Effect of Interference on Multi-Sensory Haptic Perception of Stretch and Squeeze

Zane A. Zook, Joshua J. Fleck, Tiffani W. Tjandra, and Marcia K. O'Malley

Abstract— **Multi-sensory haptic systems have the potential to transfer a wide variety of information to a human user by delivering multiple types of haptic cues simultaneously. However, these systems may cause undesirable perceptual interference, which has already been observed in wearable systems that simultaneously convey skin stretch and squeeze cues. To investigate this observed perceptual interference, we conducted a psychophysical evaluation of the just-noticeable difference (JND) in skin stretch and squeeze cue magnitudes independently as well as in the presence of an interfering cue. A haptic testbed delivered each cue to a user's proximal forearm. First, the JNDs of the two haptic cues were each measured alone. Then, the cues were delivered simultaneously and the JND values for stretch with squeeze interference and squeeze with stretch interference were measured. We found that the JND for the stretch cue increased with the addition of an interference squeeze cue, while the JND for the squeeze cue did not change with interference. Results suggest that there is an interference effect between multi-sensory haptic cues that, depending on cue type, can negatively impact haptic perception. Further development of multi-sensory devices that convey salient cues has the potential to mitigate this observed interference.**

I. INTRODUCTION

Haptic devices allow touch-based interactions in a range of application scenarios, including navigation and movement guidance, communication, and virtual reality. The devices used to convey such feedback are increasingly becoming wearable. The success of wearable haptic devices is due in part to the fact that the sense of touch is distributed across the entire body through the touch sensory organ, our skin. Through the skin, tactile sensations such as pressure, shear, and vibration are sensed by mechanoreceptors that are characterized by their temporal resolution and the size of their receptive fields [1], [2].

A variety of mechanisms have been designed to render haptic feedback via the tactile sensory channels. Skin stretch devices leverage a no-slip contact between an end effector and the skin to produce a mild skin shear sensation. Such devices can be rocker-based [3], [4], linear [5], [6], or rotational [7], [8]. Pressure-inducing devices often consist of an actuated band that tightens around the arm causing squeeze and twist sensations [9], [10], [11]. Stretch and pressure based devices have been successfully used for emotional indicators in digital communication [12] and to provide directional information [13]. The third category of wearable haptic feedback, vibration, has been used to convey a variety of meaningful information, including grasping force [13], deviation from a postural set point [14], [15], object slip [16], real-time quality of task performance [17], and navigational cues [18].

Prior work with these feedback modalities has focused on identifying the most natural or intuitive forms of feedback for a specific application. For example, radial squeeze cues seem to be more intuitive than vibration to convey kinesthetic information such as grasp force [9], [10]. Similarly, skin stretch cues seem to be more intuitive at conveying proprioceptive information such as hand aperture [19] or limb movement [20]. Recently, researchers have begun to combine these tactile cues into multi-sensory devices, such as devices that squeeze and tap [21], squeeze and twist [9], and those that can simultaneously stretch, squeeze, and twist [10]. Other systems incorporate vibration in combination with squeeze and stretch [11], [22]. While there have been studies that characterize perception of tactile cues conveyed by wearable devices (see, for example, [23], [24]), the focus of these studies has been on perception of each tactile cue alone.

In previous work by Dunkelberger et al. on perception

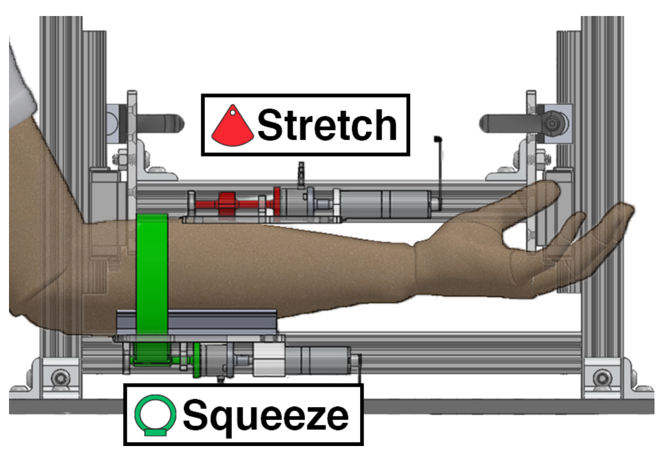

Fig. 1. 3D CAD Model of the Haptic Testbed used in the experiment with modeled forearm. The module responsible for delivering the stretch cue to the user is colored in red and the module responsible for delivering the squeeze cue to the user is colored in green.

