Back-to-Back Skin Stretch Feedback for Communicating Five Degree-of-Freedom Direction Cues

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Abstract

This paper presents the design and development of a novel device for providing tactile feedback in five degrees of freedom (5-DOF). Four translational and four rotational motions of the hand can be communicated to a user using two independently controlled 2-DOF skin stretch feedback devices placed back-to-back. An additional two rotational motions of the hand can be communicated through spiral motions of the two skin stretch feedback devices. The user's index finger and thumb grasp the device at the location of the moving contactor (tactor) of each of the 2-DOF skin stretch displays, respectively. Experiments show user responses to have high directional accuracy (> 98%) for each of the five degrees of freedom communicated by the device. A second experiment also shows a proof of concept for using the back-to-back skin stretch display to guide users' hand motions to match a specified target angle in a one degree-of-freedom wrist rotation task. Findings from this preliminary study will be used in future studies to investigate users' ability to track paths in multiple degrees of freedom or to direct the hand motions of a user, which could be relevant to tasks such as upper limb rehabilitation, swing training, or other motion training.

Keywords: Haptic interfaces, skin stretch feedback, direction identification, angle matching.

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

Haptic feedback can be used to provide additional sensory feedback to a user performing a variety of tasks. If the haptic feedback is designed to closely align with an intuitive response, it is also possible to provide haptic feedback in a way that does not require a large amount of attentional resources. While there are several forms of haptic feedback that can be used to communicate directional feedback, we are particularly interested in guiding the motion of the hand or arm of a user. This criterion has led us to focus on providing tactile feedback on the hand, so that the feedback and desired motions are collocated on the body. In addition, the fingertips are a region of high sensitivity [1], and will be capable of distinguishing precise cues.

In this paper, we investigate the use of tactile skin stretch feedback cues to provide directional information in five degrees of freedom. We have developed an initial prototype using two independently controlled 2-DOF skin stretch feedback devices placed back-to-back. The design of the 2-DOF skin stretch feedback devices and user performance in a 2-DOF direction identification task is presented in prior work [2]. However, the addition of a second 2-DOF skin stretch enables us to convey *direction cues out of the plane* of either of the two utilized parallel shear displays, which is the primary contribution of this paper.

The user's index finger and thumb grasp the back-to-back shear feedback device at the location of each of the 2-DOF skin stretch display's actuated tactors, respectively. Translational direction cues are communicated by moving the tactors in the same direction, whereas rotations are communicated by moving the tactors in the opposite directions (i.e., tactors move differentially).

This device could be used to provide haptic feedback in a wide range of applications, from medical to entertainment applications. Its compact nature permits this form of tactile feedback to be embedded within a variety of handheld items. The experiment presented in this paper is meant to show feasibility to provide high degree-of-freedom direction communication and closed-loop positioning on a single degree of freedom of wrist motion; future experiments are planned to more fully characterize the potential of the device.

We first present related work from the literature followed by a design overview of our handheld tactile feedback device. We then present experimental procedures and discuss user performance results with this device.

2 Background

Previous studies have taken advantage of haptic feedback to train motion of the arm. In [3], tactile feedback was provided to students trying to learn new motor skills. Use of the study's vibrotactile sleeve showed an improvement in accuracy of the target motion and an accelerated learning rate when compared to visual feedback of the motion path. Force feedback can also be used to guide hand motions, as was used in [4] to aid in teaching Chinese handwriting.

Other types of haptic feedback have also been applied to guiding body motions. A combination of skin stretch feedback and vibrotactile feedback was used in [5] to aid in gait retraining. Rotational skin stretch feedback was studied as a way to provide feedback for motion training in [6]. With this feedback, users were able to assess the magnitude of the feedback to position virtual objects within ±6.5 percent of their total range of motion.

