SKIN STRETCH FEEDBACK TO GUIDE HAND MOTIONS

by

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ABSTRACT

When interacting with objects, humans utilize their sense of touch to provide information about the object and surroundings. However, in video games, virtual reality, and training exercises, humans do not always have information available through the sense of touch. Several types of haptic feedback devices have been created to provide touch information in these scenarios.

This dissertation describes the use of tactile skin stretch feedback to provide cues that convey direction information to a user. The direction cues can be used to guide a user or provide information about the environment. The tactile skin stretch feedback devices described herein provide feedback directly to the hands, just as in many real life interactions involving the sense of touch. The devices utilize a moving tactor (actuated skin contact surface, also called a contactor) and surrounding material to give the user a sense of the relative motion.

Several game controller prototypes with skin stretch feedback embedded into the device to interface with the fingers were constructed. Experiments were conducted to evaluate user performance in moving the joysticks to match the direction of the stimulus. These experiments investigated stimulus masking effects with both skin stretch feedback and vibrotactile feedback. A controller with feedback on the thumb joysticks was found to have higher user accuracy.

Next, precision grip and power grip skin stretch feedback devices were created to

investigate cues to convey motion in a three-dimensional space. Experiments were conducted to compare the two devices and to explore user accuracy in identifying different direction cue types. The precision grip device was found to be superior in communicating direction cues to users in four degrees of freedom.

Finally, closed-loop control was implemented to guide users to a specific location and orientation within a three-dimensional space. Experiments were conducted to improve controller feedback which in turn improved user performance. Experiments were also conducted to investigate the feasibility of providing multiple cues in succession, in order to guide a user with multiple motions of the hand. It was found that users can successfully reach multiple target locations and orientations in succession.

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CHAPTER 1

INTRODUCTION

Human-computer systems typically provide feedback to the user through audio or visual cues. However, for many systems, such as those used for simulation, training, or rehabilitation, the system can more closely emulate the physical interaction it is trying to simulate if haptic (touch) feedback is provided to the user. Humans often interact with physical environments with their hands, and haptic feedback used in conjunction with virtual environments can create a more immersive experience by allowing the user to “feel” their interactions with the virtual environment. Haptic cues can also be used to provide information about how a person should move their hands when audio or visual cues alone may be ambiguous. Many studies have already shown that the addition of haptic feedback to simulation and training provides further benefits than visual and/or auditory feedback alone [Panait et al. 2009; Morris et al. 2007; Ström et al. 2006].

The research presented in this dissertation focuses on one particular form of haptic feedback: tactile feedback using skin stretch. Skin stretch feedback can be used to provide directional information to the hand by shearing the skin of the fingerpad or palm [Gleeson et al. 2010a]. In addition, the speed and amplitude of skin stretch feedback can be varied to provide direction cues of varying saliency. By continually adjusting the amount of skin stretch given to a person, it is even possible to guide a person’s hand to a specific position or orientation. This tactile stimulus has the potential to be used in video games, rehabilitation, training simulations, and teleguidance applications, among other uses. This document presents the results of several studies exploring the use of skin stretch feedback when more than one tactile cue is presented in sequence. Studies herein also explore using skin stretch feedback to continuously guide a user to a desired location or orientation and to guide a user through a large set of sequential motions.

Skin stretch feedback provides reliable directional information to users and has been integrated into several devices since Gleeson et al. [2010a] showing accuracy rates greater than 95% with as little as 0.2 mm of shear displacement. Skin stretch cues were used to guide planar hand motion by Norman et al. [2014], with subjects matching the motion of the hand within 10° of the stimulus direction for the eight stimulus directions in the horizontal plane. These experiments showed the feasibility for users to identify and match direction cues, and this dissertation research continues to explore user interactions with skin stretch feedback cues. One important area to investigate is how users respond to multiple skin stretch cues and how they interpret skin stretch cues used in combination with other types of haptic cues. Another area of interest involves using skin stretch cues to communicate three-dimensional (3D) direction cues to the user. Prior studies had investigated a user's ability to identify direction cues, as well as motion responses to two-dimensional direction skin stretch cues.

While various haptic devices exist that are capable of communicating directional motion cues to a user, each of these devices has some limitation that prevents them from being used to guide hand motions precisely and through a large spatial workspace. Exoskeleton devices do not allow for full range of motion of the arm and hand [Sledd and O'Malley 2006], and require safety considerations so that the force output does not harm the operator or cause system instability. Commercial force feedback devices can be used for teaching a trajectory to a user, but have a limited workspace and are constrained to sit on a desk or table top. Vibrotactile sleeves can be used to guide arm motion in a large workspace, but performance is typically similar to using vision-only cues [Bark et al. 2011; and Rotella et al. 2012] and motion cues are restricted to the upper arm, elbow, and wrist due to the spatial separation requirements between vibrotactile feedback transducers [Jones and Sarter 2008]. Other wearable haptic devices have been created to guide the amount of wrist rotation, but are limited to 1 degree-of-freedom motion at this point [Stanley et al. 2012]. Because of the limitations of each of these types of devices, a portable haptic device to communicate directional information in multiple degrees of freedom that can be used to precisely position the hand and wrist of the user has been created. This device can be used in combination with a position tracking system or attached to many tools, and in turn can be used to precisely guide a person's hand and associated collocated, teleoperated, or virtual tool to a desired position and orientation.

1.1 Contributions

Three main contributions were made through the course of this research and are outlined below:

1. Characterized human perception and responses to multiple tactile cues.

   A custom-built game controller was constructed with planar skin stretch feedback devices embedded within each thumb joystick of the game controller. Using this device, experiments were conducted to investigate possible stimulus masking effects. Stimulus masking was investigated between two skin stretch feedback cues, one cue presented to each hand of the user, with variable delay between these cues, and between skin stretch feedback cues and vibration distraction cues presented to both of the user's hands, with variable timing between these cue types.

2. Characterized human hand motion response to skin stretch cues that suggest specific hand motions.

Two devices capable of providing skin stretch cues on more than one plane were used to investigate guiding hand motions in a three-dimensional space. Experiments were conducted to determine performance with each device, and compare the capabilities of each device. In addition, performance when responding to cues in nonorthogonal directions was analyzed. Finally, an experiment was conducted to evaluate performance when responding to sequential skin stretch cues.

3. Showed feasibility of closed-loop human/device interactions via skin stretch feedback for teleoperation purposes.

Preliminary studies were conducted to investigate appropriate control strategies for closed-loop feedback with a skin stretch feedback device. Then, experiments were conducted to investigate user performance in moving to a set location or orientation. Finally, an experiment was conducted to show the feasibility of using skin stretch feedback to allow one person to guide another person's hand through a set of locations and orientations.

1.2 Chapter Overview

This dissertation is organized into five chapters. The following section briefly outlines the content of each chapter.

Chapter 2 characterizes responses to multiple skin stretch feedback cues, as well as responses to skin stretch feedback cues in the presence of a competing haptic cue caused by vibration feedback. Results show the tradeoff between user accuracy and the timing between multiple haptic cues.

Chapter 3 characterizes the ability of skin stretch feedback to provide cues directing the motion of the hand in multiple degrees of freedom. These results compare performance with two different skin stretch feedback haptic devices. The research presented in Chapter 3 also investigates human performance when responding to diagonal translation or combined rotation cues. In addition, an investigation on user response to two sequential cues is conducted.

Chapter 4 presents skin stretch feedback device capabilities for guiding a hand through space using closed-loop feedback. An example teleguidance application is also included, demonstrating the feasibility of using this device for teleguidance, training, rehabilitation, and many other applications where one may desire to track and provide target goals for another user's hand motions.

Chapter 5 provides conclusions to this dissertation. It also presents possible future work related to the research presented herein.

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CHAPTER 2

EFFECTS OF RELATIVE TIMING BETWEEN TWO-HANDED TACTILE CUES OF A VIDEO GAME CONTROLLER

In this chapter, I present two studies investigating the effects of masking with game controller devices. Participants received a variety of skin stretch cues that included varying the time in between cues to the right and left hands, as well as skin stretch cues in combination with the vibration feedback, which is commonly used in game controllers. Participants then responded to the cues given by moving the joysticks on the game controller, and response accuracies and response times were evaluated. I evaluated two game controller designs, one that presented skin stretch cues to the thumbtips on the front side of the controller and one that presented skin stretch cues to the middle fingertips on the back side of the controller. This preliminary characterization of user interaction and responses to this feedback will inform the design of gaming and training tasks possible with this device.

2.1 Introduction

Tactile feedback can be used to provide direction cues to a user. However, with multiple haptic stimuli, there is a concern with one stimulus masking a cue from another stimulus. In this chapter, I explore the effects of varying stimulus onset asynchrony times between different haptic cues. A device that uses fingertip skin stretch feedback to communicate direction information through a handheld game controller, was developed. A person places their fingertip on top of a “contactor” (also called a “tactor”), which moves and stretches the skin of the fingerpad. This custom-made game controller integrates skin stretch feedback mechanisms previously developed [Gleeson et al. 2010a]. This allows us to provide two independent direction cues to a user’s thumbs or fingertips.

The additional haptic feedback in this game controller can be used to increase immersion in a gaming scenario, as well as to provide directional cues in a gaming or training scenario. Such directional cues may already be present in these scenarios through on-screen graphics and audio feedback, but the additional haptic feedback can be used to reinforce audio and visual cues. For example, current first-person-shooter games typically have on-screen graphics to visualize a map of the gaming field, as well as on-screen graphics to indicate the direction of an enemy and audio feedback indicating when events happen and where attention should be focused. These direction cues could also be presented through haptic feedback. With multiple direction cues being presented, one scenario using haptic feedback could include providing one cue to guide direction to one hand, and providing another cue to alert the user of where the enemy is to the other hand. In this scenario, it is important to understand how the timing between different cues affects a user’s understanding of each cue.

In addition to understanding how the timing between different skin stretch cues affects user performance, it is also important to understand how vibration feedback cues and skin stretch feedback cues may interfere with each other. In a gaming scenario with added skin stretch feedback to provide direction cues, I need to also plan for the use of vibration feedback, which is present in almost all games. With both forms of feedback being delivered to the hands, I investigate if user performance and response to skin stretch cues is changed by the presence of vibration.

Along with providing information in gaming and training scenarios, this device can also be used to investigate and explain aspects of human perception and cognition. I have designed experiments to investigate human responses to multiple skin stretch cues, as well as skin stretch cues in the presence of vibration. The methods and results of these experiments are presented herein.

2.2 Background

2.2.1 Haptic Direction Cues

Several research groups have previously shown the feasibility of communicating direction cues with a variety of haptic feedback devices. Elliott et al. [2010] used a vibrotactile belt to guide participants through a wooded terrain, and compared results to those with a map and compass, a handheld GPS device, and a head-mounted GPS device. In this study, the researchers concluded that tactile navigation displays can outperform visual displays when conditions require a high cognitive and visual workload. Tan et al. [2003] used a vibrotactile array on a chair back to create sequenced pulses of eight direction cues to a user's back, and achieved 85-95% accuracy with naïve users.

While vibrotactile feedback can be used to provide direction information, there are some limitations in regards to the use of this feedback in mobile devices. One of these limitations is shown by Chen et al. [2008], as only a limited number of tactor locations could be correctly identified by participants. However, researchers also note that the layout of tactors could potentially be adjusted to account for these localization issues in [Chen et al. 2008; Oakley et al. 2006]. While some of these limitations can be overcome, vibrotactile feedback may not be the best option for communicating directional information in a mobile device, as it is difficult to create a way for multiple independent direction cues to be delivered in a small space. I am interested in providing direction cues within a handheld device, and feel it is more appropriate to communicate independent direction cues directly through the fingertip or thumbtip of each hand.

Wang and Hayward [2010] introduced a piezoelectric bimorph actuator array that is capable of communicating directional information in an array with an active surface of about 1 square cm. The size of this array is ideal for communicating at the fingertip, and is capable of communicating a wide range of tactile information, including sensations of direction, small shapes, and fine textures. However, the space needed for the entire device is 150 cubic cm; too large to embed within a handheld game controller. A compact device which uses tangential skin displacement to communicate direction has been previously developed. This previous work is described in the following section.

2.2.2 Skin Stretch Feedback Device

While the previous section presented various methods of communicating direction information through haptic feedback, I am most interested in creating a compact mechanism that can be embedded directly into handheld devices. To achieve this, I have focused on tangential skin stretch. In this form of haptic communication, a user presses their fingerpad against a contactor, which moves laterally in a given direction (Figure 2.1). As the contactor moves, it applies a shear force that stretches the skin of the fingerpad (Figure 2.2). An aperture, a conical hole, which surrounds the contactor prevents the user's finger from sliding laterally when the contactor is actuated, as shown in Figure 2.2. Previous work has found this type of haptic stimulus to be effective in communicating direction, with accuracy rates above 99% possible in a four-direction identification task [Gleeson et al. 2010b]. The compact nature of this device makes it practical to use skin stretch feedback in many handheld and portable devices.

While accuracy rates of higher than 99% were achieved in [Gleeson et al. 2010], it is important to recognize that such high accuracy may be difficult to achieve in other tasks. If more than four cue directions are used, a different fingertip is used (e.g., middle rather than index fingertip), or user attention is divided between multiple tasks, the accuracy may decrease. For example, a direction identification task with 16 cue directions rendered to a thumbtip rather than 4 directions rendered to the index fingertip resulted in an average accuracy of only 29% [Montandon and Provancher 2013]. However, the same study showed an average accuracy of 49% when a direction cue was reinforced by delivering the same cue direction simultaneously to the thumbtip of the opposite hand. In a 4-direction experiment, response accuracy was found to be about 90% when skin stretch cues were applied to a single thumbtip [Guinan et al. 2012]. While other researchers have found differences in hand posture to have an effect on touch at the fingers in certain scenarios [Tame et al. 2010], I found no statistical difference in accuracy when users held a game controller in an angled versus a straight orientation [Guinan et al. 2012]. In this chapter, I have designed experiments to investigate how multiple haptic cues can affect accuracy.

2.2.3 Tactile Stimulation Masking

When designing a device with tactile feedback, it is important to consider several different effects described by van Erp [2002]. Relevant to this research, van Erp points out that human skin has the potential to integrate stimuli, creating a percept that differs completely from the original stimuli. Spatial masking is possible when stimuli overlap in time, but not in location, and can result in a decrease in identification of the stimuli, as well as the detection of the stimuli. If two stimuli overlap in time but not location, they can also produce an apparent location effect, where a person only perceives a single stimulus, which may be a combination of the two individual stimuli. This merging of two stimuli into one is also demonstrated by Sherrick [1964]. When stimuli are presented nonsimultaneously, but closely in time, temporal effects can play a role in perception of the stimuli. In some cases, the second stimulus can be more salient to a user. Temporal masking can occur where one stimulus acts as a distracter for a different stimulus at the same location, making the target stimulus less salient. The following experiments are designed to characterize the effects multiple tactile stimuli have on perception for this device.

Several researchers have also investigated effects of a stimulus on one hand to the perception of a stimulus on the other hand. From Braun et al. [2005], one can expect left hand stimulation to interfere with right hand perception. However, this interference (contralateral, or opposite side of the body masking) is expected to be less than ipsilateral (same side of the body) masking based on the results from Levin and Benton [1973]. One can also expect interference between hands to be affected by changes in hand posture [Tame et al. 2010; D’amour and Harris 2013]. For these reasons, it is important to characterize possible masking effects for a device based on the posture it will be used in, and the types of stimuli the device can provide. With these game controllers, I assume that people will hold the devices as they would while playing video games, that is, with their hands positioned palm down, gripping the handles and their thumbs on the thumb joysticks. I set forth to investigate masking effects for skin stretch cues on different hands, as well as masking effects between skin stretch cues and a distraction vibration.

2.3 Device Description

The custom built game controllers are similar in function to modern game console controllers, but with the addition of skin stretch feedback. The controllers include buttons and thumbsticks to provide input similar to Sony PlayStation® and Microsoft® Xbox controllers. The controllers also provide vibration feedback as found in current game controllers. In addition, direction cues and tactile effects are provided to the user via skin stretch contactors integrated within controllers. The design of the skin stretch feedback mechanisms used within the controllers was previously presented in [Gleeson et al. 2010a] and [Montandon and Provancher 2013]. In one controller design, the skin stretch tactors are integrated into the top of each thumbstick, with the feedback delivered to the tips of the thumbs (see Figure 2.3). In another controller design, the skin stretch tactors are located on the back of the device, and the feedback is felt on the tips of the middle fingers (see Figure 2.4). Both designs integrate an aperture surrounding the contactors to restrain finger motion. The second design addresses concerns that user motions of the thumb joysticks during cues could have a negative impact on the saliency of the skin stretch cues. Note that standard game controller vibration motors were placed in the lower right and lower left sides of the controller shells, as shown in Figures 2.3 and 2.4.

Our game controller utilizes a microcontroller to control the position of the two skin stretch feedback devices and sets the magnitude of vibration for each vibrotactor of the game controller. The microcontroller also reads user input from the buttons and thumb joysticks, and communicates these states to a host computer. The microcontroller exchanges information with a PC through RS-232 serial communication, with the PC receiving button and thumb joystick state information and sending skin stretch contactor and vibrotactor values to the microcontroller at a rate of 60 Hz, to be compatible with the Microsoft XNA development environment. The front-tactor controller utilizes a flexure stage for converting rotary motion of servos into decoupled translational motions of the contactors, as described by Gleeson et al. [2010a]. The back-tactor controller utilizes a sliding plate and contactor linked to servo motors through spring steel wires, as described by Montandon and Provancher [2013]. To control velocity and compensate for nonlinear motions of this tactile display, a series of waypoints was used for each direction cue. A calibration rig was used to measure the tactor position using a pair of US Digital linear encoder probes (PE-500-2-I-S-L), which have a resolution of 12.5 µm. This 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 [Montandon 2013; Caswell 2013]. The direction cues were then specified as a trajectory of waypoints at a rate of 300 Hz for the back-tactor controller. An overall view of the system architecture is shown in Figure 2.5.

2.4 General Experimental Methods

In this research, my aim was to characterize human performance in recognizing multiple 4-direction skin stretch cues, in order to have a better understanding of any masking effects that may occur due to the presence of different skin stretch cues and/or the presence of vibration. Experiments were conducted to determine human response times and accuracy and to improve device applications by identifying optimal, as well as worst-case, values for the time between different cues, as well as the time between vibration and skin stretch cues. Two experiments were conducted, one exploring masking effects that may occur due to multiple skin stretch cues, and a second investigating masking effects that may occur due to vibration before, during, or after the onset of skin stretch cues. This section includes general experimental methods common to both experiments.

A stimulus was designed to convey direction in one of four cardinal directions (forward, right, backward, left). Each cue consisted of three portions: an outbound move, a pause, and an inbound return move, as shown in Figure 2.6. During the outbound move, the tactor moved radially outward from the center position, approximately 2.5 mm in the cued direction. At this point, a 300 ms pause occurred. After the pause, the tactor returned to the center position. The pause time was characterized in previous work and is necessary in order to prevent temporal out-back masking of the tactor's motion [Gleeson et al. 2010b]. Skin stretch tactor motions followed a straight line at a speed of approximately 30 mm/s. The total duration of each cue was just under 0.5 s, similar to skin stretch cue durations used in [Montandon and Provancher 2013; Guinan et al. 2013].

During the experiments, participants sat in a chair while holding a controller, without resting their hands on anything. Participants wore headphones playing white noise to mask sound from the device and environmental distractions. Participants were instructed to not look at their hands, and to respond to the cues as quickly and accurately as possible by moving the thumb joysticks in the direction of the perceived skin stretch cue. Following a response, a computer-controlled random delay from 1.8 to 2.5 s was added before another cue was given. The random variation in delay was created in order to prevent habituation. Participants were allowed to take a break after every set of 50 cues, if desired. Each experimental portion was completed on both the front-(Figure 2.3) and back-tactor (Figure 2.4) controllers, with the order balanced across participants. The experimental protocol is approved by the University of Utah Institutional Review Board.

2.5 Experiment 2.1: Skin Stretch Masking

In this experiment, I investigated possible masking effects due to multiple 4-direction skin stretch cues. Combinations of cue pairs, as well as different lag times, were included in this portion of the experiment.

2.5.1 Methods

In this experiment, responses to two simultaneous or sequential skin stretch cues were investigated. A cue was delivered to a finger on one hand, and then a second cue was delivered to a finger on the other hand after a short delay. The order of the cues were balanced, with the first cue sometimes delivered to the right hand, and other times delivered to the left hand. Cues were delivered to thumbtips with the front-tactor controller, or the tips of middle fingers with the back-tactor controller. The lag times used between the two cues were determined through pilot testing in order to capture important response characteristics with a minimum number of lag time [Guinan et al. 2013], and include: 0 ms, 100 ms, 500 ms, and 1500 ms. In cases where the lag time was zero, both tactors began their motions at the same time. The two cues were generally in different directions, as a combination of 16 pairs of stimuli were possible between the two hands, and only 4 of those pairs include both tactors moving in the same direction. A total of 320 cue pairs were included for each controller in the experiment, 5 each of the 16 directional combinations for each of the 4 lag times.

Average test durations were about 52 minutes, including the rest periods after every set of 50 cues. This experiment was completed by 12 participants (mean age = 27, 11 male, 9 right-hand dominant) with varying degrees of haptic experience.

2.5.2 Experimental Results and Discussion

Responses were determined to be correct if the participant moved the thumb joystick on the associated hand to an outward position within $\pm 45^0$ of the stimulus cue. Trials with response times outside of 3σ of the mean of a participant's response time of cues for each controller type were considered statistical outliers and were rejected prior to statistical analysis. In total, 72 out of 3840 responses (1.88%) on the front-tactor controller were rejected as outliers. For the back-tactor controller, 72 outliers (1.88%) were also rejected. Following outlier rejection, response accuracies and times of all participants were compared.

2.5.2.1 Direction Discrimination Accuracy

Participants were instructed to respond by moving the thumb joysticks in the perceived direction of the skin stretch cue delivered to each hand as quickly and accurately as possible. Figure 2.7 shows accuracy results for each tested lag time for each controller, where a response was correct when both thumb joysticks were moved in the correct direction to match their respective cues. As previous experiments were designed for cues and responses with one finger [Gleeson et al. 2010b; Guinan et al. 2012], the accuracies of those tests are higher. For example, in [Guinan et al. 2012] a response accuracy of 90% was common for cues delivered to thumbs. If a participant performs by responding correctly for 90% of the cues on one thumb, his/her performance would at best be expected to be 81% accurate when responding to two independent cues delivered to both of his/her thumbs.

As lag time increases, accuracy of responses also increases. This indicates that masking is occurring, making it more difficult for users to correctly identify the direction of both cues when the cues are presented closely together in time. For the front-tactor controller, there was no significant difference in accuracy between a 0 ms lag and 100 ms lag, but there was a significant difference in accuracy between all other groups [$F(3, 3764) = 37.6$, $p < 0.001$]. For the back-tactor controller, the only significant difference is between the responses with 0 ms lag time and 1500 ms lag time [$F(3, 3764) = 5.9$, $p < 0.001$].

As seen in Figure 2.7, participants were more accurate overall with responses for the front-tactor controller. This difference is significant [$F(1, 7534) = 319.8$, $p < 0.001$], with front-tactor controller average accuracy at 77% and back-tactor controller accuracy at 60%. This result is different than found by Caswell [2013], where no significant difference was found in accuracies between the two controllers. However, in this previous study [Caswell 2013], the task was less complex, with participants responding to a single cue direction that was simultaneously delivered to both hands. In the case of the current experiment, the task is more complex, and the collocation of the stimulus and response for the front-tactor controller could aid users in performing better in this more complicated experiment design. Accuracy improves as lag time increases for both controllers, and for the front-tactor controller, with lag times of 1500 ms, response accuracy is slightly above the level expected based on results from Guinan et al. [2012], where participants responded to one cue at a time.

Table 2.1 shows overall accuracy for each of the 16 cue combinations for the front-tactor controller. Directions are a combination of four cardinal directions, where N is forward, E is to the right, etc., and directions are listed in order of left tactor then right tactor direction. The trials where the same direction was presented to both hands are all shown on the left, followed by cues that were in opposite directions, followed by cues in orthogonal directions. The average accuracy for each lag time is shown on the right. The cells of the table are shaded with darker shading indicating higher accuracy.

For the front-tactor controller, any cues with a lag time of 1500 ms, as well as any cues with left and right cues in either the same or opposite cardinal directions, an accuracy of greater than 70% was achieved. For the back-tactor controller, accuracy is significantly lower than for the front-tactor controller, but is usually higher when the cues on the two hands are in the same direction or when the lag time is large (see Table 2.2). Directions are a combination of four cardinal directions, where N is forward, and directions are listed in order of left tactor then right tactor direction. The trials where the same direction was presented to both hands are all shown on the left, followed by cues that were in opposite directions, followed by cues in orthogonal directions. The average accuracy for each lag time is shown on the right. The cells of the table are shaded with darker shading indicating higher accuracy.

Figure 2.8 shows a comparison between different cue types, sorted into three different groups. The "same group" includes the four cue combinations where both the left and right tactors move in the same direction, while the "opposite group" includes the four cue combinations where the two tactors move in opposite directions, and the final "orthogonal group" includes the remaining eight cue combinations of orthogonal cue pairs. For both controllers, opposite and same direction cue pairs have similar response accuracies, while the orthogonal cue combinations have significantly worse accuracies. A high accuracy rate for multiple cues in the same direction is consistent with previous findings [Montandon and Provancher 2013]. A one-way within-subjects analysis of variance (ANOVA) shows a significant difference in participant response accuracies between orthogonal cues and cues in the same or opposite directions [$F(2, 3565) = 112.5$, $p < 0.001$] for the front-tactor controller, and [$F(2, 3565) = 100.7$, $p < 0.001$] for the back-tactor controller. In the case of cues in orthogonal directions, it is possible that the two cues are being perceived as one diagonal cue, causing the response of that diagonal cue to not be within the accepted ±45˚ response window for a cardinal cue. This would be similar to the apparent location effect reported by van Erp [2002].

2.5.2.2 Response Times

Figure 2.9 shows response times for the first and second cue, for each lag time used in this experiment. In a prior similar experiment with only one stimulus, response times were about 600 ms [Guinan et al. 2012]. With a second stimulus added, it is not a surprise that response times were larger in this experiment. The responses to the first cue were significantly slower than others for lag times of 100 ms and 500 ms. This is probably due to the second cue arriving before the participants respond to the first cue. With the arrival of new information, participants delayed their response to the first cue, as they likely focused on what direction the second cue was in, rather than responding as fast as normal to the first cue. The slower response times for cues with lag times of 100 ms and 500 ms is not seen when responding to the second cue, as there is not another stimulus arriving before participants respond in this case. This effect is seen in both the front- and back-tactor controller. In addition, the response time for the second cue is significantly faster than others for lag times of 1500 s. In this case, participants have already fully responded to the first cue, and are waiting for the second cue. Participants know that they only need to respond to one remaining cue, and do so more quickly than responding to all other cues.

2.5.3 Summary of Experiment 2.1

Overall, accuracy with the front-tactor controller was higher than with the back-tactor controller. With the front-tactor controller, accuracies equaled the expected value for lag times of 1500 ms, as the two cues were likely experienced as two distinct separate cues. Cue combinations with two cues in the same or opposite direction produced higher accuracies than cue combinations where the two cues were orthogonal to each other. For both controllers, if a cue was followed by another cue at either 100 ms or 500 ms later, the response time to the first cue was significantly slower than other response times.

2.6 Experiment 2.2: Vibration Feedback Masking

In the second experiment, I investigated possible masking effects due to skin stretch cues in the presence of vibration. This is an important area to explore because current games already use vibration feedback as one form of haptic feedback. With the proposed device, I am adding a second form of haptic feedback, and want to understand how the presence of the existing vibration feedback may impact user responses to the additional skin stretch feedback cues. Combinations of cue pairs, as well as differing amounts of time between the onset of skin stretch and vibration, were included in this portion of the experiment.

2.6.1 Methods

In this experiment, responses to skin stretch cues in the presence of vibration were investigated. Skin stretch cues were delivered simultaneously to both hands, with the same 16 possible direction combinations as in Experiment 2.1. In addition, a vibration was provided for 250 ms and was delivered before, during, or after the onset of the skin stretch cues. The lag times used between the vibration and skin stretch cues include: 0 ms, 100 ms, 250 ms, and 500 ms. There were seven total lag time possibilities, as each of the nonzero lag times were used with the vibration occurring before and after the skin stretch cues. A total of 224 cue pairs were included for each controller in the experiment, 2 each of the 16 direction combinations for each of the 7 lag times.