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of multi-sensory cues, the authors observed that for some combinations of cues, masking or interference would occur [22]. For example, while participants were able to identify multi-sensory (stretch, squeeze, and vibration) cues better than single sensory (vibration) cues, the stretch cue was often overlooked when squeeze was also present. Interference between tactile cues has already been shown to occur in vibration cues [25]. In order to ensure that multi-sensory cues are as salient as possible, it is necessary to better understand the perceptual interference that may occur during simultaneous tactile stimulation.

In this paper, we seek to determine the extent to which skin stretch and squeeze cues interfere with perception during simultaneous cue presentation to the arm. To quantify perception, we use the 50% just-noticeable difference (JND), a standard psychological measure of the difference between two stimuli intensities where a person can differentiate the stimuli with 50% accuracy.

JND measures (also documented as difference thresholds in some studies) have been well characterized for vibrotactors but not for stretch and squeeze cues. These experiments have characterized vibrotactile JNDs at different frequencies and amplitudes [26], [27]. Stretch cue investigation into JND have primarily been performed on the fingertip [24], [28]. Other JND investigations into stretch and squeeze have generally focused on characterizing the JND of one type of tactile feedback (skin stretch, squeeze, or vibration) at a time [4], [11]. To our knowledge, there has not been any rigorous JND investigation for simultaneous multi-sensory cue presentation where interference may occur. We present experimental results from a subject experiment comparing the JND for skin stretch and squeeze each presented alone, and then for each in the presence of an interfering cue. These results offer the haptics community insight into design considerations when developing future multi-sensory devices.

II. Experiment Methods

A. Participants

A total of 13 participants (six female, eleven right-handed, 20-29 years old, average age 23) took part in this study. Participants in the study did not suffer any cognitive or motor impairment that would affect their ability to perform the experiment. All participants gave informed consent and all procedures and methods of the experimental protocol were approved by the Rice University Institutional Review Board.

B. Experimental Setup

The haptic testbed used for this experiment is a test fixture capable of delivering stretch and squeeze cues to the forearm simultaneously and is shown in Fig.1 [29]. The main frame has an adjustable upper tier and a fixed lower tier for the stretch and squeeze modules, respectively.

The stretch module consists of a stretch rocker, an ATI Nano25 6-axis force and torque sensor, and a custom Maxon DCX22S DC motor (with GPX22HP 83:1 planetary gearhead) maximum continuous torque of 1.21Nm, nominal voltage of 12V). The stretch rocker is a 3D printed, rubber coated, and semi-circular end-effector (radius of $\frac{3}{4}$ of an inch) that is pressed against a participant's forearm by adjusting the vertical position of the main frame's upper tier. When actuated by the DC motor, the stretch rocker twists and displaces the skin under it to deliver a skin stretch cue.

The squeeze module is assembled with an ATI Nano25 force-torque sensor attached between another Maxon DCX22S DC motor (with GPX22HP 83:1 planetary gearhead) and a squeeze band adapter. The squeeze band adapter is a 3D printed, half cylinder (radius of half an inch) that connects the velcro squeeze strap with the rest of the squeeze module assembly, resulting in the band tightening around and squeezing a participant's forearm when the DC motor actuates the adapter. The squeeze was spaced on the testbed relative to the stretch module such that the modules' points of contact with the skin was separated by approximately 1.5 inches. The squeeze module's acrylic platform has slots to allow the velcro squeeze strap to loop around a participant's forearm and be secured onto the platform, strapping a participant firmly and comfortably into the haptic testbed. The module also includes an arm rest mounted onto the platform above the squeeze assembly, on which the participant rests their forearm to ensure alignment with the stretch and squeeze modules.

The DC Motors which effect stretch and squeeze are each directly controlled by a Maxon Epos 4 Controller at 2.5kHz, which receives commands over USB connection from a desktop computer at 100Hz. The force and torque sensors are integrated using a National Instruments PCIe DAQ Card, which feeds data into the control program for data-logging at a rate of 1000Hz.

