Haptic Matching of Directional Force and Skin Stretch Feedback Cues

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Abstract

This paper presents a two degree-of-freedom (2-DOF) force feedback joystick with a 2-DOF skin stretch feedback device integrated into the top of its handle (where the user rests his/her thumb). An experiment is conducted to better understand how users interpret directional information from force and skin stretch cues. Results show that users exhibit significantly greater accuracy when responding to force cues, but have significantly greater precision when responding to skin stretch cues. Precision is further improved when these cue types are combined. Integrating skin stretch and low-magnitude force cues in this manner shows promise for applications where force information is beneficial, but cannot be presented due to the risk of creating feedback instabilities. Hence skin stretch feedback could be used to supplement lower, non-destabilizing levels of force feedback, or to augment underpowered force feedback systems. Skin stretch may also be used as a lower cost, more compact substitute to force feedback.

Keywords: Haptic interface, skin stretch, tactile and kinesthetic display, direction matching, perception and psychophysics

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; J.4 [Social and Behavioral Science]: Psychology H.5.2 [Information Interfaces and Presentation]: Haptic Technology—Tactile Devices and Display

1 Introduction

Haptic feedback through force and tactile cues helps improve performance in a variety of tasks. One disadvantage of force feedback is the possibility of feedback instabilities that can affect the user's precision and control of the input device [1]. Skin stretch feedback avoids these instabilities while still providing similar directional information.

The aim of this research is to compare the directional perception of force feedback and skin stretch feedback, and to determine the possible perceptual benefits when these two feedback types are presented together.

A force feedback joystick with a skin stretch feedback display integrated into the top of its handle was developed to evaluate the effects of each feedback type separately and when combined. The device allows force and skin stretch feedback to be experienced simultaneously by its user through his/her hand and thumb pad, respectively.

Early anecdotal evidence with this joystick suggests that users interpret these two forms of haptic feedback in an additive manner. This is particularly meaningful as it implies that skin stretch feedback may be suitable to augment force feedback with low gains in safety-critical situations where force feedback is not permitted due to the possibility of feedback instabilities.

A simple haptic matching experiment is constructed to evaluate each of these modalities separately and when combined. We hypothesize that integrating skin stretch feedback with low-magnitude force feedback will improve directional perception over either feedback type separately (i.e., in a manner commensurate with optimal integration of these two feedback types as suggested by [2]) while avoiding instabilities.

The remainder of this paper presents related prior research, the device developed for this experiment, and its relevant design decisions and performance characteristics. We then present details of the haptic matching experiment and relevant results, discussion, and conclusions.

2 Background

To the best of our knowledge, no known research has been performed related to the directional perception of combined force and skin stretch feedback. However, a variety of studies have investigated the directional perception of skin stretch or force feedback separately. These studies primarily report human angular perception discrimination or identification capabilities. A brief overview of the findings of these respective studies follows.

Drewing et al. performed a directional discrimination experiment using a translating 1 mm diameter pin that was displaced by a distance of 2 mm on the fingertip [3]. They reported a range of 84% angular discrimination thresholds from 23º to 35º across the 8 directions tested in their experiment. In a similar experiment, Vitello et al. determined that tactile discrimination on the finger is decreased by movement of the user's arm [4]. Their reported 84% angular discrimination thresholds across the 3 directions they tested range from 30.9º to 40.6º for the static case.

Gleeson et al. studied the effects of varying the speed and displacement of skin stretch applied to the fingertip [5]. They found that directional perception of skin stretch cues increases as tactor speed and displacement are increased over the range of 0.05 mm to 1 mm of tactor displacement and 0.5 to 4 mm/s tactor speed. Experiments by Gleeson and Provancher report that putting a skin stretch haptic device in a rotated reference frame does not impede users from successfully identifying directional stimuli delivered to the index finger in a 4-direction identification task for small rotation angles (< 40º) [6]. However, a separate study identified a systematic counter-clockwise bias for cues delivered to the participants' forward extended right thumb [7]. Montandon further investigated participants' ability to identify skin stretch cues delivered to their forward extended thumbs in 16 directions [7]. He also observed the same rotational bias found in [7].

Similarly, previous research has investigated the directional perception of force feedback devices. A multi-direction discrimination experiment was performed in [8] using a SensAble Technologies Phantom. They determined that the direction of the reference force did not affect discrimination thresholds of forces

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applied to the index finger. They reported a discrimination threshold of 25.6º for sequentially presented forces.

