# Planar Hand Motion Guidance Using Fingertip Skin-Stretch Feedback

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**Abstract**—In this paper, we show that a simple haptic device can accurately guide users through planar hand movements. The device guides the user through skin stretch feedback on the fingerpad of the user's index finger. In an angle matching test evaluating two types of stimuli, users are able to discriminate between eight stimulus directions and match the motion of their hand to the stimulus direction with 10 degree accuracy. In two motion guidance tests, haptic cues effectively guide users' arm motions through the full extent of their reachable workspace. Real-time corrective feedback greatly improves user performance, keeping average user hand motions within 12 mm of the prescribed path and within 4 degree of the indicated directions. Additionally, the paper shows that participants exhibit distorted haptic perceptual responses, finding that the distortion causes a response direction bias, but that appropriate haptic feedback can correct for the effect. Such motion guidance has applications in human-machine interaction, such as upper-extremity rehabilitation.

**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, tactile direction cues, haptics, skin stretch, rehabilitation

## 1 Introduction

Haptic interfaces enable a vast array of applications in modern electronic devices. Simple haptic cueing in the form of vibrotactile feedback has already made its way into devices such as mobile phones to communicate an incoming call or message. Although simple haptic feedback is useful for on/off cues, haptic-based directional guidance offers a functional alternative to traditional guidance methods. In this paper, we explore the use of fingertip skin-stretch as a method of directional cueing for planar arm and hand motion. Tactile cueing for limb motion guidance has use in a range of applications including enhanced human-machine interaction and rehabilitation therapy. This is especially true in situations where a user's visual and auditory attention is engaged with critical aspects of a task, such as driving or GUI operation. Haptic-guided hand and arm motion could provide a benefit in driving or mobile navigation, where haptic navigation cues could direct steering motion, or in computing applications where hand or arm (i.e., cursor) guidance is needed.

An immediate application for haptic hand and arm motion guidance is low-cost in-home upper extremity (UE) motor therapy. Occupational therapy is helpful in restoring impaired motor function in stroke survivors [1], but the cost and availability of trained therapists limits patients' access to care. Other researchers have developed assisted planar mechanical devices for facilitating upper limb rehabilitation, such as the pantograph-based MIT-MANUS robot [2], [3] or a mobile-robot-based device by Satler et al. [4]. Assistive devices have also been extended to three dimensions in robotically assisted exoskeletons. The L-Exos is a low weight-high payload rehabilitation exoskeleton intended for automated rehabilitation [5]. Pneu-Wrex [6], [7], and BONES [8] are pneumatically actuated compliant-assistant upper extremity rehabilitation exoskeletons. ARMin utilizes a semi-exoskeleton with four active and two passive degrees of freedom to aid in audio-visual guided UE therapy [9]. Simpler, passive devices such as T-Wrex [10], and its commercial version, Armeo Spring [11] counteract the force of gravity to allow the user to complete video game task-based therapy. Comparative tests suggest that robot therapy, using the types of devices cited above, can be as effective as traditional human-guided therapy for stroke rehabilitation [6], [10], [12], [13].

While these robot devices have been shown to be effective in guiding patients through rehabilitation tasks, their size and cost make them impractical for at-home use. As a potential alternative, we investigate fingertip skin-stretch as a means of guiding hand/arm motions for therapy. In contrast to larger robotic devices, the fingertip skin-stretch device presented in this study does not provide force feedback. While force feedback can be useful for therapy, it requires complex robotic devices and may have safety risks for unsupervised at-home use. A device providing guidance alone, while more limited in the types of therapy it could facilitate, may be a valuable tool for safe, low-cost, long-term, at-home rehabilitation therapy [3], [14], [15]. As a first step towards using


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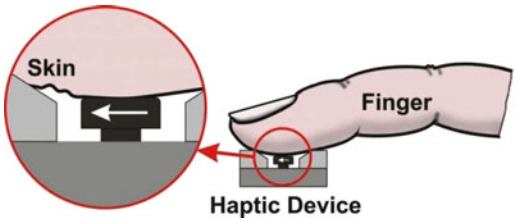


Fig. 1. Skin-stretch feedback concept.

simple haptic devices in therapeutic applications, this paper characterizes the extent to which haptic cues, without force feedback, can guide upper limb motion.

To achieve high accuracy haptic-based directional cueing, Gleeson et al. developed a lateral skin stretch device. By displacing the skin on the fingerpad in a direction tangent to the surface of the skin, Gleeson was able to communicate directional information with displacements as small as 0.1 mm at rates as slow as 2 mm/s [16]. We have adapted the lateral skin stretch display designed by Gleeson et al. [16], [17], [18] into a device intended to provide the user with high accuracy guidance in planar arm movements. In this paper, we evaluate the use of this device in three experiments. The first explores the ability of the device to accurately communicate direction information through a matching test of eight equally-spaced radial directional cues. Our prior research tested user responses in a four-direction identification task [17]. The matching test not only tests the users' identification of directional stimuli but requires contingent movement of the upper extremity in the direction of the corresponding stimuli. The latter experiments guide the user through two different types of prescribed planar motion in order to investigate user performance and characterize the spatial relationships of haptic perception.