C. Haptic Cue Conditions

This experiment consisted of four conditions over two testing days presented to participants in a random order. These four conditions tested different combinations of two types of haptic cues to determine if there is any effect of interference during simultaneous delivery of both cues. These conditions included:

- **Stretch** cue alone
  (Hereafter referred to as **stretch**)
- **Stretch** cue with squeeze cue interference
  (Hereafter referred to as **stretch x squeeze**)
- **Squeeze** cue alone
  (Hereafter referred to as **squeeze**)
- **Squeeze** cue with stretch cue interference
  (Hereafter referred to as **squeeze x stretch**)

Both stretch and squeeze cues were measured in terms of the change in angle of the rocker to control for the amount of skin displacement and to be comparable to similar, position controlled, wearable multi-sensory devices. For all of the conditions, participants were given 7 comparison cues. For the stretch condition, these cues were given at even intervals from 13 degrees to 91 degrees to maximize the variation between cues above the absolute threshold for stretch while maintaining contact with the skin. The stretch reference cue was given in the center of this range at 52 degrees. For the squeeze condition, comparison cues were independently chosen to also span 13 degrees to 91 degrees at even intervals. This range for the squeeze cue was chosen to balance variation between cues above the absolute threshold for squeeze while still being comfortable for participants to receive. The reference squeeze cue was also given in the center of the range at 52 degrees. In the interference condition, the comparison cue was given simultaneously with an interference cue at 52 degrees.

D. Procedure

The experiment was performed over the course of two sessions separated by at least six hours and no more than 48 hours. Each participant was presented with four randomized conditions split between these two sessions. Each condition consisted of 350 randomized trials comprised of 50 trials per comparison cue set. Participants were informed of the testing condition at the start of each new condition.

The stretch cue was rendered on the skin on the underside of the participant's forearm and the squeeze cue was rendered around the proximal forearm (see Fig. 1). During the experiment, the haptic testbed was covered with an opaque cloth and participants wore noise-canceling headphones playing pink noise to isolate them from visual or auditory stimuli. Participants interacted with a text interface on a computer screen that provided them with information about their input and the trial number.

For each trial, the participant was presented with a reference cue and a comparison cue in random order. The participant pressed the '1' button to indicate if they perceived the first cue as greater and the '2' button to indicate that they perceived second cue as larger. This process would repeat 350 times for each condition. Once the condition was complete, participants were given a 5 minute break before beginning the next condition.

Apart from subject responses, motor encoder data and torque data were collected from the stretch and squeeze modules. The motor encoder data was used to ensure the desired cues were properly delivered to the participant. The torque data will be discussed in section IV-D.

E. Data Analysis

The JND is measured through a variety of psychophysical tests [30]. In this experiment, we selected the method of constant stimuli to measure JND. In the method of constant stimuli, subjects are presented with sets of stimuli pairs that each consist of a reference stimuli and a comparison stimuli. The subject compares the two and indicates if the comparison stimuli is greater than or less than the reference stimuli. To provide a wide range of data for analysis, 5-11 comparison stimuli are chosen that are each evenly spaced above the absolute threshold and in between two comparison stimuli that are clearly different than the reference stimulus [31].

After all trials have been completed the response proportion is calculated as:

$$P = \frac{\sum y_i}{n} \tag{1}$$

Where $y_i = 1$ is the case where the comparison stimulus is perceived as greater than the reference stimulus for that trial and where n is the number of stimuli pairs for each comparison stimulus. These response proportions, P, then are plotted against the magnitude of the comparison stimulus.

A response proportion for each subject was calculated for each comparison cue set in each condition. For example, in the stretch only condition one subject compared the reference stretch cue at 52 degrees to a comparison cue at 65 degrees. If the subject responded that the comparison cue was larger than the reference cue for 42 trials out of 50 trials given, the subject's response proportion would be 0.82 when the 'difference to the reference cue' is 13 degrees.