In addition to use for training specific path motions, haptic feedback can also be used to guide arm motions by providing feedback when a joint position is incorrect [7]. Vibrotactile feedback, in combination with visual feedback, was proposed to improve current virtual rehabilitation systems for stroke patients. Vibrotactile feedback was also used in [8] to communicate joint misalignment of the upper body, with the haptic feedback being as effective as visual feedback for one degree-of-freedom movements of both the arm and torso. In [9], vibrotactile feedback was used to attempt to correct wrist and elbow motions, but the

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IEEE World Haptics Conference 2013
14-18 April, Daejeon, Korea
978-1-4799-0088-6/13/$31.00 ©2013 IEEE

addition of this feedback did not improve motion tracking performance. These three studies require a user to wear multiple vibrotactors either as a sleeve or as several belt-type bands. In addition, they also focus on guidance of arm or torso linkages rather than precise manipulation of a human hand.

In the work of [10], vibrotactile feedback in a band placed around the wrist was used to compare haptic cues to verbal instructions on rotation and translation. While the vibrotactile array outperformed verbal instructions for rotations, verbal instructions were superior for translations. In addition, the update rate was slower than required for fine adjustment tasks such as our envisioned use of skin stretch feedback through the fingertips.

For finer precision tasks, feedback is needed to guide the movements of a hand, as opposed to the entire upper body or arm. In [11], a comparison was made between ten forms of tactile feedback used for guiding the rotation of the wrist. The participants in that study were able to accurately move to target rotation angles (to within ±7.5° of the target angle in an average of about 2 seconds for the best of the 10 presented forms of haptic feedback) and follow trajectories. While their work is a great contribution to understanding performance under multiple types of tactile feedback in a single degree-of-freedom task, our approach of providing skin stretch feedback through the fingertips extends upon their work to potentially achieve high accuracy in multiple degrees of freedom.

Our research group's previous studies on skin stretch tactile feedback have explored the capabilities of skin stretch feedback through the fingertips and thumbtips within a single plane. It is known that users can accurately determine directional information with as little as 0.5 mm of displacement of a tactor [12]. Further research in [2] and [13] investigates user performance with two skin stretch feedback displays placed side by side within a game controller. Findings show that simultaneous cues through two fingertips result in higher accuracies than cues delivered to a single fingertip [2].

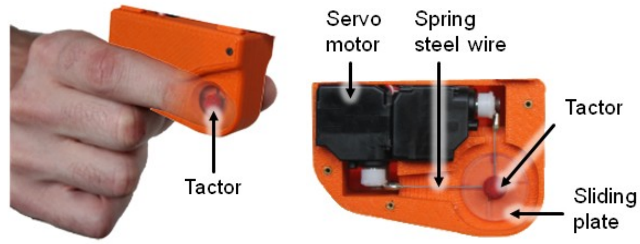
We see potential advantages to using skin stretch feedback to guide a person's hand motions. Skin stretch feedback can be used to communicate directional information with high accuracy. Furthermore, skin stretch feedback can be presented using a compact device, or embedded within a device, without adding additional bulk to a system or requiring a large contact area with the user. For these reasons, we have developed a device to guide fine hand motions and rotations. The device presented in this paper utilizes two of the previously developed skin stretch feedback devices [2], placed back to back to communicate out-of-plane rotation cues in addition to the planar direction cues that each 2-DOF skin stretch device is capable of communicating. A combination of these rotational and translational cues could potentially be used in the future to guide a human hand along a path. This could be used for surgical training or hand or arm rehabilitation, among other possible applications. Details of this device and experimental work follow.

3 Design

A combination of hardware and software was developed to evaluate the feasibility of providing tactile cues in five degrees of freedom with skin stretch feedback.

3.1 Hardware Design

Tactile cues were provided through two skin stretch display devices mounted back to back. Each skin stretch display is similar in design to those in [2] utilizing two RC hobby servo motors linked to a sliding plate on which the tactor is mounted, through spring steel wires (see Fig. 1(b)). The device is designed for a user



(a) (b)

Figure 1: An (a) external view and (b) internal view of the index-finger side of the device, showing motors, tactor, sliding plate, and spring steel wires. The design is mirrored for the tactor on the thumb-side of the device.

to hold with his/her thumb and index finger in contact with each of the skin stretch tactors, which can move independently from each other. Each tactor sits in the center of a small conical recess, which we refer to as an aperture. The purpose of an aperture is to restrain the lateral motion of the user's finger and thumb when stimulated with tactile feedback.