In a similar study in which forces were applied to a stylus, it was reported that hand motion during force cues did not influence the directional discrimination threshold, determined to be 32º [10]. Another force direction discrimination study using a joystick device is found in [11]. This paper reports that participants were able to correctly discriminate between two force cues, separated by 15º, 82.7% of the time.

The preceding tactile and force perception studies evaluate performance primarily by measuring thresholds for directional discrimination or by identifying the direction of applied stimuli. These discrimination results appear similar in magnitude for force and skin stretch feedback. However, in normal interactions with haptic environments, directional error is a result of not only perception, but also user response. Therefore, it is important to not only discriminate or identify direction cues, but to also replicate a directional cue with a user's hand motion.

A response method involving such user response was used in [12], in which the direction of a force rendered through a joystick device, in a random direction, was replicated by the participant moving the joystick in the direction of the perceived cue. They determined that the mean error across all directions was nearly zero, with an average RMS error of 10.3º. Note that this error is significantly smaller than the thresholds reported in the prior discrimination and identification experiments. The experimental approach for our study herein resembles the matching paradigm reported in [12].

3 Device Description

A novel device was developed for the experiment reported herein. It consists of a base capable of rendering forces through a joystick handle and an embedded tactile display capable of rendering skin stretch cues to a user's thumb pad.

The device is controlled by a PC communicating at 1 kHz haptic rates to a microcontroller contained in the device base. Two Maxon RE35 motors, powered by a two-channel H-bridge amplifier (TI #DRV8833PWPR), provide force cues through a spherical 5-bar linkage. The design is similar to that used in the Immersion Impulse Engine 2000. Position feedback is provided through two 1000 count US Digital E2 optical encoders. The device base is fabricated from PVC sheet stock on a water jet cutter and is similar to the haptic paddle described in [13]. PVC was chosen due to its low cost, availability, and material toughness.

When powered using a 10.4 V source, the device is capable of applying a maximum continuous torque of ±1.53 N-m to the joystick. This correlates to a force of ±10.9 N at a location 140 mm above the pivot point of the joystick, near the base of the user's thumb. **All forces mentioned in this paper are given at this 140 mm reference point**, which is labeled in Fig. 1.

The device was calibrated to ensure high accuracy in a range of forces between 0 N and 6 N. Three force samples were taken at each voltage level. Voltage levels ranged from 0 V to 9 V in steps of 0.25 V. These samples were measured by applying a force through the joystick to a mass scale while the joystick was mounted orthogonally to the scale. A piecewise function consisting of a 4th order polynomial and a line was fit to the collected data, relating the voltage output of the H-bridge to the force applied at the reference point of the handle (see Fig. 2). Each curve fit has an R^2 value greater than 0.99. Both axes of motion were determined to have the same force-voltage profile. This calibration ensures that the appropriate force magnitude and direction is applied to the participant's hand when rendering force cues.

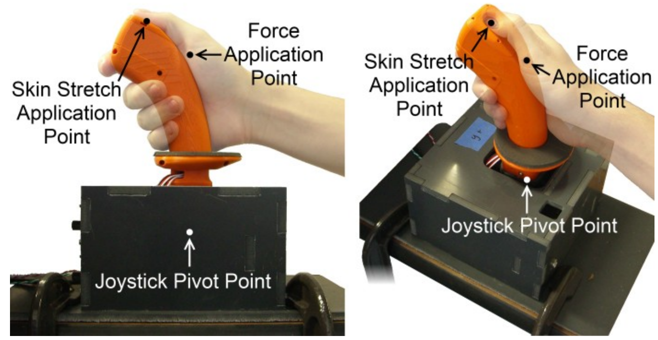

Figure 1. Joystick device with relevant reference points.

The joystick's skin stretch tactor is located 29.2 mm above and 40.3 mm forward from the reference point for measuring applied force (i.e., 169.2 mm above the joystick pivot). The plane of motion of the skin stretch tactor is tilted back out of plane 27º from the joystick's base plane. Our pilot tests indicate that the skin stretch cues are perceived as being in the same frame as the rendered force despite this rotation and translation; this is in agreement with previous research [6]. The joystick is free to move between ±25º in both the distal/proximal and lateral directions, but is constrained by a virtual fixture to move only ±12º during the experiment.