Psychophysical studies have shown that the relationship between response proportion and comparison stimulus magnitude often follows a sigmoid curve [32]. By fitting the data to a sigmoid curve, the 50% JND can be estimated by dividing the difference between the 25% response proportion and the 75% response proportion on the curve fit by 2.

Ideally, with perfect perception, a subject would have a response proportion of 0 for any negative 'difference to reference cue' and a response proportion of 1 for any positive 'difference to reference cue'. However, since humans do not have perfect perception, their response proportions do not follow this step function shape and instead follow a sigmoid curve.

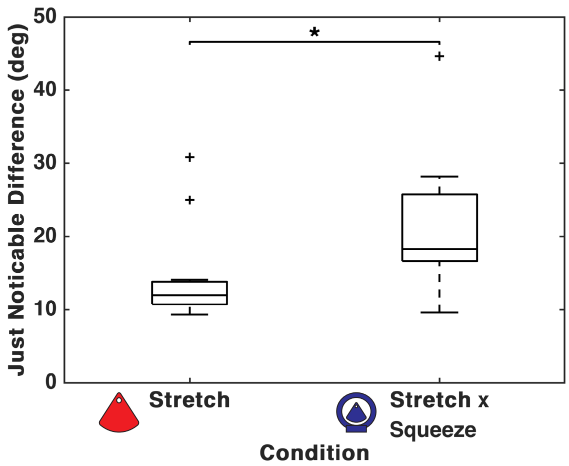
III. RESULTS

A. JND Analysis

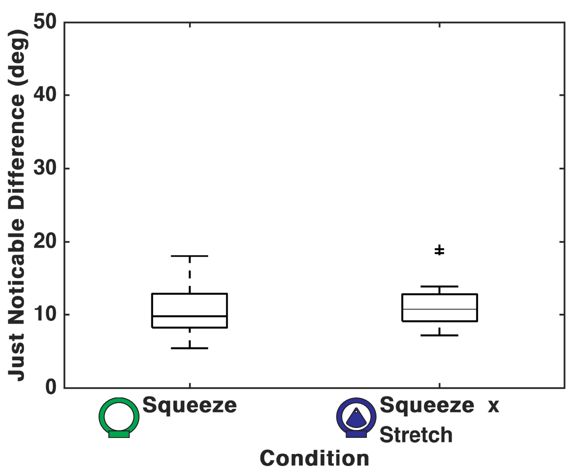
We computed JNDs from sigmoid curve fits on each subject's experimental data for each condition. Fig. 2a shows the JNDs across all subjects for the stretch and the stretch x squeeze conditions while Fig. 2b shows the JND across all subjects for the squeeze and the squeeze x stretch conditions. A paired t test was done on the stretch conditions and the squeeze conditions to determine if interference had a statistically significant effect on the JND of stretch or of squeeze. The JND for the stretch condition (M=14.13°, SD=6.36°) showed a statistically significant difference compared to the stretch x squeeze condition (M=21.2°, SD=8.82°) as determined by a paired t test; $t(12) = -4.79, p \leq 0.05$. The JND for the squeeze condition (M=10.49°, SD=3.62°) failed to show a statistically significant difference compared to that of the squeeze x stretch condition (M=11.6°, SD=3.7°); $t(12) = -1.65, p = 0.12$.

B. Sigmoid Curve Fits

To better understand the impact of cue interference on JNDs, we conducted additional analysis of the results. Fig. 3 shows the distribution, average and standard deviation of response proportions for all subjects for each comparison cue. In Fig. 3b, the averages and standard deviations are similar in both regions for both squeeze conditions. In contrast, in Fig. 3a, the averages and standard deviations for each comparison cue are similar when the comparison stretch is greater than the reference stretch (white region) but vary when the comparison stretch is smaller than the reference

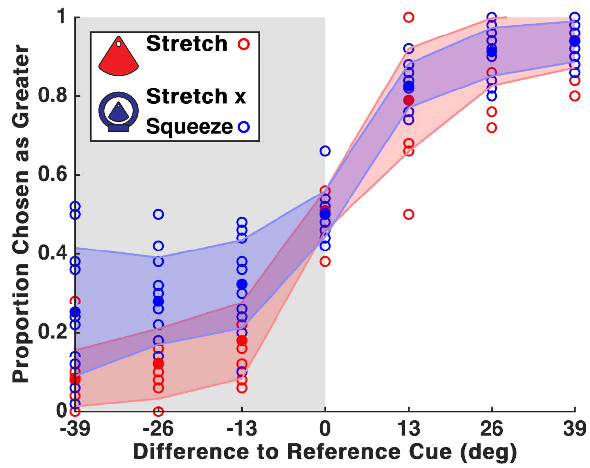


(a)