The device tactor is the point of contact between the user's finger and the tactile feedback device, which is actuated to create sensations on the user's fingertips. Translational direction cues are communicated by moving the tactors in the same direction, whereas rotations are communicated by moving the tactors in the opposite direction (tactors move differentially) to create a simulated "force couple" or torqueing sensation on the fingertips. The tactors have a workspace of ±2.5 mm in each direction.

Our device was mounted to the stylus of a Phantom Premium six degree-of-freedom device that has an instrumented stylus gimbal, allowing for high precision tracking of device position

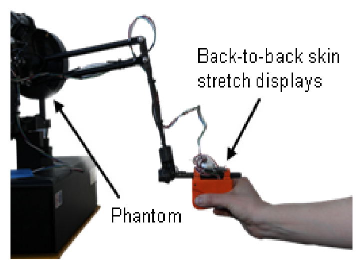


Figure 2: Back-to-back shear display mounted to a SensAble Phantom Premium 1.5. A participant responds to cues in all 10 directions/rotations from his/her centered/home position of his/her hand. His/her responses are recorded using the Phantom.

and rotation during testing.

3.2 Software Interface

Software was developed in Visual Studio C++ to command the motion of the skin stretch tactors and to track the position and rotation of the Phantom Premium stylus. The software communicated with the skin stretch device through USB communication interfaced with a dsPIC33E microcontroller to manage the position and motion of each of the skin stretch tactors.

A calibration of each skin stretch display ensures that the commanded direction cues resulted in straight, radial movements of the device's tactors, as in [2]. Calibration resulted in a 5x5 grid of known tactor locations, which were stored on the PC for table lookup and bi-linear interpolation, in order to provide the proper motion of each tactile display. The calibration utilized an alignment fixture that used a pair of US Digital linear encoder probes (PE-500-2-I-S-L, 12 µm resolution), which were positioned orthogonally to record the tactor paths along the axes of the spring steel wires.

4 EXPERIMENTAL METHODS

A two-part experiment was performed to characterize user responses to the ten different directional cues (5-DOF). Fourteen participants (mean age = 27.9, 12 male, 12 right-hand dominant) performed both portions of the experiment, with all participants first completing the direction matching task portion, followed by the target angle matching task. This ordering allowed participants to begin with the simpler directional response task before moving on to the target angle matching task. All participants had no previous experience with our device. Participants wore noise cancelling headphones playing white noise to cancel out noise from the servo motors and minimize environmental distractions. Experiment protocol is approved by the University of Utah IRB.

For each portion of this experiment, participants were instructed to begin with the stylus and their right hand in a centered "home" position. The home position was with their hand slightly in front and to the side of their torso, so that users would be comfortable and could perform all ten possible motions without reaching the limits of the device or the range of motion of their wrist. The home position was not exactly the same every trial due to drift in the user's home position. The software therefore used their position at the beginning of each trial when calculating each participant's relative response.

4.1 Tactile Cues

Distinct tactile cues were developed to communicate four translations and six rotations with the device. These ten motions were used as the haptic cues in the experiment.

In addition to the ten motion combinations, the cues were presented in two ways to participants: pulsed and sustained. In the pulsed mode, the tactors used a pulsing motion, moving outward toward the direction of the cue at a rate of 5 mm/s, and then back towards the center of the aperture as shown in Fig. 3(a), repeating this back and forth motion once every 1.2 seconds until the participant responded to the cue. In contrast to our lab's past experiments (e.g., [2, 12-14]), a pause between the outbound and return motions of the tactors was not included because the tactor displacements were so large that they were deemed unnecessary.