## 2 Methods

### 2.1 Stimulus Description

Our study utilized a skin-stretch haptic device capable of providing direction cues to a user's fingertip by stretching the skin on the underside of the user's index finger, as shown in Fig. 1. The user's finger is held stationary by surrounding restraints while a tactor, a 7 mm diameter rounded rubber cylinder, contacts the exposed pad of the finger. The tactor moves in a horizontal plane, displacing and stretching the skin of the fingerpad. Users are able to perceive the direction of these skin-stretch stimuli with high accuracy, as reported in Gleeson et al. [17].

We used two types of haptic direction cues in this study: sustained cues and pulsed cues. Both types began with the tactor centered on the fingerpad. When a cue began, the tactor moved 1 mm in a given direction at a speed of 4 mm/sec.

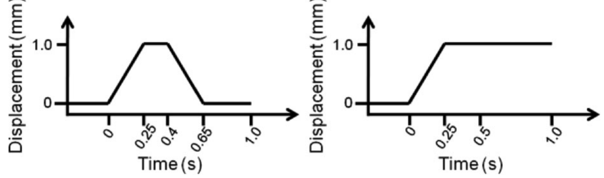


Fig. 2. Tactor displacement as a function of time for pulsed (left) and sustained (right) cues.

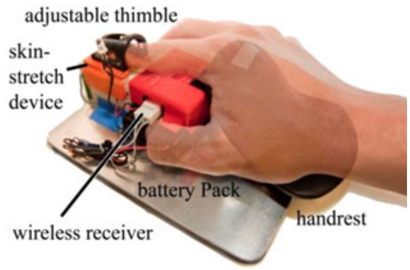


Fig. 3. Wireless skin-stretch device.

In the case of sustained cues, the tactor remained in this displaced position, 1 mm from the center of the fingerpad, applying a constant shear force to the fingerpad. In the case of pulsed cues, the tactor reciprocated back and forth between the displaced position and the center position at 1 Hz, applying pulsed shear forces to fingerpad. During pulsed cues, the displaced position was held for 150 ms and the center position was held for 350 ms. The pulsed cues are similar in cadence to a turn signal in a car, where the signal is repeated until the cue is complete. Cue trajectories are shown in Fig. 2.

While the haptic device is capable of delivering direction cues at any angle, we used only eight directions, equally spaced at 45 degree increments around a circle, as shown in Fig. 5.

### 2.2 Device Description

For our experiment we adapted a portable haptic device originally described by Gleeson et al. [16], [17], [18]. The haptic device was mounted on an aluminum base along with a battery pack, a wireless communication module, and an adjustable hand support, as show in Fig. 3. The device can be adjusted for both right and left-handed users. The user can easily move the entire assembly around the plane of the workspace on a low-friction base, as shown in Fig. 4. The user's index finger is held stationary, with respect to the device, by an interchangeable thimble that is sized to fit the user. We tracked the position of the device in the workspace with 1.37 mm precision using an overhead web camera (resolution: 640 $\times$ 480) and an infrared LED mounted to the device.

### 2.3 Experiment Design

Ten healthy participants took part in this study. Of those participants, nine were male, and all were right handed. Their ages ranged from 20 to 33, with a mean age of 25 years.

Fig. 4. Experimental workspace.

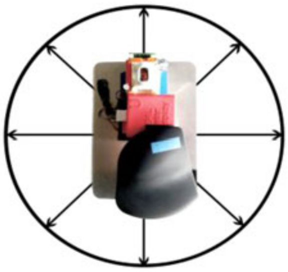

Fig. 5. Overhead layout depicting the eight directions rendered by the haptic device.

The participants completed three experimental tasks: an angle matching test, a motion guidance test, and a box-shaped motion guidance test. The angle matching test benchmarked user performance by measuring the resolution at which participants could discriminate and respond to discrete skin-stretch direction cues. The motion guidance test evaluated the capability of the haptic device to lead users through prescribed arm motions. The box-shaped motion test evaluated the use of haptic motion guidance at the limits of the participant's reachable workspace. These three tests are described in greater detail below.

Participants were trained and completed the angle matching test in a session lasting between 29 and 55 minutes (mean 44 minutes), then completed the two motion guidance tests in a second session lasting between 77 and 128 minutes (mean 96 minutes). The two sessions were separated by at least one day. Session time varied between subjects and depended on the time needed for training, participant speed, the length of breaks between trials, and any retrials that may have been required as a result of lost tracking or participant confusion. All experiments were conducted under University of Utah Institutional Review Board approval and all participants gave written informed consent.

Participants performed all tests while seated at a table such that the centerline of their body was roughly 100 mm to the right of the leftmost edge of the workspace (see Fig. 4). Participants were asked to maintain an upright posture throughout the experiment to prevent any slouching or bending of the torso that might affect the position of their arm and hand. Participants were blindfolded and wore noise-cancelling headphones that played white noise and provided audio cues signaling the beginning and end of each trial.

Before data collection began, the participants were familiarized with haptic cues in all eight possible directions and trained to move their hand within the workspace at approximately 50 mm/s. Participants did not wear the blindfold or headphones during training.

Once participants were familiarized with the device, we measured the extent of each participant's workspace. Participants extended their arm and swept it around the workspace without moving their shoulder or torso. This maximum reach path was entered into a path planning algorithm to ensure that we never guided participants outside of the range of their natural reach.