The average test duration was about 35 minutes, including the rest periods after every set of 50 cues. This experiment was completed by 12 participants (mean age = 27.4, 11 male, 10 right-hand dominant) with varying degrees of haptic experience.

2.6.2 Experimental Results and Discussion

Responses were once again determined to be correct if the participant moved the joystick to an outward position within $\pm 45^0$ of the stimulus cue. Response times outside of 3σ of each participant's mean response time for each controller type were considered statistical outliers and were rejected prior to statistical analysis. In total, 54 out of 2688 responses (2.01%) using the front-tactor controller were rejected as outliers. For the back-tactor controller, 40 outliers (1.49%) were rejected. Following outlier rejection, response accuracies and times of all participants were compared.

2.6.2.1 Direction Discrimination Accuracy

Participants were instructed to respond by moving the thumb joysticks in the direction of the perceived skin stretch cue as quickly and accurately as possible. Figure 2.10 shows accuracy results for each tested lag time for each controller, where a response was correct only when both thumb joysticks were moved in the correct direction to match their respective cues. Negative values indicate that the distractor (vibration) occurred before the target (skin stretch) stimulus.

For the front-tactor controller, the lowest accuracy was seen when the skin stretch cues and vibration began simultaneously. This is expected, as the amount of masking was greatest when the test stimulus was presented near the onset of the masking stimulus in both [Abramsky et al. 1971] and [Gesheider et al. 1989]. The only significant difference in accuracy for the front-tactor controller was found at lag times of 0 ms and 500 ms [$F(6, 2627) = 2.31$, $p < 0.05$]. There is no significant difference for the response accuracies for each lag time with the back-tactor controller [$F(6, 2641) = 0.83$, $p = 0.54$]. Once again, the front-tactor controller produced higher accuracies than the back-tactor controller. This difference is significant, with front-tactor controller accuracy on average of 67.5% and back-tactor controller accuracy on average of 59% [$F(1, 5280) = 40.4$, $p < 0.001$], but as expected these average accuracies are very similar to average accuracy reported in Experiment 2.1 when right and left hand skin stretch cues were delivered simultaneously, as was done in Experiment 2.2. When cues were delivered simultaneously in Experiment 2.1, the average response accuracy was 68.7% for the front-tactor controller. While slightly higher than the average accuracy of 67.5% when vibration was present, there was no significant difference between the accuracy with no vibration and any of the response accuracies for the seven different vibration lag times. For the back-tactor controller in Experiment 2.1, participant response accuracies averaged 56.4%, compared to an average of 59% accuracy in Experiment 2.2. There is once again no significant difference between this accuracy and any of the seven groups with vibration. While not significantly different from other groups, response accuracies were highest when the vibration stimulus occurred 500 or 250 ms before the skin stretch cues. It is possible that in these cases, the vibration stimulus could have improved performance by drawing attention to the device (i.e., priming) and signifying that a skin stretch cue was about to arrive. As the time between response to a previous cue and the start of the next cue was random between 1.8 and 2.5 s, the vibration cues were consistently 500 ms or less before the skin stretch cues.

Figure 2.11 shows a comparison between different cue types. The "same group" again includes the four cue combinations where both the left and right tactors move in the same direction, while the "opposite group" includes the four cue combinations where the two tactors move in opposite directions, and the "orthogonal group" includes the remaining eight cue combinations. A one-way within-subjects analysis of variance (ANOVA) shows a significant difference in participant response accuracies between orthogonal cues and cues in the same or opposite directions [$F(2, 2631) = 345.2$, $p < 0.001$] for the front-tactor controller. For the back-tactor controller, there is a significant difference between each of the three direction combination possibilities [$F(2, 2645) = 446.5$, $p < 0.001$]. With cues that move in orthogonal directions, it is again possible that the two cues are being perceived as one diagonal cue, causing the response of that diagonal cue to not be within the accepted $\pm 45^{\circ}$ response range for a cardinal direction cue. When comparing these results to their corresponding groups from Experiment 2.1 with no vibration, there is no significant difference between any of the accuracies for the front-tactor controller. For the back-tactor controller, there was a significant difference between the "same group" with and without vibration. Participants achieved accuracy rates of 80% when no vibration was present, and were 89.7% accurate when vibration was present and both skin stretch tactors moved in the same direction [$F(1,895) = 13.71$, $p < .001$]. There was also a significant difference in performance with "opposite group" cues for the back-tactor controller. Participants achieved accuracy rates of 70.6% when no vibration was present, and were 77.1% accurate when vibration was present and the skin stretch tactors moved in opposite directions [$F(1,893) = 3.94$, $p < 0.05$].

A direct comparison between Figures 2.8 and 2.11 might suggest significantly lower performance for orthogonal cues in the presence of vibration. However, as Figure 2.8 includes all lag times between skin stretch cues from Experiment 2.1, Figure 2.12 shows only the responses from Experiment 2.1 with zero lag time, which are more appropriate for comparison to the results of Experiment 2.2. As can be seen in Figure 2.12, the vibration has nearly no effect on performance, and the only significant but minor differences between comparable groups are for the back-tactor controller for cues presented in the same direction [$F(1, 895) = 13.71$, $p < 0.001$] and opposite direction [$F(1,893) = 3.94$, $p = 0.0475$].

2.6.2.2 Response Times

Figure 2.13 shows a comparison between response times for each vibration lag time. With the front-tactor controller, the slowest response time is when the vibration precedes the skin stretch feedback by 100 ms. This response time is significantly slower than the response time when the vibration precedes the skin stretch feedback by 500 ms, and there are no other significant differences in response time [$F(6, 2627) = 2.08$, $p = 0.05$]. For the back-tactor controller, there is no significant difference between any response times, but the slowest response times are when the vibration follows the skin stretch feedback by 250 or 500 ms. This could be due to the longer overall response time for the back-tactor controller due to the fact that the cue and response are not collocated. Participants took about 100 ms longer to respond to cues on the back-tactor controller. In the cases where vibration occurred after the onset of skin stretch cues, the added vibration distraction could have caused an even later response for the back-tactor controller.

2.6.3 Summary of Experiment 2.2

Overall, accuracy with the front-tactor controller was again higher than with the back-tactor controller. When comparing these results to those from Experiment 2.1 with skin stretch cues delivered simultaneously, the added vibration distraction did not seem to have an overall effect on performance. This indicates that users are able to focus on the skin stretch cues even in the presence of vibration for this type of task, which could possibly be due to the differences between the test stimulus (skin stretch) and distraction stimulus (vibration). Similar to results from Experiment 2.1, cue combinations with two cues in the same or completely opposite direction again produced higher accuracies than cue combinations where the two cues were orthogonal to each other.

2.7 Conclusions

Two skin stretch haptic feedback game controllers have been designed to provide directional information, one that provides tactile feedback applied to the thumbtips, and the other provides tactile feedback to the tips of the middle fingers. Experiments were designed to evaluate participant responses to multiple skin stretch cues, and skin stretch cues in the presence of vibration. Participants achieved higher accuracy responding to cues applied to the thumbs, likely due to the collocation of the stimulus and response. Participants also achieved higher accuracies as the time between two cues increased, as the two cues became more and more like two individual cues than simultaneous cues with the potential to cause masking. When vibration feedback was used as a masking stimulus, accuracy was lowest when the vibration was simultaneously occurring with the skin stretch feedback, though this decrease in accuracy was not very substantial. For both experiments, participants performed better when the two skin stretch cues given were either in the same direction, or opposite direction, achieving more than 85% accuracy on average with the front-tactor controller and more than 75% for the back-tactor controller.

When planning how to use skin stretch feedback, designers should feel confident that cues separated by 1500 ms are likely perceived and interpreted as two separate cues. Designers should also consider the tradeoff that occurs with accuracy when cues are delivered at the same time, or at times less than 1500 ms apart. He/she should also be aware of the slight decrease in accuracy when a vibration occurs near the onset of skin stretch feedback. In particular, cues that are not in the same or opposite direction have a high tendency of confusing human users when the two cues are placed closely together in time, or are delivered while another type of haptic feedback is also being delivered to the hands (in this example, vibration feedback present in game controllers). Therefore, initial implementations of skin stretch feedback may want to avoid indicating different cue directions on different hands, to ensure the best communication with the user. This recommendation parallels the prior findings of Montandon and Provancher [2013] that suggest delivering a direction cue simultaneously to both hands for greatest efficacy, which also holds true for communicating more subtle direction cues than 4 orthogonal directions presented herein.

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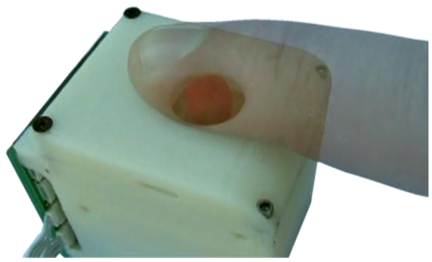

Figure 2.1. A tactile skin stretch device with a finger placed on the aperture (conical hole). The contactor (shown in red) stretches the skin of the fingertip as it moves. The aperture on the top of the skin stretch display restrains finger motion in the plane of tactor motion.

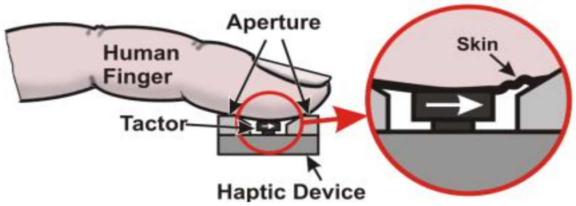

Figure 2.2. Motion of the contactor under the fingerpad stretches the skin of the finger. When the skin is stretched, users can determine the direction of the displacement with 95% or greater accuracy with as little as 0.2 mm of tactor displacement.

Figure 2.3. A custom-made game controller with skin stretch feedback provided on the front of the device, underneath the thumbs.

Figure 2.4. A custom-made game controller with skin stretch feedback provided on the back of the device, where the middle fingers rest.

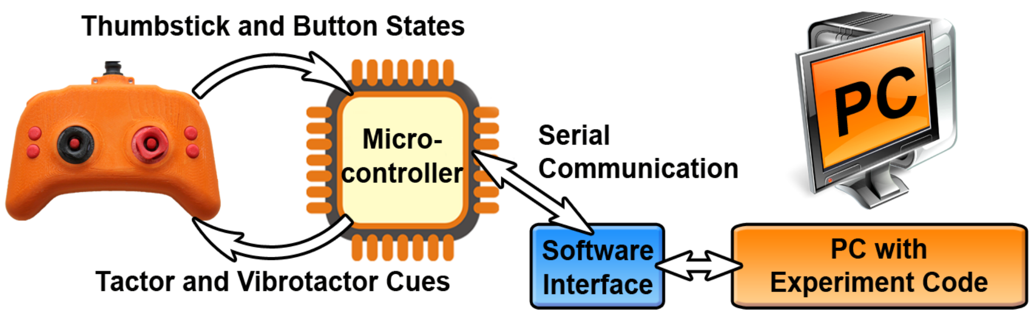

Figure 2.5 System schematic. A microcontroller inside the game controller communicates thumb joystick and button states to a PC and controls the vibrotactors and skin stretch feedback movements.

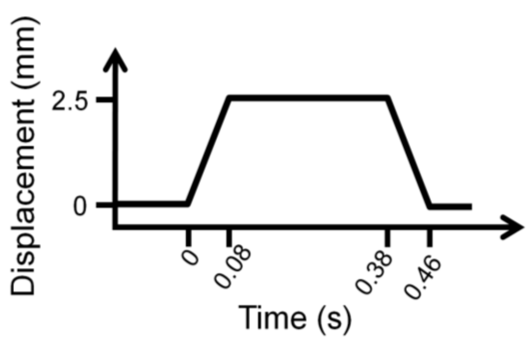

Figure 2.6. Tactor displacement from the center of the aperture, including a 300 ms pause between the outbound and return movements.

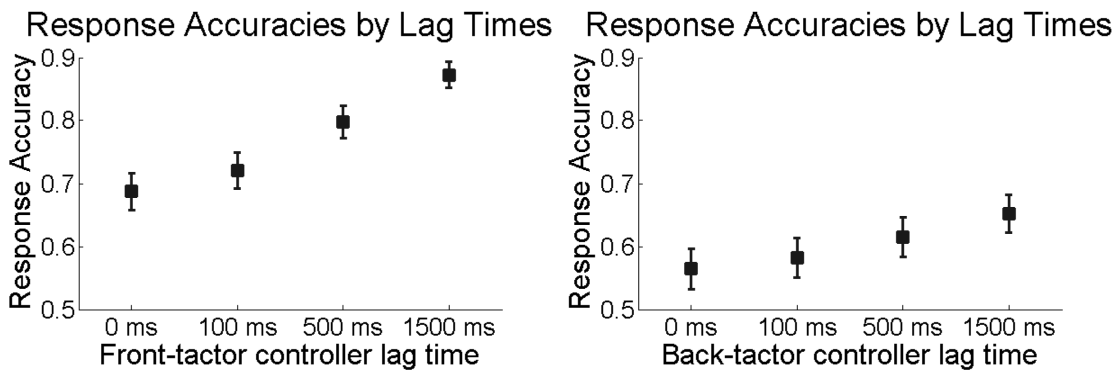

Figure 2.7. Percent accuracy and 95% confidence intervals of each tested lag time. The "front-tactor controller" delivered directional skin stretch cues to the participants through the thumb joysticks, whereas the "back-tactor controller" delivered skin stretch cues to the participants' middle fingers on the back side of the controller. A correct answer, as reported on this plot, is composed of correct responses by the participants on both the left and right thumb joysticks.

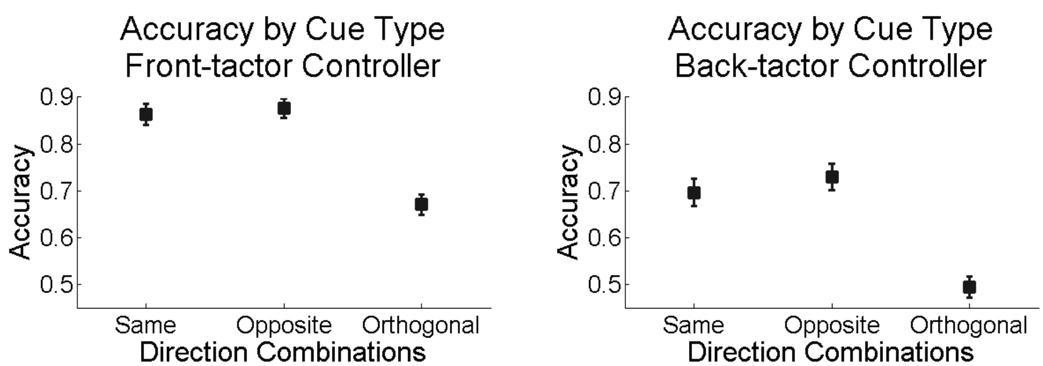

Figure 2.8. Accuracy and 95% confidence intervals for the three categories of cue combinations.

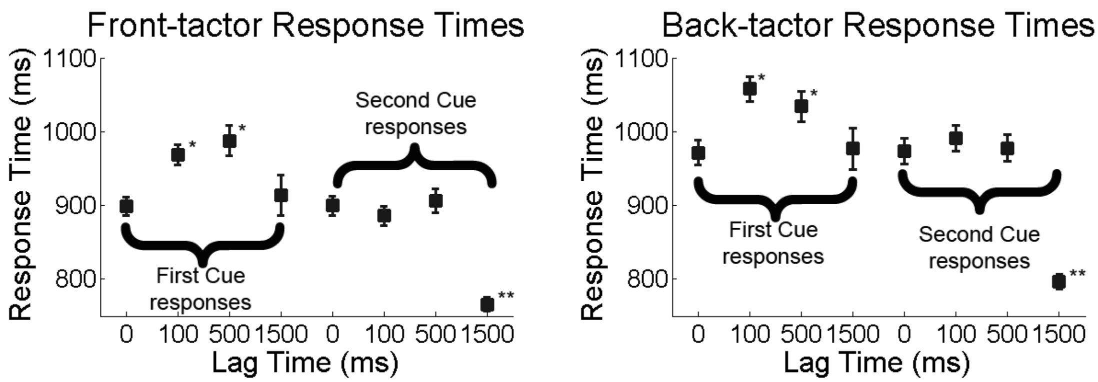

Figure 2.9. Response times and 95% confidence intervals for responding to both the first and second cue for each lag time for both controllers. Significantly different response times are indicated by * or **.

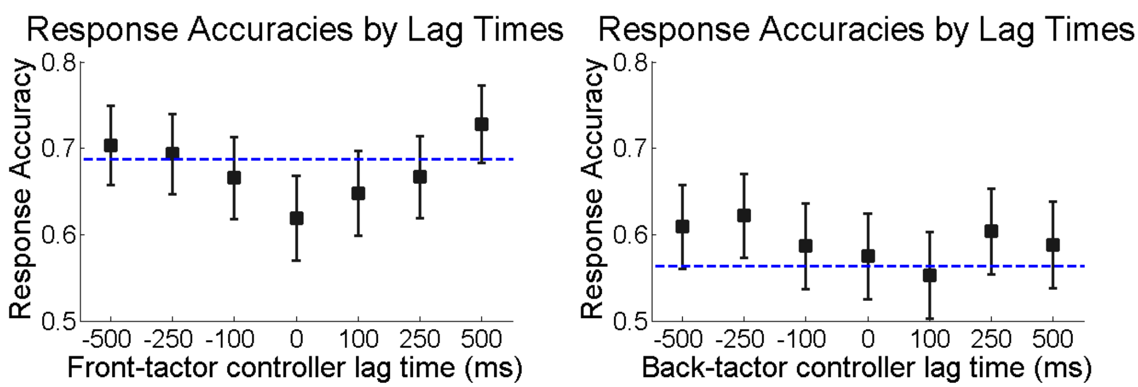

Figure 2.10. Response accuracies to skin stretch cues when vibration occurred before, during, and after the onset of skin stretch cues. The dashed blue line on each figure represents the corresponding accuracy from Experiment 2.1 when right and left hand skin stretch cues were delivered simultaneously. This is the expected average accuracy when there is no vibration.

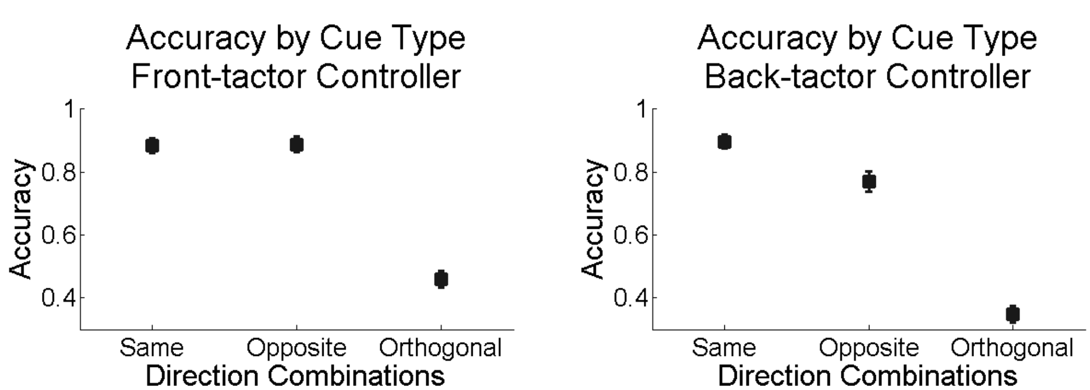

Figure 2.11. Accuracies and 95% confidence intervals for the three categories of cues.

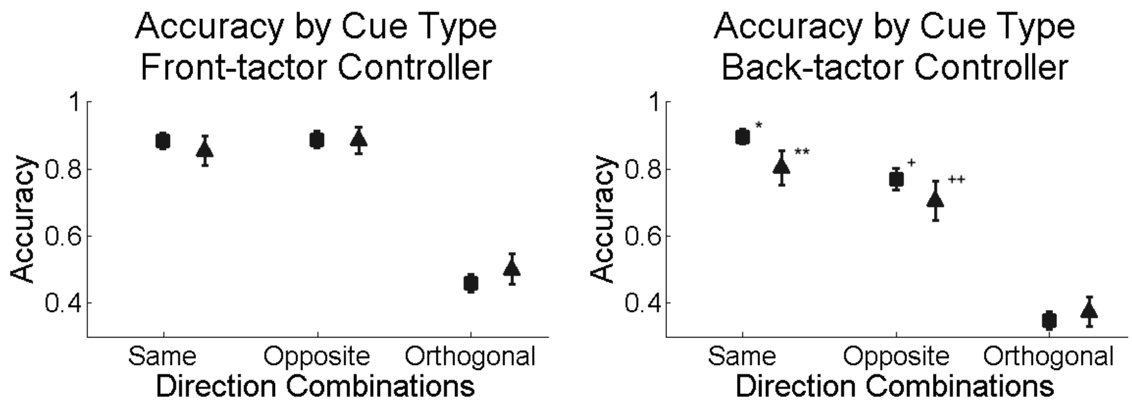

Figure 2.12. Accuracies and 95% confidence intervals for the three categories of cue combinations. Experiment 2.2 results have square shapes representing the mean, whereas comparable (zero lag) cases from Experiment 2.1 have triangle shapes representing the mean. Significantly different response times are indicated by * or **.

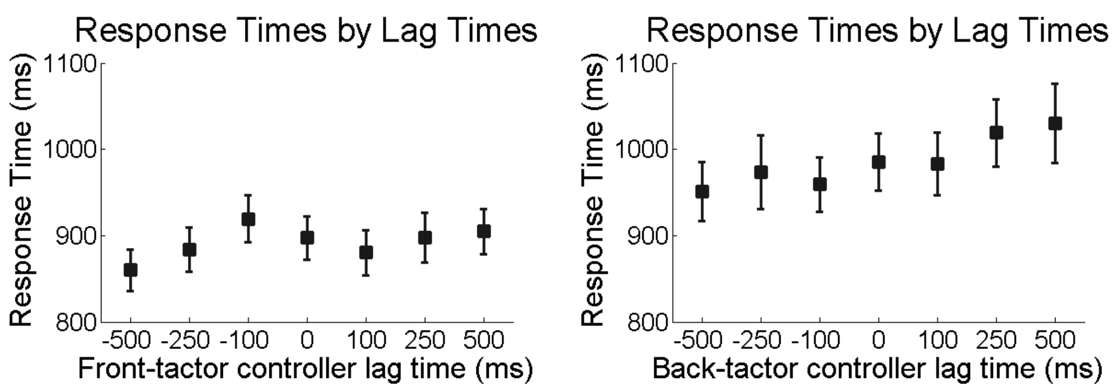

Figure 2.13. Response times and 95% confidence intervals for the different lag times between vibration and skin stretch.

Table 2.1 Accuracy by lag time and cue type for the front-tactor controller

	E E	W W	N N	S S	E W	W E	N S	S N	N E	S E	N W	S W	E N	W N	E S	W S	Average
0 ms	0.80	0.88	0.92	0.82	0.98	0.75	0.86	0.95	0.67	0.67	0.59	0.38	0.50	0.50	0.31	0.38	0.69
100 ms	0.81	0.97	0.96	0.84	0.97	0.77	0.93	0.88	0.76	0.55	0.72	0.48	0.56	0.51	0.36	0.43	0.72
500 ms	0.85	0.70	0.95	0.83	0.88	0.77	0.92	0.85	0.82	0.73	0.78	0.83	0.73	0.66	0.78	0.70	0.80
1500 ms	0.90	0.92	0.88	0.79	0.93	0.83	0.83	0.92	0.88	0.88	0.93	0.83	0.88	0.87	0.85	0.83	0.87

Table 2.2 Accuracy by lag time and cue type for the back-tactor controller

	E E	W W	N N	S S	E W	W E	N S	S N	N E	S E	N W	S W	E N	W N	E S	W S	Average
0 ms	0.76	0.66	0.93	0.86	0.67	0.50	0.79	0.88	0.38	0.45	0.36	0.42	0.41	0.44	0.29	0.23	0.56
100 ms	0.61	0.52	0.95	0.83	0.71	0.58	0.87	0.92	0.58	0.38	0.29	0.42	0.42	0.46	0.37	0.39	0.58
500 ms	0.37	0.32	0.83	0.80	0.57	0.62	0.86	0.93	0.70	0.61	0.49	0.55	0.49	0.55	0.57	0.55	0.61
1500 ms	0.47	0.47	0.80	0.93	0.40	0.50	0.95	0.95	0.60	0.60	0.67	0.53	0.66	0.72	0.58	0.61	0.65

CHAPTER 3

SKIN STRETCH FEEDBACK FOR COMMUNICATING DIRECTION CUES

In this chapter, I present four studies related to using skin stretch feedback cues to command directional hand motions to users. First, user performance is evaluated with two different skin stretch feedback devices. Then, additional experiments are performed using the device that is more promising for commanding motions of the hand. With one device, skin stretch feedback is provided to the tip of the pointer finger and the tip of the thumb. The user's index finger and thumb grasp the device at the location of the moving contactor (tactor) of each of the two degree-of-freedom (2-DOF) skin stretch displays, respectively. With the other device, skin stretch feedback is provided to the entire palm, through sliding plate contactor plates embedded into the handle of the device. Participants indicated the direction of each stimulus by moving their hand or rotating about their wrist to match the direction of the perceived translation or rotation. Findings from these experiments will be used to further examine users' ability to follow paths in multiple degrees of freedom, which could be used in many tasks, such as teleguidance, rehabilitation, and many motion training tasks.

3.1 Introduction

There are several existing forms of haptic feedback that can be used to communicate direction to a user. While some haptic systems are concerned with guiding the position and joint angles of the upper arm or giving direction cues to the person as a whole, I am particularly interested in guiding the motion of the hand or arm of a user. This criterion has led me to focus on providing tactile feedback to the hand, so that the haptic feedback and desired hand motions are collocated on the body.

In this chapter, I examine the use of tactile skin stretch feedback cues to provide directional and rotational information to users. I developed two different haptic devices and explored user interactions with cues from each device.

The first device (Figure 3.1) is a precision grip device that utilizes two independently controlled two degree-of-freedom (2-DOF) skin stretch devices placed back to back. Previous studies have quantified user hand motion performance using a single planar 2-DOF skin stretch device [Gleeson et al. 2010; Norman et al. 2014]. These direction identification and motion tasks with the previous planar devices revealed the promise for skin stretch feedback to be used to guide planar hand motions. With the addition of a second 2-DOF skin stretch device, I am able to convey rotation cues as well as translation direction cues to the user.

The second device (Figure 3.2) utilizes four sliding plate contactors (tactors) that move on the surface of the device handle, and produce in-hand shear forces against the palm and fingers. Users grasp the device using a power grip, wrapping their fingers around the device handle. Previous studies investigated the capability of this device for providing force and torque cues through the independent motion of each of the four sliding plate tactors

[Guinan et al. 2014]. Like the precision grip skin stretch device, the power grip device is capable of communicating translation and rotation cues to a user.

For each device, a translation cue is communicated by simultaneously moving all the contactors in the same direction, and rotation cues are communicated by moving tactors in opposite directions. Each device is compatible with any tracking device, which can track the position and orientation of the user's hand and the device, while the motion of the tactors provide haptic feedback to users.

This chapter presents four experiments evaluating human performance in response to direction cues in multiple degrees of freedom with these devices. The first experiment examines responses to five degree-of-freedom (5-DOF) cues using the precision grip device. The second experiment examines responses to 5-DOF cues using the power grip device. I then compared the performance levels seen with each device and determined that the precision grip device is the most promising for communicating direction cues to guide the motion of a user's hand. The third experiment uses the precision grip device to investigate the possibility of providing direction cues in non-orthogonal directions for both translations and rotations. Finally, the fourth experiment uses the precision grip device to investigate user responses to sequential cues.

The following section provides a brief background exploring current haptic devices that can be used to provide direction cues to the arm or hand. I then present a detailed description about each haptic device and the cues used in these experiments. Next, I outline the general methods used during all experiments. Then, each experiment is discussed, with individual methods and results included. Finally, an overall summary and plans for future work is presented.

3.2 Background

Many haptic devices have been created to aid in guiding the arms and hands to a specific location and orientation. While each of these can provide haptic feedback for certain tasks, there is still a need for a form of haptic feedback that can be used with a handheld tool, while still allowing the user full range of motion, and providing precise cues to the user on how to position their hand and the tool.