In the sustained mode, the tactors moved to a sustained position, moving outward at a rate of 5 mm/s toward the direction of the cue and remaining there until the participant responded to the cue as shown in Fig. 3(b). Following a response, the tactors would return to the center of the respective aperture.

In both the pulsing and sustained modes, the outbound motion of the tactor was the same. The maximum tactor displacement for each mode was 2.5 mm from the starting (centered) position, with the tactor moving at a rate of 5 mm/s towards the maximum outbound position. Tactor displacement over time is shown in Fig. 3. The ten tactor motions and resulting hand motions are described in greater detail in the following subsections.

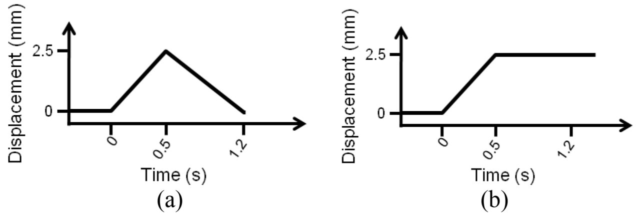


Figure 3: Tactor displacement from center of aperture for (a) pulsing and (b) sustained feedback modes.

4.1.1 In-plane Translations

The fore, aft, up, and down translation cues were delivered by simultaneously moving both the index and thumb tactors together towards the front, aft, top, or bottom end of the device, respectively, as indicated in Fig. 4.

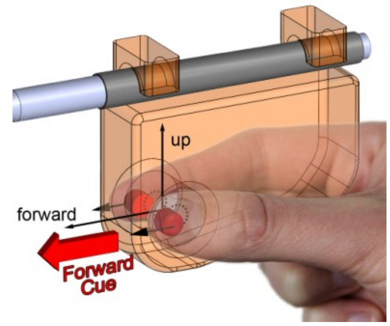


Figure 4: Two in-plane translations are indicated with the up and forward axes. Black arrows adjacent to the red tactors indicate the direction of tactor motion. The forward tactor motions indicate a "forward cue." The dashed black circle in the center of the apertures indicates the centered positions of the tactors.

4.1.2 Out-of-Plane (Roll/Yaw) Rotations

The out-of-plane roll and yaw rotation cues were delivered by simultaneously moving the index and thumb tactors, but in opposite directions. For roll rotation cues, one tactor moved towards the top of the device and one tactor moved away from the top of the skin stretch device. For yaw rotations, one tactor moved towards the front of the device and one tactor moved away from the front end of the device. These four out-of-plane rotations are shown in Fig. 5 below.

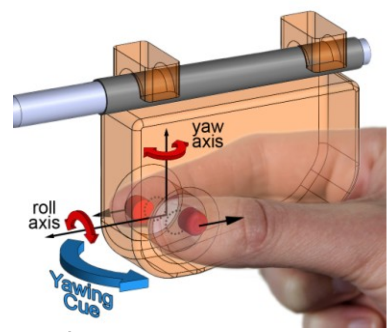


Figure 5: Two out-of plane rotation axes are indicated with the roll and yaw axes. Black arrows adjacent to the red tactors indicate the direction of tactor motion. The depicted fore/aft tactor motions indicate a left "yawing cue." The dashed black circle in the center of the apertures indicates the centered positions of the tactors.

4.1.3 In-Plane (Pitch) Rotations

The pitch rotation cues were delivered by the two tactors moving together in a spiral circular motion, either rotating clockwise or

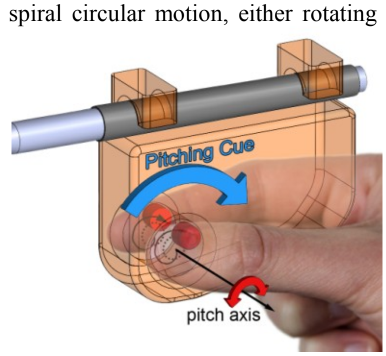


Figure 6: One in-plane rotation is indicated with the pitch axis. A spiral tactor motion, indicated with a spiral arrow adjacent to the tactors, depicts the path of the tactors for indicating a "pitching cue." In response, a user would pitch the device upward.

