Holdable Haptic Device for 4-DOF Motion Guidance

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***Abstract*— Hand-held haptic devices can allow for greater freedom of motion and larger workspaces than traditional grounded haptic devices. They can also provide more compelling haptic sensations to the users' fingertips than many wearable haptic devices because reaction forces can be distributed over a larger area of skin far away from the stimulation site. This paper presents a hand-held kinesthetic gripper that provides guidance cues in four degrees of freedom (DOF). 2-DOF tangential forces on the thumb and index finger combine to create cues to translate or rotate the hand. We demonstrate the device's capabilities in a three-part user study. First, users moved their hands in response to haptic cues before receiving instruction or training. Then, they trained on cues in eight directions in a forced-choice task. Finally, they repeated the first part, now knowing what each cue intended to convey. Users were able to discriminate each cue over 90% of the time. Users moved correctly in response to the guidance cues both before and after the training and indicated that the cues were easy to follow. The results show promise for holdable kinesthetic devices for haptic feedback and guidance in applications such as medical training, teleoperation, and virtual reality.**

I. Introduction

Humans regularly receive guidance from electronic devices through visual or audio cues. A smart phone can give verbal instructions to drivers or show arrows on its screen. Augmented reality headsets can provide instructions and show trajectories to users as they complete assembly or manipulation tasks [1]. The sense of touch is a rich platform for this kind of information. Touch cues can encode direction, magnitude, and timing. They can be discreet, whereas audio cues may be disruptive. Additionally, they can be easier to process than visual or auditory cues when attention is divided [2]. Touch guidance is central to learning in the physical world: a tennis instructor may adjust a novice's racket, and a guitar teacher may move a student's fingers. Especially for tasks that have temporal components, guidance through the sense of touch can be beneficial in training [3]. In teleoperation tasks, such as minimally invasive robotic surgery or remotely operating a robot to complete tasks around a home, haptic feedback and guidance may be able to improve performance in ways that visual or audio information cannot.

*This work was supported by a National Science Foundation Graduate Research Fellowhsip, a Chateaubriand Fellowship, National Science Foundation Grant 1812966, a Stanford Graduate Fellowship, and the Human-centered AI seed grant program from the Stanford AI Lab, Stanford School of Medicine and Stanford Graduate School of Business.

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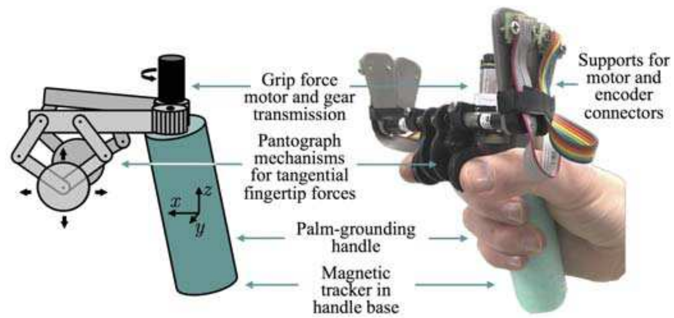

Fig. 1. This holdable haptic device has two back-to-back pantograph mechanisms that provide tangential displacements to a user's fingertips. 4-DOF guidance can be generated: 2-DOF translation and 2-DOF rotation. The two pantographs are mounted to a gear mechanism driven by a DC motor, providing the potential for grip force feedback. The reaction forces are distributed at the handle, and thus are not noticeable.

Traditional kinesthetic devices can provide clear forces or torques to move a user's hand or resist motion [4]. Unfortunately, the end-effector must be physically grounded through rigid links. Larger workspaces require larger, more expensive devices. Holdable or wearable devices can be mobile and allow more freedom of motion, but it is more difficult to provide compelling directional information because they lack grounding to a world coordinate frame.

Although they cannot provide net forces or torques, exoskeleton designs or hand-grounded devices can generate guidance forces on the fingertips because reaction forces can be distributed across a larger or less sensitive area such as the user's palm. Holdable devices are easy to use because they can be picked up and put down without attaching straps to the fingers. They may also integrate naturally with virtual reality systems, as they are similar to existing controllers. So far, many holdable devices for virtual reality or teleoperation have focused on applying normal forces to the users' fingers or recreating textures [5], [6]. Their use for motion guidance beyond navigation has not been fully explored.