Exoskeleton devices can be used to produce very low error and move a human arm or wrist nearly perfectly along a given trajectory [Gupta et al. 2008]. However, there are a wide range of design decisions and tradeoffs that are made that are application specific, and may limit human motion abilities [Sledd and O'Malley 2006]. In addition, while exoskeletons have been made to control the motion of fingers [Agarwal et al. 2015], the bulkiness of exoskeletons makes their use unrealistic for fine motions of the hand in tight spaces. Further, as these devices use force to move arm, wrist, and finger joints, the user has to physically fight against the device if they see something that needs to be avoided in the device trajectory.

Commercial force feedback devices, such as the Geomagic® Touch™, Phantom® Premium™, or Force Dimension Sigma, Omega, or Delta, among others, typically allow for the natural range of motion of the hand within the device workspace. These types of devices are capable of exerting forces and torques on the user to cause translations and rotations of the hand and wrist, and many experiments have shown their effectiveness in training with a motion trajectory [Feygin et al. 2002; Teo et al. 2002; Morris et al. 2007]. However, these devices are expensive, and limit users to these devices' small workspace area. Additionally, the force feedback used with these devices can create instabilities in the system.

Vibrotactile sleeves have been successfully used to guide arm motion in several experiments. However, these same studies show that visual feedback is just as effective as the haptic vibrotactile feedback [Bark et al. 2011; Rotella et al. 2012]. In addition, spatial separation requirements between vibrotactile feedback transducers prevent this type of haptic feedback from being used to provide direction cues to the fingertips [Jones and Sarter 2008].

Suction pressure applied through several points at the fingertips can be used to provide haptic feedback representing forces and torques in a handheld tool [Maemori et al. 2014]. However, the pump required to create this pressure makes it so the device is not able to be fully portable and wireless in the near future. Because of this, the use will be constrained to a desktop area, where the handheld tool and haptic device can be attached to the pump.

Each of the above mentioned forms of haptic feedback are useful for certain applications. However, I am concerned with providing haptic feedback in a handheld tool, while at the same time allowing for a full range of motion of the user’s arm and hand. Skin stretch feedback has been shown to provide reliable directional information to users and is able to be integrated into several devices [Gleeson et al. 2010; Koslover et al. 2012; Norman et al. 2014]. The previously conducted experiments with skin stretch feedback focused on cue matching and guiding hand motions on a two-dimensional plane. The following experiments expand this work by investigating cue matching and hand motion guidance in three-dimensional space.

3.3 Experiment Software and Device Design

In order to communicate directional tactile cues to users, software was developed to be used with the two haptic devices and the tracking device. This section describes the software interface as well as the hardware design of the haptic devices.

3.3.1 Hardware Design of Precision Grip Skin Stretch Feedback

The precision grip skin stretch feedback device was created by mounting two individual planar skin stretch displays back to back. Each skin stretch display utilizes two radio control (RC) hobby servo motors connected to spring steel motors to move the tactor in two-dimensional directions (Figure 3.3), similar to the displays used in [Montandon and Provancher 2013]. In order to ensure the motion of each tactor display was in straight, radial movements, calibration was performed on each skin stretch display, as in [Montandon and Provancher 2013]. This calibration resulted in a 5x5 grid of known tactor locations, which were then stored on the PC for table lookup and bi-linear interpolation.

Each tactor sits in the center of a small conical recess in the device, which helps to restrain the lateral motion of a user's finger and provide a grounding reference for tactile cues. A user creates contact with each tactor by placing his/her thumb and index finger on each tactor (Figure 3.4). Each tactor is the sandpaper-like nub that is sold as part of an assortment of caps for the Lenovo Thinkpad® and has a diameter of 7 mm and a workspace of ±2.5 mm from the center location.

3.3.2 Hardware Design of Power Grip Skin Stretch Feedback

The power grip skin stretch feedback device also utilizes four RC hobby servo motors to move the tactors with one motor for each of the four sliding plates. The motion of each sliding plate is constrained by rails on the frame of the device. Each tactor (shown in black in Figure 3.2) can slide up and down independently along the length of the handle. A user creates contact with the tactors by wrapping his/her palm and fingers around the handle of the device. The frame of the device (shown in white in Figure 3.2) helps provide a grounding reference for tactile cues. The tactors are approximately 90 mm long, 5 mm thick, and 11.5 mm wide, and each has a motion workspace of ±4.5 mm from the center location. Each sliding plate tactor is tapered at its ends to fit comfortably into the user's palm and prevent pinching of skin at the ends of travel.

3.3.3 Tracking Hardware

Both devices were built to attach to the stylus of a Phantom Premium six degree-of-freedom device. This allows for high precision tracking of device location and orientation during experimental testing. There are many types of tracking that could be used in conjunction with these devices. This is just one such mode of tracking position and orientation accurately for experimental testing.

3.3.4 Software Interface

Software was developed in Visual Studio C++ to track the position and orientation of the Phantom Premium stylus, and in turn track the skin stretch device and user's hand. The C++ software also controlled the motion of the skin stretch tactors. To move the tactors, the software communicated with the devices by sending commands to a dsPIC33E microcontroller through USB communication. The microcontroller interfaced with the RC servos to manage the motion and position of the skin stretch tactors.

3.3.5 Direction Cue Design

For each device, translational direction cues are conveyed to the user by simultaneously moving all the tactors at the same rate and in the same direction. When tactors move in opposite directions, a simulated torque sensation is created, which conveys a rotation cue to the user.

For the precision grip tactor device, translation cues in two degrees of freedom can be presented along the axes of the device. Translation cues can also be communicated in diagonal directions by moving the tactors together along an axis diagonal. Figure 3.5 shows the forward and up direction axes and demonstrates a forward cue. The precision grip tactor device can also convey rotation cues in two degrees of freedom by moving the tactors differentially. Figure 3.6 shows the yaw and roll axes and demonstrates a yaw left cue. For roll rotation cues, one tactor moves towards the top of the device and one moves towards the bottom of the device. For yaw rotations, one tactor moves towards the front of the device and one moves towards the back of the device. For this device, the tactors move to the outbound position at a rate of 5 mm/s. The tactor displacement from the center of the aperture to the outbound position was 2.5 mm. As such, each cue takes 0.5 s for the tactors to reach their outbound position. Tactor displacement over time is shown in Figure 3.7. The tactors remain in the outbound position until the participant responds to the cue. The tactors then return to the center of the aperture.

For the power grip device, translation cues in one degree of freedom can be presented in the up and down directions. The device can also convey rotation cues in two degrees of freedom by moving the tactors differentially. Figure 3.8 shows the position of the tactors when centered, during a downward cue, and during a rotation cue. For this device, the tactors move to the outbound position at a rate of 9 mm/s. The tactor displacement from the center location to the outbound position is 4.5 mm. As such, each cue takes 0.5 s for the tactors to reach their outbound position. Tactor displacement over time is shown in Figure 3.9. The tactors remain in the outbound position until the participant responds to the cue, and then return to the center location.

3.4 General Experimental Methods

This chapter presents four separate experiments to characterize user responses to directional skin stretch cues. The first two experiments investigate user responses to one of ten different skin stretch direction cues for both the precision grip skin stretch device and the power grip device. The third and fourth experiments utilize only the precision grip skin stretch device to investigate user responses to diagonal direction cues, as well as performance when responding to sequential cues.

For all experiments, participants wore noise canceling headphones playing white noise to mask the sound from the device as well as the environment. Participants held the device with their right hand and were instructed to begin each cue with their right hand in a centered "start" position, without resting their arm or elbow on anything. This start position was near the middle of the workspace of the Phantom Premium, so that users would be able to comfortably perform all possible translations and rotations while remaining within the workspace of the haptic device and instrumented stylus. The exact start position was not the same every trial, and the software kept track of the start position of each trial when calculating the relative response for each trial. When ready, each participant was instructed to press the space bar on a computer keyboard. After a one second pause, the computer would begin delivering the tactile cue to the user. Participants were instructed to respond to cues as quickly and accurately as possible by moving their hand and wrist in the direction of the perceived skin stretch cue. At the end of each trial, a ding noise played through the headphones, indicating to the user that the trial was complete, and that the user could move their hand back to the “start” position. All portions of the following experiments were self-paced, allowing participants to take the time they needed to get ready for the next cue, at which point they would press the spacebar on a keyboard to start a new trial. The experimental setup is shown in Figure 3.10.

3.5 Experiment 3.1: 5 DOF, 10 Cue Direction Matching with Precision Grip Skin Stretch Haptic Device

In this experiment, I investigated user performance identifying and responding to cues in five degrees of freedom. This experiment is partially discussed in [Guinan et al. 2013].

3.5.1 Tactile Cues

For this experiment, cues were developed to communicate four translations and six rotations. Upward, downward, forward, and backward cues were delivered by simultaneously moving both tactors towards the top, bottom, front, and back of the device, respectively. Figure 3.5 shows an example translation cue. Out-of-plane roll and yaw rotation cues were delivered by simultaneously moving the two tactors in opposite directions, as shown in Figure 3.6. In addition to these four rotation cues, two pitch rotation cues were developed for this experiment. Pitch rotation cues were delivered by simultaneously moving both tactors together in a spiral circular motion. An example in-plane pitch rotation cue is shown in Figure 3.11.

3.5.2 Methods

Fourteen participants (mean age = 27.9, 12 male, 12 right-hand dominant) performed this experiment. Each participant began with a short training period consisting of 12 cues, then responded to 200 direction cues-20 cues for each of the 10 possible motions described in the previous section. Once the participant translated the stylus more than 5 cm or rotated the stylus more than 0.15 radians (8.6˚), a ding noise was played on the noise-canceling headphones to indicate that the response was recorded, and the tactors reset to the center of the aperture. The participant could then begin the next cue by moving their hand back to the start position and pressing the space bar.

3.5.3 Results and Discussion

Cue identification, response motions, and response times were compared for each of the ten direction cues used in this experiment. Prior to analyzing results, outlier rejection was performed on the data. Cues were split into three categories due to the differences in the tactile cues or response motions: translations, out-of-plane rotations, and in-plane rotations (pitch). Responses with completion times outside of 3σ of the mean of an individual participant's response time of cues in the corresponding analysis group (translations, out-of-plane rotations, or in-plane rotations) were considered statistical outliers and were rejected. In total, 58 of 2800 responses (2.07%) were rejected as outliers. Following outlier rejection, an analysis on cue identification, response times, and response motions was completed.

3.5.3.1 Cue Identification and Response Time Analysis

In order to guide hand motions with haptic cues, it is important that human users can correctly identify the cue and the direction it is communicating. Participants' response motions were analyzed to determine the direction of the response. For translation responses (requiring greater than 5 cm translation to be counted as a response), the direction of the motion was compared to forward, backward, upward, and downward motions. For rotation responses (requiring greater than 0.15 radians), the type of rotation was compared to roll clockwise, roll counter-clockwise, yaw left, yaw right, pitch up, and pitch down rotations. These rotation directions are relative to the user's point of view, with yaw left and roll counter-clockwise motions being towards the midline of the user's body.

Overall, participants correctly identified direction cues with 98.6% accuracy, and a mean response accuracy of at least 98% for translations, in-plane rotations, and out-of-plane rotations (Figure 3.12). Each of the ten direction cues had greater than 96% accuracy, and individual accuracies are shown in Table 3.1. The average response time for all direction cues was 1.05 s, though this time varied based on the type of direction cue. Response times for each direction cue are shown in Table 3.2. For both tables, translation cue responses are shown in violet, while in-plane rotation cue responses are shown in blue and out-of-plane rotation cue responses are shown in orange. Table 3.3 shows a confusion matrix for cue identification. Each row represents a direction cue, and each column a response.

A one-way analysis of variance (ANOVA) on response accuracies for each cue type shown in Figure 3.12 (translation, in-plane rotation, out-of-plane rotation) suggests no significant difference between response accuracies [$F(2,2739) = 0.94$, $p > 0.39$]. When breaking responses down further into each of the ten direction cues, a one-way ANOVA on cue response accuracy suggests a significant difference in accuracy between the roll counter-clockwise direction cue and the downward, yaw left, and yaw right direction cues [$F(9,2732) = 2.49$, $p = 0.008$]. A one-way ANOVA on response times shows a significant difference between each group of response (translation, out-of-plane rotation, in-plane rotation) [$F(9,2732) = 107.88$, $p < 0.0001$], but no significant differences within each type of direction cue.

Results from this test show participants have greater than 96% accuracy in identifying tactile direction cues with the device for each of ten possible directions. These results demonstrate the ability to guide user hand motions in five degrees of freedom with this precision grip skin stretch device.

3.5.3.2 Analysis of Response Motions

Correct responses were also analyzed to determine how close they were to the direction cue. For instance, a "forward" response was compared to the device's forward axis. In addition, correct responses were analyzed to determine the amount of coupling between rotations and translations. The human wrist is a complex piece of anatomy, and motion of the wrist results in the wrist and hand rotating and translating on multiple axes relative to the distal end of the radius (arm) [Moojen et al. 2002]. Based on several previous studies of wrist kinematics, it is expected that the deliberate motion of the wrist in one rotation direction also results in a deviation of the wrist in other directions. The following results investigate this coupling of motions.

Table 3.4 shows the amount of translation error for correct translation responses, where a translation response with zero error would be exactly along the device axis. Any deviation from this axis results in an angular difference between the response vector and the direction cue vector. Table 3.4 also shows the amount of rotation that occurs while the user translates. Both columns show the mean and standard deviation for each translational motion response.

Table 3.5 shows the amount of rotation error for correct rotation responses, where a rotation response with zero error would be the rotation exactly about the corresponding device axis. Any deviation from this perfect rotation results in an angular difference between the response rotation and expected rotation. Table 3.5 also shows the amount of translation that accompanies a user rotation. Both columns show the mean and standard deviation for each rotation motion response. Yaw responses correspond to flexion/extension, roll responses correspond to pronation/supination, and pitch responses correspond to radial/ulnar motions of the wrist. As expected from the results of [Moojen et al. 2002], there is motion on other rotation axes during rotation of the wrist, and the wrist does not rotate exactly about the device axes shown in Figure 3.5, Figure 3.6, and Figure 3.11.

Results from this analysis indicate that participants do not respond exactly along the intended direction axes, but are very near the expected direction on average. In addition, there is a slight amount of rotation when responding in a translation direction, and a slight translation when rotating the device. These results demonstrate that after identifying the direction of the response, a user's response motions are near the desired motion. The variations can be used to inform future plans for guiding human hand motions with this device.

3.6 Experiment 3.2: 3-DOF, 10 Cue Direction Matching with Power Grip Device

In this experiment, I investigated user performance identifying and responding to cues with the 4-sliding-plate Power Grip Device.

3.6.1 Tactile Cues

For this experiment, cues were developed to communicate two translations and eight rotations. Upward and downward cues were delivered by simultaneously moving the four sliding plate tactors towards the top and bottom of the device. Figure 3.8b shows an example translation cue. In addition, roll and pitch rotation cues were delivered by simultaneously moving two tactors at a time in opposite directions, as shown in Figure 3.8c. A pitch rotation cue was communicated by moving the front and back tactor in opposite directions, while a roll cue was communicated by moving the left and right tactor in opposite directions. In addition to these four on-axis rotation cues, four off-axis rotation cues were used, which combined two on-axis rotations at a time. For example, by moving both the left and back tactor up and the right and front tactor down, a rotation combining roll right and pitch down could be communicated. Similarly, the other off-axis rotations communicated the remaining combinations of roll and pitch rotations.

3.6.2 Methods

Ten participants (mean age = 29.7, 7 male, 10 right-hand dominant) performed this experiment. Each participant began with a pretest direction matching task with 50 direction cues, followed by training and the full direction matching experiment. The full experiment consisted of 200 direction cues, 20 cues for each of the 10 possible motions. Once the participant translated the stylus more than 5 cm or rotated the stylus more than 0.15 radians (8.6˚), a ding noise was played on the noise-canceling headphones to indicate that the response was recorded, and the tactors reset to the center of the aperture. The participant could then begin the next cue by resetting their hand to the start position and pressing the space bar.

3.6.3 Results and Discussion

Cue identification, response motions, and response times were compared for each of the ten direction cues used in this experiment. Prior to analyzing results, outlier rejection was performed on the data. Cues were split into three categories due to the differences in the tactile cues or response motions: translations, on-axis rotations, and off-axis rotations. Responses with completion times outside of 3σ of the mean of an individual participant's response time of cues in the corresponding analysis group (translations, on-axis rotations, or off-axis rotations) were considered statistical outliers and were rejected. In total, 42 of 2000 responses (2.10%) were rejected as outliers. Following outlier rejection, an analysis on cue identification, response times, and response motions was completed.

3.6.3.1 Cue Identification and Response Time Analysis

Response motions were analyzed to determine the direction of the response. For translation responses (greater than 5 cm translation), the direction of the motion was compared to upward and downward motions. For rotation responses (greater than 0.15 radians), the type of rotation was compared to rotating the top of the device straight forward (pitch down), at a 45° angle to the front and right (pitch down and roll clockwise), to the right (roll clockwise), etc for all four on-axis rotations and all four off-axis rotations.

Overall, participants correctly identified direction cues with 41.6% accuracy. Accuracy for translation cues was highest, at 69.2%, followed by on-axis rotation accuracy at 50.4%. Off-axis accuracy was minimal at 19.0%. Response accuracies and 95% confidence intervals for each cue type is shown in Figure 3.13. A one-way ANOVA shows a significant difference in response accuracies for each cue type [$F(2,1955) = 185$, $p < 0.00001$]. A one-way ANOVA shows a significant difference in response times between on-axis and off-axis responses, with off-axis rotation responses taking significantly longer time [$F(2,1955) = 9.53$, $p < 0.0001$]. Table 3.6 summarizes response accuracies and response times for each of the direction cue types.

While investigating the effect of cue direction on accuracy, a direction confusion was found. Table 3.6 shows a confusion matrix, with a trend visible for the incorrect responses to rotation cues. For this table, rotation cues are designated by the direction the top of the device is pointed towards. For example, a pitch down cue involves the user rotating their wrist downward and away from their body, and the top of the device points towards the N direction. Therefore, on-axis cues are represented by N, E, S, and W, and off-axis cues are represented by the combination of these directions, as NE, SE, SW, and NW. Translation directions are labeled as “up” and “down.” The trend for incorrect responses to rotation cues shows that when subjects responded incorrectly to off-axis rotation cues, they often responded with a nearby on-axis rotation. More specifically, each off-axis rotation cue was often responded to with the on-axis rotation clockwise to the cue (for NE cues, subjects often responded in the E direction, etc.). In addition, each on-axis rotation cue was often responded to with the off-axis rotation clockwise to the cue (for N cues, subjects responded in the NE direction more often than in the NW direction). The only cues with greater than

50% accuracy (shown in dark gray) were the up and down translation cues, and the rotation cues along the N, S, and W orthogonal axes.

3.7 Comparison of Precision Grip and Power Grip Devices

After analyzing the results from Experiment 3.1 and Experiment 3.2, where each device was tested with 10 distinct direction cues, a decision was made to utilize the precision-grip device for future experiments aimed at guiding the hand motions of a user. The precision grip device is capable of rendering direction cues in more degrees of freedom, and results in a much higher rate of direction cue identification than the power grip device. While the power grip device still has many benefits and can increase immersion in virtual reality by giving a sense of forces and torques [Guinan et al. 2014], the precision grip device appears to be the most promising device for guiding hand motions.

For this reason, the precision grip device was the device used for Experiment 3.3 and Experiment 3.4. In addition, based on the amount of rotation that accompanied translations in Experiment 3.1 (as seen in Table 3.4), the required rotation amount to be recognized as a "response" was increased from 8.6˚ (0.15 radians) to 20˚ (.349 radians) for future experiments. This was done to help ensure that all intended translations are considered a translation by the computer software. The amount of translation that accompanies rotations (shown in Table 3.5) was low enough for yaw and roll rotations that the translation amount required for a response remains at 5 cm.

Finally, experiments after this point include a more comfortable "start" position for the wrist. This start position is not only more comfortable for participants, but allows for more range in the dorsiflexion motion of the wrist. Participants were allowed to start with the back side of their hand in-line with the top of the arm. In Experiment 3.1, participants were encouraged to start with their thumb in-line with the bottom part of the arm, so that the device was perfectly perpendicular to the Phantom tracking device. Example starting positions are shown in Figure 3.14.

3.8 Experiment 3.3: 4-DOF, 16-Cue Direction Matching with Precision Grip Device

In this experiment, I investigated user performance identifying and responding to cues in two translational and two rotational degrees of freedom, for a total of four degrees of freedom using the precision-grip skin stretch feedback device. Diagonal translation cues and combined rotation cues were included, for a total of 16 possible direction cues.

3.8.1 Tactile Cues

For this experiment, cues were developed to communicate eight translations and eight rotations. Similar to Experiment 3.1, two translational degrees of freedom were used, and cues were delivered by simultaneously moving both tactors. Once again, four translation cues were created by moving the tactors along the device axes, resulting in upward, downward, forward, and backward cues. In addition, four diagonal translation cues were created by moving the tactors diagonally from the center position and along a 45 degree angle relative to the device axes. However, the pitch-up and pitch-down cues that were included in Experiment 3.1 were not included in the following studies, as the pitch cues were previously communicated as spiraling tactor motions, which could be interpreted for an identification task but would be difficult to interpret for closed-loop hand motions. Furthermore, the net hand motion could be accomplished by the combination of the above hand rotations. Hence pitch rotations were eliminated from the below experiments.

Out-of-plane roll and yaw rotation cues were delivered by simultaneously moving both tactors in opposite directions, just as in Experiment 3.1. Four combined rotation cues were added to this experiment, and combined a roll motion with a yaw motion. The tactors moved simultaneously, and in opposite diagonal directions from the center position and along a 45 degree angle relative to the device axes. For all 16 direction cues, the tactors moved simultaneously from the center position to an outbound position. The motion was in a straight line for each cue, and at a rate of 5 mm/second.

3.8.2 Methods

A power analysis using the results from Experiment 3.1 and the number of trials to be used for Experiment 3.3 suggested utilizing at least sixteen participants for this experiment. Eighteen participants (mean age = 27.1, 14 male, 18 right-hand dominant) performed this experiment. Each participant began with a short pretest consisting of 16 cues, one for each possible direction cue. This was done to see what their intuitive response was prior to providing further instructions. Participants were then provided instructions detailing each of the possible 16 motions, and completed a short training period of at least 16 cues, one for each possible direction cue. If a participant chose to repeat some cues, they were allowed to. The most training cues used by any one participant was 22. Following training, participants then responded to 192 direction cues, 12 cues for each of the 16 possible motions described in the previous section in pseudorandom order. Once the participant translated the stylus more than 5 cm or rotated the stylus more than 0.349 radians (20˚), a ding noise was played on the noise-canceling headphones to indicate that the response was recorded, and the tactors reset to the center of the aperture. The participant could then begin the next cue by resetting their hand to the start position and pressing the space bar.

3.8.3 Results and Discussion

Prior to evaluating results, outlier rejection was performed on the data. Cues were split into two categories due to the differences in the response motions: translations and rotations. Responses with completion times outside of 3σ of the mean of an individual participant's response time of cues in the corresponding analysis group were considered statistical outliers and were rejected. In total, 61 of 3456 responses (1.77%) were rejected as outliers. Following outlier rejection, an analysis on cue identification, response times, and response motions was completed.

3.8.3.1 Cue Identification and Response Time Analysis

Response motions were analyzed to determine the direction of the response. For translation responses (greater than 5 cm translation), the direction of the motion was compared to forward, backward, up, down, up/forward, up/backward, down/backward, and down/forward motions. For rotation responses (greater than 0.349 radians (20°)), the type of rotation was compared to roll clockwise, roll counter-clockwise, yaw left, yaw right, yaw left/roll counter-clockwise, yaw left/roll clockwise, yaw right/roll counter-clockwise, and yaw right/roll clockwise rotations. With eight possible translation responses, a correct translation response was required to have a planar projection within ±22.5˚ of the intended translation vector. Likewise, a correct rotation response was required to have a planar projection within ±22.5˚ of the intended rotation axis. Overall, participants correctly identified translation cues with 55.6% accuracy and rotation cues with 53.4% accuracy. This is much lower than the overall accuracy of 98.6% observed from Experiment 3.1, but a reduction of accuracy is expected when increasing planar skin stretch direction cues from 4 to 8 or 16 cue directions [Montandon 2013; Caswell 2013]. Individual direction cue accuracies are shown in Table 3.8. The average response time for translation cues was 1.14 seconds, and the average response time for rotation cues was 1.06 s. Individual direction cue response times are shown in Table 3.9. For both tables, translation cues are shown in violet, while rotation cues are shown in blue.

A one-way ANOVA on response accuracies for translation cues shows a significant difference in accuracies between two groups: one group with higher accuracy including forward, backward, up/backward, and down/forward cues, and the other group with lower accuracy including up, down, up/forward, and down/backward cues [$F(7,1685) = 50.24$, $p < 0.0001$]. These differences in accuracy are clear in Table 3.8, as the high accuracy group all have higher than 63.9% accuracy, and the low accuracy group all have lower than 41% accuracy. In addition, there is also a significant difference in accuracy within the higher accuracy group. Response accuracy for backward cues (63.9%) is significantly lower than both the up/backward and down/forward cues. Within the lower accuracy group, response accuracy for down cues (27.23%) is significantly lower than for up cues (40.76%).

A one-way ANOVA on response accuracies for rotation cues shows four different groupings for the eight different cue types [$F(7,1694) = 97.03$, $p < 0.0001$]. The highest accuracy group includes roll clockwise and roll counter-clockwise. Yaw left accuracy is significantly lower than roll clockwise, but not significantly lower than roll counter-clockwise. There is no significant difference in response accuracies between yaw right and diagonal yaw left/roll clockwise cues or between yaw right and diagonal yaw right/roll counter-clockwise cues. All three of these rotations have a significantly lower response accuracy than roll clockwise, roll counter-clockwise, and yaw left. Finally, the diagonal yaw left/roll counter-clockwise and diagonal yaw right/roll clockwise cues have significantly lower response accuracies than any of the other rotations.

Table 3.10 shows a confusion matrix for cue identification. Each row represents a direction cue rendered, and each column a response. Shaded boxes represent 70%, 50%, 30%, and 10% of the corresponding direction cues rendered were responded to in the direction noted by the column title. Darker colors represent 70% and 50% response rates, while lighter colors represent the 30% and 10% response rates. Several instances of direction bias and direction confusion were found through the investigation of the confusion matrix. When subjects perceived translation stimuli, they most often responded with an up/backward motion or down/forward motion. Most of these responses were for cues near the biased response. The majority of up/backward responses were to an up, up/backward, or backward cue. Similarly, the majority of down/forward responses were seen in responses to a forward, down/forward, or down cue. For the most part, when translation stimuli were misidentified, they were confused for a nearby translation cue, but there does not seem to be a directional pattern to this confusion.

When rotation cues were misidentified, there was no directional pattern to this confusion, but participants responded to an orthogonal rotation cue with a related combined rotation cue, and vice-versa. A small amount of trials included responses with yaw left/roll counter-clockwise or yaw right/roll clockwise rotations. Instead, participants' rotation response was closer to one of the orthogonal rotations used for that cue. For yaw right/roll clockwise cues, there were more responses with a yaw right rotation or a roll clockwise rotation than to the combined rotation. For yaw left/roll counter-clockwise cues, participants did respond with the combined rotation more often than with a roll counter-clockwise rotation, but responded with a yaw left rotation in more than half of the trials. In addition, participants responded with a roll counter-clockwise rotation in more than half of the yaw right/roll counter-clockwise trials.

3.8.3.2 Analysis of Response Motions

Correct responses were analyzed to determine how close they were to the direction cue. As noted in Experiment 3.1, the wrist is a complex piece of anatomy, and it is expected that deliberate motions of the wrist result in some motions in other directions that are not intended.

Table 3.11 shows the amount of translation error for correct translation responses, where a translation response with zero error would be exactly along the device axis for orthogonal translations or at a 45° angle for diagonal translations. Any deviation from this direction vector results in an angular difference between the response vector and the direction cue vector. Table 3.11 also shows the amount of rotation that occurs while the user translates. Both columns show the mean and standard deviation for each correct translation motion response.

Table 3.12 shows the amount of rotation error for correct rotation responses. In this case, a rotation response with zero error would be a rotation exactly about the corresponding rotation vector. Table 3.12 also shows the amount of translation that accompanies each correct rotation response. Both columns show the mean and standard deviation for each rotation motion response. Once again, as expected from the results of [Moojen et al. 2002], there is motion on other rotation axes during rotation of the wrist. This could contribute to the incorrect responses to rotation cues as seen in the confusion matrix (Table 3.10).