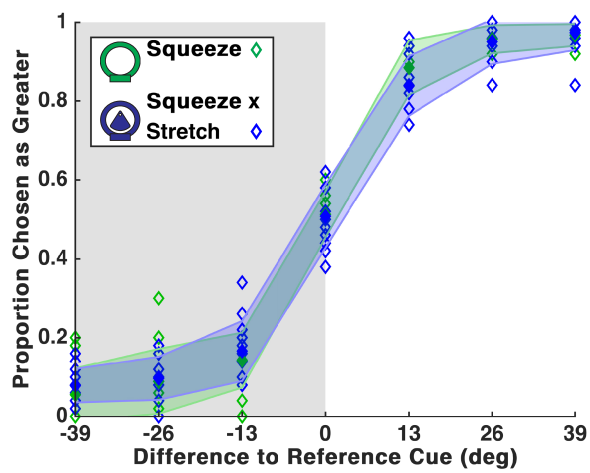


(b)

Fig. 2. Just-noticeable difference for stretch conditions and squeeze conditions. Participants tried to feel the bolded cue while the unbolded cue was given as interference.
(a) The stretch x squeeze condition significantly differed from the stretch condition $p < .05$
(b) The squeeze conditions did not significantly differ $p < .12$



(a)



(b)

Fig. 3. Response proportion for all subjects at each comparison cue set in each condition. Average response proportion for each comparison cue set is shown with a filled in marker. One standard deviation from the average response proportion is represented by the shaded region. Participants responded to the bolded cue while the unbolded cue was given as interference.
(a) Response proportion for the stretch condition and the stretch with squeeze interference condition.
(b) Response proportion for the squeeze condition and the squeeze with stretch interference condition.

stretch (gray region). For a sigmoid curve to fit perfectly, its y-intercept would be at a response proportion of 0 and the curve would approach a response proportion of 1 infinitely. In the stretch, squeeze, and squeeze x stretch conditions, we can visually confirm that a sigmoid curve fits the data well because the average response proportion starts near 0 and ends near a response proportion of 1. However, as shown in Fig 3a, the average response proportion for the stretch x squeeze condition does not start near 0, suggesting that a sigmoid curve would not fit the data in the condition well.

To quantify this goodness of fit, an R^2 value was calculated for each sigmoid curve fitted to each subject in each condition. The stretch (M=.96, SD=.03), squeeze (M=.97, SD=.03), and squeeze x stretch (M=.97, SD=.03) conditions were fit well by a sigmoid curve (R^2 values all averaged above .95 where $R = 1$ is a perfect fit). In contrast, a sigmoid curve did not fit the stretch x squeeze condition well (the average R^2 value was approximately .86 with a large standard deviation of .12). Since the R^2 values indicate that the sigmoid curve does not fit the data well for the stretch x squeeze interference condition, the values derived from these curves are not representative of the true JNDs in this condition.

C. Average Response Proportion Difference

Since the sigmoid curve does not reasonably approximate the stretch x squeeze condition, another metric was used to compare this condition with stretch alone. As shown in Fig. 3a, there is a difference between the response proportions in the stretch and the stretch x squeeze conditions when the comparison stretch is smaller than the reference stretch (gray region) but not when the comparison stretch is larger than the reference stretch (white region). This difference in response proportions between the stretch and the stretch x squeeze condition was calculated for each subject. If there was no effect of squeeze interference on stretch perception, these differences in response proportion should be similar in the gray and white regions. To compare these differences, the average response proportion difference for each subject was calculated by averaging these differences in the gray region and in the white region.

For example, looking at Fig. 3a, a single subject has 6 average response proportions in the gray region, one for each stretch condition, at 3 points, -39, -26, and -13, on the 'difference to reference cue' axis. The difference between these two condition response proportions at each of these points, at -39, -26, and -13 degrees, is averaged to calculate the average response proportion difference when the comparison stretch cue is smaller than the reference cue (gray region) for this subject.