counter clockwise. The tactor motion began by spiraling outward over one half rotation in 0.32 s to get to the circle radius of 0.75 mm. Once the tactor reached this radius of 0.75 mm, it circled at a rate of one rotation per second until the user responded (or an approximate tactor speed of 4.7 mm/s, similar to the 5 mm/s tactor speeds for translational and out-of-plane rotational cues).

4.2 Direction Matching Task

This portion of the experiment was broken into two subsections: one subsection with pulsing skin stretch cues, and one subsection with sustained skin stretch cues. The ordering of these sections was balanced across participants. All participants began with a short training period, of six sustained and six pulsing cues, provided in the order the participant would complete the experiment. Each subsection consisted of 200 cues, 20 cues for each of the ten possible motions described in the prior section. The provided in-plane rotation (pitch) cues were rendered the same way, as described in section 4.1.3, in both the pulsing and sustained mode tests, since we didn't want to modify the circular motion of the tactors for pitch-type cues to make them resemble the pulsing or sustained nature of the other cues. Therefore, these cues were included in both portions of the experiment in order to keep both the pulsed and sustained cue portions of the experiment with an equal number of directions that users had to distinguish between. This circular motion was interpreted differently by different users due to the nature of the circular motion of the cue. Some users naturally desired to translate the entire device in a circular pattern, while others naturally interpreted the cue as the desired in-plane pitch motion. To mitigate this issue, the desired angular hand motion response was explained in participant training.

At the start of a trial, participants began at their home position, and pressed the spacebar on a keyboard for a new cue, which began after a short pause. Once the participant translated the stylus more than 5 cm or rotated the stylus more than 0.15 radians (8.6 degrees), a ding noise was played on the headphones to indicate that the response was recorded. Participants then returned the stylus to the home position, and pressed the spacebar to receive the next cue.

Participants were instructed to respond to each cue as quickly and accurately as possible. The software recorded the time from the start of a cue to a response, as well as the target, beginning, and end positions/rotations of the stylus.

4.3 Target Angle Matching Task

An angle matching task was performed on a single axis in this initial experiment as a simple demonstration of controlling closed loop positioning of human limb movements with this technology. Our initial demonstration uses only the pronation and supination directions, to allow for a comparison to [11]. As this is a rotational cue in the pronation and supination directions, the tactor motions are in the opposite direction from each other, with the tactors either moving towards or away from the top of the device.

The target angle was communicated by applying a ramp motion profile to the two tactors, where each tactor moved at 1 mm/s to the location corresponding to the desired angle of wrist rotation. A wrist rotation of 40 degrees was linearly mapped to 1.25 mm tactor motions, from their centered position. Tested target wrist rotation angles were at least 10 degrees but less than 40 degrees from the starting wrist orientation.

This target angle matching task consisted of both open-loop and closed-loop portions. The open-loop target angle matching is based on scaled tactor-to-wrist rotation motions. This initial experiment also used closed-loop position matching with proportional rate-based feedback. The proportional rate-based closed-loop controller applies a relative tactor velocity that is in proportion to the user's current angular error.

After training with 5 cues, we recorded the participants' next 20 target matching trials. This was repeated for both portions of the target matching experiment, with all participants completing this task in the same order: open-loop and then proportional rate-based feedback.

4.3.1 Open-Loop Target Angle Matching

In this mode, participants received a skin stretch cue proportional to the magnitude of the angle to rotate their wrist and the device. The user's maximum wrist rotation of 40 degrees was proportionately mapped to 1.25 mm of tactor motion relative to the tactors' centered position. This range was used so that additional feedback could be given beyond the initial cue with the closed-loop proportional controller, while remaining within the total workspace of ±2.5 mm from the center position of each tactor. The target angle was communicated by applying a ramp motion profile to the two tactors, where each tactor moved at 1 mm/s. Participants rotated the device in the perceived magnitude and direction, and then held the device steady for one second for a response to be recorded. Training for the open-loop portion of the experiment included experiencing the full 40 degree wrist rotation and related 1.25 mm tactor motion in each direction, to give participants a sense of relative scaling.