When comparing Table 3.11 to its corresponding table from Experiment 3.1 (Table 3.4), each translation response has higher error for Experiment 3.3 than the amount of error seen in Experiment 3.1 (mean error of 9.02° ± 5.29 versus 16.86° ± 10.66). This is likely due to the additional translation options. In Experiment 3.1, participants knew that translations would only be aligned with the device axes, and were very good at responding in a motion close to the axis. In Experiment 3.3, there were 4 translations along the device axes and 4 diagonal translations. As can be seen in Table 3.10, there was some confusion where participants misidentified an orthogonal translation and responded with a diagonal translation, and vice-versa. The results from Table 3.11 show that even when the participant did correctly identify and respond to the direction cue, the motion of their response was farther away from the desired motion. With more translation response options, participants tended to vary their answers more, and weren't as exact in matching the motion of the cue. The higher rotation amount that accompanies translation responses in Experiment 3.3 could be due to the difference in the hand posture at the beginning of the cue, as explained in Figure 3.14.

When comparing Table 3.12 to its corresponding table from Experiment 3.1 (Table 3.5), there are again some noticeable differences in rotation error for this experiment. First, the rotation error when responding to yaw cues has decreased for Experiment 3.3 (up to 25.68° ± 10.73 versus up to 13.16° ± 7.06). This is likely due to the change in hand posture, which made yaw motions more comfortable to users, and in turn could have reduced rotation error. While there was a noticeable difference in rotation error for yaw responses, the rotation error for roll responses remains steady from approximately 11° to 13.5° in both experiments. The translation amount that accompanies rotations has increased when compared to Experiment 3.1 (up to 0.81 ± 0.54 versus up to 2.82 ± 1.22). One possible explanation for this is the increased rotation threshold required for a response. Experiment 3.1 software logged a response once a user had rotated 0.15 radians (8.6°), whereas Experiment 3.3 software required a user to rotate 0.349 radians (20°) before logging a response. With the increased rotation amount, users likely tend to translate slightly more for each rotation in Experiment 3.3.

3.8.4 Conclusions

Results from this experiment indicate that human users cannot identify and respond to this combination of 16 direction cues at a high rate. The addition of diagonal translation cues and combined rotation cues caused a large decrease in response accuracy when compared to Experiment 3.1, which used the same device and the same method for providing cues through the motion of the tactors. In addition, response motions are not as close to the desired motion with the added translation cues. This new knowledge will be used in the formulation of future experiments with this device. If high accuracy is desired, this experiment suggests that direction cues should be limited to four orthogonal translations and four orthogonal rotations.

3.9 Experiment 3.4: 4-DOF, 8 Cue Sequential Direction Matching with Precision Grip Device

In this experiment, I aimed to evaluate user performance in identifying and responding to two sequential direction cues. Eight possible direction cues were used, and through the sequential rendering of two cues in each trial, several different combinations of rotations and translations can be communicated to the user.

3.9.1 Tactile Cues

This experiment utilized cues to communicate four translations and four rotations using the precision-grip skin stretch feedback device. All cues were delivered by simultaneously moving both tactors. For translation cues, the tactors moved together along the device axes, resulting in upward, downward, forward, and backward direction cues. For rotation cues, the tactors moved differentially along the device axes, resulting in yaw left, yaw right, roll clockwise, and roll counter-clockwise rotation cues.

Cue combinations were created to evaluate user responses to a translation followed by a translation, translation followed by a rotation, rotation followed by a translation, and a rotation followed by a rotation. By using all of these combinations, the experimental results should provide information about human responses to these cues in varying hand positions and orientations. It will also allow us to compare sequential cue results to those in Experiment 3.3 that included combined motions in one cue. For example, diagonal translations from Experiment 3.3 are now broken into two separate orthogonal translations to attempt to achieve an end position that is similar to a diagonal translation relative to the starting location. The same can be done for combined rotations. In addition, Experiment 3.4 allows for evaluation of translation motions with the hand first rotated away from the home position and vice-versa.

With two cues given in sequence, I experimented with two different types of tactile cues: one that reset to the center position after each sequential cue response, and one that added the relative tactor motion of the second skin stretch cue to the endpoint of the tactor motion from the first cue, and did not reset to the center position until the user responded to the second cue in the series. For both of these types of tactile cues, the tactors traveled only 1.25 mm for each cue, half of the tactor displacement for Experiments 3.1 and 3.3. This way, the tactor would not saturate if a sequence of cues with "no reset" required the tactor to move in the same direction for both cues. The "reset" cues ran no risk of reaching the end of the workspace; however the travel distance was still halved to be able to make a comparison between reset and no reset cues. For both the "reset" and "no reset" cue types, there was a one second pause where the tactors did not move before the tactors began moving to communicate the second cue in the sequence. Figure 3.15 shows the tactor displacement over time for a "reset" forward cue followed by a yaw right cue. Figure 3.16 shows the tactor displacement for the same sequence of cues for a "no reset" cue type.

3.9.2 Methods

Eighteen participants (mean age = 27.1, 14 male, 18 right-hand dominant) performed this experiment. Prior to performing this experiment, each participant completed Experiment 3.3 as described earlier in this chapter. Each participant began with a short pretest consisting of 6 pairs of sequential cues, for both the "reset" and "no reset" cases. Participants were then provided instructions explaining that their hand should be held in the same position and orientation after responding to the first cue, and returned to the approximate home position after responding to the second cue. Instructions also explained that the second response should be relative to the hand position at the beginning of the second cue. Auditory cues were modified for this experiment: after responding to the first cue, a chime noise played, and after responding to the second cue, the same ding noise played as used in Experiments 3.1-3.3. This differentiation was used to help remind participants which cue they were responding to. As in Experiment 3.3, the ding signified that the trial was complete and the participant should return to the home position and push the space bar for the next set of cues. The chime noise signified that the hand should be kept still, and the next cue would arrive shortly.

Next, participants responded to 48 pairs of cues for both the “reset” and “no reset” cases. The order of these portions was balanced across participants with ten participants completing the “no reset” portion first, and the other ten completing the “reset” portion first. The 48 cue combinations included every combination of the eight cues followed by the six remaining possible cues. No trials had a repeat of cues on the same axis (forward cue followed by backward cue, etc.). Just as in Experiment 3.3, a translation of 5 cm or a rotation of 0.349 radians (20˚) was required to register a response. At the end of both portions, participants were asked which cue type they preferred, and their response was recorded by the experiment proctor.

3.9.3 Results and Discussion

Prior to performing result analysis, outlier rejection was performed on the data. Cues were split into four categories: “no reset” rotations, “no reset” translations, “reset” rotations, and “reset” translations. Response times were compared to the mean of an individual participant’s response time, and trials with completion times outside of 3σ of the mean were considered statistical outliers and were excluded from further result analysis. In total, 41 of 1728 (2.37%) “no reset” cues and 36 of 1728 (2.08%) “reset” cues were rejected as outliers. Following outlier rejection, analysis of response times and response accuracies of each of the four categories was completed. In addition, an analysis of response motions was done.

3.9.3.1 Cue Identification and Response Time Analysis

To determine participant cue identification accuracy rates, response motions were analyzed to determine the direction of the response. As in Experiments 1 and 3, these response motions were binned into four translation and four rotation categories. Overall, evaluating each cue response individually, participants correctly identified “no-reset” direction cues with 92.06% accuracy, and “reset” direction cues with 92.91% accuracy. Analyzing just the first cues in the sequence, overall accuracy was 91.43% for “no-reset” cues and 93.74% for the “reset” cues. These accuracies are lower than the 98.6% accuracy seen in Experiment 3.1, where the cues were more salient and the tactors traveled twice as far as this experiment. However, participants still had a high amount of accuracy responding to these eight direction cues. When comparing to Experiment 3.3, where there were 16 direction cues resulting in accuracy rates of 54.5%, results from this experiment with 8 direction cues show a much higher accuracy.

Table 3.13 shows participant response accuracy for each of the eight direction cues for the “no reset” portion of this experiment. Participant accuracy in responding to yaw right cues was significantly less than accuracy for all other seven direction cues [$F(7, 1679) = 14.67$, $p < 0.0001$]. The accuracy for yaw right cues was only 76.08%, while all of the other seven direction cues had response accuracies of at least 89.1%. In addition, participant accuracy in responding to down cues was significantly less than responding to up and forward cues.

Table 3.14 shows participant response accuracy for each of the eight direction cues for the “reset” portion of this experiment. Once again, participant accuracy in responding to yaw right cues was significantly lower than accuracy for all other seven direction cues [F(7,

1684) = 10.69, $p < 0.0001$]. The accuracy for yaw right cues was lowest at 79.80%, while each of the other seven direction cues had response accuracies of 91.5% or higher. Table 3.15 shows participant response times for the “no reset” portion of this experiment, and Table 3.16 shows response times for the “reset” portion of this experiment.

Through further investigation of the low response accuracy to yaw right cues, many of the incorrect responses to yaw right cues were identified as translation responses. In the “no reset” portion, a yaw right cue was responded to with one of the four translation responses 14.83% of the time. In the “reset” portion, a yaw right cue was responded to with a translation 16.26% of the time. This could be due to the difficulty of the yaw right motion. As can be seen in the confusion matrices in Table 3.17 and Table 3.18, many yaw right cues were responded to with a backward translation motion. It is possible that in these cases, the user first pulled their hand slightly backwards in order to rotate their wrist, or that the rotation and translation occurred simultaneously. In either case, it is possible that the user intended to respond with a yaw right motion, but due to the difficulty of this rotation, the response was recorded as a translation. There could also be some confusion which caused the user to identify the cue as a translation, but as can be seen in Table 3.17 and Table 3.18, it is rare that a user confuses a rotation cue for a translation cue. There are also a high amount of roll counter-clockwise responses to yaw right cues. Again, it is possible that users intended to respond with yaw right rotations, but simultaneously rolled their wrist counter-clockwise, and the software determined that the user had responded with a roll counter-clockwise motion.

The results were also broken into four cue combination categories: translation followed by translation, rotation followed by rotation, translation followed by rotation, and rotation followed by translation. For this analysis, responses to both cues in the pair were required to be correct in order for a cue combination to be correct. Accuracy for each combination can be seen in Figure 3.17 and Figure 3.18. For the “no reset” portion of the experiment, the combination of a rotation followed by a rotation is significantly worse than the three other combinations [$F(3, 845) = 7.87$, $p < 0.0001$]. For the “reset” portion of the experiment, there is no significant difference in response accuracies between the four combination categories [$F(3, 840) = 2.05$, $p = 0.1054$].

Overall, There is no significant difference between individual translation cues that are either first or second in the sequence for either the “no reset” [$F(1, 842) = 1.1$, $p = 0.2955$] or the “reset” cues [$F(1, 845) = 2.93$, $p = 0.0875$]. There is no significant difference between individual rotation cues that are either first or second in the sequence for either the “no reset” [$F(1, 841) = 0.16$, $p = 0.689$] or the “reset” cues [$F(1, 843) = 0.11$, $p = 0.7412$]. However, there are some cue combinations where the response accuracy to the second cue is significantly less than the mean accuracy for when the cue is presented first. For translation cues, there is no significant difference between translation cues applied first in the sequence and translation cues applied after a translation or after a rotation for either the “no reset” [$F(2, 841) = 0.63$, $p = 0.5303$] or the “reset” [$F(2, 844) = 1.51$, $p = 0.2225$] portions. Each of the translation groups (first cue, after a rotation, and after a translation) have accuracies of 92.91% or greater.

For rotation cues in the “no reset” portion of the experiment, the response accuracy for a rotation cue after another rotation cue is 80.71% and is significantly lower than for a rotation cue after a translation cue (95.07%) and for a rotation cue that arrives first in a sequence (89.50%) [$F(2, 840) = 10.98$, $p < 0.0001$]. For the rotation cues in the “reset” portion of the experiment, there is no significant difference in response accuracies between first rotation cues, rotation cues after a rotation, and rotation cues after a translation [$F(2, 842) = 0.74$, $p = 0.4788$], with all of these rotation groups having an accuracy of at least 88.49%.

The decrease in accuracy for the second rotation cue in a rotation/rotation sequence for “no reset” cues could be due to mental rotation. While [Gleeson and Provancher 2012] demonstrated that mental rotation effects are minimal for translation cues given in a rotated reference frame of 40˚ or less, the decrease in accuracy of this experiment is seen only when a rotation cue is given in a rotated reference frame. It is also possible that this decrease in performance is due to the second rotation cue being provided with the tactors at a different starting location than the first rotation cue. The first rotation cues results in the two tactors being offset from the center location, and offset from each other. For the “no reset” cues, the tactors remain offset, and the second rotation is provided to the user. It is possible that this offset of the tactors at the beginning of the second rotation cue causes some confusion and decreases accuracy, as this decrease in accuracy is not seen in the “reset” portion of the experiment, where the tactors are not offset when the second rotation cue begins.

3.9.3.2 Analysis of Response Motions

Correct results from both portions of this experiment were also analyzed to determine how close they were to the direction cue given. Table 3.19 and Table 3.20 show the amount of translation error for correct translation responses, and the amount of rotation that occurs while the user translates for the “no reset” and “reset” portions of the experiment, respectively. Table 3.21 and Table 3.22 show the amount of rotation error for correct rotation responses, as well as the amount of translation that occurs while the user rotates their wrist relative to the prior rest position and orientation for the “no reset” and “reset” portions of the experiment, respectively.

When comparing Table 3.19 to Table 3.20, the results are similar between the two cue types in this experiment. However, when comparing these tables to Table 3.11 from Experiment 3.3 and Table 3.4 from Experiment 3.1, each translation response has higher error for Experiment 3.4 than for Experiments 3.1 and 3.3. There are several reasons why there may be higher error in motion responses for this experiment. One possibility is that the cues are less salient, causing users to be unsure of the direction of the cue, which leads to more error.

Another possibility that could cause higher error when compared to Experiment 3.1 is the difference in the hand position, as also explained in Experiment 3.3 results. For Experiment 3.1, users were sitting with their waist and shoulders parallel to the front of the Phantom, and with their arm and the device perpendicular to the front edge of the Phantom. This setup helped align the Phantom coordinates with the local body coordinates. However, this setup made it difficult to rotate the wrist in the yaw motions, and a decision was made to allow participants to sit more naturally for longer experiments. This more natural setup allows us to see how people would interact with the device for longer times, and in a way where they can comfortably complete motions in all directions desired. This difference in orientation between the hand and the Phantom device could lead to more error in motions.

A third possible difference in motion error between this experiment and both Experiments 3.1 and 3.3 could be due to higher motion errors when the hand is first moved away from the original home location. In the results for Experiment 3.4 (shown in Tables

3.19-3.22), the responses to the second cues are included in the analysis. Because these were sequential cues in which users did not reset their hand to the home position after responding to the first cue, responses to the second cue are done from a less common hand starting orientation or position. To investigate if the second response motions caused higher error, the results were divided into first cue responses and second cue responses. Table 3.23 through Table 3.26 show response motions to the first cue and are more comparable to Experiments 3.1 and 3.3. Table 3.27 through Table 3.30 show response motions to the second cue.

The results from this extra analysis show that for both cue types, the mean translation error, rotation error, rotation amount, and translation amount is lower for each direction response for the first cue response compared to the overall motion analysis response shown in Table 3.19 through Table 3.22. Therefore, it is very possible that the starting position and orientation of the hand has an effect on the motion error. Comparing Table 3.23 through Table 3.26 to those from Experiment 3.3 (Table 3.11 and Table 3.12), the motion error for Experiment 3.4 is closer to that seen in Experiment 3.3, but still higher for most directions. With the only difference between the first cues in Experiment 3.4 and the cues in Experiment 3.3 being the amount of skin stretch applied, this difference could be due to participants being less sure of the direction of the skin stretch cue due to the reduced amplitude of the skin stretch cue.

3.9.3.3 User Preferences

User performance for the “no reset” and “reset” cues was very similar for each area analyzed in the previous two sections. When asked which mode they preferred, 11 users responded with “no reset” and 7 responded with “reset.” Common reasons why users preferred the “no reset” portion were that the “reset” portion reset cues were confusing in that the user thought the reset was an additional cue. Participants who preferred the “reset” portion often said that this allowed them to tell which direction the second cue was easier than the “no reset” portion.

3.10 Conclusions

This chapter presented methods and results for four different experiments focused on direction identification of tactile cues. The main findings from these experiments help create a foundation for using tactile skin stretch cues to communicate motions a user should make with their hands. One key finding is that the precision grip device results in higher cue identification accuracy than the power grip device. Another key finding is that limiting the cues to be along the device axes creates higher accuracy than trying to communicate diagonal translation cues or combined rotation cues. Finally, users are able to correctly identify direction cues when the stimulus is limited to a motion of 1.25 mm of the tactor. Users can also identify direction cues at a high rate when the cues are given in sequence of up to two cues in a row, however, if the user’s hand is first rotated, the accuracy in identifying and responding to a second rotation cue may be reduced for “no reset” cues.

3.11 Future Work

Future work will utilize the information learned from these experiments to continue to study the capabilities of the precision grip skin stretch device to command hand motions to users. Future experiments will focus on using skin stretch cues to help users reach a specific position and orientation using closed-loop control. These experiments are discussed in Chapter 4. The motion analysis findings from Chapter 3 provide a foundation for what can be expected in these future experiments. In addition, the results for sequential cue accuracy from Chapter 3 suggest that future work can use sequential motions to guide a user to a location and orientation through a chain of motions. While Experiment 3.3 shows the difficulties associated with diagonal translation cues, the results also suggest that a position diagonally away from the starting position can be achieved through sequential translations. Future work will continue to explore this by investigating sequential cues with more than two cues in a row.

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Figure 3.1. The precision grip skin stretch tactor device. A user places their thumb over one tactor, and their index finger over the second tactor (shown in red).

Figure 3.2. The power grip skin stretch feedback device. A user grips the handle, and the tactors (shown in black) slide against the palm and fingers.

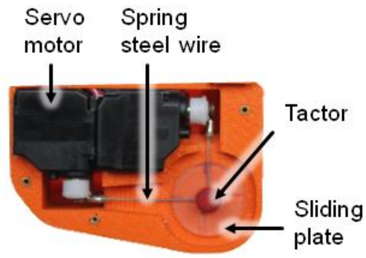


Figure 3.3. An internal view of the precision grip skin stretch feedback device. This shows the RC hobby servos, tactor, sliding plate, and spring steel wires used to move the tactor for the index finger side of the device. The design is mirrored on the opposite side of the device.

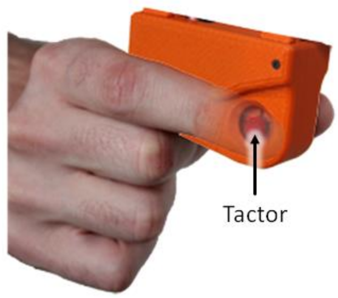


Figure 3.4. An external view of the precision grip skin stretch feedback device. The user holds the device in their hand, making contact with each tactor with his/her index finger and thumb.

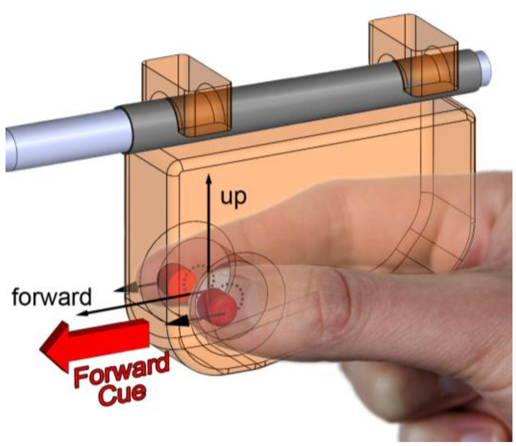


Figure 3.5. An example translation cue in the forward direction. The up and forward axes are shown with long black arrows. The dashed black circles show the centered positions of the tactors, and the short black arrows centered on the tactors indicate the direction of tactor motion.

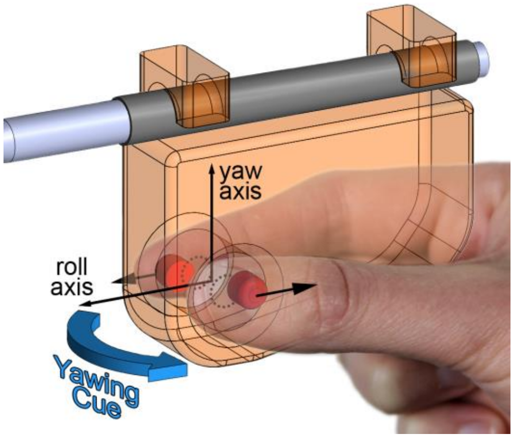


Figure 3.6. An example rotation cue in the yaw left direction. The yaw and roll axes are shown with long black arrows. The dashed black circles show the centered positions of the tactors, and the short black arrows centered on the tactors indicate the direction of tactor motion.

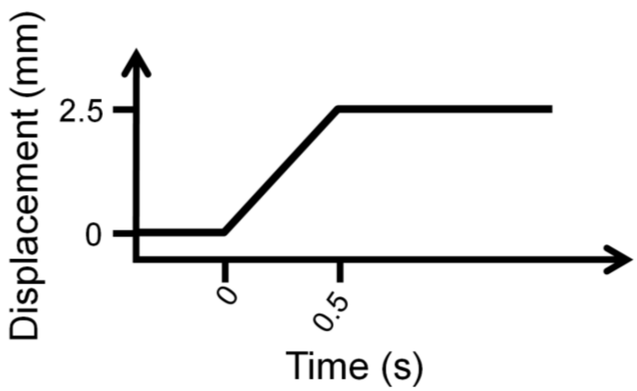
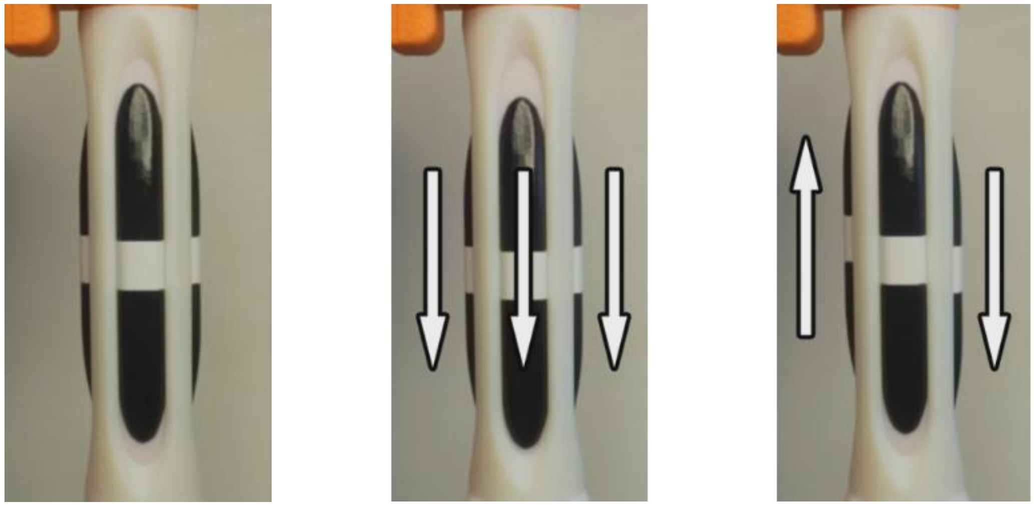


Figure 3.7. Tactor displacement over time from the center of aperture for precision grip skin stretch device. Tactor speed was 5.0 mm/s for all applied skin stretch cues.



(a) (b) (c)

Figure 3.8. Example tactor locations for the power grip device. Tactor locations shown are for the (a) centered, (b) down, and (c) differential position. Image (b) communicates a downward translation, and (c) communicates a clockwise rotation.

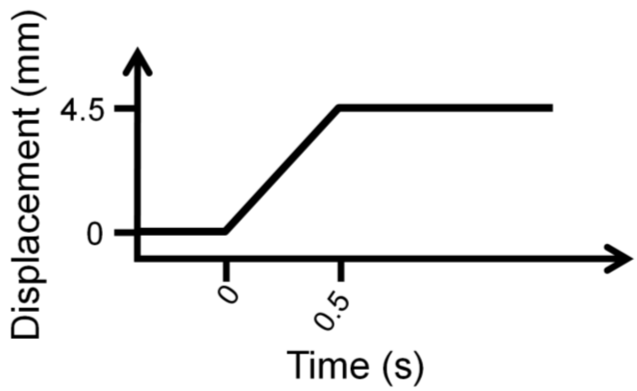


Figure 3.9. Tactor displacement over time from the center location for the power grip device. Tactor speed was 9.0 mm/s for all applied skin stretch cues.

Figure 3.10. An experiment participant. Participants wore noise canceling headphones and held their hand and device at the start position before beginning a trial. A simple computer dialog indicated which trial number they were currently on.

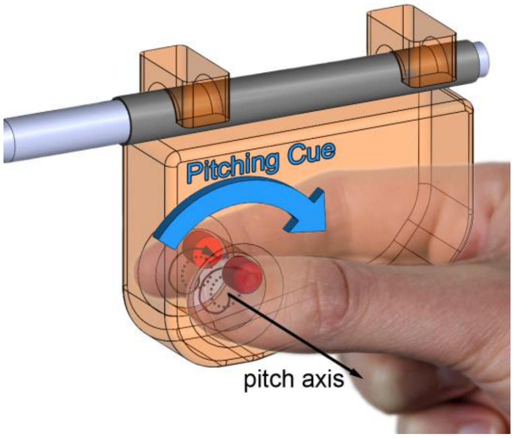


Figure 3.11. An example pitch rotation cue. One in-plane rotation is indicated with the pitch axis. The dashed black circles show the centered positions of the tactors, and black spiral arrow adjacent to the tactors indicates the motion path of the tactors.

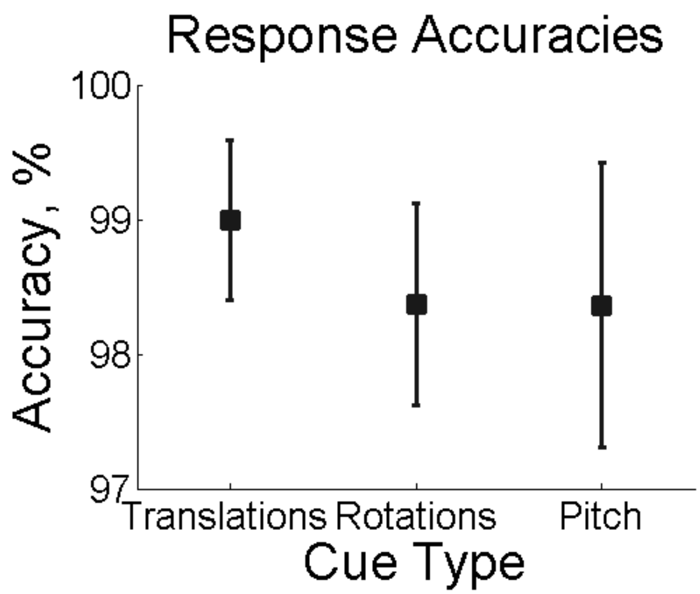


Figure 3.12. Response accuracies for each type of direction cue.