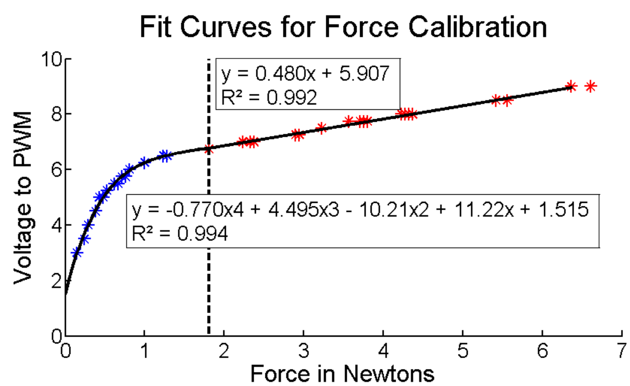

Figure 2. Piecewise data fit for force calibration. The dashed line indicates the transition point between the two fits.

For the experiment, the entire device is located at waist level such that the participant can move the joystick handle freely and comfortably while seated (see Fig. 4). Three padded hand supports of differing heights are provided to help prevent fatigue during the experiment. A support is also provided for the participant's elbow/arm.

The current shape of the joystick handle is the result of multiple design iterations. The joystick handle is designed to be ergonomic and effective at rendering cues to users with a variety of hand sizes and shapes. Its design also imitates the size, shape, angle, and hand-grip of commercially available gaming joysticks. The ergonomics of the handle design and 27º tilted plane of the tactile display allow the user to localize the skin stretch cues on the distal portion of their thumb pad, improving perception of skin stretch cues and avoiding thumb-joint discomfort.

Skin stretch stimuli are provided to the participant's thumb tip using a ThinkPad TrackPoint tactor. The tactor is placed in the center of a 14 mm diameter conical hole (aperture), which is used to restrain the motion of the user's thumb when skin stretch cues are applied. The tactor is attached to a 2-axis flexure that is driven by two Futaba S3154 Digital High-Torque Micro Servos. The design and fabrication of the skin stretch portion of the device are modeled after the details found in [7] and [14]. Fig. 3 exemplifies the interface between the thumb and the skin stretch tactor used in the experiment.

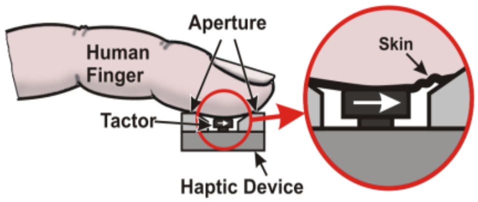

Figure 3. Skin stretch tactor interface, including aperture finger restraint.

Positioning accuracy of the tactor was characterized by connecting the tactor to two orthogonal US Digital linear encoders (PE-500-2-I-S-L), which have 12 µm resolution, with spring steel wires. The path of the tactor is repeatable in each of the 16 directions used in the experiment, with a standard deviation of at most 0.42º. Hysteresis in the flexure results in approximately 0.07 mm of center drift of the tactor. However, this has a minimal impact on the rendered path direction, as the center drift is small when compared to the total tactor displacement during cues.

4 Experimental Methods

The experiment consists of four sections, each corresponding to one of the four cue types given. A reduced Latin Squares is used to reduce the number of permutations needed for balanced testing. Participants receive cues via the specified cue type and respond by moving the joystick in the perceived direction of the cue.

Of the 19 participants who completed the experiment, 15 were male and 4 female. Participant ages ranged from 21 to 53. All but 5 participants reported right hand dominance.

Procedure

Directional cues are provided to the participants in 16 directions distributed nearly evenly over 360º, though participants are told that they can receive cues in any direction. The cues are not evenly distributed due to small offsets (< 2.7º) between the equally spaced tactor commands and their resulting motions. However, as these motions are straight and repeatable, force cues are modified to match the rendered directions of the skin stretch cues.

The experiment is limited to 16 directions to ensure proper calibration and matching between the skin stretch and force cues. Results from a prior 16-direction identification experiment indicate that participants would not be able to discern between 16 or more directions [7].

Each test section consists of 10 repetitions of the 16 directional cues, presented in a random order. Test sections take approximately 12 minutes to complete, resulting in a total experiment duration of 50 minutes.

Each participant holds the device in his/her right hand such that the tip of the thumb pad makes contact with the tactor and the thumb is constrained by the aperture. The hand and arm supports are adjusted to fit the participant. The participant's arm and the device are covered by an opaque cloth throughout the duration of the experiment to prevent any visual cues from joystick or tactor motion. Instructions are provided on the computer monitor, but no other visual feedback is provided. White noise is played on noise cancelling headphones during testing to eliminate any auditory cues from the device's motion. Fig. 4 shows the experimental setup.