In this paper, we present a holdable device that provides four-degree-of-freedom (DOF) motion guidance (Fig. 1). Two 2-DOF pantograph mechanisms attached to a handle displace the user's thumb and index finger to elicit pulling sensations in various directions. We show that it prompts users to move their hands up/down and forward/backward as well as to twist (flex/extend) and tilt (pronate/supinate) their wrists. Applications include guidance for dexterous tasks like suturing in surgical simulations, guidance or force feedback in teleoperation and robotic shared control, and feedback of forces or object weight in virtual reality.

A. Related Work

1) Wearable Cutaneous Devices: Several wearable devices applying cutaneous cues to the fingertips or hand have shown promise for virtual object interaction and teleoperation [7], [8]. Although they provide directional information to the fingerpad, reaction forces felt on the back of the finger can make guidance cues confusing. These devices must be fixed carefully to the hand and take some time to don and doff. Wearable vibrotactile guidance can be easy to implement, but requires the user to learn a vibration pattern mapping and interpret each cue before acting [9], [10]. Asymmetric vibrations can generate intuitive direction cues for simple guidance, but the actuators must be attached very precisely to the user's hand [11].

2) Holdable Guidance Devices: Net forces can be generated by holdable haptic devices through air jets [12] or propellers [13]. Some researchers have had success with net-zero guidance cues for navigation through holdable haptic "compasses." They use shape changing [14], gyroscopic effects [15], asymmetric vibration pulses [16], or weight shifting [17]. Higher DOF guidance can be produced by reorienting the gyroscopic or vibration pulses [16], [18], but these devices must use an asymmetric pulsing pattern that can be unpleasant in extended use. Guinan et al. developed a device similar to the one presented here that uses small tactors to stretch the skin on the user's fingertips and grounds to the outer edges of the fingertips [19].

Our holdable device provides compelling guidance cues in 4-DOF by stretching and displacing both the thumb and index finger in 2-DOF and grounding the forces through the device's handle. In a user study, we demonstrate that guidance in each DOF is easy to discriminate and intuitive to follow.

II. Device Design and Implementation

The device was inspired by joysticks in robotic surgery simulators, which allow for translating, rotating, and gripping. We aimed to design a holdable alternative that included haptic guidance. The design goals were:

- allow for two-fingered gripping interactions in virtual environments or during teleoperation
- give directional haptic cues
- allow for free motion through a large workspace

The fingertips are highly sensitive, especially to tangential forces [20]. For these reasons, we focused on applying cues tangentially to the thumb and index finger while holding a gripper. This includes up/down and distal/proximal (forward/backward) translations for each finger. Additionally, we can take advantage of the fact that there are two fingers involved in gripping and a natural center of motion at the point being pinched by the gripper. By applying tangential cues in opposite directions, the device can generate a torque sensation, cuing the user to rotate in the extension/flexion directions (twist) or the pronation/supination directions (tilt).

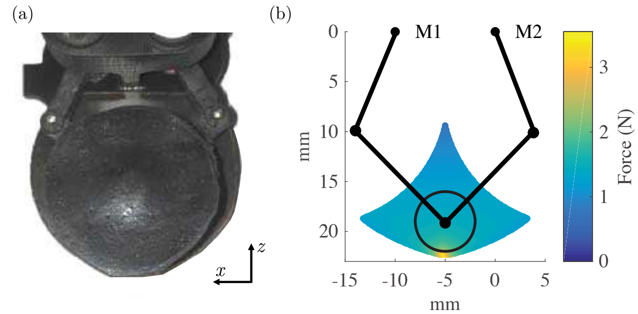

Fig. 2. (a) Pantograph mechanism. (b) Pantograph workspace and isotropic force output: the maximum force that can be applied in all directions from each point in the workspace. The circle indicates the region of the workspace where the cues took place during the experiments in Section III.

A. Design

As shown in Figure 1, two pantograph mechanisms are attached to horizontal arms extending from a handle. Pantograph 5-bar linkages are common mechanisms in kinesthetic interfaces [21]. In our device, each pantograph has 10 mm long upper links and 13 mm long lower links (Fig. 2(a)). The forward and inverse kinematics equations are given by [21], and link lengths were selected based on guidance in [22]. The isotropic force output of the end-effector is given in Fig. 2(b). The end-effector stayed within the 3mm radius circle during experiments (described in Section III) to maintain high quality forces in each direction.