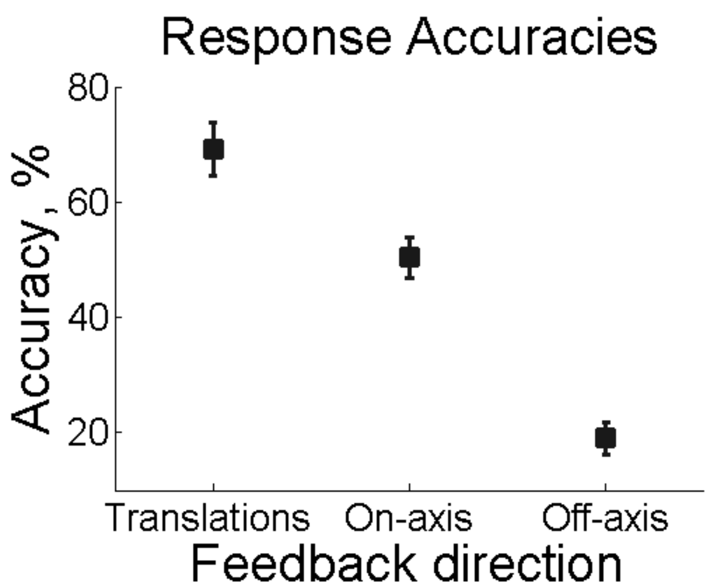
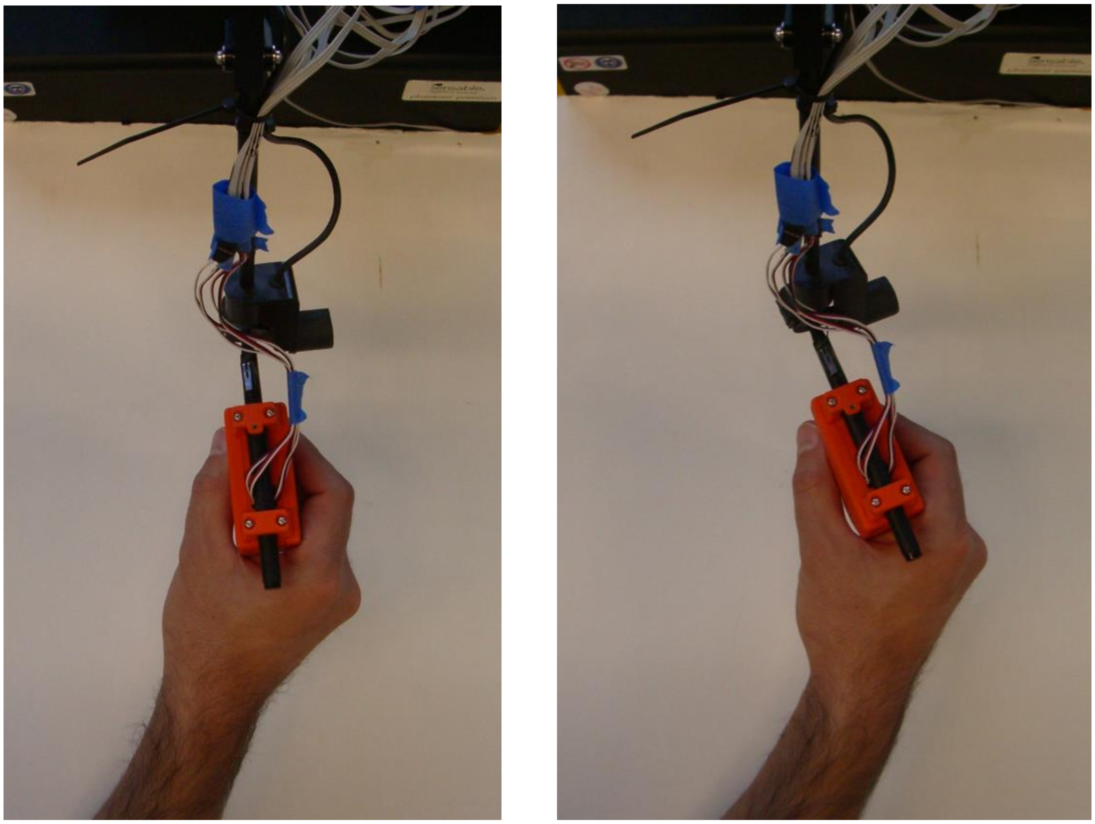


Figure 3.13. Response accuracies for direction cues with the power grip device. Responses are grouped into translations, on-axis rotations, and off-axis rotations.



(a) (b)

Figure 3.14. Start position for Experiment 3.1 (a) and start position for future experiments (b). For future experiments, participants hold their hand in a more natural position, with the stylus no longer perpendicular to the Phantom base.

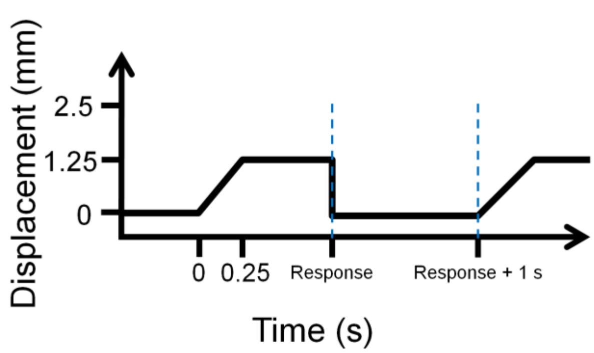


Figure 3.15. Tactor displacement over time from the center of aperture for a “reset” cue. After the user response, the tactor resets to the center position, and the second cue begins following a 1 s pause.

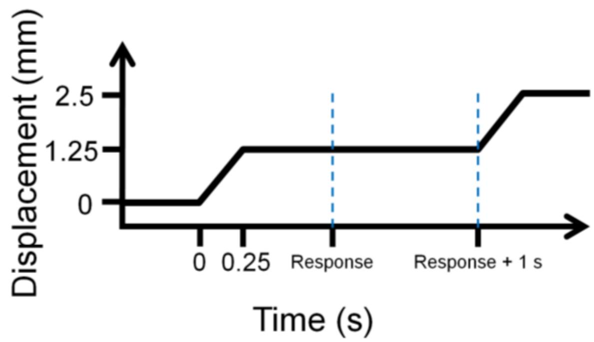


Figure 3.16. Tactor displacement over time from the center of aperture for a “no reset” cue. After the user response, the second cue begins following a 1 s pause.

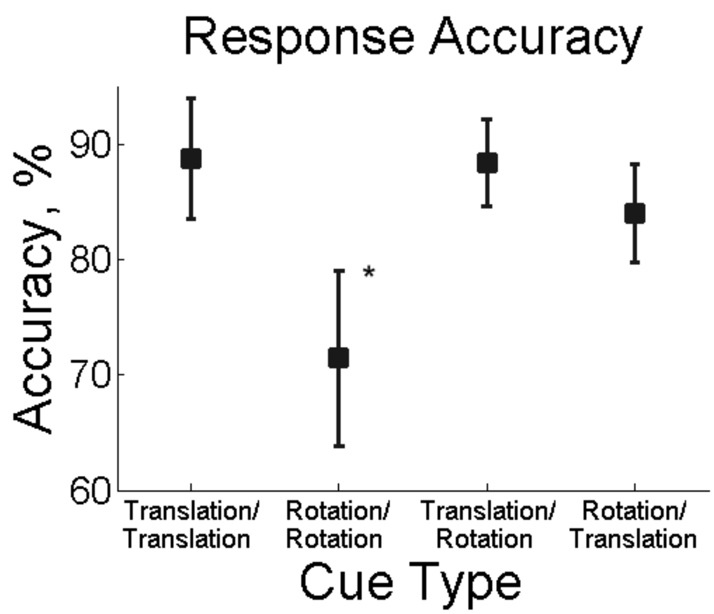


Figure 3.17. Response accuracies and 95% confidence intervals for the four cue combinations for the “no reset” portion of the experiment.

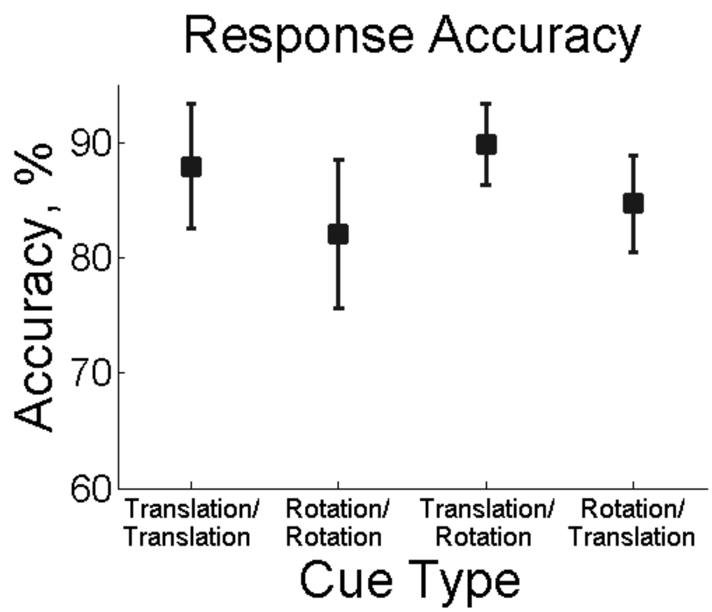


Figure 3.18. Response accuracies and 95% confidence intervals for the four cue combinations for the "reset" portion of the experiment.

Table 3.1 Response accuracy for each direction cue.

Cue Type	Percent Correct	Cue Type	Percent Correct	Cue Type	Percent Correct
Forward	98.20%	Yaw Left	99.30%	Pitch Up	97.80%
Up	98.90%	Yaw Right	99.60%	Pitch Down	98.90%
Backward	98.90%	Roll CCW	96.10%		
Down	100%	Roll CW	98.50%		

Table 3.2 Mean response times for each direction cue.

Cue Type	Response Time	Cue Type	Response Time	Cue Type	Response Time
Forward	1.04 s	Yaw Left	0.80 s	Pitch Up	1.52 s
Up	1.01 s	Yaw Right	0.86 s	Pitch Down	1.53 s
Backward	1.12 s	Roll CCW	0.82 s		
Down	1.03 s	Roll CW	0.79 s		

Table 3.3 Confusion matrix

Direction Cue Rendered	Direction of Response									
	Forward	Up	Backward	Down	Yaw Left	Yaw Right	Roll CCW	Roll CW	Pitch Up	Pitch Down
Forward	272	0	0	0	3	1	0	0	1	0
Up	0	271	0	0	0	0	0	0	2	1
Backward	0	0	267	0	3	0	0	0	0	0
Down	0	0	0	269	0	0	0	0	0	0
Yaw Left	0	0	0	0	273	0	0	0	2	0
Yaw Right	1	0	0	0	0	274	0	0	0	0
Roll CCW	0	0	0	0	10	0	268	0	1	0
Roll CW	0	0	0	0	0	2	0	269	2	0
Pitch Up	0	0	0	0	0	0	0	0	274	0
Pitch Down	0	0	0	0	0	0	1	0	0	275
Σ	273	271	267	269	289	277	269	269	282	276

Table 3.4 Motion analysis for translation responses, reported as mean error ± standard deviation.

Motion Response	Translation Error (degrees)	Rotation Amount (degrees)
Forward	9.70° ± 4.85	2.69° ± 1.40
Up	6.66° ± 4.69	3.59° ± 2.13
Backward	13.64° ± 6.21	3.58° ± 2.11
Down	6.07° ± 5.40	3.07° ± 1.85

Table 3.5 Motion analysis for rotation responses, reported as mean error ± standard deviation.

Motion Response	Rotation Error (degrees)	Translation Amount (cm)
Yaw Left	22.08° ± 12.68	0.59 ± 0.34
Yaw Right	25.68° ± 10.73	0.81 ± 0.54
Roll CCW	13.37° ± 5.23	0.28 ± 0.21
Roll CW	11.00° ± 6.70	0.34 ± 0.25
Pitch Up	15.91° ± 9.28	1.67 ± 0.82
Pitch Down	19.47° ± 9.95	0.99 ± 0.68

Table 3.6 Summary of Power Grip response accuracies and response times.

Cue Type	Response Accuracy	Response Time
Translation	69.23%	1.35 s
On-axis Rotation	50.38%	1.29 s
Off-axis Rotation	19.01%	1.42 s

Table 3.7 Confusion matrix for directional matching experiment with power grip device. Each cell contains the total number of responses in a given direction, as a function of the actual cue rendered. A “N” (north) cue resulted in the top of the controller being pitched forward.

Direction Cue Rendered	Direction of Response									
	Up	Down	N	NE	E	SE	S	SW	W	NW
Up	149	1	7	9	10	2	3	3	8	5
Down	4	121	12	7	4	12	13	10	8	2
N	2	2	99	67	12	1	7	4	1	1
NE	3	17	25	32	62	24	7	8	7	8
E	1	9	6	5	80	50	16	5	15	4
SE	3	32	6	4	12	35	58	28	15	4
S	1	0	5	1	1	2	116	50	15	1
SW	25	0	8	3	4	6	50	46	36	17
W	13	3	11	0	9	3	6	12	100	37
NW	26	0	46	24	25	5	2	5	25	36
Σ	227	185	225	152	219	140	278	171	230	115

Table 3.8 Response accuracy for each translational and rotational direction cue.

Cue Type	Percent Correct	Cue Type	Percent Correct
Forward	75.58%	Yaw Left	73.46%
Up/Forward	35.05%	Yaw Right	51.22%
Up	40.76%	Roll CCW	80.47%
Up/Backward	82.41%	Roll CW	89.25%
Backward	63.90%	Yaw Left/Roll CCW	19.07%
Down/Backward	40.58%	Yaw Left/Roll CW	58.14%
Down	27.23%	Yaw Right/Roll CCW	46.30%
Down/Forward	78.57%	Yaw Right/Roll CW	8.53%

Table 3.9 Mean response times for each translational and rotational direction cue.

Cue Type	Response Time	Cue Type	Response Time
Forward	1.12 s	Yaw Left	1.03 s
Up/Forward	1.13 s	Yaw Right	1.24 s
Up	1.09 s	Roll CCW	0.98 s
Up/Backward	0.99 s	Roll CW	0.96 s
Backward	1.35 s	Yaw Left/Roll CCW	1.08 s
Down/Backward	1.26 s	Yaw Left/Roll CW	0.99 s
Down	1.13 s	Yaw Right/Roll CCW	1.02 s
Down/Forward	1.06 s	Yaw Right/Roll CW	1.18 s

Table 3.10 Confusion matrix

Direction Cue Rendered	Direction of Response: Fwd	Diagonal Up/Fwd	Up	Diagonal Up/ Back	Back	Diagonal Down/ Back	Down	Diagonal Down/ Fwd	Yaw Left	Yaw Right	Roll CCW	Roll CW	Diagonal Yaw Left/ Roll CCW	Diagonal Yaw Left/ Roll CW	Diagonal Yaw Right/ Roll CCW	Diagonal Yaw Right/ Roll CW
Forward	164	14	0	0	0	0	0	27	2	1	1	0	0	6	2	0
Up/Forward	75	75	50	8	0	0	0	0	0	0	0	3	0	2	1	0
Up	2	9	86	101	2	0	0	1	0	1	2	4	0	3	0	0
Up/Backward	0	0	13	178	19	2	0	0	1	0	1	0	0	1	1	0
Backward	0	0	0	33	131	22	3	0	11	1	1	1	0	2	0	0
Down/Backward	0	0	0	1	44	84	66	4	2	0	2	1	1	1	1	0
Down	0	0	0	0	0	3	58	133	1	0	5	7	0	1	5	0
Down/Forward	21	0	1	0	1	0	4	165	1	0	12	1	1	1	2	0
Yaw Left	3	0	0	2	1	0	0	1	155	0	1	2	1	45	0	0
Yaw Right	1	2	2	2	9	12	9	9	0	105	0	2	0	2	47	3
Roll CCW	1	0	3	4	0	0	2	0	0	0	173	0	5	0	27	0
Roll CW	0	0	1	0	1	0	0	2	0	1	0	191	0	17	0	1
Yaw Left/Roll CCW	1	2	3	0	1	0	0	0	120	0	30	0	41	16	1	0
Yaw Left/Roll CW	2	0	0	0	0	0	1	1	7	0	1	78	0	125	0	0
Yaw Right/Roll CCW	1	0	0	4	0	0	2	0	0	3	103	2	0	0	100	1
Yaw Right/Roll CW	3	2	5	5	2	16	1	7	0	48	0	88	0	2	14	18
Σ	274	104	164	338	211	139	146	350	300	160	332	380	49	224	201	23

Table 3.11 Motion analysis for translation responses

Motion Response	Translation Error (degrees)	Rotation Amount (degrees)
Forward	18.16° ± 13.36	4.09° ± 1.89
Up/Forward	18.78° ± 12.41	3.81° ± 2.29
Up	16.82° ± 9.40	3.85° ± 2.97
Up/Backward	13.37° ± 8.14	4.41° ± 2.70
Backward	19.15° ± 12.59	4.49° ± 2.11
Down/Backward	18.34° ± 12.98	4.46° ± 2.44
Down	17.47° ± 9.40	3.90° ± 2.30
Down/Forward	12.77° ± 6.97	4.81° ± 2.94

Table 3.12 Motion analysis for rotation responses

Motion Response	Rotation Error (degrees)	Translation Amount (cm)
Yaw Left	12.44° ± 6.16	1.90 ± 0.95
Yaw Right	13.16° ± 7.06	2.82 ± 1.22
Roll CCW	11.22° ± 5.48	1.28 ± 0.76
Roll CW	12.06° ± 5.67	1.26 ± 0.89
Yaw Left/Roll CCW	17.11° ± 8.26	2.11 ± 0.93
Yaw Left/Roll CW	18.89° ± 7.60	1.18 ± 0.98
Yaw Right/Roll CCW	17.45° ± 6.22	1.14 ± 0.91
Yaw Right/Roll CW	31.32° ± 14.32	2.57 ± 0.95

Table 3.13 Response accuracy for each direction cue when responding to "no reset" cues.

Cue Type	Percent Correct	Cue Type	Percent Correct
Forward	97.18%	Yaw Left	93.00%
Up	97.17%	Yaw Right	76.08%
Backward	93.27%	Roll CCW	95.33%
Down	89.10%	Roll CW	95.15%

Table 3.14 Response accuracy for each direction cue when responding to "reset" cues.

Cue Type	Percent Correct	Cue Type	Percent Correct
Forward	97.21%	Yaw Left	91.59%
Up	92.02%	Yaw Right	79.80%
Backward	96.63%	Roll CCW	95.35%
Down	92.89%	Roll CW	97.18%

Table 3.15 Mean response times for each direction when responding to "no reset" cues.

Cue Type	Response Time	Cue Type	Response Time
Forward	1.10 s	Yaw Left	0.98 s
Up	1.00 s	Yaw Right	1.10 s
Backward	1.20 s	Roll CCW	0.86 s
Down	1.04 s	Roll CW	0.89 s

Table 3.16 Mean response times for each direction cue when responding to "reset" cues.

Cue Type	Response Time	Cue Type	Response Time
Forward	1.06 s	Yaw Left	0.94 s
Up	0.95 s	Yaw Right	1.12 s
Backward	1.15 s	Roll CCW	0.85 s
Down	1.03 s	Roll CW	0.82 s

Table 3.17 Confusion matrix for “no reset” cues.

Direction Cue Rendered	Direction of Response: Forward	Up	Backward	Down	Yaw Left	Yaw Right	Roll CCW	Roll CW
Forward	207	1	0	2	2	0	1	0
Up	1	206	1	0	0	0	2	2
Backward	0	1	194	0	9	1	1	2
Down	5	2	0	188	0	1	8	7
Yaw Left	6	0	3	0	199	0	2	4
Yaw Right	2	3	19	7	0	159	18	1
Roll CCW	0	3	0	1	3	3	204	0
Roll CW	0	4	0	2	0	3	1	196
Σ	221	220	217	200	213	167	237	212

Table 3.18 Confusion matrix for “reset” cues.

		Direction of Response							
		Forward	Up	Backward	Down	Yaw Left	Yaw Right	Roll CCW	Roll CW
Direction Cue Rendered	Forward	209	0	1	0	1	3	1	0
	Up	1	196	2	0	0	0	4	10
	Backward	0	1	201	1	5	0	0	0
	Down	5	0	1	196	1	0	7	1
	Yaw Left	4	1	5	2	196	0	1	5
	Yaw Right	5	5	14	9	0	162	6	2
	Roll CCW	0	4	0	0	4	2	205	0
	Roll CW	1	3	0	0	1	1	0	207
	Σ	225	210	224	208	208	168	224	225

Table 3.19 Motion analysis for translation responses to "no reset" cues

Motion Response	Translation Error (degrees)	Rotation Amount (degrees)
Forward	24.32° ± 18.67	4.12° ± 2.31
Up	22.09° ± 11.18	3.68° ± 2.14
Backward	24.54° ± 16.53	4.95° ± 2.89
Down	25.29° ± 12.88	4.68° ± 3.02

Table 3.20 Motion analysis for translation responses to "reset" cues

Motion Response	Translation Error (degrees)	Rotation Amount (degrees)
Forward	23.00° ± 18.80	3.90° ± 2.51
Up	22.62° ± 11.55	3.65° ± 1.92
Backward	25.13° ± 17.09	4.77° ± 2.98
Down	24.58° ± 12.58	4.96° ± 3.49

Table 3.21 Motion analysis for response rotations to "no reset" cues

Motion Response	Rotation Error (degrees)	Translation Amount (cm)
Yaw Left	15.89° ± 9.03	1.81 ± 1.01
Yaw Right	14.06° ± 8.59	2.26 ± 1.10
Roll CCW	14.74° ± 10.18	1.00 ± 0.69
Roll CW	10.00° ± 5.62	0.99 ± 0.55

Table 3.22 Motion analysis for response rotations to "reset" cues

Motion Response	Rotation Error (degrees)	Translation Amount (cm)
Yaw Left	16.69° ± 9.17	1.61 ± 0.95
Yaw Right	14.21° ± 9.14	2.05 ± 1.08
Roll CCW	14.54° ± 10.79	0.98 ± 0.58
Roll CW	10.66° ± 6.45	1.03 ± 0.64

Table 3.23 Motion analysis for translation responses to first "no reset" cues

Motion Response	Translation Error (degrees)	Rotation Amount (degrees)
Forward	21.23° ± 17.10	3.52° ± 1.93
Up	19.56° ± 5.60	3.06° ± 1.39
Backward	21.68° ± 14.88	3.73° ± 1.93
Down	22.11° ± 6.26	3.94° ± 2.21

Table 3.24 Motion analysis for translation responses to first "reset" cues

Motion Response	Translation Error (degrees)	Rotation Amount (degrees)
Forward	20.58° ± 17.87	3.41° ± 2.08
Up	19.44° ± 6.79	3.21° ± 1.60
Backward	21.05° ± 14.69	4.19° ± 2.22
Down	21.09° ± 7.41	3.93° ± 1.87

Table 3.25 Motion analysis for rotation responses to first "no reset" cues

Motion Response	Rotation Error (degrees)	Translation Amount (cm)
Yaw Left	14.44° ± 8.52	1.81 ± 0.98
Yaw Right	12.73° ± 6.73	2.18 ± 1.01
Roll CCW	15.08° ± 9.98	0.98 ± 0.63
Roll CW	8.75° ± 4.69	0.85 ± 0.42

Table 3.26 Motion analysis for rotation responses to first "reset" cues

Motion Response	Rotation Error (degrees)	Translation Amount (cm)
Yaw Left	15.27° ± 7.61	1.55 ± 0.89
Yaw Right	13.28° ± 8.54	1.96 ± 1.09
Roll CCW	13.15° ± 8.92	1.00 ± 0.59
Roll CW	9.56° ± 5.32	0.92 ± 0.49

Table 3.27 Motion analysis for translation responses to second "no reset" cues

Motion Response	Translation Error (degrees)	Rotation Amount (degrees)
Forward	27.39° ± 19.72	4.72° ± 2.50
Up	24.40° ± 14.42	4.28° ± 2.53
Backward	27.32° ± 17.59	6.11° ± 3.16
Down	28.20° ± 16.61	5.44° ± 3.52

Table 3.28 Motion analysis for translation responses to second "reset" cues

Motion Response	Translation Error (degrees)	Rotation Amount (degrees)
Forward	25.54° ± 19.50	4.41° ± 2.82
Up	25.89° ± 14.55	4.10° ± 2.11
Backward	29.00° ± 18.66	5.36° ± 3.50
Down	28.17° ± 15.79	6.03° ± 4.37

Table 3.29 Motion analysis for rotation responses to second "no reset" cues

Motion Response	Rotation Error (degrees)	Translation Amount (cm)
Yaw Left	17.41° ± 9.34	1.81 ± 1.04
Yaw Right	15.52° ± 10.09	2.33 ± 1.19
Roll CCW	14.42° ± 10.40	1.03 ± 0.74
Roll CW	11.06° ± 6.13	1.11 ± 0.61

Table 3.30 Motion analysis for rotation responses to second "reset" cues

Motion Response	Rotation Error (degrees)	Translation Amount (cm)
Yaw Left	18.09° ± 10.32	1.68 ± 1.01
Yaw Right	15.15° ± 9.66	2.14 ± 1.07
Roll CCW	15.96° ± 12.31	0.96 ± 0.58
Roll CW	11.75° ± 7.27	1.13 ± 0.75

CHAPTER 4

TARGET MATCHING FOR HAND MOTIONS WITH SKIN STRETCH FEEDBACK

In this chapter, I present four experiments related to using skin stretch feedback to command a user to translate or rotate his/her wrist and hand to a given position and orientation. First, an initial experiment is performed to investigate human performance responding to closed-loop skin stretch cues to reach a target angle for cues for one rotation of the wrist. Then, several pilot studies are completed in order to improve the closed-loop controller feedback. A second experiment is then presented, which investigates user performance responding to closed-loop skin stretch cues to reach a target angle or position for four degrees of freedom (two rotations of the wrist and two translations of the hand). The third experiment presented in this chapter examines user performance responding to two sequential closed-loop cues. Finally, the fourth experiment utilizes the closed-loop skin stretch cues to create a teleguidance scenario where one person can guide the motion of another person's hand and wrist through haptic cues only.

4.1 Introduction

There are many applications that could benefit from the addition of haptic feedback to guide a user to a specified target angle or location. As a user moves their arm, haptic feedback can be presented to help them "feel" how to adjust their movements. Several existing haptic devices are used to do just this, through the use of vibrotactile feedback on the arm or through the use of force feedback applied to the arm or hand. I am particularly interested in achieving high accuracy results such as those seen with force feedback while maintaining a user's ability to ignore the feedback if needed for safety reasons as is possible with vibrotactile feedback. Tactile feedback provided directly to the finger tips has the potential to do so, and the precision grip skin stretch feedback device can be used to do so without adding a bulky haptic device that limits the range of motion or forces the user to be grounded (or located) to a specific location.

In this chapter, I build upon the results from Chapter 3 to examine the use of tactile skin stretch cues to provide directional and rotational information to a user's hand. These tactile cues use closed-loop feedback to guide a user to a specified location or orientation of their wrist. I once again used the precision grip skin stretch feedback device, and developed several studies to investigate user performance with open-loop and closed-loop target matching cues.

This chapter presents four experiments and two pilot studies. The first experiment investigates user responses to open-loop and closed-loop target matching cues for one degree of freedom rotation of the wrist. Through the results of this experiment, changes were made to the closed-loop feedback and several possible changes were investigated in two pilot studies. The second experiment utilized the modified and improved closed-loop feedback and examines user performance for open-loop and closed-loop target matching cues in four degrees of freedom. The third experiment investigates user responses to sequential closed-loop feedback cues, which could be used to guide a hand through space with more than one motion in a sequence. Finally, the fourth experiment investigates the feasibility of one person guiding another person's hand and wrist motions from a remote location through the use of the precision grip skin stretch device and the closed-loop cues.

This device could be used to provide haptic guidance feedback in a variety of applications, from medical teleguidance to training scenarios and entertainment and gaming applications. The compact nature of the device allows this feedback to be embedded within a variety of handheld items. In addition, this device could be implemented as a wireless stand-alone device, and therefore does not have a limited workspace and could be used for even larger motions of the arm than discussed in this chapter.

I first present a brief background exploring related work with current devices that can be used to guide the hand and arm through haptic feedback. I then provide a description of the device and software used to complete these experiments, as well as the tactile cues designed for the experiments. Next, I outline the general methods used for all experiments in this chapter. Then, each experiment is presented, with individual methods, tactile cues, and results included. Finally, I provide an overall summary and possibilities for future work.

4.2 Background

Several applications exist that already utilize or could potentially utilize haptic feedback to guide a user's hand to a specified location or orientation. While existing haptic devices and methods help accomplish this goal, there remains a need for the ability to provide feedback to guide precise motions of the hand through a compact and ungrounded device, while meeting safety standards. This feedback could be used in rehabilitation, training, and teleguidance or teleoperation applications.

Rehabilitation patients can benefit from an interactive gamified task rather than a repetitive task [Cameirao et al. 2012]. In these rehabilitation tasks, it is imperative to provide feedback to the user so that they know how to improve each motion. Haptic feedback in rehabilitation applications has been limited to force feedback and vibration feedback to this point. While patients in several studies perform better with vibration feedback than without [Cameirao et al. 2012; Duff et al. 2012; Abdollahi et al. 2013], the nature of vibration feedback limits this form of haptic feedback to providing magnitude information only. Skin stretch feedback for rehabilitation patients would allow the patient to be fully in control of their hand motions as they are with vibration feedback. Skin stretch feedback could also improve rehabilitation outcomes over those seen with vibration feedback, as it is capable of delivering both magnitude information and directional information in a compact device.

