. 1b.

In each trial, the rocker provided a stretch cue on the upper arm by rotating to both a reference angle and non-reference angle in a random order, as shown in Fig. 4a. Once the rocker reached the commanded angle, a beep indicated when the final stretch value was reached. The stretch was held for two seconds before it traveled back to the zero position with the same velocity. After a two second pause, the rocker began the second cue of the trial. After returning to zero again, the participant reported which cue, the first or second, felt larger in intensity using a drop-down menu on a GUI, shown in Fig. 4b. Once the participant chose their response and confirmed their selection, they proceeded to the next trial.



(a)



(b)

Fig. 4. (a) In each trial, the reference and comparison stimulus are presented to the observer one at a time in a random order, and a beep informs the observer when the final stretch value is reached. (b) The participants interact with a GUI that progresses them through the trials. Once the second cue is completed, the GUI prompts the participant to indicate which cue from the trial was larger.

The experiment was separated into ten sessions. Each session lasted approximately one hour and was separated from the previous session by at least three hours to mitigate fatigue effects. During each session, the participant was given the slow velocity case (C1) of 30 deg/s and the fast velocity case (C2) of 90 deg/s, with presentation order randomized across sessions. Each block consisted of ten trials per comparison angle for a total of 90 trials. The constant reference angle was set at 30 degrees from the rockers neutral position (i.e. its midpoint). The nine comparison non-reference angles were 22 to 38 degrees, incremented by 2 degrees, and given in a random order. After each block, the device was removed from the participant and they filled out a Likert-style survey. The surveys were used to gauge the effectiveness of the experimental design, their confidence in their responses, and participants' overall impression of their performance. After a five minute break, the participant completed the second block for that session. When the experiment was completed, participants were given an exit survey, where participants were asked to complete two short answer questions explaining which condition they preferred and under which they felt was easier to discern cues.

E. Data analysis

The resulting JND for each participant in each velocity condition was computed from a psychometric curve fitted to the aggregate data across all sessions. Outlier blocks were determined in one of two ways, and removed from the data set. First, if a participant reported being particularly inattentive in the comments at the end of the Likert survey, that block was eliminated from their data. Second, blocks that did not contain data points with proportion values less than 0.25 among the angles smaller than the reference value and points greater than 0.75 for those larger than the reference value were excluded from the data analysis, as a psychometric curve cannot be reasonably fitted to the data. Participants that had more than 40 percent of their data excluded were considered outliers, resulting in three participants' data being excluded from the final analysis. There were at least seventy data points per comparison value, out of the one hundred collected, for each participant included in the analysis. Once the outliers were removed, the proportion values for each comparison were calculated for both cases, and used to calculate the aggregate curve, shown in Fig. 5.

For the Likert survey, responses were averaged in each session to calculate an overall response value to compare across all participants. The exit survey consisted of short answers for two questions, which they preferred (fast or slow), and which they thought was easier to tell the difference between the cues in a trial. Participants were also asked to explain their responses. Survey responses are only discussed if shared by more than half of participants.

III. RESULTS

In this experiment, we determined the JND of skin stretch perception under two presentation velocity conditions. Subjects completed two surveys, one immediately after completing each block and another after completing all sessions, to provide their impressions on their performance and the experiment as a whole.

A. Psychophysical Results

A dependent sample t-test was performed for the JND values for the two velocities across subjects. The analysis showed no significant difference between the slow (7.22 $\pm$ 2.85) and fast (7.26 $\pm$ 2.58) velocity cases ($t(6) = 0.089$, $p = .932$, $d = 0.03$). The JND values for each subject are shown in Fig. 6. The presentation velocity of the stretch had no impact on the perceptual resolution of the skin stretch cue. If a difference does exist between the two velocity cases, a power analysis reveals nearly 8,000 participants would be required to detect it [19].