### 2.3.1 Angle Matching Test

We designed an angle matching test to measure the precision with which a participant could perceive and respond to directional tactile cues. Participants were presented with direction cues spaced in 45° increments (as used in our corrective feedback study, Section 2.4). The test was composed of 80 randomized direction cues, 10 in each of the eight equally spaced directions (shown in Fig. 5). Eight directions were tested in a matching task since our prior research only tested user responses in a four-direction identification task [17]. Participants were instructed to respond to each cue by moving their hand in the direction indicated by the cue, until the cue ceased. Each cue was sustained until the participant had moved 100 mm from their starting point. After each cue, the participant returned his/her hand to a point at the center of the workspace with the assistance of test proctor.

For each stimulus, we tracked the location of the device as the participant moved it in response to the direction cue. We fit a line to the outward (away from center) portion of the path and used the angle between this line and the stimulus direction as a measure of performance accuracy.

Each participant completed this test twice (in a randomized order): once with pulsed cues and once with sustained cues.

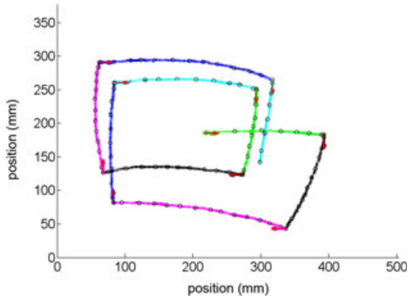


Fig. 6. Typical motion guidance test path. Lines indicate the path of the participant's hand, with the color of the line changing for each segment of the path. The onset of the new haptic direction cues are shown by small arrows. While only the onsets of the cues are shown, the cues were sustained for the duration of each path segment. Small circles along the path indicate the cadence of the pulsing cue.

### 2.3.2 Motion Guidance Test

The motion guidance test guided the user through a regime of psuedorandom planar arm motions. During the test, the participant moved his/her arm throughout his/her reachable workspace in response to haptic cues.

The test comprised four trials, with ten direction cues given during each trial. Each cue was given continuously until the participant moved his/her hand a desired distance in the indicated direction, at which point the cue would end. After an 800 ms pause, the next cue would begin, with the participant continuing from his/her current position. At the end of each trial (after 10 direction cues), the participant returned his/her hand to the center of the workspace with the aid of a proctor. A motion path from a typical trial is shown in Fig. 6.

Path planning for the test was executed by an algorithm that guided the user through randomly ordered directions and distances and kept the user within his/her workspace. Path direction was chosen from four cue directions, in four cardinal directions, and with an approximately equal number of stimuli given in each direction (within the constraints

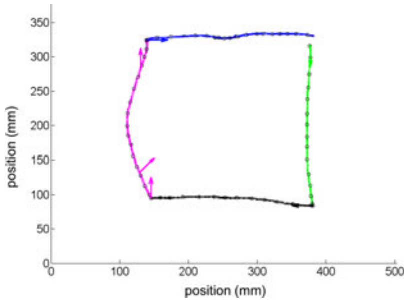


Fig. 7. Typical box-shaped motion guidance test path, drawn using the same conventions as Fig. 6. Stimuli providing real-time corrective feedback can be seen the left (magenta) segment: as the participant deviates from the intended path, the device provides a corrective stimulus that is sustained until the participant returns to within 6.85 mm of the intended path.

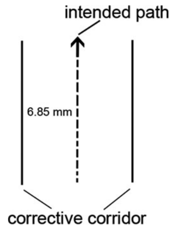


Fig. 8. Illustration of corrective corridor. When corrective feedback was active, participants would receive a corrective cue when they crossed a boundary of the corridor.

of the workspace). Path segment lengths were selected from a normal distribution with a mean length equal to 62.5 percent of the participant's corresponding workspace size. This resulted in an average path segment length of 184 mm across all subjects.

Each participant completed the motion guidance test with pulsed cues and sustained cues and with and without real-time corrective feedback (described in Section 2.4). We combined these two factors in a full-factorial design, for a total of four conditions: pulsed with feedback; pulsed without feedback; sustained with feedback; sustained without feedback.

As in the angle matching test, we fit a line to each segment of the participant's path and compared the angle of this line to the stimulus angle. As a second performance metric, we calculated the mean distance between the participant's path and the intended path.

#### *2.3.3 Box-Shaped Motion Guidance Test*

A third test, the box-shaped motion guidance or "box" test was administered. While the motion guidance test directed participants through motions of varying lengths throughout the workspace, the box test focused on long motion trajectories at the limits of the participants' workspaces. The box test was the same as the motion guidance test, with the following two exceptions: each trial began with the participant's hand in a corner of their workspace (randomized between trials), and participants were directed in large box-shaped paths around the edges of their workspaces.

We conducted this separate box-shaped test because we wanted to see how well people could execute orthogonal motions when they knew the path shape in advance. In this case, we assume that any deviation from an orthogonal movement would be due to perceptual or motor bias.

A typical box path is shown in Fig. 7, which also includes real-time corrective feedback. On average, the length of each path segment was 235 mm. Each participant completed the box test under the same four conditions as the motion guidance test.

### 2.4 Real-Time Corrective Feedback

To help users of our device accurately follow an intended path, we implemented a system for providing real-time corrective feedback. There are many reasons why a user could require corrective feedback, including natural errors in direction perception and motion precision, or, in the case of rehabilitation applications, motor or perceptatual impariments. Kappers et al. have shown that perception of haptic input is non-euclidian and the directions we perceive differ from reality as a function of hand location and orientation [19], [20], [21]. To correct for path errors, we provide corrective feedback to return users to the intended path.