Training simulations also benefit from haptic feedback, especially when training skills such as laparoscopic suturing or knot tying. Force feedback is utilized to help surgical trainees reduce task completion times and improve their precision with difficult suturing tasks [Ström et al. 2006; Botden et al. 2008; Panait et al. 2009]. Training for robot-assisted minimally invasive surgery with haptic feedback can also help reduce surgical errors [van der Meijden and Schijven 2009]. However, in the training simulations discussed, force feedback is used. Force feedback does not always provide improvements in training simulations, as users can rely on the feedback to make the motions and do not learn as much [Feygin et al. 2002; Lee and Choi, 2010]. In addition, force feedback is not safe to use for robot-assisted minimally invasive surgery as it can create instabilities, and another form of haptic feedback is needed to allow for the same use of haptic feedback in training and application of these tasks [Okamura 2009].

Haptic feedback can also be used to have an experienced person train a novice from the same location or a remote location. It can be used to allow expert surgeons help mentor trainee surgeons in a task [Nudehi et al. 2005], or for an expert calligraphist to guide a beginner [Teo et al. 2002]. While these haptic devices are used to provide haptic feedback in a teleguidance task, they utilize force feedback which requires the user to be grounded to a specific location. In addition, force feedback systems can be very costly, and would not be practical for some remote teleguidance or teleoperation tasks. Skin stretch feedback with the precision grip device could provide feedback for a teleguidance task without the need for the user to pay a large amount for such a system and without the need for the user to be limited to a specific location.

As I am focused on providing haptic feedback to guide a user to a specific location or orientation while allowing a full range of motion of the user's arm and hand, while keeping costs of the system low, and keeping the system safe for safety-critical applications, skin stretch feedback will be used in these experiments. While Chapter 3 demonstrated the ability of users to respond to skin stretch feedback in multiple degrees of freedom of rotations and translations, this chapter expands upon that work and investigates the ability of users to arrive at a specific location and orientation.

4.3 Experiment Software and Device Design

This section describes the hardware design of the haptic device used for the experiments in this chapter. Additionally, this section describes the software developed to command the tactor motion of the device and track user responses.

4.3.1 Hardware Design of Precision Grip Skin Stretch Feedback

For all experiments described in this chapter, the precision grip skin stretch feedback device used in Chapter 3 experiments was used. There were no modifications made to the device, which consists of two contactors capable of moving in two-dimensional directions utilizing two RC hobby servo motors as shown in Figure 3.3.

4.3.2 Tracking Hardware

The precision grip skin stretch feedback device was attached to the stylus of a Phantom Premium 1.5 six degree-of-freedom device. This allows for high precision tracking of the device location and orientation during experimental testing. While other tracking devices could be used to allow for a larger workspace of the skin stretch feedback device, the high precision tracking capabilities of the Phantom Premium are desirable for experimental applications.

4.3.3 Software Interface

Software was developed in Visual Studio C++ to provide the open- and closed-loop feedback cues through the motion of the skin stretch tactors. To track the Phantom Premium stylus and the user's hand, the position tracking software from Chapter 3 was used. As in Chapter 3, the software communicated with a dsPIC33E microcontroller through USB communication.

4.3.4 Direction Cue Design

As in Chapter 3, translational direction cues are conveyed to the user by simultaneously moving both tactors in the same direction, at the same rate. Rotational cues are conveyed to the user by simultaneously moving both tactors in opposite directions, and at the same rate.

For the experiments presented in this chapter, translation cues in two degrees of freedom are presented along the axes of the device. Additionally, two degrees of freedom of rotation cues are presented with the precision grip skin stretch device. Figure 3.5 and Figure 3.6 show the forward, up, yaw, and roll axes of the device.

For the precision grip skin stretch device, the maximum tactor travel is 2.5 mm in any direction from the center position. With the target matching experiments discussed in this chapter, part of the tactor displacement needs to be reserved for additional feedback after the initial cue in order to have additional tactor workspace for providing closed-loop position cueing. For this reason, target angles were communicated using a ramp motion profile of the two tactors, where a maximum rotation or translation amount was linearly mapped to 1.25 mm tactor motions. For rotations, the maximum value was 40˚ from the starting wrist rotation, allowing users to comfortably reach the target rotation (i.e., 1.25 mm of tactor motion, where the two tactors moved in opposite directions, was mapped to 40˚ of hand rotation). For translations, the maximum value was 6 cm (i.e., 1.25 mm of tactor motion equals 6 cm of hand motion), in order to ensure the target position was within the workspace of the Phantom Premium and could be reached by the user. Human performance in identifying skin stretch direction decreases as the total tactor displacement decreases [Gleeson et al. 2010], so the minimum value for targets was kept at 25% of the maximum: 10˚ for rotations, and 1.5 cm for translations. The tactor displacement for these minimum values was 0.31 mm, which can still be reliably identified by a human user [Gleeson et al. 2010]. The tactors moved at a rate of 1 mm/s to the location corresponding to the target angle or position.

4.4 General Experimental Methods

This chapter presents four separate experiments to characterize user abilities to match target angles or target locations communicated through skin stretch feedback. The first experiment investigates open-loop and closed-loop angle matching for one rotation of the wrist. The second experiment investigates open-loop and closed-loop angle or position target matching for two rotations of the wrist and two translations of the hand. The third experiment investigates closed-loop angle or position target matching for sequential cue motions. Finally, the fourth experiment investigates the feasibility of a teleguidance task, where one person guides the rotations and translations of another person, with skin stretch feedback as the only means of communication.

For all experiments, participants wore noise canceling headphones playing white noise to mask the sound from the device as well as the environment. Participants held the device with their right hand and were instructed to begin each trial with their right hand in a centered “start” position, without resting their arm or elbow on anything. The start position was near the center of the workspace of the Phantom Premium, allowing users to comfortably perform all possible rotations and translations while remaining within the workspace. The start position was chosen by the participant every trial, and as such, was not the same every trial, so the software kept track of the starting position and judged motions relative to the start position for each individual trial.

When ready to begin a trial for the first three experiments, each participant was instructed to press the space bar on a computer keyboard. Following a one second pause, the cue would begin to be delivered to the user. Because the fourth experiment was a teleguidance task, participants would verbally say when they were ready to begin a trail, at which point the person providing the cues from the master side of the system would start providing cues.

For all experiments, participants were instructed to respond to the cues as accurately as possible by moving their hand or wrist to match the target angle or location. For open-loop portions, participants had to hold their hand steady within a $\pm 2^\circ$ or ± 0.3 cm range of any location for one second for the response to be recorded. For closed-loop portions, participants had to hold their hand steady within $\pm 2^\circ$ or ± 0.3 cm of the target angle or position for one second for the response to be recorded. This means the trial time was equal to the settling time plus one second.

At the end of each trial, a ding noise played on the headphones and the tactors reset to the center of the aperture, indicating that the trial was complete. At this point, the user could move their hand back to the center of the workspace and start a new trial. All portions of these experiments were self-paced, allowing participants to take the time they needed to get ready for another trial, at which point they would press the space bar to begin. The experimental setup for the first three experiments is shown in Figure 4.1. The experimental protocol is approved by the University of Utah Institutional Review Board.

4.5 Experiment 4.1: Target Angle Matching for One Wrist Rotation

In this experiment, I investigated user performance identifying cue direction and magnitude. I also investigated user performance in responding to the cue and adjusting the amount of rotation of the wrist until a target rotation angle was reached. This experiment is partially discussed in [Guinan et al. 2013].

4.5.1 Tactile Cues

For this experiment, cues communicated one of two rotations: pronation and supination of the wrist. This experiment focused solely on the roll rotation of the wrist to allow for a comparison to a [Stanley and Kuchenbecker 2012] while investigating the feasibility of target angle matching with skin stretch feedback. These roll rotation cues were delivered by simultaneously moving the two tactors in opposite directions towards the top or bottom of the device.

Rotation amounts ranged from 10° to 40° for both the pronation and supination of the wrist. Results are shown with negative degrees representing a pronation (counter-clockwise roll of the wrist) and positive degrees representing a supination (clockwise roll of the wrist) rotation.

4.5.2 Methods

Fourteen participants (mean age = 27.9, 12 male, 12 right-hand dominant) performed this experiment. Each participant also participated in Experiment 3.1 of Chapter 3 prior to completing this experiment. This target angle matching task consisted of both open-loop and closed-loop portions. Each participant began with a training period consisting of 5 cues, then completed 20 target matching trials for each portion of the experiment. All participants completed the open-loop portion, followed by the closed-loop feedback portion. For this experiment, the tactors moved at a rate of 1 mm/s until they reached the corresponding position for the target angle. In addition, the proportional gain for the closed-loop target angle matching portion was set to $K_p = 5$ mm/s/radian. This feedback was superimposed on the feed-forward tactor travel that matches the target wrist rotation angle for each trial. Following the feed-forward cue, the tactors were constantly moving, unless they were saturated or the user had rotated to the exact target angle.

4.5.3 Results and Discussion

Results were analyzed for both the open-loop and closed-loop target angle matching portions of this experiment. Prior to analyzing results, trials with completion times outside of 3σ of a participant's mean trial time were rejected as outliers. In total, 8 out of 280 trials (2.86%) were rejected as outliers for the open-loop portion and 10 out of 280 trials (3.57%) were rejected as outliers for the closed-loop portion. Following outlier rejection, an analysis on trial time and rotation angles was completed for open-loop target angle matching. For closed-loop target angle matching, settling times and percent overshoot were analyzed.

4.5.3.1 Open-Loop Target Angle Matching

The mean response time for the open-loop responses was 1.21 s (2.21 s for the full trial time). Participants demonstrated the ability to closely match a given tactor motion to a wrist rotation angle. Figure 4.2 shows participant responses as a function of the target rotation cue and a linear best-fit line. The best-fit trend line of all data points shows a correlation of 1.01 with an offset of 1.0˚, 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.

To further investigate the relationship between the target angle stimulus and perceived magnitude of the stimulus, the data was also fit to a power function. This fit line is shown in Figure 4.3. The resulting power fit has an exponent of 1.04. This nearly linear curve is similar to the findings by Stevens [1968] for tactile vibration at 60 Hz, and as the exponent is near 1.0, this suggests that future experiments can continue to use a linear scaling of tactor motion to target angle.

While a close approximation was achieved on average in this open-loop feed-forward mode, the mean absolute error between the goal and response angles was 7.39˚. This mean error is within the deadband of ±7.5˚ used for the closed-loop angle matching task used by Stanley and Kuchenbecker [2012]. By adding closed-loop feedback to this haptic device and requiring a smaller deadband around the target angle, a user's targeting accuracy could be further improved.

4.5.3.2 Closed-Loop Target Angle Matching

Through the addition of closed-loop proportional rate-based control, user angle matching accuracy improved, allowing users to achieve response angles within ±2˚ of the corresponding target angle. This increase in accuracy also increased the average response time when compared to the open-loop target angle matching results. For closed-loop matching, where participants were required to be within ±2˚ of the target angle for one second, the average settling time was 4.27 s (average trial time was 5.27 s). This increase in trial times was expected, as participants were required to adjust to the additional feedback, and could not complete the trial until their response rotation was correct.

Figure 4.4 shows example user responses to a given target angle. The tactor displacement is shown with the participant's response trajectory. The initial response delay to the scaled feed-forward tactor cue causes additional tactor motion to occur as soon as the initial cue ends. This leads to an overshoot of the desired wrist rotation angle. When the overshoot occurs, the tactors reverse direction, and the participant responds to this reversal of tactor motion and reverses their direction of wrist rotation. Finally, the participant settles on the final target angle, the tactors stop moving, and the participant holds the rotation for one second. After staying within the acceptable range of ±2˚ of the target angle for one second, the trial ends.

There was a high amount of overshoot observed in this experiment, with an average percent overshoot of 51.79%. This behavior was not observed during pilot testing, as pilot test participants had a quicker response to the initial cue, and did not experience as much additional feedback following the initial cue. Additional characterization of the closed-loop system and participant behavior can improve the stability of the system. These improvements could improve participant trial time and decrease the overshoot seen. However, this initial experiment demonstrates the ability to provide accurate guidance of users' hand motions through the use of closed-loop skin stretch feedback. Participants were able to match the given target angle within ±2˚ for one rotation of the wrist, which is an improvement upon matching a target angle within ±7.5˚ for the same rotation of the wrist in [Stanley and Kuchenbecker 2012].

4.6 Pilot Study to Improve Closed-Loop Controller

Based on Experiment 4.1 results, extra analysis and studies were done to improve user performance in closed-loop tasks. In Experiment 4.1, the feedback was continuous, accumulating error from the time the initial feedforward cue completed. However, users took some time to respond to the initial cue, and possibly could not tell the difference between the initial cue and the extra feedback. This potentially caused users to believe the initial cue was larger, and could be the cause for the high percent overshoot seen in Experiment 4.1. In addition, often times the tactors saturated (reached the limit of movement and stopped giving continuous feedback). The following discusses the analysis and experimentation that lead to the final experiment feedback conditions. I ran 2 pilot studies with a total of 11 different variations of feedback control designs. When comparing results from the pilot studies, I focused on percent overshoot, trial time, and trials that included saturation of the tactors. A low percent overshoot, low trial time, and low amount of trials with tactor saturation are desired.

4.6.1 Additional Analysis of Experiment 4.1

When modeling human motion, a second-order system is often used due to the musculoskeletal system of the arm [Wang et al. 2010]. As explained by Jagacinski and Flach [2003], human limbs have mass and cannot reach high velocity instantly as first-order systems do. There is also some neuromuscular lag expected in the system [Jagacinski and Flach 2003], as well as the lag time from the stimulus to participant identification of the signal direction and magnitude for these experiments. While extensive experiments on human motion have been completed by others, I first verified that user responses from Experiment 4.1 were similar to a second-order system. By investigating the wrist rotation position and velocity throughout the open-loop trials, I observed peaks in velocity near the midpoint of motion, as expected from [Jagacinski and Flach 2003; Wang et al. 2010].

I then used the Plant Identification available in Matlab 2014 to model a typical open-loop response from each participant in Experiment 4.1. Using this, I found the initial response delay for each participant. The delay for the open-loop portion of Experiment 4.1 ranged from 0.45 to 0.9 s, with an average delay of 0.694 s. I suspected that this delay may have led to excess overshoot of the target in the closed-loop portion of Experiment 4.1, as the closed-loop error feedback was provided as soon as the initial cue finished, and participants may have believed the initial cue was larger due to the combined initial cue and error feedback. I also suspected that the gain for the closed-loop error feedback in Experiment 1 was too high and led to saturation of the tactors, causing participants to have no haptic feedback from the time the tactors saturated until they overshot the target. Using the extra knowledge from Experiment 4.1, I created two pilot studies to improve user performance.

4.6.2 Pilot Study 1-Determining When to Provide Closed-Loop Error Feedback

Two experienced haptic users participated in this pilot study. Four cases were tested, with each case providing the additional error feedback at different points in the trials. The proportional gain for the closed-loop error feedback remained the same as in Experiment 4.1, at 5 mm/s/radian. The cases were as follows:

1. Closed-loop feedback beginning as soon as the initial cue motion is complete. This case was the same as in Experiment 4.1. As soon as the initial scaled motion cue completed, additional error motion was provided, based on the amount of error.
2. Closed-loop feedback beginning 0.694 s after the trial began. This was the average response delay from the participants in Experiment 4.1.
3. Closed-loop feedback beginning as soon as the participant had rotated their hand at least ±2˚ from the start rotation. This case provides additional error feedback once the user begins moving. It allows for ±2˚ of hand unsteadiness, and once the user moves outside of that range, it assumes the user is intending to respond to the initial cue.
4. Closed-loop feedback beginning as soon as the participant had rotated their hand at least ±4˚ from the start rotation. Similar to Case 3 above, this provided additional

error feedback once the user has started moving. This case had a larger safe range of ±4˚ to ensure that small unintentional rotations of the hand did not trigger the closed-loop error feedback to begin.

The pilot study participants varied their responses in order to feel the feedback provided based on different initial response delays. After completing several trials for each of the four cases, both pilot study participants stated that Case 4 was preferred, as it led to tactors saturating less often. In addition, only motions the users intended to make triggered the additional closed-loop error feedback. Future experiments should benefit from waiting for the user to intentionally move before providing additional feedback. The user will be able to distinguish the initial magnitude cue from the additional feedback, and should have a better sense of the magnitude of their motion, which could lead to a decrease in target overshoot. Additionally, the tactors should not saturate as often, because the tactors are not moving to its travel limits in the time before the participant starts moving.

4.6.3 Pilot Study 2-Determining the Nature of Closed-Loop Error Feedback

In Experiment 4.1, the error feedback was proportional to the amount of error, with the tactors moving at 5 mm/s/radian. This feedback was always present, and the tactors were continuously moving for the entire trial, as long as the tactors were not saturated due to the limits of the device. This pilot study was completed to investigate other alternatives to providing feedback to the target rotation. Four different modes with two gains for each mode were tested by four participants with varying haptics experience. Prior to the pilot study, all modes were first tested by two experienced haptics users and one novice user to ensure they gave feedback as planned. The two gains used were equal to the original gain of 5 mm/s/radian from Experiment 4.1 (high gain), and half of that value, 2.5 mm/s/radian (low gain). The ordering of the eight modes was balanced across the participants. Each of the following modes utilized the criteria established from Pilot Study 1 and did not begin providing additional feedback to a user until the user had rotated their hand at least 4˚. At that point, the feedback provided was different for each mode. The additional feedback modes used were:

1. Continuous feedback based on the amount of error from the target. This was the same as in Experiment 4.1. In this case the tactors slow down when they near the target, as there is a lower angular error near the target, but they only stop moving when they are exactly at the target and there is zero error between the user's wrist rotation and target rotation. Figure 4.5 shows an example.
2. Continuous feedback based on amount of error, but when within ±2˚ of the target, the error is considered to be zero. This mode is continuous any time the user is outside of the acceptable range for an answer. When the user is within the acceptable range, the tactors stop. Figure 4.6 shows an example.
3. Continuous feedback with a tick <u>reset to the **feedforward position**</u> when within ±2˚ of the target. This tick reset motion gives a secondary cue to the user that they are at the target. It also could potentially help minimize saturation of the tactors. Any time the user enters the acceptable range around the target, the tactors instantly move to the position they were in when the initial cue finished. Figure 4.7 shows an example.
4. Continuous feedback with a tick <u>reset to the **center** of the aperture</u> when within ±2˚ of the target. This tick reset motion is larger than in Mode 3 and again gives a secondary cue to the user that they are at the target. It also could potentially help

minimize saturation of the tactors. Any time the user enters the acceptable range around the target, the tactors instantly move to the center of the aperture. Figure 4.8 shows an example.

The pilot study was run to reduce percent overshoot from the high overshoot observed in Experiment 4.1 (51.79%). While the main goal of the pilot study was to reduce overshoot, I also wanted to compare trial time and tactor saturation between each mode in the pilot study.

For comparison of the 8 pilot study modes, Modes 1-4 are the modes described above, with the lower gain of 2.5 mm/s/radian. Modes 5-8 are the modes described above with the higher gain of 5 mm/s/radian (Mode 5 is similar to Mode 1 but with a higher gain, etc.). Figure 4.9 shows the mean percent overshoot for each of the feedback modes. While there is no significant difference between modes [$F(7,210) = 1.0$, $p = 0.4349$], Modes 2 and 8 have the lowest average overshoot. Mode 4 has the highest percent overshoot, at 50.83%, and all modes have a lower percent overshoot than the observed percent overshoot in Experiment 4.1, with percent overshoot in the pilot modes ranging from 18.33% to 50.83%, compared to 51.79% in Experiment 4.1.

Figure 4.10 shows the percent of trials that saturated during the pilot testing for each mode. There are no significantly different groups between any of the modes [$F(7,210) = 1.6$, $p = 0.1379$]. Feedback Mode 6 has high saturation, with 58.92% of trials saturating at some point, and this value is significantly larger than the saturation values observed with Mode 2 [$F(1,54) = 8.55$, $p = 0.005$] and Mode 5 [$F(1,53) = 6.01$, $p = 0.0176$].

Figure 4.11 shows the average completion time for a trial for each of the eight pilot test modes. Modes 2 and 8 have the lowest completion times, but there is no significant difference between any of the completion times [$F(7,210) = 1.09$, $p = 0.372$]. Completion times for the pilot study were higher than in Experiment 4.1 in all cases, with pilot mode completion times ranging from 6.70 s to 9.09 s, compared to a mean completion time of 5.27 s in Experiment 4.1. However, with only eight trails for each mode, it is possible that participants may become faster using one specific mode after training and through the practice of additional trials.

When comparing high gain modes to low gain modes, there is no significant difference between any group. The difference in overshoot is not significant, but the higher gains have a lower overshoot percentage [$F(1,216) = 1.37$, $p = .24$]. The difference in saturation is also not significant, though the lower gains have a lower percentage of saturation [$F(1,216) = 2.48$, $p = .116$]. Both groups have nearly the same completion time, with higher gains having a mean completion time of 7.51 s and lower gains having a mean completion time of 7.53 s, and the difference in completion times is not significant [$F(1,216) = 0$, $p = 0.9745$].

In addition to the metrics compared, pilot study participants were asked to rank each mode on a scale of 1-10, where 10 meant the mode was "completely clear and I always knew how the feedback was trying to lead me." Participants rated Modes 2 and 3 the highest, with both receiving an average score of at least 7.5. Table 4.1 shows the average scores given for each of the pilot test modes.

4.6.4 Determining Closed-Loop Modes for Future Experiments

Following the completion of the pilot modes, the modes to be used for future closed-loop experiments was determined. From Pilot Test 1, it was determined that all future closed-loop experiments would benefit from waiting until the user moved their wrist at least 4˚ before providing closed-loop error feedback. This helps decrease the percent overshoot from Experiment 4.1, as each of the pilot test modes in Pilot Test 2 had lower percent overshoot than the Experiment 4.1 trials.

Due to the different nature of the feedback modes in Pilot Study 2, and because there was no clear separation between modes in the pilot study, I wanted to continue using one of each type of mode in future experiments. One of the mostly continuous modes (Modes 1, 2, 5, and 6) and one of the modes with a tick reset (Modes 3, 4, 7, and 8) was chosen. For the mostly continuous modes, Mode 2 had the highest user rating, the lowest completion time, the lowest percent overshoot, and the lowest percent of trials that saturated, so Mode 2 will be used in future experiments. Mode 2 differs from the closed-loop feedback in Experiment 4.1 in that it waits for users to move 4° before providing closed-loop error feedback, the gain for the error feedback is half as high (at 2.5 mm/s/radian), and when the user is within the acceptable answer range of ±2°, the tactors stop moving as if there is no angular error.

For the modes with a tick reset, Modes 3, 7, and 8 were very similar, with the only main difference between the three being the user rating. Some participants also commented that Mode 8 was very confusing, as it felt like the large reset cue was telling them to move in the opposite direction. These same participants liked Mode 3, and found the small reset to the feedforward tactor position useful in finding the target. Mode 3 was rated higher or equal to Modes 7 and 8 by 3 of the 4 pilot participants and had a higher average rating. For these reasons, Mode 3 will also be used in future experiments. Mode 3 differs from the closed-loop feedback in Experiment 4.1 in that it waits for users to move 4° before providing closed-loop error feedback, the gain for the error feedback is half as high (at 2.5

mm/s/radian), and when the user is within the acceptable answer range of ±2°, the tactors are set to the feedforward position they were in when the initial feedforward (open loop) cue was complete (before any closed-loop error feedback was given).

4.7 Experiment 4.2: Target Angle and Position Matching in Four Degrees of Freedom

This experiment builds on Experiment 4.1 and uses the improved closed-loop controllers from the pilot studies to investigate user performance identifying and responding to closed loop cues in four degrees of freedom. Two degrees of freedom were for rotations, and required users to adjust the rotation of their wrist until the target angle was reached. Two degrees of freedom were for translations, and required users to adjust the position of their hand and wrist until the target position was reached.

4.7.1 Tactile Cues

For this experiment, cues communicated one of four rotations or one of four translations. Rotation cues were provided to guide the pronation, supination, dorsiflexion, and palmar flexion of the wrist. These rotation cues were delivered by simultaneously moving the two tactors in opposite directions towards the top or bottom of the device for a roll rotation cue and towards the front or back of the device for a yaw rotation cue. Rotation amounts ranged from 10° to 40° for all rotations of the wrist. For this experiment, rotation amounts were exactly 10°, 20°, 30°, and 40° in each direction. The acceptable range for a trial to be complete in the closed-loop portion remained at ±2° from the target angle.

Translation cues were provided to guide the forward, backward, upward, and downward motions of the hand. These translation cues were delivered by simultaneously moving the two tactors in the same direction towards the top or bottom of the device for an up or down translation cue and towards the front or back of the device for a forward or backward rotation cue. Based on the workspace of the Phantom Premium 1.5, a maximum translation of 6.0 cm was chosen. Similar to the rotation cue, this maximum translational cue was provided through moving the tactors 1.25 mm from the center of the aperture, in the direction of the cue. Also like in the case of rotation cues, there were four translation amounts in each direction, and the translations were 25%, 50%, and 75% of the maximum cue. As such, the translation amounts used for this experiment were exactly 1.5 cm, 3.0 cm, 4.5 cm, and 6.0 cm in each direction. The acceptable range for a trial to be complete in the closed-loop portion was 0.3 cm, 5% of the maximum target amount, just as it is for rotation cues.

4.7.2 Methods

Eighteen participants (mean age = 27.1, 14 male, 18 right-hand dominant) performed this experiment. Each participant also participated in Experiments 3 and 4 of Chapter 3 prior to completing this experiment. This target angle matching task consisted of both open-loop and closed-loop portions. All participants completed the open-loop portion, followed by the closed-loop feedback portion. Open-loop testing was performed in this experiment because Experiment 4.1 above only included open-loop testing on the roll axis as opposed to all four degrees of freedom tested here.

For the open-loop portion, each participant began with a training period, where open-loop cues were given while the participant could see an on-screen indication of the magnitude of the cue and the magnitude of their motion. A maximum, minimum, and two medium value cues were given for each degree of freedom of motion, for a total of 16 training cues. Then, the open-loop portion testing began with a total of 32 cues, one for each of the 8 possible targets for each of the four degrees of freedom.

The closed-loop portion included two modes: a “continuous” mode where the tactors continuously provide closed-loop error feedback once the user starts responding, and a “tick reset” mode where the tactors continuously provide closed-loop error feedback once a user starts moving, unless the user is within the acceptable range for a response. Once a user reaches the acceptable range, the tactors provide a “tick” reset and reset back to the feedforward position for each target position. These are the two modes chosen from the pilot studies results (Section 4.6). The order of the two modes were balanced across participants, with 9 participants first completing the continuous mode, and the other 9 participants first completing the tick reset mode. After completing 10 training cues, each mode contained 96 closed-loop cues, 3 repetitions for each of the 8 targets in all four degrees of freedom, which were all intermixed in pseudorandom order.

4.7.3 Results and Discussion

Results were analyzed for both the open-loop and closed-loop target angle matching portions of this experiment. Prior to analyzing results, trials with completion times outside of 3 of a participant’s mean trial time were rejected as outliers. In total, 42 out of 1728 trials (2.43%) were rejected as outliers for the continuous mode and 40 out of 1728 trials (2.31%) were rejected as outliers for tick reset mode. Following outlier rejection, an analysis on trial time and the amount of translation or rotation was completed for open-loop target angle matching. For closed-loop target angle matching, rise times, settling times, percent overshoot, percent of trails with saturated tactors, percent of trials which immediately settle once entering the acceptable range, and the number of oscillations were analyzed.

4.7.3.1 Open-Loop Target Matching

The mean response time for the open loop responses was 1.79 s (2.79 s for the full trial time). While this response time is higher than in Experiment 4.1 (mean response time of 1.21 s), this is likely due to the addition of three more degrees of freedom for the cues. Participants were required to determine the type of motion, as well as the direction and magnitude for each trial in Experiment 2, whereas in Experiment 4.1 participants had to determine the direction of one rotation motion as well as the magnitude of the cue.

The mean error for rotations was 3.42˚, which is better than for Experiment 4.1 (7.39˚). However, Figure 4.12 and Figure 4.13 as well as Table 4.2 and Table 4.3 show there is a large amount of variance in answers. The mean error for translations was 0.50 cm. Figure 4.14 and Figure 4.15, as well as Table 4.4 and Table 4.5 show the results for each target translation amount. The mean error for rotations was 8.55% of the maximum target rotation and 8.33% of the maximum target translation.