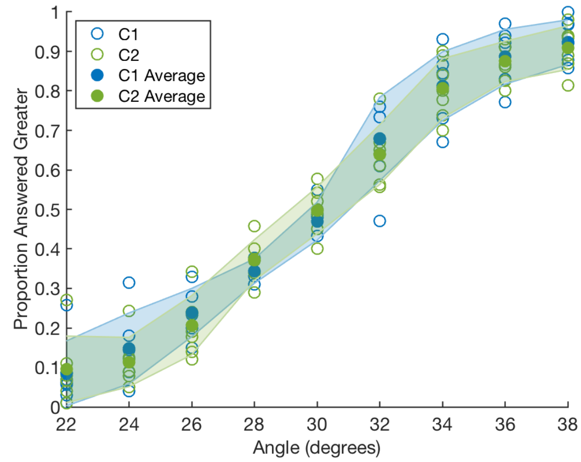


Fig. 5. The average and individual proportion values at each comparison angle for every subject and case. The shaded envelopes represent one standard deviation from the mean values.

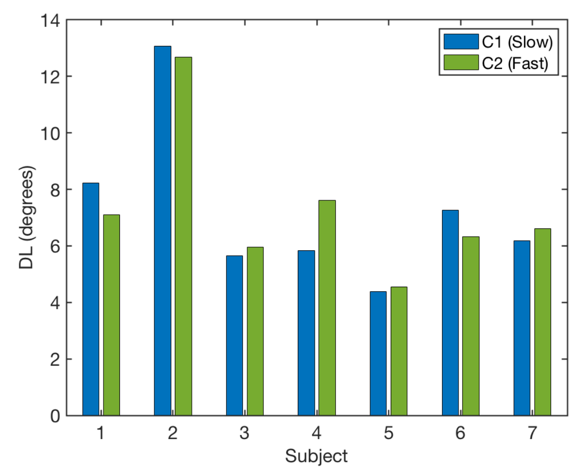


Fig. 6. The JND values for all included subjects for each case. There was no significant difference in the JND values between C1 and C2 (p-value = .932)

B. Survey Responses

Results of the Likert-style survey are presented in Table I, and are compared with dependent t-tests. There were no significant differences in subject responses between the two experimental conditions. For questions pertaining to experimental design, subjects reported both the overall device and the stretch sensation as comfortable, with a straightforward and easy to follow experiment. Subjects responded that stretch was not difficult to feel during the experiment, but were neutral in their confidence levels.

In the additional exit survey given after the completion of the ten sessions, all subjects indicated that they found the faster cues to be easier to discriminate during the trials. Six of seven participants also reported preferring the faster cue. For both questions, subjects reported similar reasons. Subjects preferred the faster cue due to the decreased time per cue, which impacted their attention to the task. The

Questions	Case 1 (Slow)	Case 2 (Fast)	$t(6)$	p-value	d
The device felt comfortable	5.34 ± 1.64	5.35 ± 1.65	0.29	.79	0.11
The device felt uncomfortable	2.59 ± 1.56	2.61 ± 1.38	0.18	.86	0.068
The stretch felt comfortable	6.12 ± 0.93	6.19 ± 1.11	0.41	.70	0.15
The stretch felt uncomfortable	1.71 ± 0.96	1.85 ± 0.95	1.52	.18	0.58
The experiment was straightforward and easy to follow	6.96 ± 0.079	6.94 ± 0.097	0.42	.69	0.16
The experiment was confusing and difficult to follow	1.11 ± 0.16	1.03 ± 0.05	1.87	.11	0.71
It was easy to feel the skin stretch.	5.50 ± 1.31	5.86 ± 1.05	2.19	.071	0.82
It was difficult to feel the skin stretch.	2.47 ± 1.27	2.20 ± 1.09	2.42	.052	0.92
I was confident in my answers.	4.48 ± 0.76	4.76 ± 0.86	1.62	.16	0.61
I was unsure of my answers.	3.66 ± 0.72	3.25 ± 0.88	2.22	.068	0.84

TABLE I

RESULTS OF THE LIKERT SCALE SURVEY. THE SCALE IS 1 (STRONGLY DISAGREE) TO 7 (STRONGLY AGREE). THE MEAN, STANDARD DEVIATION, T-STATISTIC, PROBABILITY, AND EFFECT SIZE OF THE RESPONSES WERE FOUND. ALL THE POSITIVELY WORDED QUESTIONS AND NEGATIVELY WORDED QUESTIONS WERE GROUPED TOGETHER DURING THE SURVEY.

slow speed was found to be harder to focus on due to its prolonged actuation time. The one subject that preferred the slow presentation velocity indicated that it was reasons related to comfort, not performance.