The links and all mountings are 3D printed rigid polyurethane. Metal pins connect each joint, and a circular pad rotates freely on the bottom pin. Faulhaber coreless micro DC motors (64:1 gear ratio) with optical encoders (50 counts/rev) power each upper joint. The end effectors have nylon on their inner surfaces so that they slide smoothly against a vertical support (Fig. 2(a)). A high-friction rubber material on the outer surfaces prevents slip between the end effector and the users' finger pads. As the end-effectors move they stretch the skin and displace the fingers, producing a salient sensation. The reaction forces simultaneously applied at the handle are not noticeable, and the user feels almost as if an object held in a precision grip is being pulled or rotated by an external force.

The arms connect at a geared hinge at the top of the handle. One gear is driven by a DC motor (Pololu 50:1 micro metal gear motor) with a magnetic encoder. The gears allow the arms to open and close symmetrically relative to the vertical plane of the handle. The motor can be used to apply a constant force holding the pads against the users' fingers as they open or to provide grip force feedback if used to interact with virtual objects. Because the studies presented in this paper focus on guidance, this motor was not used. The handle has a stiff core and a foam exterior. The arms adjust to accommodate different length fingers. The entire device weighs 76.0 g.

B. System

An Ascension TrakStar 6-DOF magnetic tracking system records the haptic device's position and orientation at 80 Hz.

A sensor is mounted in the bottom of the handle. This location was chosen to keep the motors from affecting the tracking quality, which was checked using Ascension's proprietary software. The sensor's position and orientation is transformed to a point centered on the handle at the height of the pantograph end-effector. A Sensoray 826 PCI card controls the system. Linear current amplifiers (LM675T, 0.1 A/V gain) and a 13V external power supply (Mouser) power the motors. The motor positions θ are current-controlled using a proportional-derivative controller:

$$i = \frac{k_p \theta_{\text{err}} + k_d \dot{\theta}_{\text{err}}}{N k_t}, \tag{1}$$

where the gains $k_p = 5.5$ Nm/rad and $k_d = 0.004$ Nm-s/rad, the gear ratio $N = 64$:1, and the torque constant $k_t = 0.00196$ Nm/A. The system runs at 830 Hz in an application written using Visual C++.

III. User Study

A. General Methods

In a user study we tested two hypotheses about the device's performance:

1) 4-DOF cues can be easily discriminated by users
2) the guidance cues are intuitive (don't need to be explained to users in advance)

The user study had three parts. First, users moved their hands in response to eight guidance cues (positive and negative in each DOF), without an explanation of each cue's intent. Then, users were shown what each cue was instructing them to do. They completed a forced-choice task identifying each of the cues. Finally, they repeated the first part, moving their hands in response to the cues.

20 right-handed users aged 22 to 42 participated in the experiment. All participants completed all three parts of the study. Seven were female, and thirteen were male. 12 of the users had experience with haptic devices beyond just a few demonstrations. The protocol was approved by the Stanford University Institutional Review Board, and the subjects gave informed consent. In all parts of the study, users stood in front of a computer, wearing headphones to mask any noises. Users held the device with their right hand. They aligned their wrist so that they could rotate comfortably in all directions. A handkerchief was placed over the hand and the haptic device to hide it from view. The handkerchief did not interfere with the magnetic tracking or device.

Eight direction cues were included in the study, which we call forward (distal), backward (proximal), up, down, twist left (extension), twist right (flexion), tilt left (pronation), and tilt right (supination). We expected to see displacement in x for forward/backward cues, displacement in z for up/down cues, yaw rotation (about the z axis) for twisting cues, and roll rotation (about the x axis) for tilting cues. We expected to see minimal y and pitch displacement, which were not cued. For translation cues, the pantograph end-effectors move in the same direction either up, down, forward, or backward. For rotation cues, the end-effectors move in opposite directions. The reference frame in Fig. 1 illustrates the axis conventions used. Fig. 3 shows the directions of the end-effector motion for each cue. All cues had the same magnitude and speed. The end-effectors each moved 3 mm from the center position over 0.2 s, paused at the peak for 0.6 s, and returned to the center position more slowly, over 0.5 s (shown in Fig. 5(a)). This displacement and speed was chosen because they are higher than those felt with 100% success in [23], ensuring that the cues would be easy to feel.

B. Part 1: Movement Experiment Before Training

In the first part of the study, we asked users to move their hands in response to the haptic guidance cues. Users were not told that there were eight different cues or what they were supposed to convey. We hoped to understand whether the device's cues are intuitive. After completing 24 practice trials to get used to the experiment procedure, users completed 80 experimental trials, experiencing each cue 10 times in a randomized order. They started each trial by pressing the space bar and could repeat cues if desired. We recorded the position and orientation of the user's hand throughout.