The results from the open-loop target angle matching tasks demonstrate that participants can distinguish the direction and magnitude for cues in four different rotations and four different translations. However, the resulting response motions have a high standard deviation. By adding closed-loop feedback cues and requiring the participant to be within an acceptable range of the target, user accuracy can be improved to be consistently near the goal.

4.7.3.2 Closed-Loop Target Matching

Through the addition of closed-loop proportional rate-based control, users received additional feedback after the initial cue and were required to be within an acceptable range of the target of ±2˚ for a rotation or ±0.3 cm for a translation. This ensured that users reached and held their position at the target for one second before the trial was complete. This requirement increased the average response time when compared to the open-loop target angle matching results. For the "continuous" feedback mode, the average settling time was 6.55 s and for the "tick reset" (to feedforward tactor postion) feedback mode, the average settling time was 4.99 s (compared to 4.27 s observed in Experiment 4.1). The difference in settling time between the two modes was significant [$F(1,3376) = 98.73$, $p < 0.00001$]. However, the difference in rise time, or time it took the user to first reach the acceptable range, was not significant between the two modes [$F(1,3376) = 3.33$, $p = 0.0681$], as the "continuous" feedback mode had an average rise time of 2.54 s while the "tick reset" mode had an average rise time of 2.66 s. This is expected, as both modes provide the same feedback until the user reaches the acceptable range. The feedforward cues are the same in each mode, both modes wait until the user moves 4˚ or 0.6 cm to provide closed-loop error feedback, and the error feedback gains are the same.

Participants did a better job of settling on the target once they reached the target with the "tick reset" feedback, doing so in 2.33 s versus 4.01 s using the "continuous" feedback. This difference is significant [$F(1,3376) = 151.1$, $p < 0.00001$], and suggests that the "tick reset" mode gave a better indication of where the target was and helped participants stop at the target when they arrived. In fact, participants instantly stopped at the target in 41.33% of trials for the "tick reset" mode, meaning they settled at the target value the first time they entered the acceptable range around the target. In the “continuous” mode, participants only did so 12.08% of the time, significantly fewer times than in the “tick reset” mode [$F(1,3376) = 414.15$, $p < 0.00001$]. This means that participants were able to successfully use the tick to help recognize their proximity to the target position.

In addition, participants had significantly higher percent overshoot with the “continuous” mode (64.34%) when compared to the “tick reset” mode (43.64%) [$F(1,3376) = 52.03$, $p < 0.00001$]. Participants also passed through the acceptable range significantly more times with the “continuous” mode, with an average amount of oscillations at 2.06 versus in the “tick reset” mode where the average amount of oscillations was 1.39 [$F(1,3376) = 100.98$, $p < 0.00001$].

The one metric where participants performed better in the “continuous” mode over the “tick reset” mode was in percent of trials with the tactors saturating at some point. In the “continuous” mode, this was observed in 36.47% of trials, which is significantly lower than the observed value of 43.64% for the “tick reset” mode [$F(1,3376) = 18.14$, $p < 0.0001$]. One possible reason for this is that in the “tick reset” mode, the reset could eventually lead to saturation of the tactors in the opposite direction of the original signal after the user overshoots the target. The “tick reset” moves the tactors partly back to the center of the aperture when a user enters the acceptable range for the first time. If the user greatly overshoots the target, the tactors will continue to move towards the center of the aperture, and then past the center towards the edge of their range of motion. Conversely, when you greatly overshoot a target in the “continuous” mode, the tactors have not received a reset motion when first passing through the target, so the tactors start out farther from the center of the aperture and have a greater distance available to travel to tell the user to move in the opposite direction.

Table 4.6 shows a comparison of each metric used for the two feedback modes in this experiment. Boxes highlighted in green are significantly better than the corresponding value for the other mode.

Figure 4.16 and 4.17 show target distances and mean settling times for each closed-loop target. In Figure 4.16, the pink triangle data points indicate responses to the “continuous” forward or backward direction cues, the green cross data points indicate responses to the “continuous” up or down cues, the black square data points indicate responses to the “tick reset” forward or backward direction cues, and the gray circles indicate responses to the “tick reset” up or down cues. In Figure 4.17, the pink triangle data points indicate responses to the “continuous” yaw rotation cues, the green cross data points indicate responses to the “continuous” roll rotation cues, the black square data points indicate responses to the “tick reset” yaw cues, and the gray circles indicate responses to the “tick reset” roll cues.

Tables 4.7 and 4.8 show target distances and mean settling times alongside the index difficulty defined by Fitts’ law as $ID = log2\left(\frac{2d}{w}\right)$, where d is the target distance and w is the target width (0.3 cm for translations or 2˚ for rotations). In general, each table shows higher settling times for the targets with a higher index of difficulty. However, as users adjust to the maximum target locations, they overshoot the maximum targets less, and the settling time for those locations is similar or less than the next highest target with a lower index of difficulty. This is likely similar to the perceptual anchoring effects seen in [MacLean and Enriquez 2003], as participants were aware of the maximum motions required from the closed-loop cues, and knew not to expect motions larger than those maximum motions.

Results from this experiment suggest that users are able to use the precision grip skin stretch feedback device to move to within ±2° or ±0.3 cm of a target rotation or location. While the settling time is higher than the ~2-4 s observed in [Stanley and Kuchenbecker 2012], the experiments presented in this chapter used a target deadband (±2˚ or ±0.3 cm) for the acceptable range that was 27% of the deadband used in [Stanley and Kuchenbecker 2012] (±7.5˚). This difference in deadband size means that the index difficulty is different for the two experiments, with a Stanley and Kuchenbecker's experiments having an index difficulty of 3.42 for a 40 degree rotation target, while the experiments in this chapter have an index difficulty of 5.32 for the same 40 degree rotation target. In addition, Experiment 4.2 used closed-loop feedback in four degrees of freedom rather than one degree of freedom as used in Experiment 4.1 and [Stanley and Kuchenbecker 2012], so the increase in settling time is expected. The "tick reset" mode in this experiment greatly improved with 38.18% as opposed to the percent overshoot of 51.79% observed in Experiment 4.1 in Section 4.5.

The "tick reset" mode appears to be superior to the "continuous" mode based on the results of this experiment. However, if more than one closed-loop cue is given in sequence to a user, the tick motion of the tactors might confuse users, as the tactors also use the same motion to get back to a centered location after the user has held their position in the acceptable range for 1 s. Experiment 4.3 investigates user performance in responding to two sequential closed-loop cues. Both modes are again used to compare the performance in such a scenario.

4.8 Experiment 4.3: Target Angle and Position Matching for Sequential Motions

This experiment uses both of the closed-loop feedback modes from Experiment 4.2 to investigate user performance responding to two closed-loop cues in sequence. The cues were in four degrees of freedom, two degrees of freedom of rotation and two degrees of freedom of translation.

4.8.1 Tactile Cues

As in Experiment 4.2, rotation cues were provided to guide the pronation, supination, dorsiflexion, and planar flexion of the wrist. Rotation targets again ranged from 10˚ to 40˚ for all rotations of the wrist, and the acceptable range around the target was ±2˚. Translation targets again ranged from 1.5 cm to 6 cm for the forward, backward, upward, and downward translation targets, and the acceptable range around each target was ±0.3 cm.

Initial direction and magnitude cues were given by mapping the magnitude of the cue to a tactor displacement, where a 1.25 mm tactor displacement signified a maximum cue of 40˚ or 6 cm. Once a user began responding by moving their hand either 4˚ or 0.6 cm, additional feedback was provided through the motion of the tactors to guide the user to the target. As in Experiment 4.2, the “continuous” mode and “tick reset” modes were used. While the “tick reset” mode greatly outperformed the “continuous” mode in Experiment 4.2, it is possible that the tick motion will confuse users when two or more cues are provided in sequence, so both modes are still used in Experiment 4.3.

4.8.2 Methods

Eighteen participants (mean age = 27.1, 14 male, 18 right-hand dominant) participated in this experiment. Each participant also completed Experiments 3.3 and 3.4 and Experiment 4.2 prior to participating in this experiment. The order of the two feedback modes was balanced across participants, with nine participants completing the “tick reset” portion before the “continuous” portion and vice-versa.

Participants were instructed to keep their hand in the same position and orientation after responding to the first cue, and were also instructed to make their second response motion relative to this position. After responding to the first cue and holding the hand in the acceptable range for one second, the tactors reset to the center position, and an auditory chime noise played. Following a one second pause, the second cue was delivered. After completing the second cue, an auditory ding noise played and the tactors reset to the center position. Each participant began with a short training session of two pairs of sequential cues. Participants then completed the experimental portion of 49 pair cues for each feedback mode. 49 cue pairs were used to include every combination of the 8 motions with each of the 6 remaining motion possibilities (there were no combinations of opposite direction cues, i.e., a forward followed by a backward translation). In addition, one cue pair investigated a total roll right rotation of 80˚, with one roll cue followed by another roll cue.

4.8.3 Results and Discussion

Prior to performing result analysis, outlier rejection was performed on the data. Each individual cue in each pair was split into rotations and translations for each feedback mode, and response times were compared to the mean of each individual participant’s response time for each category of cue. Trials with completion times outside of 3σ of the mean were rejected as outliers. In addition, because the aim of this experiment is to investigate sequences of cues, if one of the two cues in the pair was rejected as an outlier, both cues in the pair were not included in the result analysis. Overall, 64 of 1764 (3.68%) “continuous” mode cues and 50 of 1764 (2.83%) “tick reset” mode cues were rejected from this analysis. Following outlier rejection, rise times, settling times, percent overshoot, percent of trials with saturated tactors, percent of trials with no overshoot, and the number of oscillations were analyzed.

As in Experiment 4.2, participants performed better in most metrics with the “tick reset” feedback mode. Once again, differences in settling time and settling time minus rise time were both significant between the two modes [$F(1,3412) = 283.42$, $p < 0.00001$] and [$F(1,3412) = 330.17$, $p < 0.00001$], while the rise time for the two modes was not significantly different [$F(1,3412) = 3.18$, $p = 0.0748$]. It is expected that the rise time would be the same for each mode, as users are responding to the same initial cue, and there is no difference in the additional feedback up to that point in the trial. The differences in settling time suggest that users are able to better identify and stop at the target location with the “tick reset” mode.

Participants once again stopped at the target once reaching the acceptable range more often with the “tick reset” mode (42.68% versus 10.01%) [$F(1,3412) = 543.06$, $p < 0.00001$], and had fewer oscillations about the acceptable range (1.28 versus 1.79) [$F(1,3412) = 86.27$, $p < 0.00001$]. Additionally, percent overshoot was significantly less with the “tick reset” feedback mode [$F(1,3412) = 1009.37$, $p < 0.00001$], with 15.28% for “tick reset” and 44.06% for the “continuous” mode. A side-by-side comparison of the metrics for each mode is shown in Table 4.9.

The only comparison metric that changed from Experiment 4.2 to Experiment 4.3 is the amount of trials in which the tactors saturated at some point. In Experiment 4.3, there is no longer a significant difference in the amount of trials with observed tactor saturation (37.90% versus 35.61%) [$F(1,3412) = 1.93$, $p = 0.1651$]. This could be due to the decrease in overshoot for the "tick reset" mode, as it was hypothesized in Experiment 4.2 that the saturation occurred when a participant greatly overshot the target and the tactors ran out of space while trying to communicate this overshoot to the user. Table 4.10 shows the values for each metric for Experiment 4.3. The significant differences are highlighted in green where one feedback mode outperformed the other.

When comparing the responses to the first cue in the sequence to the second cue in the sequence, there are a few differences in user performance. For "continuous" feedback cues, there is a significant difference between the percent overshoot, with the first cue having an average overshoot of 39.01% compared to the second cue with an average overshoot of 49.90% [$F(1,1697) = 49.9$, $p < 0.00001$]. This increase is not entirely unexpected, as the users are farther away from the home position when the second cue begins, and this difference could lead to some decreases in performance. For the "tick reset" feedback mode, there is also a significant difference in the percent overshoot, with the first cue having an average of 13.17% and the second having an average of 17.43% [$F(1,1713) = 15.49$, $p < 0.0001$]. In addition, the number of oscillations is lower for the second cue for the "tick reset" mode, with an average of 1.37 oscillations for the first cue and 1.19 oscillations around the second cue [$F(1,1713) = 4.83$, $p = 0.0281$]. This could possibly be due to the workspace of the Phantom Premium 1.5, as users may have to slow down as they approach the second target if it is near the edge of the workspace, causing them to be able to stop faster and oscillate about the target fewer times. However, the cues combinations were designed to fit comfortably within the workspace of the tracking device, and there is no significant difference in the percentage of instant stops between first and second cues, so this difference could be caused by a different factor.

Results from this experiment were also compared to the results from Experiment 4.2 to investigate if users improve with practice. Based on this comparison, there appears to be a learning effect, as five out of seven metrics saw a significant improvement from Experiment 4.2 to Experiment 4.3 for each of the two feedback modes. These metrics are shown in Table 4.10 and Table 4.11, with green shading indicating a significant improvement between the two experiments.

Results from this experiment suggest that users are able to successfully complete sequential closed-loop cue motions. In addition, the "tick reset" mode once again appears to be superior to the "continuous" feedback mode, and it does not appear that it caused confusion for users when responding to cues in sequence. Finally, these results indicate that users can learn and improve their performance through extended use of the haptic feedback cues.

4.9 Experiment 4.4: Target Angle and Position Matching in a Teleguidance Task

This experiment uses the "tick reset" feedback mode from Experiments 4.2 and 4.3 to investigate the feasibility of a teleguidance task. An expert operator ("operator") sets the target through the motions of their hand on a second Phantom Premium. Then, a mentee ("participant") responds to the haptic cues given to mimic the motions of the expert operator.

4.9.1 Tactile Cues

For this experiment, rotation targets again ranged from 10˚ to 40˚ for the pronation, supination, dorsiflexion, and palmar flexion rotations of the wrist and translation targets ranged from 1.5 cm to 6 cm for the up, down, forward, and backward translations of the hand. The acceptable range around targets remained the same at ±2˚ for rotations and ±0.3 cm for translations.

The target location was set by the expert operator. This expert had a visual prompt on their computer screen, which indicated the direction and magnitude they should make for their motion. When the expert motion was complete and near the intended target, the expert pressed the space bar to save the target. The mentee then received the initial direction and magnitude cue, which was given by mapping the magnitude of the expert's motion to 1.25 mm of tactor displacement for a 40˚ rotation or 6 cm translation. Once a mentee began responding by moving their hand either 4˚ or 0.6 cm, the computer utilized the "tick reset" feedback mode to provide additional feedback to guide the mentee to the target. This approach makes these results more comparable to the above results in Experiment 4.3, but would also allow a target position to be communicated to a remote location, while the closed-feedback could be controlled and applied locally (to avoid cross-network delays, which can be destabilizing)

4.9.2 Methods

Ten participants (mean age = 28.6, 8 male, 10 right-hand dominant) participated in this experiment as mentees. Each participant also completed Experiments 3.3, 3.4, 4.2, and 4.3 prior to participating in this experiment. I was the expert operator for each of the ten experiment sessions.

There were 6 sequences of 24 motions each in this experiment. Each sequence of motions involved a combination of translations and rotations to explore a space. These sequences were modeled after potential motions made while performing an ultrasound on either a heart or lung. In these scenarios, rotations help achieve a different angle of the heart or lung through a fan, angle, or rotate motion. Translations can be used to move along the body to get a different view, or to press in to the body to improve the quality of the image. All of these motions are motions that could potentially be used in a thoracic ultrasound, and ultrasounds are completed by making one individual motion at a time followed by observing the ultrasound's visual display. In addition, there is a need for teleguidance in some ultrasound tasks. This makes an ultrasound task a practical application for teleguidance with skin stretch feedback. However, there are many other applications that could utilize skin stretch feedback teleguidance. While these cue sequences are modeled after ultrasound motions, the sequences cover a wide range of cue combinations and the results can be applied to any teleguidance task within a similar workspace, and therefore are not constrained strictly to an ultrasound teleguidance application.

Participants were instructed to hold their hand in the same position and orientation at the end of each sequence of motion cues, and were also instructed to make their response motions relative to the ending position and orientation of the prior trial. If participants got stuck on any trial and could not match the goal position or orientation, they were instructed to verbally say they needed to reset and redo that trial. They were instructed to return their hand to the position and orientation they believed they were in before that individual trial began. This was the only verbal or visual communication between the participant and operator during the experiment. In a teleguidance application with an expert located in a remote location, the two could potentially communicate verbally in the same way, and there could even be a verbal communication to return to a landmark location. For example, if teleguidance were to be used to guide an ultrasound technician in a remote location, the expert could tell them to move to a certain intercostal space (a gap between two ribs) or another known location on the body to begin again if they got lost. Therefore, as this is a verbal communication within an experiment, there could be even more verbal communication in a real world application of teleguidance. In all 1440 trials (across all 10 participants) of this experiment, participants verbally asked to restart the cue 23 times (1.6% of trials). At that time, the operator would move towards the target and lock their position change in to the computer, and the participant would receive an initial motion cue and closed loop feedback (to mirror and be more comparable to Experiment 4.3).

A dividing wall prevented the participant and expert operator from seeing each other, and the participant wore noise canceling headphones with white noise so that they could not hear the operator, the motions of the tactors, or any possible distracting noises. The experimenter moved the stylus of a second Phantom Premium 1.5 to indicate the intended position to the participant. This experimental setup is shown in Figure 4.18.

4.9.3 Results and Discussion

Prior to analyzing results, outlier rejection was performed on the data, with cues split into rotations and translations and response times compared to the mean of each participant's response time for each category of cue in the response sequence. Trials with completion times outside of 3σ of the mean were rejected as outliers. In total, 16 out of 1440 trials (1.11%) were rejected as outliers. Following outlier rejection, all trial results were grouped together and analyzed based on each individual motion (regardless of their order in the cue sequence).

First, an analysis on the operator motion was done to compare the operator-set target to the desired goal target. For example, while a goal target may have been a rotation of 30˚ for each participant, there was some error each time the operator set the target, and some participants may have received an actual target of 29˚ or 31˚. The operator error was 0.06 cm ± 0.0036 cm for translation targets and 0.092˚ ± 2.49˚ for rotation targets. However, the participant was to match the operator's target positions and the participants' target position was relative to the operators supplied positions. On average across all targets, the operator overshot the original target by 1.36%. Further analysis on participant responses utilized the operator-set target, so any percent overshoot seen in participant responses is comparable to Experiments 4.2 and 4.3.

Table 4.12 shows a comparison between the results in Experiment 4.3 with the "tick reset" feedback mode and the results of Experiment 4.4. Statistically significant performance values are highlighted in green. While there are some areas that improve for Experiment 4.4, there are also some areas with significantly better performance in Experiment 4.3. In general, results indicate that participants improved again with more experience with this feedback mode. Settling time, the time from first entering the acceptable range until settling in the acceptable range, the percentage of times a participant instantly stopped at the target, and the number of oscillations significantly improved over Experiment 4.3. Together, these suggest that participants improve in their ability to distinguish they have reached the target and in their ability to remain at the target once they reach it.

While Experiment 4.3 results have significantly lower rise times [$F(1,3113) = 8.49$, $p = 0.0036$] and percent overshoot [$F(1,3113) = 6.19$, $p = 0.0129$], this is not completely unexpected. As observed in Experiment 4.3, when the participant begins at a different location than the centered home position, percent overshoot is expected to increase. In Experiment 4.4, 23 out of 24 trials (95.83%) in each cue sequence did not start at the centered home position. In those trials, the percent overshoot is expected to increase. With some trials beginning at very different orientations and locations, an average percent overshoot of only 29.04% is a very promising result, as it suggests that this feedback mode is able to limit overshoot for many starting orientations and positions of the hand.

The increase in rise time for Experiment 4.4 could also be related to the many starting orientations and positions for each trial. Participants may be taking slightly longer to determine the relative motion they should make after identifying the initial direction cue. This difference could also be due to the difference in experimental methods. In Experiment 4.3, participants can expect the initial cue to begin one second after they press the space bar to begin the trial. In Experiment 4.4, participants do not know when to expect the initial cue to begin, as the initial cue is based on the expert operator's actions when the operator moves to the target and presses the space bar. It is possible that the difference in rise time is due to the participants taking longer to react due to not knowing when the cue will arrive.

Results from this experiment suggest that closed loop skin stretch feedback with this precision grip device can be used for a teleguidance or teleoperation application. Participants can adjust to these cues fairly quickly (mean settling time of 3.53 seconds), and can match a target angle within $\pm 2^{\circ}$ or a target position within ± 0.3 cm. This can reliably be completed from a variety of starting orientations and locations of the hand, and many cues can be put together in sequence to guide a hand through three-dimensional space. There is a wide range of applications that could utilize this feedback for teleguidance tasks. Within these experimental cue sequences, many different motions of the wrist were investigated, and the results apply for any teleguidance task. In addition, while the experiments were constrained to the workspace of the Phantom Premium 1.5, any tracking device can be used to track the position and orientation of the hand, and the computer could potentially communicate wirelessly to the precision grip device to apply closed-loop feedback to the user. The compact nature of the device allows it to be attached to any handheld tool, and the user can move the tool normally while receiving haptic feedback.

4.10 Conclusions

This chapter presented methods and results for utilizing the precision grip skin stretch tactor device (shown in Figure 3.1) to guide a user to a specified goal rotation angle or goal translation position. The main findings from these experiments create a foundation for closed-loop tactile feedback to communicate hand position and orientation to a user. One key finding is that providing a “tick” motion when the user arrives at the target greatly improves user performance (as one may expect) by decreasing settling time, percent overshoot, and the number of oscillations, while increasing the frequency of trials where the user instantly stops at the target as soon as reaching the acceptable range. Another key finding is that these closed loop cues can be given to a user in sequence, with users able to respond to as many as 24 sequential closed loop cues to adjust the location and orientation of their hand several times. These results suggest that this device can be used to guide a user’s hand through space solely through the use of haptic feedback in a teleguidance or teleoperation task. In the case of a medical procedure, this can allow an expert to guide a medical technician that is untrained for a particular procedure, or even someone without any training to provide critical diagnosis or care.

4.11 Future Work

Future work regarding this chapter is centered upon using this feedback in a clinical application. Many applications could utilize the closed-loop feedback described in this chapter to lead a user to different locations and orientations of their hand. Each application will have different results, as the workspace can be made larger and the tactile cues and closed-loop feedback would need to be adjusted accordingly to command larger motions of the hand and arm. Additionally, clinical applications could have improved results, as there may be a reference point to utilize. For a possible ultrasound application, the intercostal spaces between the ribs could be used as a reference point, and the mentee could be able to hold their hand steady and perform more precise motions through the contact between the ultrasound probe and the body. For a possible arm rehabilitation application, users could be commanded to move their arms through larger workspaces, and could potentially have some visual reference cues in a virtual reality scenario. Clinical applications could also have decreased results, as additional lag could be introduced through wireless communication or tracking precision could decrease through the use of different tracking systems. However, these potential issues could be accounted for in changes in software. In addition, performance with this device can be compared to performance with other haptic feedback devices in experimental or clinical applications. The potential future work is limitless, as there is a wide range of changes that could be made to the feedback to explore the many applications of this device.

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Figure 4.1. Experimental setup.

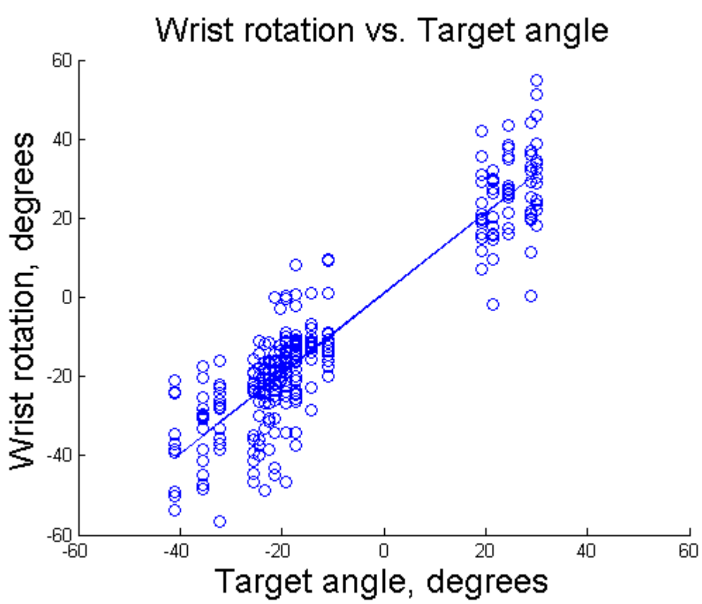

Figure 4.2. Response wrist rotation angles versus target angles, with a linear best-fit line.

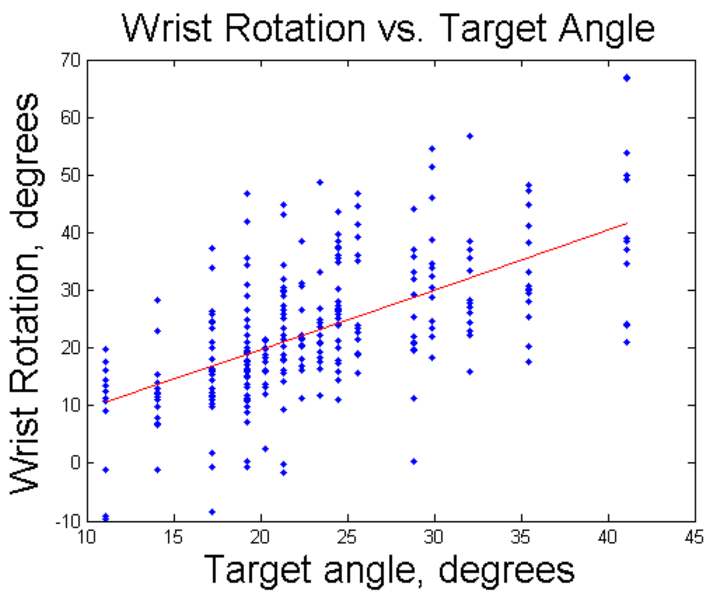

Figure 4.3. Response wrist rotation angle versus target angle, with a power fit line (shown in red).

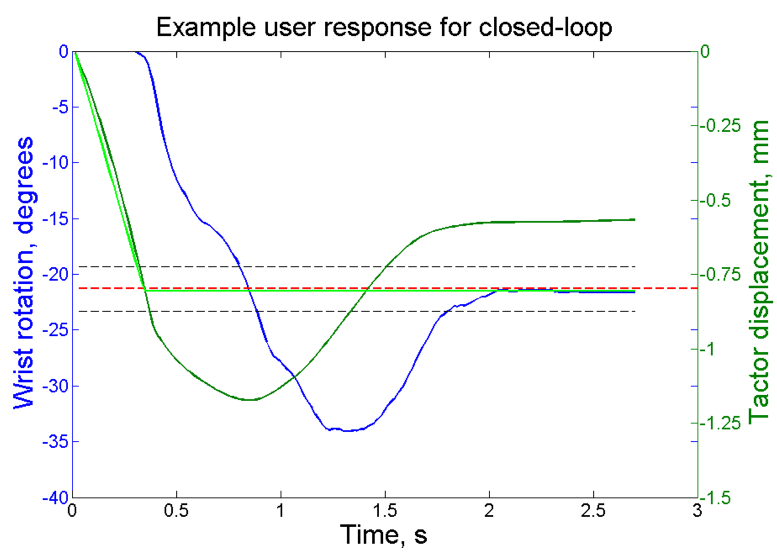

Figure 4.4. Target angle, wrist rotation, feed-forward tactor displacement, and total tactor displacement for an example user response. User wrist angle is shown in blue and lags the relative tactor feedback, which is shown in green.

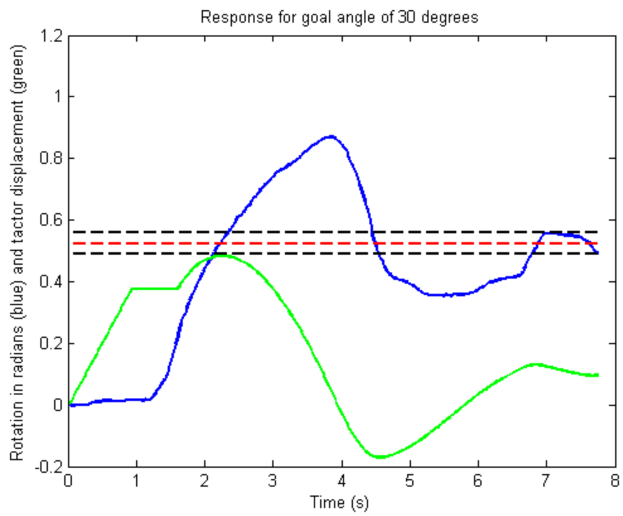

Figure 4.5. An example user response and tactor motion for Mode 1. The tactor (position shown in green) moves continuously unless the user rotation (shown in blue) is exactly at the target (red dashed line).