IV. DISCUSSION

The objective of this experiment was to assess the influence of stretch velocity on perceptual resolution of a skin stretch cue administered with the Rice Haptic Rocker. The JND for stretch magnitude was determined about a thirty degree rotation under two rotational speed conditions (slow, 30 deg/sec, and fast, 90 deg/sec). We found no significant difference in perceptual resolution, measured with the JND, although after completing the experiment participants indicated they did prefer the fast velocity.

In the exit survey, all participants indicated that the faster velocity produced cues that were easier to discriminate. Despite this, the JND comparison result suggests that the perceptual resolution, when subjects are asked to discriminate cue intensity, is not affected by how quickly the cue is presented for the two velocities included in the experiment. Fig. 5 shows significant overlap between the average psychometric curve for the two velocities. Furthermore, survey responses show no significant difference in confidence of psychophysical responses within each trial. The combination of these results suggest a distinction between long term impressions and immediate performance. While making a subjective judgment between two cues within the experiment, the subjects were able to distinguish the cues equally as effectively in both velocity cases, and rated their responses with the same amount of confidence and ease in feeling the skin stretch cue. Despite these immediate judgments, their post-experiment feedback comparing the two velocity conditions agrees with anecdotal subject feedback from previous experiments [15], where faster stretch velocities were associated with more easily discerned cues.

This result, that varying stretch velocity does not affect the perceptual resolution of cue intensity measured with the JND, is encouraging for the broad applications of skin stretch feedback on the upper arm, from prosthesis proprioception to navigational tasks. Particularly, this finding is beneficial for prosthesis applications, where the speed is dictated by user intent, where they may make quick or slow motions, suggesting a simple position control is sufficient. If the stretch velocity affected perceptual resolution, corrections within the control scheme may have been required to attain a consistent cue. This also suggests a benefit for device characterization. Devices are often translated to new applications, possibly with different actuation speeds, and this result implies the performance of the device can be expected to be maintained in the new application.

Several aspects of this study require further investigation. First, the study should be expanded to include faster stretch velocities, comparable to language transmission applications, to provide a better picture of whether there exists a presentation velocity threshold that does affect perceptual resolution. Different types of mechanoreceptors have varying firing periods, response times, adaptation rates, and respond to different components of the sensations involved in skin stretch, such as continuous pressure and lateral stretch [20]. Thus it is possible that mechanoreceptors which respond to velocity specific cues may have some inherent velocity threshold due to biological limitations. Additionally, it is not known how these results inform on other areas of the body, such as fingertips, which contain higher densities of mechanoreceptors. Another factor is subject-to-subject variability, as seen in Fig. 6, which could be better accounted for either by testing more subjects or by controlling anthropometric features, such as body mass index (BMI), arm circumference, or other factors, in order to reduce the differences in skin characteristics, and therefore the contact surface interfacing with the haptic device. Last, we should consider controlling for potential temporal bias, where longer pauses between cues causes a bias toward responding that the second, and most recent, cue is stronger [17]. This should be balanced with mechanoreceptor adaptation, where the neural response requires time to return to its original state after receiving a stimulus [21].

V. CONCLUSION

Skin stretch has been used as a feedback mechanism in a variety of haptic devices and applications, from prosthetic hand aperture to language transmission. Changes in the parameters of the stretch cue, such as magnitude, normal force, and velocity can affect user perception and should be considered in device implementation. In this work, skin stretch cues presented at two different velocities with the Rice Haptic Rocker were compared. All subjects considered the faster velocity to be easier for the intensity discrimination task, although there was no significant difference in subjects' perceptual resolution for the two velocities included in the study. Further work is required to cover a broader range of skin stretch velocities and assess the biological mechanisms at play, whether they be the behavior of mechanoreceptors or anthropometric factors. This work suggests the performance of skin stretch devices can translate to other applications with different velocity requirements within the range of velocities presented, and are especially suited for applications where the velocity varies within the application.

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