C. Part 2: Training and Forced Choice Experiment

Before starting the second part of the experiment, the experimenter demonstrated to the users what motion each cue intends to convey. Then users felt cues in a pseudorandom order and identified them from the eight choices. A diagram of the cues similar to Fig. 3 was shown during the trials. They completed one practice trial of each cue followed by 24 randomized experimental trials. Again, users began each trial by pressing the space bar, and could repeat the cue if desired. They selected one direction from eight labeled keys. If incorrect, the correct response was shown on the screen to help the users learn.

D. Part 3: Movement Experiment After Training

In the third part of the experiment, users repeated the movement experiment from Part 1. Now, they knew the eight possible cues and had practiced discriminating them in the second part of the experiment.

E. Analyses

We analyzed the effects of cue, set, and subject on motion directions and delay times for Parts 1 and 3. We analyzed the ease of discriminating cues in Part 2. MATLAB's Statistics and Machine Learning Toolbox was used for all analyses.

Motion Direction: Linear regressions were performed relating peak displacement in x, y, z, yaw, pitch, and roll to the set of trials, subject (as a random variable), and cue (as a categorical variable). A multi-way ANOVA was performed comparing peak x, y, z, yaw, pitch, and roll displacements for each cue, followed by multiple comparison tests with the Bonferroni correction.

Motion Delay: Delay time was identified as the time from the start of a cue to the first peak of acceleration in any DOF. We fit a linear regression model predicting delay from set number, experience with haptics (self-rated by users on a 1-4 scale), and cue (included as a categorical variable).