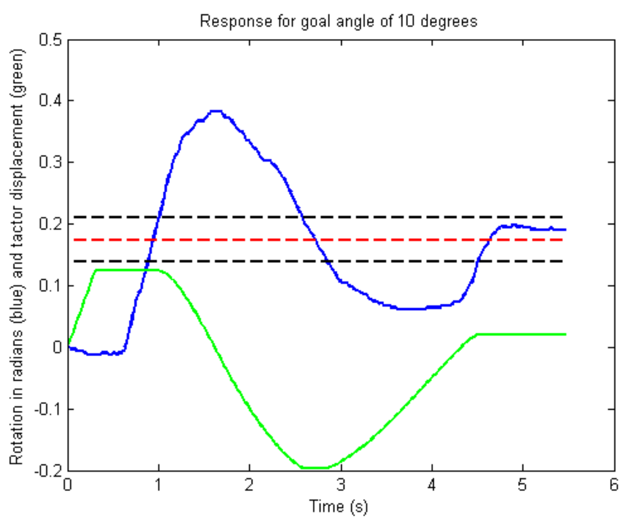

Figure 4.6. An example user response and tactor motion for Mode 2. The tactor (position shown in green) moves continuously unless the user rotation (shown in blue) is within the acceptable range of ±2° of the target (two black-dashed lines).

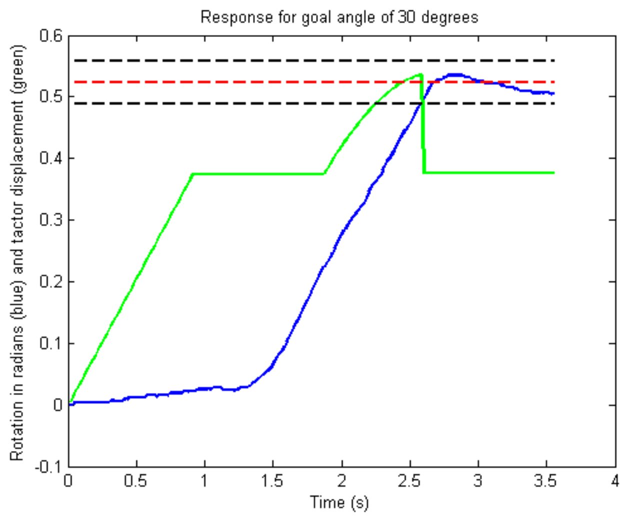

Figure 4.7. An example user response and tactor motion for Mode 3. The tactor (position shown in green) moves continuously unless the user rotation (shown in blue) is within the acceptable range of ±2˚ of the target (two black dashed lines). When within the acceptable range, the tactor resets to the feedforward position.

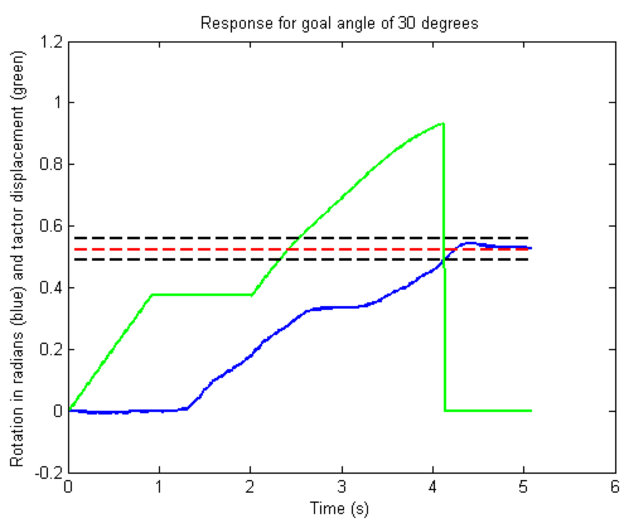

Figure 4.8. An example user response and tactor motion for Mode 4. The tactor (position shown in green) moves continuously unless the user rotation (shown in blue) is within the acceptable range of ±2˚ of the target (two black-dashed lines). When within the acceptable range, the tactor resets to the centered position.

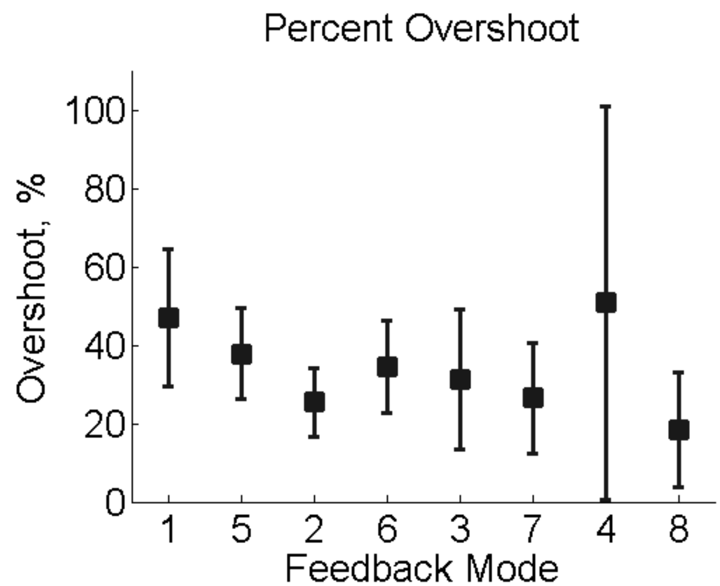

Figure 4.9. The mean percent overshoot and 95% confidence intervals for trails in each of the eight pilot test modes.

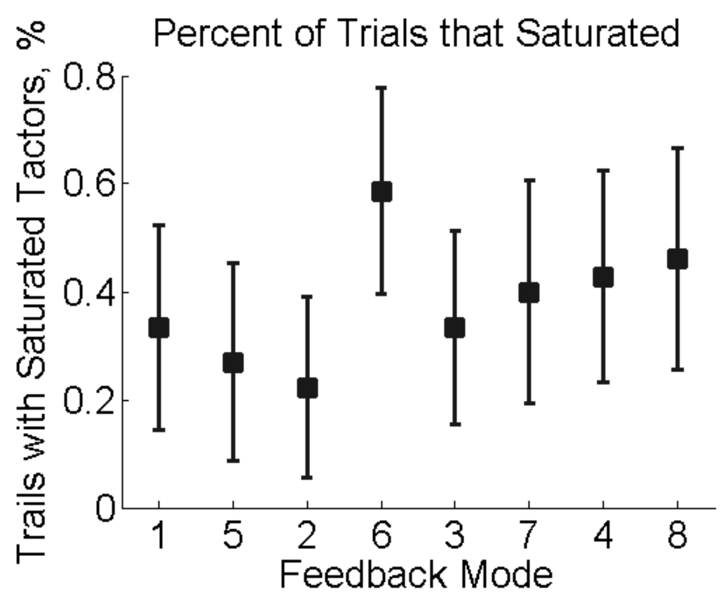

Figure 4.10. The percent of trials in each of the eight pilot test modes that included tactors saturating at some point in the trial.

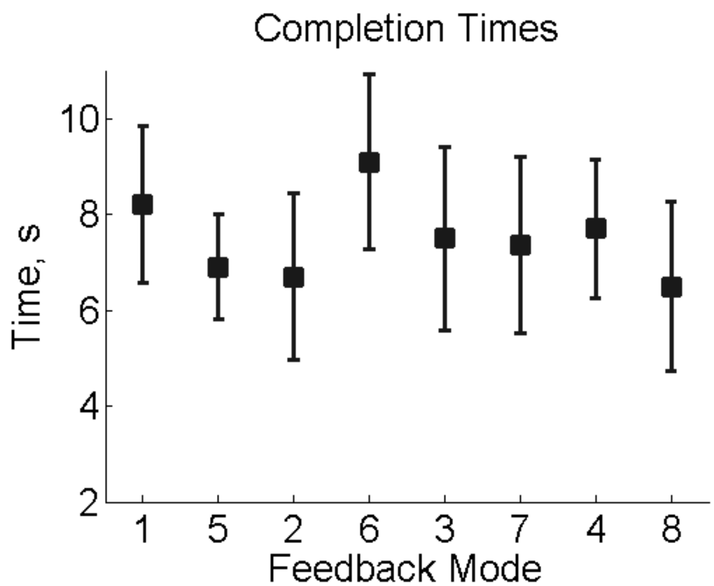

Figure 4.11. The mean completion times and 95% confidence intervals for each of the eight pilot test modes.

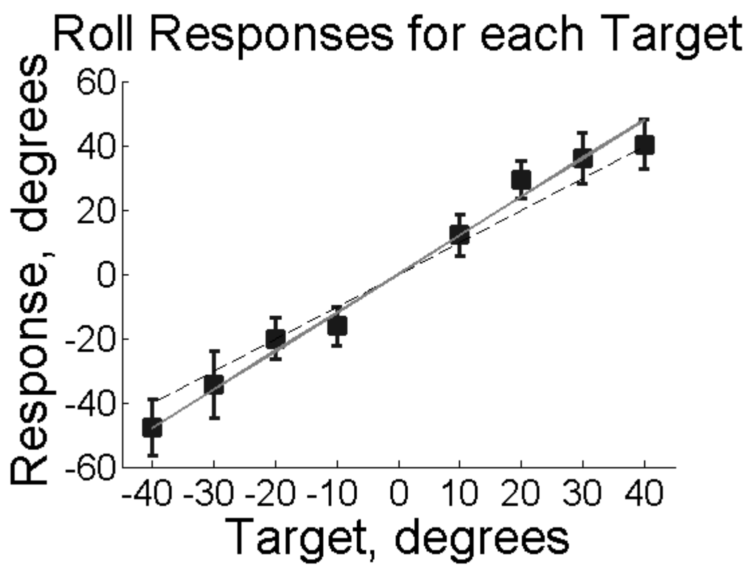

Figure 4.12. Mean response angles and 95% confidence intervals for each of the target angles roll rotations. A negative roll is a counter-clockwise rotation of the wrist, while a positive roll is a clockwise rotation of the wrist. The dashed line shows a linear slope, passing through each target and perfect response, while the solid gray line is a linear fit line to the participant data.

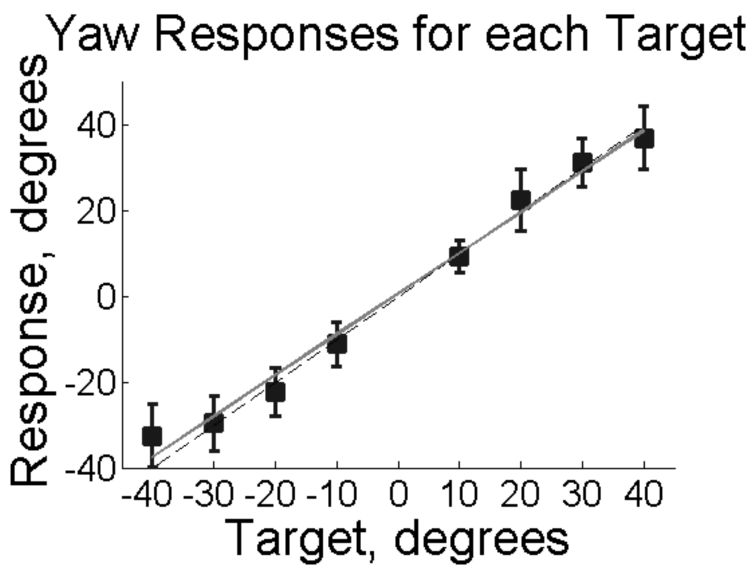

Figure 4.13. Mean response angles and 95% confidence intervals for each of the target angles yaw rotations. A negative yaw is rotation of the wrist moves the hand towards the midline of the body, while a positive yaw moves the hand away from the midline of the body and towards the outer/top part of the forearm. The dashed line shows a linear slope, passing through each target and perfect response, while the solid gray line is a linear fit line to the participant data.

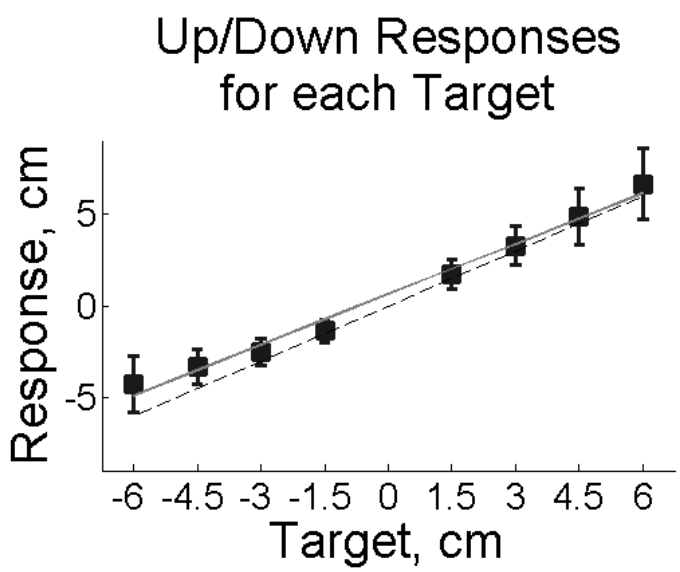

Figure 4.14. Mean response angles and 95% confidence intervals for each of the target translations for up and down motions. A negative value indicates a downward motion, while a positive value indicates an upward motion. The dashed line shows a linear slope, passing through each target and perfect response, while the solid gray line is a linear fit line to the participant data.

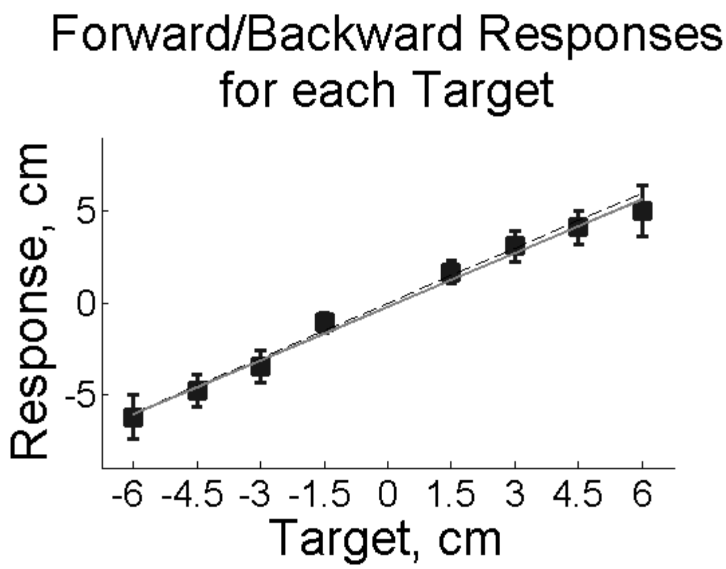

Figure 4.15. Mean response angles and 95% confidence intervals for each of the target translations for forward and backward motions. A negative value indicates a backward motion, while a positive value indicates a forward motion. The dashed line shows a linear slope, passing through each target and perfect response, while the solid gray line is a linear fit line to the participant data.

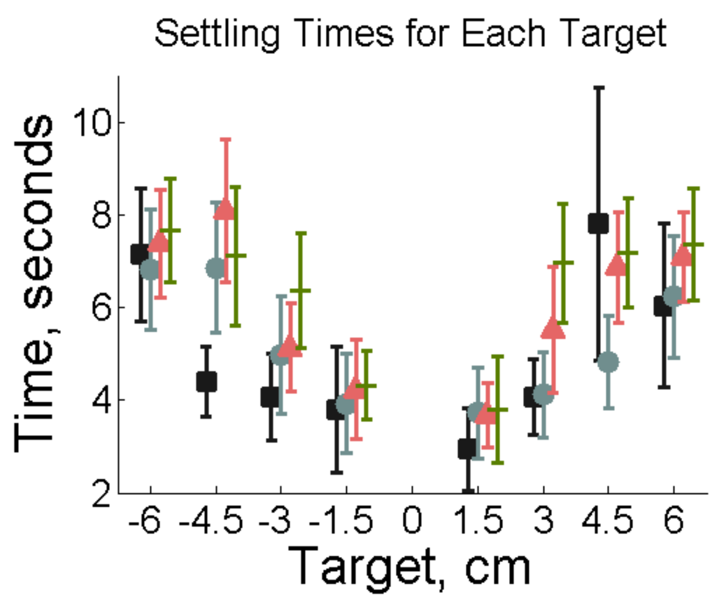

Figure 4.16. Mean settling times and 95% confidence intervals for translation responses to closed-loop cues. Pink triangle points mark “continuous” forward/backward, green cross points mark “continuous” up/down, black square points mark “tick reset” forward/backward, and gray circles mark “tick reset” up/down responses.

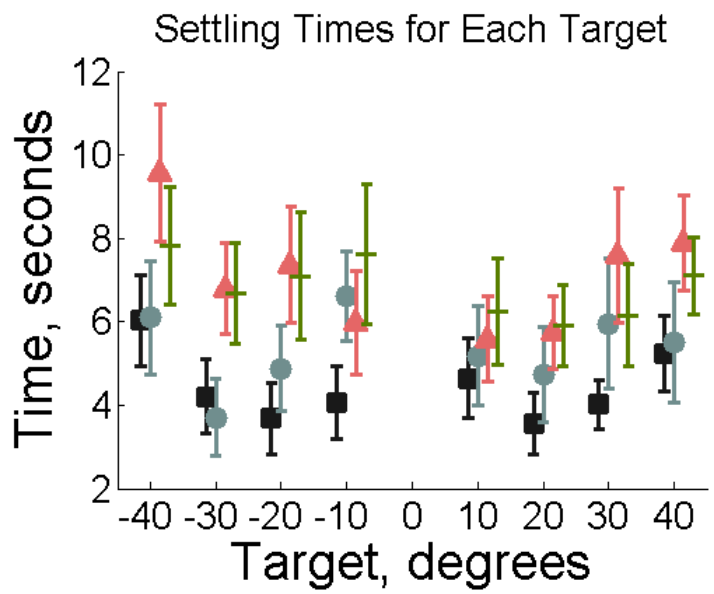

Figure 4.17. Mean settling times and 95% confidence intervals for rotation responses to closed-loop cues. Pink triangle points mark “continuous” yaw, green cross points mark “continuous” roll, black square points mark “tick reset” yaw, and gray circles mark “tick reset” roll responses.

Figure 4.18. Experimental setup for the teleguidance procedure. The participant (on the right side) cannot see or hear the operator or see the motion cues provided to the operator on the computer screen. The expert operator cannot see the participant, but can hear if they need to redo a specific trail within the series of motions.

Table 4.1 Average score of each pilot test mode.

Mode	Average
1	6.75
2	**7.5**
3	**7.75**
4	6.375
5	6.25
6	6.625
7	7
8	6.75

Table 4.2 Response rotations for each target angle for the roll rotation of the wrist. Responses include the mean and standard deviation.

Target	**Response**
-40°	-47.55° ± 17.60°
-30°	-34.37° ± 21.18°
-20°	-20.04° ± 13.32°
-10°	-16.19° ± 12.12°
10°	12.12° ± 12.92°
20°	29.36° ± 11.69°
30°	36.08° ± 15.59°
40°	40.35° ± 15.69°

Table 4.3 Response rotations for each target angle for the yaw rotation of the wrist. Responses include the mean and standard deviation.

Target	**Response**
-40°	-32.51° ± 14.68°
-30°	-29.63° ± 13.03°
-20°	-22.39° ± 11.24°
-10°	-11.15° ± 10.26°
10°	9.34° ± 7.58°
20°	22.44° ± 14.37°
30°	31.08° ± 11.26°
40°	36.83° ± 14.96°

Table 4.4 Response translations for each target for the up and down translation of the hand. Responses include the mean and standard deviation.

Target	**Response**
-6 cm	-4.29 cm ± 3.03 cm
-4.5 cm	-3.34 cm ± 1.89 cm
-3 cm	-2.53 cm ± 1.45 cm
-1.5 cm	-1.39 cm ± 1.31 cm
1.5 cm	1.75 cm ± 1.61 cm
3 cm	3.28 cm ± 2.11 cm
4.5 cm	4.87 cm ± 3.11 cm
6 cm	6.66 cm ± 3.90 cm

Table 4.5 Response translations for each target for the forward and backward translation of the hand. Responses include the mean and standard deviation.

Target	**Response**
-6 cm	-6.24 cm ± 2.40 cm
-4.5 cm	-4.81 cm ± 1.80 cm
-3 cm	-3.45 cm ± 1.79 cm
-1.5 cm	-1.09 cm ± 1.06 cm
1.5 cm	1.65 cm ± 1.23 cm
3 cm	3.09 cm ± 1.74 cm
4.5 cm	4.10 cm ± 1.86 cm
6 cm	5.01 cm ± 2.76 cm

Table 4.6 Mean values for the metrics used to compare the "continuous" feedback mode to the "tick reset" feedback mode.

	Continuous	Tick Reset
Settling Time, T_s	6.55 s	4.99 s
Rise Time, T_r	2.54 s	2.66 s
T_s - T_r	4.01 s	2.32 s
% Instant Stop	12.08%	41.33%
Percent Overshoot	64.34%	38.18%
Number Oscillations	2.06	1.39
Percent Saturation	36.47%	43.64%

Table 4.7 Index difficulty, target distance, and mean settling times for translations.

		Forward/Backward Translations		Up/Down Translations	
Index difficulty	Target (cm)	Continuous	Tick Reset	Continuous	Tick Reset
5.32	-6.0	7.38	7.14	7.67	6.81
4.91	-4.5	8.09	4.40	7.11	6.86
4.32	-3.0	5.14	4.07	6.36	4.96
3.32	-1.5	4.22	3.80	4.32	3.93
3.32	1.5	3.68	2.94	3.80	3.72
4.32	3.0	5.52	4.06	6.95	4.12
4.91	4.5	6.87	7.80	7.19	4.82
5.32	6.0	7.09	6.04	7.37	6.23

Table 4.8 Index difficulty, target distance, and mean settling times for rotations.

		Yaw Rotations		Roll Rotations	
Index difficulty	Target (deg)	Continuous	Tick Reset	Continuous	Tick Reset
5.32	-40.0	9.57	6.03	7.82	6.09
4.91	-30.0	6.79	4.21	6.69	3.71
4.32	-20.0	7.37	3.69	7.10	4.88
3.32	-10.0	5.98	4.07	7.61	6.61
3.32	10.0	5.59	4.64	6.25	5.18
4.32	20.0	5.74	3.56	5.91	4.73
4.91	30.0	7.59	4.02	6.15	5.94
5.32	40.0	7.89	5.23	7.10	5.50

Table 4.9 Mean values for the performance metrics used to compare "continuous" feedback to "tick reset" feedback.

	Continuous	Tick Reset
Settling Time, T_s	5.68 s	3.93 s
Rise Time, T_r	2.40 s	2.31 s
Ts - Tr	3.28 s	1.62 s
% Instant Stop	10.01%	42.68%
Percent Overshoot	44.06%	15.28%
Number Oscillations	1.79	1.28
Percent Saturation	35.61%	37.90%

Table 4.10 Comparison of analysis metrics for the "continuous" feedback mode.

	Experiment 4.2	Experiment 4.3
Settling Time, T_s	6.55 s	5.68 s
Rise Time, T_r	2.54 s	2.40 s
Ts - Tr	4.01 s	3.28 s
% Instant Stop	12.08%	10.01%
Percent Overshoot	64.34%	44.06%
Number Oscillations	2.06	1.79
Percent Saturation	36.47%	35.61%

Table 4.11 Comparison of analysis metrics for the "tick reset" feedback mode.

	Experiment 4.2	Experiment 4.3
Settling Time, T_s	4.99 s	3.93 s
Rise Time, T_r	2.66 s	2.31 s
Ts - Tr	2.32 s	1.62 s
% Instant Stop	41.33%	42.68%
Percent Overshoot	38.18%	15.28%
Number Oscillations	1.39	1.28
Percent Saturation	43.64%	37.90%

Table 4.12 Mean values for the performance metrics used to compare Experiment 4.3 to Experiment 4.4, which had many sequential motions.

	Experiment 4.3	Experiment 4.4
Settling Time, T_s	3.93 s	3.53 s
Rise Time, T_r	2.31 s	2.47 s
Ts - Tr	1.62 s	1.06 s
% Instant Stop	42.68%	59.00%
Percent Overshoot	15.28%	29.04%
Number Oscillations	1.28	0.7
Percent Saturation	37.90%	38.43%

CHAPTER 5

CONCLUSION

This dissertation presented and explored tactile skin stretch feedback, a type of haptic feedback that provides cues to the finger tips or palm of the hand. The first study presented device designs for embedding skin stretch feedback into a game controller, both in the thumb joysticks for contact at the thumbs, and in the back of a game controller for contact with the middle fingers. Experiments were conducted to determine the requirements for lag time between two differing skin stretch feedback cues, and skin stretch feedback cues in the presence of vibration feedback. The results of these experiments showed that participants achieve higher accuracy responding to tactile cues provided through the thumb joystick tactors versus the tactors contacting the middle fingers. This result was likely due to the collocation of the stimulus and response. The results also showed that higher accuracies can be obtained as the time between two cues increases. In addition, performance is decreased when vibration feedback occurs near the start of a skin stretch feedback cue. For two skin stretch cues given in different directions, users performed best when the two cues were the same, or opposite directions, and did not perform well when the two cues were orthogonal in direction to each other.

The second set of experiments investigated user performance responding to skin stretch feedback cues that convey a three-dimensional motion. First, a five degree-of-freedom experiment quantified user performance with a precision grip skin stretch feedback device.

Then, a five degree-of-freedom experiment quantified user performance with a power grip skin stretch feedback device, which applied the skin stretch to the palms of the hand. The results between the two experiments were compared, and it was decided that the precision grip device was the most promising for future experiments. Then, a four degree-of-freedom experiment quantified user performance responding to diagonal translation and combined rotation cues with the precision grip device. User performance decreased significantly, so cues were then limited to be along a translational axis or about a rotational axis of the device. An experiment was then done to investigate methods of providing sequential direction cues as well as user performance in responding to sequential direction cues. The results of these experiments showed that users can identify and respond to direction cues provided by the precision grip device with a high accuracy, as long as the direction cues are along the device axes. In addition, users are able to correctly identify direction cues when the stimulus is limited to a tactor motion of 1.25 mm. Participants also achieved a high accuracy in responding to a sequence of motion cues.

The third set of experiments investigated user performance responding to directional translation and rotation cues with the correct direction and a specific magnitude for the response. First, an initial open-loop and closed-loop study was performed on one degree of freedom. Then, the closed-loop feedback was analyzed and improved through two pilot studies. Next, an open-loop and closed-loop study was performed using four degrees of freedom for the cues. This was followed up by an investigation into user performance responding to sequential closed-loop cues in four degrees of freedom. Finally, a teleguidance experiment investigated the feasibility of an expert user guiding multiple hand motions of a mentee. The results showed that percent overshoot of the target can be improved by making improvements to closed-loop error feedback. In addition, humans map skin stretch magnitudes to the physical motion magnitude in a nearly linear way. Participants with little to no training can achieve a hand orientation within ±2˚ of a target angle or a hand position within ±0.3 cm of a target position in approximately 5 s. A feedback mode that provides a tick reset when the user reaches the target provides better results than one that just has the tactors slow down and reverse direction when the user passes the target. Users are able to complete a sequence of closed-loop cues, and with minimal experience can improve their performance to achieve a hand orientation within ±2˚ of a target angle or a hand position within ±0.3 cm of a target position in approximately 4 s. Furthermore, an expert can guide up to 24 sequential motions of a novice's hand in a teleoperation or teleguidance task where the two people communicate these hand motions through haptic feedback only.

5.1 Future Work

Future work includes using the new information now known about skin stretch feedback and applying it to specific applications. Results from Chapter 2 can be used to include skin stretch feedback in gaming applications alongside vibration feedback. These results can also be used for any application that desires to provide skin stretch feedback cues that may differ from each other to each hand. Results from Chapters 3 can be used in training and rehabilitation tasks that could benefit from haptic feedback that can provide directional information without limiting the workspace of the user and while keeping the system cost reasonable. Results from Chapter 4 can be used in training, rehabilitation, teleoperation, and teleguidance tasks to guide hand motions to a specified position and orientation.