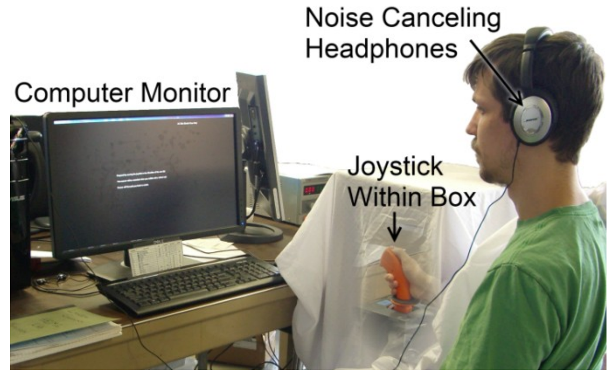

Figure 4. Experimental setup. Cloth and box are shown as transparent for clarity.

Participants are instructed to hold the device as stationary as possible while direction cues are rendered. This is done so that participants perceive cues based on the experienced forces (and skin stretch) rather than from the motion of their hand. This also helps demonstrate that the low-level forces used in the experiment are not capable of destabilizing the device while it is held by the participant.

Direction cues are presented in the following sequence. A virtual fixture helps move the joystick to within 4.3º of its vertical (centered) position before each cue. Once centered, a tone indicates that a haptic cue will be delivered. After rendering the cue, a second tone is played through the participant's headphones to indicate that he/she should now respond. The participant responds by moving the joystick in the perceived direction of the cue. After responding to the cue, the participant returns the joystick to the center position with the assistance of the virtual fixture and the next cue is rendered.

Before testing, a brief training period familiarizes participants with each of the cue types and the response process. Before each section, cue-specific training is also provided to help familiarize participants with the cue type being given during that section. Participants are instructed to take as much time as needed to familiarize themselves with the cues and find a good cue-response cadence. On average, training takes 2 minutes. The experimental protocol is approved by the University of Utah IRB.

Cue Types

Four haptic cue types are presented in this test. Three of these cue types include force feedback, skin stretch feedback, and combined force and skin stretch feedback, all rendered in a "pulsed" manner. The fourth cue type consists of skin stretch feedback rendered in a "sustained" manner.

Pulsed cues are linearly ramped from zero to their specified maximum magnitude over 300 ms to prevent instabilities due to suddenly changing cue conditions. The maximum magnitude of force cues is 1.25 N. The maximum tactor displacement of skin stretch cues is 0.75 mm. This cue magnitude is then held constant for a 300 ms pause to prevent out-back stimulus masking [15]. Pulsed cues are then ramped back to zero magnitude over a period of 200 ms. The cue profile is shown in Fig. 5. Using the same profile for force and skin stretch cues ensures that each cue feedback condition is directly comparable and matches when combined.

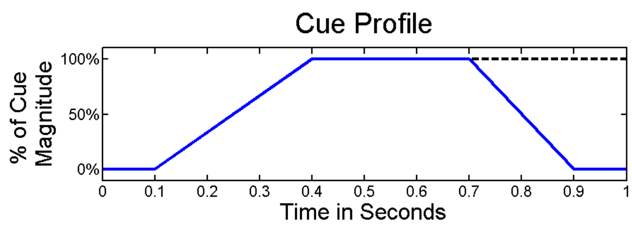

Figure 5. Profile of pulsed (solid) and sustained (dashed) cues.

Sustained cues are rendered in the same manner as pulsed cues, with the exception that instead of ramping back to zero, the magnitude is held constant at its maximum until a response is recorded. Sustained cues are only given during skin stretch feedback as sustained force cues would affect the participants' response.

Force and displacement magnitudes and time profiles are selected based on pilot testing as well as previous research [5], [8]. The force magnitude is selected to be high enough that its direction is perceivable, but still low enough to be unlikely to create instabilities in haptic simulations. Skin stretch displacement and speed are selected to match the profile of the force cues while providing a comparable level of performance. Force and skin stretch cue magnitudes are also selected to avoid ceiling effects in user performance, allowing potential improvement during the combined force and skin stretch condition.

Data Analysis

Two response characteristics are of interest in this study: the ability to respond in the correct direction (accuracy) and the variation between those responses (precision). An ANOVA with a post hoc Dunnett's T3 test was performed on the response direction error, which serves as a measure of accuracy, and the standard deviation of the response error, which serves as a measure of precision.