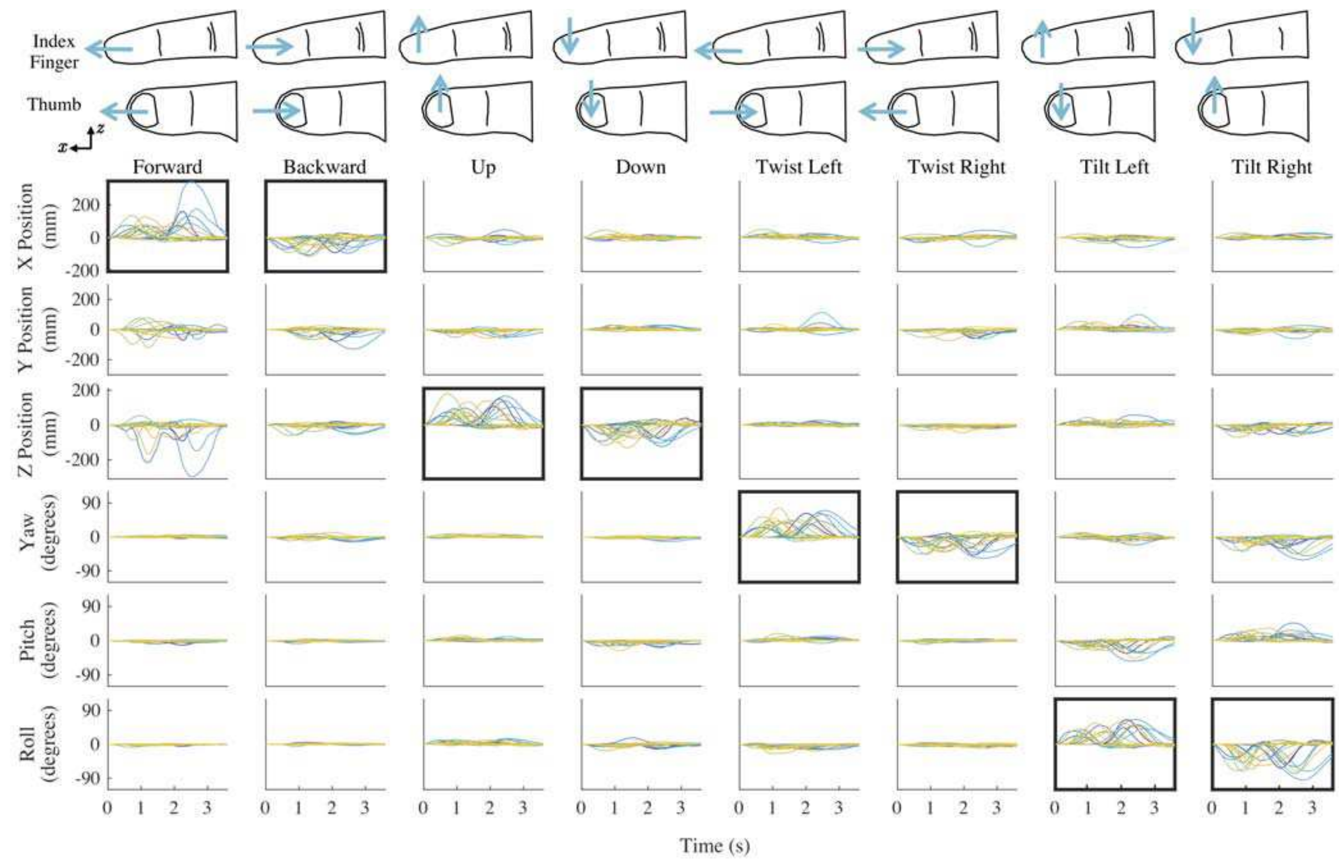

Fig. 3. Mean trajectories for each subject's hand for each cue, with Part 1 and Part 3 together. 20 subjects are each represented as a different color line. Trajectories are separated by DOF. The intended motion direction is highlighted for each cue. Each subject's data is shown with a different color line.

Discrimination: We analyzed the percent correct responses. A multi-way ANOVA was performed on the number of repeats by cue and by subject (as a random variable).

IV. Results

A. Motion Direction

In both sets of movement experiments, users translated or rotated their hands primarily in the expected direction for each cue. Fig. 3 shows mean trajectories for each user separated by cue and DOF for all trials. Fig. 4 shows the mean peak x, y, and z translation and yaw, pitch, and roll rotation separated by cue and set. Whether a trial was in the first or second set had no significant effect on the peak motion magnitude or direction. Comparisons of peak x, y, z, yaw, pitch, and roll displacements showed that the two relevant cues for each (e.g. forward and backward cues for x displacement) had the largest effects, the two cues' effects opposed each other, and they were significantly different from all other cues' effects ($p < 0.01$). Although pitch displacement was not targeted by any cue, there was a significant effect from tilt right and tilt left cues. For y displacement, no cues had a significant effect.

Users rarely needed to repeat cues (median $= 0$ repeats/trial, mean $= 0.39$ repeats/trial). Up/down cues had significantly higher numbers of repeats than other cues (mean $= 0.51$, $p < 0.01$)) .

B. Delay Before Motion

For all users, there was some delay between the start of a haptic cue and the onset of motion. Set number did not have a significant effect on delay ($p > 0.05$), but experience with haptic devices had a slight positive effect (0.08 s for each increasing experience point, $p < 0.001$). Rotation cues had significantly longer delay times than translation cues (0.17 s longer on average, $p < 0.01$). The delays for all trials have a bi-modal distribution with peaks at 0.33 s and 1.56 s. Longer delay correlates with higher variance in peak displacement magnitude ($p < 0.05$). Clustering by variance of peak magnitude and delay time reveals two distinct groups: 13 fast responders and 7 slow responders. Fig. 5(b) shows example mean and standard deviation trajectories for a user from each of the distributions. Fig. 5(c) shows the distributions of delay time separated by subject and colored by experience level.

C. Forced Choice Experiment

Users were able to discriminate all eight cue directions over 90% of the time in the discrimination task. Table I shows the percent correct and mistaken for each cue direction. On average, users rated the difficulty of the device as 2.2 on a scale out of 4, corresponding to *easy*. Several users reported that the rotation cues were more salient to them than the translation cues. There was no significant difference in