When a participant deviated from the intended path, the device gave a 45 degree diagonal cue directing the users back towards the intended path, as shown in Fig. 7. These cues were administered when the participant strayed by over 6.85 mm from the center of the intended path (rounded to the nearest pixel on our tracking camera), as measured perpendicularly from the path. A projected "corridor" of 13.7 mm total width parallel to the intended path direction can be visualized (Fig. 8), where the participant receives corrective feedback whenever they venture outside the corridor.

Corrective path feedback was intentionally delivered in the same manner as non-correctional cueing. However, the method of corrective feedback slightly differed between pulsed and sustained cues, due to the nature of the cueing types. We delivered feedback cues using the same cadence conventions as non-feedback cues. As such, pulsed cues would update continuously (at 1 Hz) with feedback, with the possibility of changing direction on each pulse of the cue, while sustained cues would not. To deliver corrective feedback using sustained cues, the tactor first returned to center, pausing for the same period of time as if the path segment had ended, and then rendered the corrective cue. This was done so that the participant could not differentiate between receiving corrective feedback and simply receiving a new cue direction.

It would clearly be possible to make it more obvious to the user when path corrections were being given by changing the cadence or timing of the feedback. This could improve communication with the user, but in this study we wanted the corrective cues to be indistinguishable from normal direction cues to ensure that users were correcting their hand motions even without being alerted to the path error.

## 3 Results and Discussion

### 3.1 Overall Participant Hand Motions

Participants' average time spent per line segment was 5.68 sec for the motion guidance test and 7.25 sec for box-shaped motion guidance tests. Once corrective feedback

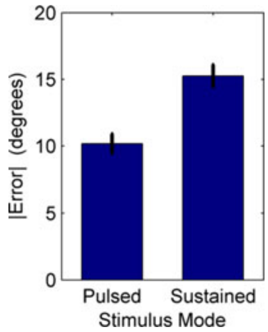


Fig. 9. Angle matching error magnitude for pulsed and sustained stimuli with 95 percent confidence intervals. Errors were significantly smaller for pulsed stimuli.

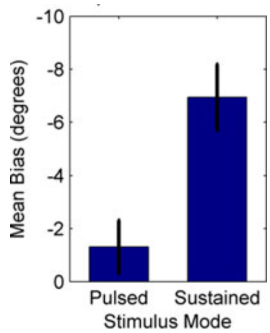


Fig. 10. Response angle bias for pulsed and sustained stimuli, with confidence intervals. In general, participants responded with a slight bias in the clockwise direction. The bias was significantly less for pulsed stimuli.

was set to be administered, the device could take up to a full second to render the cue via tactor displacement. Before each test, the test proctor demonstrated an approximate target hand velocity of 50 mm/s. This velocity was chosen as the maximum speed at which the participant would have adequate time to sense and respond to changes in the haptic cueing. The resulting mean hand velocity across all participants was 32.4 mm/sec (standard deviation 13.0 mm/sec).

We calculated reaction time as the time for a participant to initiate movement after the onset of a skin-stretch cue. The mean reaction time across all participants was 1.05 sec (standard deviation 0.28 sec). This is the total time measured from the start of tactor motion, but we presume that a user did not actually perceive the stimuli until the tactor moved some distance. Therefore, while this measurement is an indication of a user's response time to our system as a whole, we do not consider it to be a measurement of the minimum response time for a skin stretch stimulus.

### 3.2 Angle Matching Test

Participants were able to match their hand motion to stimulus direction with high accuracy; the mean absolute error was 10.2 degree for pulsed stimuli and 15.3 degree for sustained stimuli (Fig. 9). This is similar to the results reported in [22] where their participants responded to pulsed and sustained cues using a 2 degree-of-freedom joystick. Stimulus mode and stimulus direction both affected performance, with interaction between these two factors (in all cases, $\mathrm{F} > 3.43, \mathrm{p} < 0.005$). The accuracy difference that we observed between stimulus modes is highly significant $(\mathrm{t}(1598) = -9.22, \mathrm{p} < 0.001)$. We defined a "correct" response as a motion direction within 22.5 degree of the cue direction, i.e., a 45 degree "window." The average accuracy across all subjects as defined within this "window" was 88.6 percent $(+/-5.0$ percent ) for pulsed cues and 84.3 percent $(+/-7.1$ percent ) for sustained cues.

Participants exhibited a rotational bias in their responses (based on mean response error); average responses were 1.3 degree clockwise for pulsed stimuli and 6.9 degree clockwise for sustained cues, as can be seen in Fig. 10. The bias was significantly smaller for pulsed stimuli $(\mathrm{t}(1598) = 6.91, \mathrm{p} < 0.001)$. In order to visualize the relationship between cue-direction and rotational bias, a radial layout representing the workspace in front of the participant is depicted in Fig. 11, where responses for each cue direction are grouped into a histogram and placed in their respective orientation.

While we did find an effect of stimulus angle on accuracy here and in our other studies, we do not consider these results to be meaningful. While an analysis of angle using Tukey's HST showed some significant differences in angle accuracy for each experiment, each experiment and condition showed different results. No reliable pattern emerged and accuracy patterns differed between experiments and conditions. Speaking anecdotally, accuracy rates were often somewhat lower on oblique angles, but this pattern was neither universal nor reliable.