4.3.2 Closed-Loop Target Angle Matching

In this mode, participants received a ramped open-loop skin stretch cue, as described above in Section 4.3.1, while also receiving closed-loop feedback. The closed-loop proportional rate-based feedback cues guide a participant to within ±2 degrees of the target angle. The closed-loop proportional cues move the tactors at a velocity in proportion to the user's current angular wrist error. The proportional gain was set to K_p = 5 mm/s/Radian, which commands the velocity of the tactors to force the user in the correct direction. This proportional rate-based (velocity) feedback is superimposed on the feed-forward tactor travel that matches the target wrist rotation angle for each trial. When the device was held within a range of ±2 degrees of the target angle for one second, the response time was recorded.

5 Results and Discussion

5.1 Directional Matching Results

The results from the directional matching task were split into three categories for both the pulsing and sustained tactor motions: translations, out-of-plane rotations (roll and yaw), and in-plane rotations (pitch). The rotations were separated this way due to the different nature of the tactile cues.

Responses with completion times outside of 3σ of the mean of a participant's response time of cues in each analysis group (up/down and fore/aft translations, roll and yaw rotations, and pitch rotation) were considered statistical outliers and were rejected prior to statistical analysis. In total, 113 out of 5600 responses (~2%) were rejected as outliers. Following outlier rejection, response accuracies and times of all participants were compared for each group and each tactor motion type.

A one-way within subjects analysis of variance (ANOVA) shows no significant difference in participant response accuracies between different cue types [$F(5,5481) = 0.77$, $p > 0.57$]. Participants had a mean response accuracy of at least 98% for each cue type (Fig. 7). This is consistent with [11], in which all

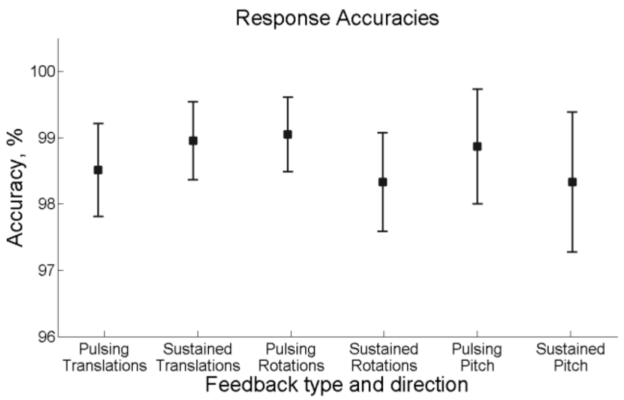


Figure 7: Mean response accuracies and 95% confidence intervals for each cue type.

but two of the ten modes reported by Stanley and Kuchenbecker had mean response accuracies of 95% or greater.

Subject response times among cue types are shown in Figure 8. A one-way ANOVA shows a significant effect of cue type on response time [$F(5,5481) = 256.98$, $p < 0.0001$]. A post hoc comparison using Tukey's honestly significant difference criterion shows that the mean response time of rotations are faster than translations under the same rendering mode. Additionally, both translations and rotations showed significantly faster response times when rendered in sustained mode over pulsed mode. This improvement is likely due to sustained mode's similarity to real world interactions, and is consistent with findings in [14] where users performed better in video games when provided with sustained feedback.

Due to the spiral path of pitch cues, their response times were found to be significantly longer than all other cue types with the exception of pulsing translation cues. While the spiral pitch cues were delivered in the same manner in both the sustained and pulsed cue subtests, pitch cues during the sustained portion of the test were found to have a significantly longer response time than those during the pulsing portion of the experiment. One possible explanation for this is that the pitch cues were a greater contrast to the pulsing cues, and participants were able to distinguish these cues quicker during the pulsing portion of the test.