Participants' responses are recorded by fitting a line to their outbound response motions. This ensures that responses are not influenced by returning to a slightly different center position between each cue. Responses are only accepted if they meet the following 3 criteria:

1) The response starts within 5.7º of the workspace center, i.e., minimal hand-position drift occurred during the applied cue.
2) The R^2 value of the line fit is above 0.8, indicating that the participant's response is a relatively straight line.
3) The response error is less than 3σ from the participant's mean.

These criteria help provide more meaningful data and eliminate erroneous data points that misrepresent actual participant performance. Of the participants tested, 3 are removed from the analysis for not following instructions, leaving 16 participants. One disqualified participant responded over 60% of the time before the cue finished and thus provided little meaningful data during the response phase. The other two participants self-reported that they had responded only in the four cardinal directions, despite being instructed that cues would be delivered in any direction and that they were to respond in that exact direction. Only 2.4% of the remaining responses are rejected based on the 3 criteria listed above. The majority of these responses, 2.2%, are rejected for being preemptive (before the response tone). These early responses do not provide adequate data for line fitting and bias the response motion during cues where force is present. Only 0.2% of responses are rejected based on a poor linear fit. Very few responses are rejected as outliers.

5 Results and Discussion

Both the response error and its standard deviation fail a Levene's test, indicating unequal variances [$L(3,1020) = 14.8$, $p < 0.0001$] [$L(3,1020) = 30.65$, $p < 0.0001$]. These metrics pass an omnibus one-way ANOVA test performed using SPSS, correcting for unequal variances between cue types [$F(3,1023) = 48.07$, $p < 0.0001$] [$F(3,1023) = 15.81$, $p < 0.0001$]. Figs. 6 and 7 show the participants' mean response error and its standard deviation under each cue type. Error bars indicate 95% confidence intervals.

Also, while not of particular interest in this study, the average response time is 0.86 seconds across all cue types, which marks the time from when the response tone was played to when participants reached the ±12º virtual fixture with the joystick.

A post hoc Dunnett's T3 test (for unequal variances) on accuracy indicates two significant levels of response error. One level consists of the skin stretch cue types, both pulsed and sustained. These cues provide a significant counter-clockwise rotational bias between 10.2º and 12.2º, respectively. This is in agreement with the findings in [7] and [7], which used a similar thumb orientation. This bias may be an effect of the specific thumb orientation used in these experiments, which strains the user's thumb slightly to hold their thumb in an extended position. Pilot studies indicated cue magnitude had little effect on this bias.

The other level found in post hoc testing consists of both force feedback and combined force and skin stretch feedback. Both of these cue types show significantly higher accuracy than the skin stretch cue types. Force feedback provides no significant bias, [$F(1,255) = -0.50$, $p = 0.6213$] which is consistent with findings in [12]. Interestingly, integrating skin stretch cues with force cues did not significantly increase response bias over force cues alone. This suggests that the force cues have a more dominant effect on accuracy than skin stretch cues.

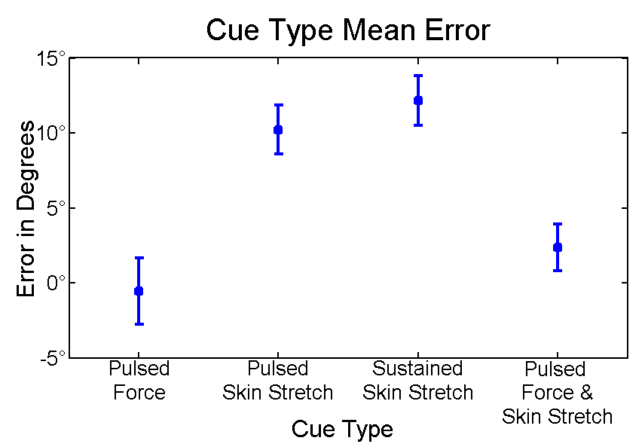

Figure 6. Mean error and 95% confidence interval for each cue type.

The post hoc Dunnett's T3 Test on the standard deviation of the error indicates three levels of significance. Force cues performed worst with a standard deviation of 22.9º (RMS ~ 20.4º). This is almost twice the 10.3º RMS error reported by [12]. This difference could possibly be attributed to the significantly higher forces used in their experiment. Both pulsed and sustained skin stretch cues performed nearly the same, with a standard deviation of approximately 19.6º. Finally, participants performed the best with combined force and skin stretch cues, with a standard deviation of 15.5º. This improvement implies an additive and integrable relationship between force and skin stretch cues (i.e., either can be used in place of the other). Therefore, combining skin stretch feedback with force feedback improves precision without a significant detriment to accuracy.