From this test we conclude that participants' ability to perceive and respond to haptic stimuli is suitably high for use in a guidance task. While previous experiments with our device (e.g., [17]), established that users are able to perceive four-direction stimuli with high accuracy, we show here that users' perceptual acuity is sufficient for reliable matching of eight stimulus directions. While we are not aware of any similar research involving hand motion response to directional skin stretch stimuli, our results are quite similar to a perceptual experiment conducted by Keyson and Houtsma which found perceptual thresholds (JNDs) of approximately 14 degree over eight directions using a large powered trackball-type device that rotated under the fingerpad, stretching and displacing the skin [23]. It is encouraging that users appear to be capable of

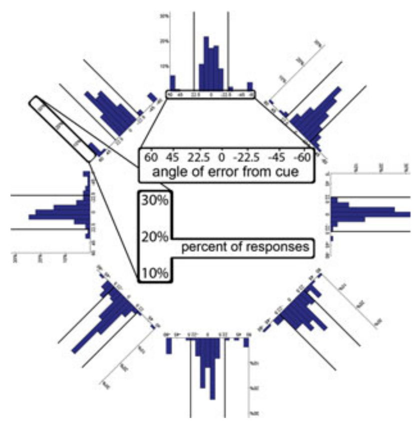


Fig. 11. Histograms showing frequency of participants' response angle for each of the eight directions during the pulsed cue test condition. Sustained cues (not show) produced similar patterns.

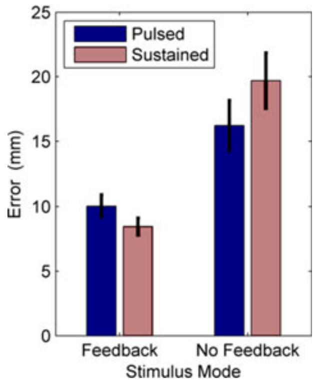


Fig. 12. Motion guidance results: distance error (mm) from intended paths for the four test conditions. Corrective feedback significantly reduced error, but stimulus mode did not have an effect.

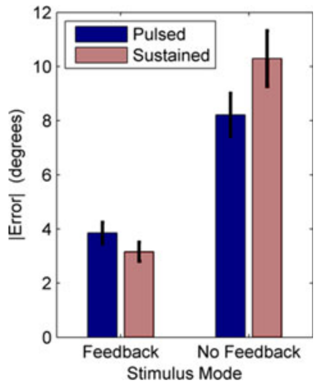


Fig. 13. Motion guidance results: angle error (deg) from intended paths for the four test conditions. Corrective feedback significantly reduced error, but stimulus mode did not have an effect.

executing guided hand motions with average direction errors that are no larger than the reported perceptual thresholds for skin stretch stimuli.

The clockwise bias in response direction is predicted by previous work. Given the placement and orientation of the participant's hand in our experiment, the model of haptic direction perception developed by Kappers et al. predicts that the directional stimuli should be perceived with a clockwise skew [19], [20], [21]. This suggests that participants may be moving their hands in the direction they perceive to be indicated by the haptic cue, but that the perception itself may be inaccurate due to the hand's current position offset.

The higher accuracy and lower bias provided by the pulsed stimuli appears to suggest that these stimuli may be superior for guidance tasks, but this trend does not always hold, as we will discuss in the results of the following guidance tests. When discussing error and bias here and elsewhere in the paper, it is important to note that bias and error are coupled; an increase in bias could also result in an increase in error.

### 3.3 Motion Guidance Test Results and Discussion

During the motion guidance test, participants were guided through the workspace in a series of randomized orthogonal movements. The goal of this test was to evaluate the participants' abilities to execute prescribed planar arm motions using haptic guidance. We used two metrics to evaluate path following accuracy: distance error and angle error. Distance error is the mean perpendicular distance between the participant's path and indicated path. Angle error is the absolute value of the angle between the intended path and a line fit to the participant's path. These two metrics are not independent, but they measure different aspects of the users' performance. Distance error evaluates the ability of the user to remain on the prescribed path, on a point-by-point basis, while angle error evaluates the ability of user move, on average, in the correct direction.

Distance errors are shown in Fig. 12, angle errors in Fig. 13, and angular response direction bias in Fig. 14. All error bars represent 95 percent confidence intervals.

Participants exhibited an average distance error of 16.2 mm for pulsed cues and 19.7 mm for sustained cues. With real-time corrective feedback enabled these errors reduced to 10.0 mm and 8.5 mm for pulsed and sustained cues, respectively. Participants matched the stimulus direction with an average error of 8.2 degree for pulsed cues and 10.3 degree for sustained cues. With real-time corrective feedback enabled, those averages dropped to 3.9 and 3.2 degree for pulsed and sustained cues, respectively.

By either distance or angle metric, stimulus angle and corrective feedback had main effects on accuracy (in all cases, $F > 12.71, p < 0.001$) but stimulus mode did not (for both, $F < 1.07, p > 0.30$). By both metrics the addition of real-time corrective feedback halved the error. This effect was highly significant (on distance error: $t(1598) = -11.10$, $p < 0.001$; on angle error: $t(1598) = -16.09, p < 0.001$). Interestingly, stimulus mode did not significantly affect performance (on distance error: $t(1598) = -1.17, p = 0.24$; on angle error: $t(1598) = -1.81, p = 0.07$).