Response times from our tests are much quicker than those in [10], where the fastest mean response time was 5.9 s, but slower than reported in [11]. The difference in response times could be partially due to the experiment requirements for the amount of motion needed before a response was registered, the possible degrees of freedom to distinguish between, or due to differences in experiment hardware. While it is difficult to compare between experiments because each has different requirements, our findings

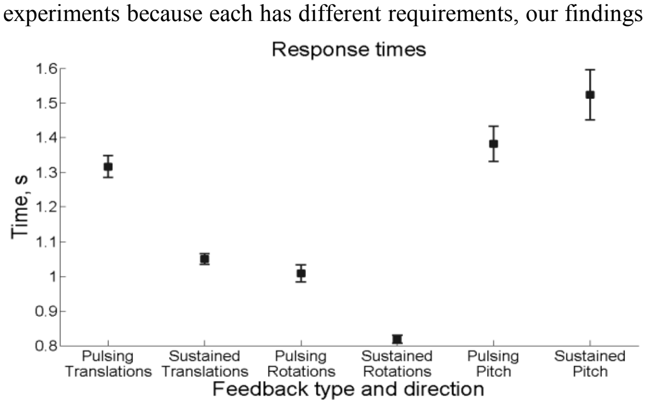


Figure 8: Mean response times and 95% confidence intervals for each cue type.

were consistent with [10], as rotation response times were faster than translation response times.

Results from this test demonstrate our ability to provide guidance of users' hand motions in 5 degrees of freedom via skin stretch feedback with back-to-back skin stretch displays.

5.2 Target Angle Matching Results

Trials with completion times outside of 3σ of a participant's mean trial time for either open-loop or closed-loop cues were rejected as outliers. Across all participants, 15 out of 840 target angle matching cues were rejected as outliers. Following individual outlier rejection, trial times of all participants were compared for each portion of the target angle matching task. The trial was complete once a user stayed at a constant angle for the open-loop case, and within the correct angle range for the closed-loop task, meaning the trial time is equal to settling time plus one second.

5.2.1 Open-loop target angle matching

During the open-loop target angle matching, a reference skin stretch cue was provided at 1 mm/s until the tactors reached the relative position that mapped to the intended target angle. The mean response time for open loop responses was 1.21 seconds (this would be 2.21 seconds if we include the 1 second participants held the position). Participants demonstrated the ability to closely match a given tactor motion to a wrist rotation angle. Figure 9 shows participant responses as a function of target rotation. Target rotations were chosen to be greater than ten degrees and comfortably within the workspace of the wrist (< 40 degrees). Figure 9 also shows the trend line of all the data points combined. The best-fit trend line of all data points shows a correlation of 1.01 with an offset of 1.0 degrees, and an R^2 value of 0.9157. This indicates that participants were able to map the magnitude of the tactor motion to a corresponding angular rotation. A participant's typical response trajectory for open loop target angle matching is shown in Fig. 10(a).

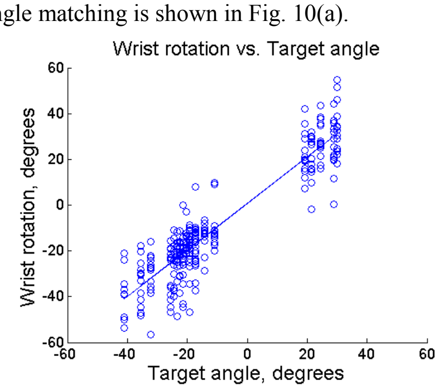


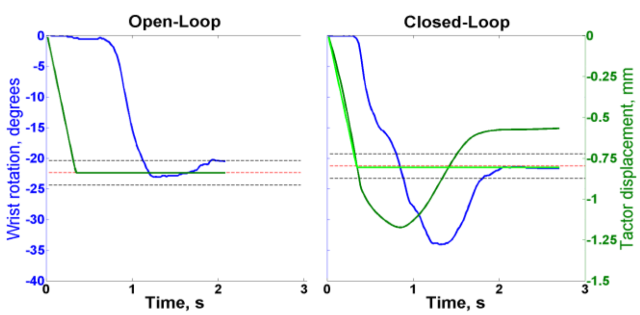
Figure 9: Response wrist rotation angle versus target angle, with best-fit line.