There was a significant difference in this average response proportion difference between the stretch condition and the stretch x squeeze condition; $t(12) = 7.47, p < .05$. This confirms the previous result from the JND t tests in section III-A that showed there is an effect of squeeze interference on the stretch JND. For completeness, average response proportion difference was also calculated for the squeeze conditions. As expected, there was no significant difference in this measure for the squeeze conditions; $t(12) = 0.15, p = .44$.

IV. DISCUSSION

The JNDs for stretch, stretch x squeeze, squeeze, and squeeze x stretch indicate that there is a significant effect of squeeze interference on stretch JND. Further analysis shows that interference only affects stretch for small stretch cues.

A. Squeeze Interference On Stretch Perception

Results of this experiment show that squeeze interference has a significant effect on the perception of stretch cues. Interestingly, as shown in Fig. 3a, this interference effect only occurs when the stretch comparison cue is smaller than the reference cue (gray region) indicating that squeeze interference has an asymmetric effect on stretch perception. This makes intuitive sense as the squeeze interference would be more likely to mask a small stretch cue as compared to a large stretch cue. However, it is likely that the magnitude of the interference squeeze cue also has an effect on stretch perception. Further it is also possible that the asymmetric effect of interference on stretch perception changes with the magnitude of squeeze interference, warranting further investigation.

B. Effect of Cue Location on Interference

In this study, the stretch and squeeze modules' points of contact were separated by 1.5 inches. Although not examined in this study, it is likely that the amount of interference between cues is directly related to the distance in between them. Further research into how the relative location of cues affect interference will inform future device designs.

C. Effect of Surface Area on Interference

In contrast to squeeze interference on stretch perception, stretch interference had no effect on squeeze perception. This could be due to the difference in skin surface area covered by each haptic module. As discussed in section II-B, the stretch rocker stretches the skin directly below its tactor on the underside of the forearm, while the squeeze band wraps around the entire forearm. Although both haptic modules were actuated to the same positions, the band covered a much wider surface area of the skin compared to the rocker. The different surface areas acted upon by these modules may influence perceived strength of each cue. As such, the effect of surface area on interference should be investigated. If the surface area covered by a cue is related to its perceived strength, then it is possible that the effect of interference would also be magnified if the interference cue covered a large surface area. If this is the case, one potential solution could lie in strategically designing a multi-sensory haptic device to act over surface areas that minimize this interaction.

D. Comparison of Cue Torque

Another factor to explain why the squeeze interference affected the perception of stretch but the stretch interference did not affect the perception of squeeze could be the difference in torque between the stretch and squeeze modules. Maximum torque on the squeeze actuator along the axis of rotation during the study reached approximately 0.8Nm. In contrast, maximum torque on the stretch actuator along the axis of rotation during the study reached approximately 0.2Nm. Since this experiment was designed to control the displacement of the skin to learn about the effect of interference in a standard position controlled wearable haptic device, the torque delivered to the skin was allowed to vary. Torque data was recorded but was used only to confirm that the haptic cues were delivered successfully. A useful extension to this work would be to study how varying torques affect the perception of haptic cues with interference. If there is a significant effect of torque on the perception of haptic cues, this would inform future multi-sensory haptic devices to consider torque control to minimize the effect of interference.

V. CONCLUSIONS

This study investigated the effect of interference on the perception of haptic cues in a multi-sensory haptic device. A haptic testbed, capable of giving stretch and squeeze cues simultaneously, was used to evaluate the just-noticeable differences when the device provided four conditions: stretch alone, stretch with squeeze interference, squeeze alone, and squeeze with stretch interference. Data showed that squeeze interference significantly affects the perception of stretch cues when the stretch cues are small. This result has direct implications on the design of multi-sensory devices and warrants further investigation. The relationship between the extent of this interference and other relevant design parameters such as proximity between cues, torque used to apply cues, or surface area acted upon must be investigated to inform designs that can minimize interference in these devices. Moving forward, future studies should consider and investigate haptic cue interference with the goal of creating salient multi-sensory haptic devices.

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