As in the angle matching test, participants exhibited a clockwise bias in the direction of their responses. Participants exhibited average biases of 4.7 and 4.9 degrees clockwise for pulsed and sustained cues, respectively. Real-time corrective feedback reduced their resulting path bias to 1.5 and 1.1 degrees clockwise for pulsed and sustained cues, respectively. While the bias does not appear to be affected by stimulus mode $(t(1598) = -0.52, p = 0.61)$, the effect of corrective feedback was highly significant $(t(1598) = 7.09$, $p < 0.001)$.

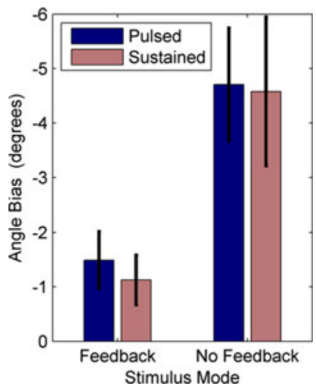


Fig. 14. Motion guidance results: angle bias for the four test conditions. In general, participants responded with a clockwise bias. The bias was significantly lower when corrective feedback was used. Stimulus mode did not have an effect.

TABLE 1
Guidance: Angle Bias by Workspace Quadrant

| | Northwest | | Northeast | |
|---|---|---|---|---|
| | horizontal | vertical | horizontal | vertical |
| pulsed | -4.36 | -2.03 | -6.86 | -7.64 |
| with feedback | -1.83 | -2.42 | -6.00 | -0.11 |
| sustained | -4.13 | -7.25 | -6.76 | -10.08 |
| with feedback | -0.07 | -1.06 | -2.81 | -0.97 |
| | Southwest | | Southeast | |
| | horizontal | vertical | horizontal | vertical |
| pulsed | -2.88 | -7.11 | -2.69 | -10.09 |
| with feedback | -0.88 | -0.92 | -2.43 | -2.30 |
| sustained | 1.41 | -5.07 | -5.58 | -8.68 |
| with feedback | -1.03 | -1.26 | -1.37 | -1.67 |

*All units in degrees. Both stimulus (pulsed/sustained) modes are shown, with and without corrective feedback. For the purpose of naming quadrants, 'North' is forward, in the distal direction.*

To characterize angle bias as a function of workspace position, we divided the workspace into quadrants. We considered any motion path with two-thirds of its length in a given quadrant to be a member of that quadrant. For this analysis, we discarded any path that could not be classified into a quadrant by this criterion (e.g., 50 percent in 2 quadrants). Table 1 shows average biases for all test conditions, sorted by quadrant. Without corrective feedback, biases generally grew larger as the hand moved away from the body, with an average bias exceeding 10 degree in the most distal quadrant. Corrective feedback tended to reduce biases overall and to equalized them over the workspace. These trends are shown graphically in Fig. 15.

Users completed 80 paths during the motion guidance test with corrective feedback enabled. Users received corrective path feedback on an average of 45.9 paths out of the possible 80 (standard deviation 15.3). That is, they strayed far enough from the intended path for the motion guidance to experience a corrective feedback cue that differed from the nominal cue direction.

In general, the haptic cues were successful in guiding users through prescribed arm motions. The addition of corrective feedback proved highly effective in keeping users on the prescribed path and reducing direction errors and direction biases. With average distance errors of less than 10 mm and average angle errors of less than 4 degree, we consider this test to be a successful demonstration of the use of haptic feedback to guide planar arm motion.

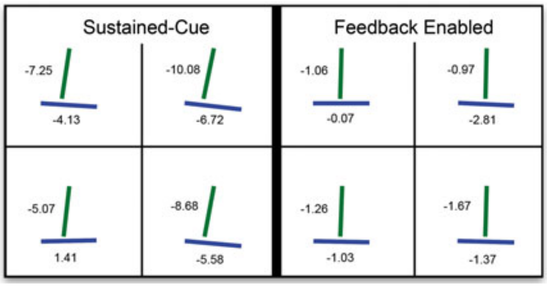


Fig. 15. Average response bias (deg) for horizontal and vertical paths using sustained direction cues, divided by workspace quadrant. In general, motion paths were skewed in a clockwise direction, with the largest effect seen in the quadrant furthest from the user. Corrective feedback reduced the bias. Bias patterns for pulsed cues (not shown) were similar.

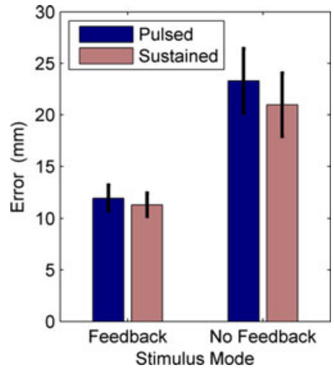


Fig. 16. Box guidance results: distance error (mm) from intended paths for the four test conditions. Corrective feedback significantly reduced error, but stimulus mode did not have an effect.

The non-euclidean perception of haptic space reported by Kappers et al. [19], [20], [21] is a potential difficulty for haptic guidance when used over a large workspace. The direction bias patterns observed in our data are consistent with the predictions of Kappers et al. and provide a large source of error in participants' performance. Fortunately, the addition of corrective feedback largely compensated for the effects of this perceptual distortion.