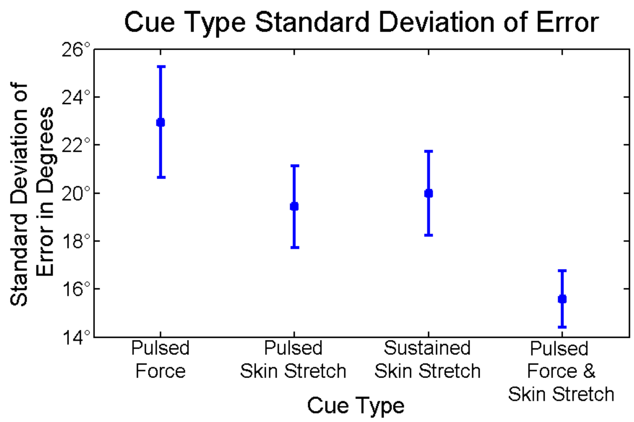

Figure 7. Standard deviation of error and 95% confidence interval for each cue type.

While the force and skin stretch cues are shown to have significantly different precision, their performance can be adjusted by changing their respective magnitudes. However, skin stretch cues cannot cause feedback instabilities and thus can be increased to higher performance levels than force cues by increasing the magnitude of applied skin stretch.

Although mean error for participant responses to force-based cues across all directions is nearly zero, significant anisotropy exists in the error [$F(15,303) = 14.10$, $p < 0.0001$] (see Fig. 8), similar to that seen by [12]. Force cue responses are very accurate in the four cardinal directions, with responses to oblique cues biasing towards the lateral directions. Since skin stretch cues do not demonstrate similar anisotropy (see Fig. 8), this is likely a result of the relative stiffness of the arm in the distal/proximal directions compared to the lateral directions [12]. Participants reported that cues in the lateral directions felt stronger than in the distal/proximal directions, supporting this theory. Direction, however, is not a significant predictor of standard deviation under each cue type [$F(15,303) < 0.83$, $p > 0.6326$]. Fig. 8 shows the effect of cue direction on response error. Both reported ANOVA tests include correction for non-uniform variances between directions.

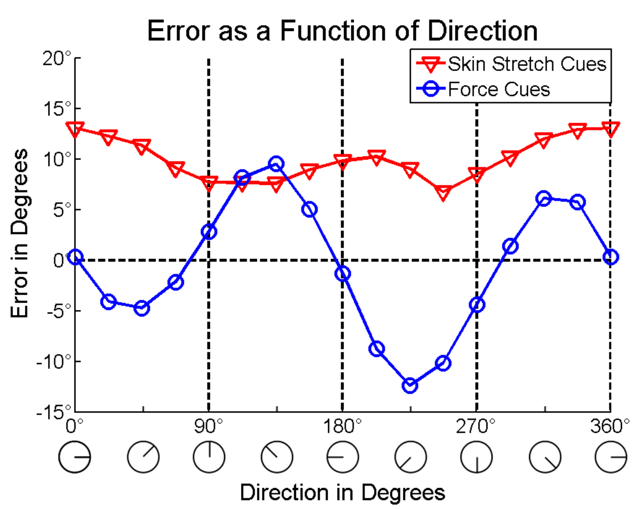

Figure 8. Directional dependence of error for force and skin stretch cues.

6 Conclusions/Future Work

A force feedback joystick with an integrated skin stretch display was prototyped and is used in a directional matching experiment to evaluate the perception of force and skin stretch cues, individually and when combined. The handle of the joystick was designed to provide an ergonomic grip and placement of the user's thumb tip in the center of the skin stretch display that is located at the top of the joystick's handle.

Our results suggest that force and skin stretch cues are additive and integrable, indicating that skin stretch cues can be used to supplement or replace low magnitude force cues. Skin stretch cues result in higher precision, but lower accuracy, than force cues. Integration of the two cue types results in improved precision, while retaining high accuracy. Skin stretch cue magnitude can also be increased without the risk of creating instabilities, making it a viable candidate to augment or replace force feedback in safety-critical situations.

Future work will investigate the effectiveness of skin stretch cues at replacing or supplementing low magnitude forces in a path following task representative of a medical insertion procedure. Additionally, the minimum force magnitude at which performance benefits are still seen when integrated with skin stretch feedback will be investigated.

7 Acknowledgements

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