While a close approximation was achieved in this open-loop feed-forward mode, the mean absolute error between the goal and response angles was 7.39 degrees. While this mean absolute angle error does not fall within our requirements for a target angle deadband, it is within the deadband used in the closed-loop angle-targeting task reported in [11]. In our open-loop angle matching task, subjects settle on an angle within ±7.5 degrees in 1.21 seconds, without additional closed-loop feedback. In the closed-loop portion of [11], settling time ranged from just below 2 s to about 4 s for the same rotation angle deadband. However, we sought to further improve upon user's targeting accuracy using closed-loop feedback.

5.2.2 Closed-loop target angle matching

By adding closed-loop proportional rate-based control to the system, user angle matching accuracy improved and participants are able to achieve response angles within ±2 degrees of the given target angles. The average response time for our closed-loop controller is 4.38 seconds, which is 5.38 seconds if including the required 1 second for the participant to remain within ±2 degrees of a given target. Trial times were expected to increase for the closed-loop target angle matching as participants adjusted to the additional feedback. In addition, the feedback during a user's initial motion caused the system to be underdamped, which created overshoot of the target angle. This behavior wasn't observed during pilot testing, but clearly additional controller tuning or investigation of other controller designs could have improved the participant's response time. Nonetheless, our tests demonstrate our ability to provide accurate guidance of users' hand motions via closed-loop skin stretch feedback with back-to-back skin stretch displays.

Figure 10 shows a comparison between user responses for a similar angle of rotation in the open-loop and closed-loop conditions. Both the open-loop and closed-loop plots show the green profile of the ramped tactor motion. While this participant's open-loop response is a little delayed from the application of the tactile display's suggested motion trajectory, his response is quite accurate. However, his delayed response in the closed-loop case causes additional tactor motion to occur which leads to an overshoot of the desired wrist rotation angle. However, he is able to respond to the reversal of tactor motion and quickly settle on the final target angle. Characterization of the closed-loop system behavior, including the participant, can clearly improve the closed loop stability of our system.



(a) (b)

Figure 10: (a) Target angle, wrist rotation, and tactor displacement for one response in the open-loop portion. (b) Target angle, wrist rotation, tactor displacement, feed-forward only tactor displacement for a response during the closed-loop portion.

6 Conclusions and Future Work

We have designed and built a back-to-back skin stretch feedback device capable of communicating directional cues in five degrees of freedom (2 translational and 3 rotational DOFs). In an experiment evaluating user performance with this device, users were able to achieve greater than 98% accuracy in recognizing cues in all five degrees of freedom under two tactile cue modes: sustained and pulsed skin stretch cues. Participants responded to sustained tactile cues quicker than to pulsing tactile cues. Their responses to out-of-plane (roll and yaw) rotation cues are faster than their responses to translational direction cues.

We have also investigated and demonstrated users' ability to match a given target angle of rotation with their wrist rotation in one degree of freedom. Users could match the target angle with an average of 7.39 degrees of error with open-loop skin stretch feedback. The addition of proportional rate-based skin stretch feedback allows users to match the given target angle within ±2 degrees.

Future plans include exploring other closed-loop controller designs for improved performance with the device. We may also explicitly model the dynamic response of the operator in our future controller designs. We also plan to investigate user performance for target angle matching on other axes and combined axes of motion.

Acknowledgments

This work was supported, in part, by the National Science Foundation under awards IIS-0746914, IIS-0904456, and DGE-0654414.

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