### 3.4 Box-Shaped Motion Guidance Test Results and Discussion

During the box-shaped motion guidance test, participants followed haptic guidance in a series of box-shaped movements around the edges of their reachable workspace. We used the same performance metrics here as in the previous guidance test. Fig. 16 reports distance error results, Fig. 17 reports angle error results, and Fig. 18 shows response biases. All error bars indicate 95 percent confidence intervals.

Participants exhibited an average distance error of 23.1 mm for pulsed cues and 21.9 mm for sustained cues. With real-time corrective feedback enabled these errors reduced to 12.0 and 11.3 mm for pulsed and sustained cues, respectively. Participants matched the stimulus direction with an

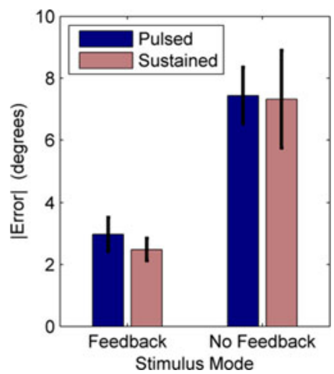


Fig. 17. Box guidance results: angle error (deg) from intended paths for the four test conditions. Corrective feedback significantly reduced error, but stimulus mode did not have an effect.

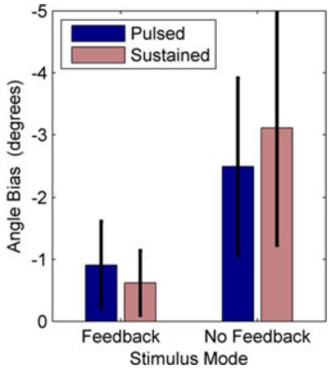


Fig. 18. Box guidance results: angle bias for the four test conditions. In general, participants responded with a clockwise bias. The bias was significantly lower when corrective feedback was used. Stimulus mode did not have an effect.

average error of 7.4 degree for pulsed cues and 7.3 degree for sustained cues. With real-time corrective feedback enabled, those averages dropped to 3.0 and 2.5 degree for pulsed and sustained cues, respectively. As before, participants exhibited a clockwise bias in response direction, averaging 2.5 and 3.1 degree degrees clockwise for pulsed and sustained cues, respectively. Real-time corrective feedback reduced the bias to 0.9 and 0.6 degree degrees clockwise for pulsed and sustained cues, respectively.

Again, by either distance or angle metric, stimulus angle and corrective feedback had main effects on accuracy (in all cases, $\mathrm{F} > 2.66, \mathrm{p} < 0.05$) but stimulus mode did not (for both, $\mathrm{F} < 1.63, \mathrm{p} > 0.20$). The addition of corrective feedback significantly reduced distance error $(\mathrm{t}(638) = -8.84, \mathrm{p} < 0.001)$, angle error $(\mathrm{t}(638) = -9.51, \mathrm{p} < 0.001)$, and bias $(\mathrm{t}(638) = 3.19, \mathrm{p} < 0.01)$. Stimulus mode (pulsed vs. sustained) did not have an effect on any performance metric (for all: $\mathrm{t}(638) < 1.20, \mathrm{p} > 0.20$).

Users completed 32 paths during the box-shaped motion guidance test with corrective feedback enabled. Users received corrective path feedback on an average of 20.5 paths out of the possible 32 (standard deviation: 5.4). That is, they strayed far enough from the intended path for the motion guidance to experience a corrective feedback cue that differed from the nominal cue direction.

As in the previous test, we characterized angle bias as a function of the position of the hand in the workspace by sorting data into workspace quadrants. Because each path segment was evenly divided between two quadrants in the box test, we divided the segments and kept the 66 percent of each segment that was furthest into each quadrant. Biases were largely similar between quadrants and were uniformly reduced by the addition of corrective feedback, as is illustrated in Fig. 19. Table 2 gives the average biases for all test conditions.

The results of the box test further emphasize the ability of the skin-stretch device to guide the user around a planar workspace with accuracy and precision. Again, both performance metrics show the significant effect that real-time path feedback has on the user in correcting their movements in the planar workspace. Where the previous test showed that haptic guidance is useful in a general planar motion task, this test shows that haptic cues are effective even at the

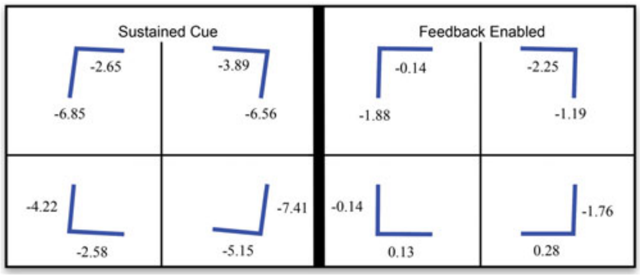


Fig. 19. Box guidance results: average response bias for horizontal and vertical paths using sustained direction cues, divided by workspace quadrant. In general, motion paths were skewed in a clockwise direction. Corrective feedback reduced the average bias across all quadrants. Bias patterns for pulsed cues (not shown) were similar.

edges of the workspace, where perceptual distortions could most affect performance.

Participant performance characteristics differed between this test and the motion guidance test. Average distance errors in the box guidance test were about 25 percent larger than in the motion guidance test while angle errors were about 20 percent smaller. That is, when being guided on long paths around the edges of the workspace, participants were better able to move in the correct direction but had more difficulty staying on the prescribed path. We had expected an overall performance drop in the box test, where participants were required to work at the extremes for their reachable workspace, but it is possible that the closed rectangular path used in the box test simplified the guidance task and resulted in the observed decrease in angle error.

Studies of haptic direction perception [19], [20], [21] predict that direction biases should be greatest in this box task, where the hand is in the most extreme positions. However, we observed an average bias approximately 40 percent smaller in box test. This effect is coupled to the overall decrease in angle error observed in the box test, and we presume that the decreased bias is also related to the reduced path complexity in the box test. As in the previous guidance test, the addition of corrective feedback largely eliminated angle bias and appears to be effective in correcting for any haptic perceptual distortions.

TABLE 2
Box Guidance: Angle Bias by Workspace Quadrant

| | Northwest | | Northeast | |
|---|---|---|---|---|
| | horizontal | vertical | horizontal | vertical |
| pulsed | -1.44 | -2.20 | -6.22 | -7.01 |
| with feedback | -1.22 | 0.49 | -3.55 | 0.70 |
| sustained | -2.65 | -6.85 | -3.89 | -6.56 |
| with feedback | -0.14 | -1.88 | -2.25 | -1.19 |
| | **Southwest** | | **Southeast** | |
| | horizontal | vertical | horizontal | vertical |
| pulsed | -2.32 | 0.08 | -2.14 | -5.40 |
| with feedback | -0.42 | -0.33 | -1.22 | -0.51 |
| sustained | -2.58 | -4.22 | -5.15 | -7.41 |
| with feedback | 0.13 | -0.14 | 0.28 | -1.76 |

*All units in degrees. Both stimulus (pulsed/sustained) modes are shown, with and without corrective feedback. For the purpose of naming quadrants, 'North' is forward, in the distal direction.*

### 3.5 General Discussion

When executing the guidance tests, participants' angle errors were comparable to those found in the angle matching experiment. That is, participants could perform both guidance tasks without experiencing any substantial degradation in haptic direction perception and response. This result suggests that the users will be capable of achieving approximately 10 degree response accuracy for a range of similar guidance tasks. An unexpected difference between the angle matching task and the guidance tasks is the changing importance of stimulus type. The type of stimulus rendered (sustained cues vs. pulsed cues) had a strong effect in the angle matching test, but did not have an effect in either of the motion guidance tests. From this, we conclude that the ideal stimulus type may vary depending on the task, and that the stimulus type should be chosen to fit the task. Although we observed no difference between stimulus types in our motion guidance tasks, we suspect that the faster 1 Hz update rate of the pulsed stimuli may provide an advantage on complex paths where frequent direction changes are required. However, corrective feedback in the sustained feedback condition was given in an artificially slow manner in our experiments, so as to not provide participants with an indication that they were receiving feedback corrections. In practice, corrective feedback could be provided immediately, rather than pausing first. If sustained cues were delivered in the manner used in the target tracking task of [25], then sustained cues could provide corrective feedback at 60+ Hz, and thus couldprovide particularly agile feedback corrections. A limitation of our experimental design is that we cannot independently measure perception accuracy (how accurately the user can feel the direction of the cue) and response accuracy (how accurately the user can move her hand in response to the cue). For the current study, however, this distinction is not required; to evaluate the utility of haptic cues, we only need to know the overall system performance characteristics.

## 4 Conclusions

Throughout the three tests, skin stretch stimuli proved highly effective in guiding participants through prescribed planar arm motions. The angle matching test established that users can distinguish between eight-direction haptic cues and respond with accurate hand motions. In the motion guidance test, the haptic cues effectively guided users on randomized paths throughout their workspaces, while in the box test showed that haptic feedback is effective at the limits of the reachable workspace. In both guidance tests, the addition of corrective feedback greatly improved user performance, reducing average angle errors to less than 4 degree and average distance errors to less than 12 mm.

A potential difficulty with the use of haptic direction cues is the non-euclidean perception of haptic direction. While we observed response angle biases that are consistent with this perceptual distortion, we were able to largely correct for these errors using real-time corrective feedback.

By successfully guiding users along prescribed paths, we show that haptic skin stretch cues are effective in planar motion tasks. Corrective path feedback effectively augmented haptic guidance, significantly improving participants' path accuracy, and compensating for the effects of perceptual distortion. With precise and accurate haptic guidance of user arm motions, our skin stretch device could be an effective low-cost tool for uses for advanced human-machine interaction including upper-extremity rehabilitation, mobile GPS guidance, and PC peripherals.

### 4.1 Future Work

We are currently developing a tactile display with higher precision actuation. This device will likely improve user performance, with potential to render up to 16 distinguishable directions. This device would enable more precise control of users' motion paths. While we currently only track hand position, in future work we will track orientation as well, providing insight into the effect of hand orientation on direction perception and task performance. During this study, corrective feedback cues were given in a manner such that they were indistinguishable from non-corrective cues. This will not be required of future applications, and communication bandwidth could be significantly improved by providing feedback in the manner described for the target tracking task of [25]. While we have shown that directional skin stretch cues can effectively guide user motions, this study did not evaluate any short or long term retention effects that may appear due to path correction. A future longitudinal study is required to characterize the effects of motion guidance over time.

In related work, we are exploring the use of skin stretch feedback in video-game controllers and joysticks [22], [24], [25].

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