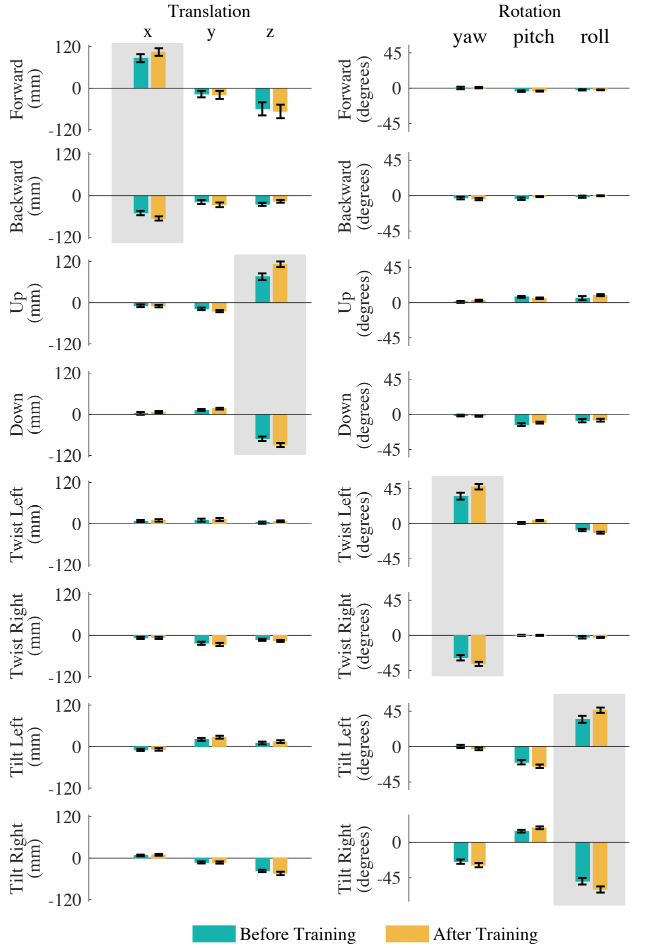

Fig. 4. Mean peak hand displacements in Part 1 and Part 3 separated by cue direction. The intended motion direction is highlighted for each cue. Error bars show 95% confidence intervals for the mean (each bar represents 20 users each completing 10 trials).

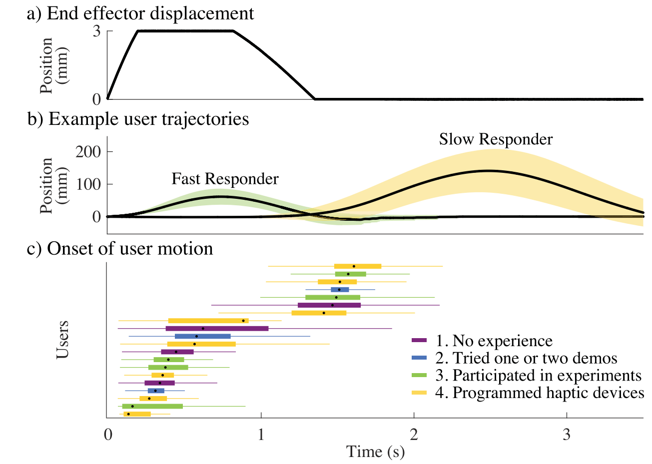

Fig. 5. (a) Trajectory of end-effector during an *up* cue. For all cues, the end-effectors followed this trajectory moving either horizontally or vertically. (b) Mean and standard deviations of two example users with different delay times responding to *up* cues. (c) Box plots of delay time for each subject, marked with the mean delay. Colors indicate the subject's level of experience with haptic devices.

TABLE I

CONFUSION MATRIX FOR PART 2: FORCED CHOICE EXPERIMENT

Correct Direction	**User Responses:** Forward	Backward	Up	Down	Twist Left	Twist Right	Tilt Left	Tilt Right
Forward	96.7	1.7	1.7	0.0	0.0	0.0	0.0	0.0
Backward	1.7	95.0	0.0	3.3	0.0	0.0	0.0	0.0
Up	1.7	0.0	93.3	0.0	1.7	0.0	0.0	3.3
Down	1.7	1.7	3.3	91.7	0.0	0.0	1.7	0.0
Twist Left	0.0	1.7	0.0	0.0	93.3	3.3	1.7	0.0
Twist Right	0.0	0.0	0.0	0.0	1.7	96.7	0.0	1.7
Tilt Left	0.0	0.0	0.0	1.7	0.0	0.0	96.7	1.7
Tilt Right	0.0	0.0	0.0	0.0	0.0	3.3	1.7	95.0

*Cells are shaded corresponding to percentage of user responses.

the number of repeated cues between directions (median = 0, mean $= 0.575$, $p > 0.05$).

V. DISCUSSION

There are several key findings from the user study. First, our handheld kinesthetic device can provide clear guidance in 4-DOF. Second, the haptic cues are intuitive enough that accuracy was high before training, and delay times are small. Finally, there is variability between users' responses to the cues.

A. Differentiable Cues

All cues were successfully identified during the forced choice experiment in more than 90% of the trials. Even more encouraging is that the users' motion responding to each cue in both Part 1 and Part 3 was accurate to the cued direction (Fig. 4). Although the actuation was always the same magnitude, the magnitude of the response motion varies by direction and user. Human force perception is anisotropic [24]. For ungrounded haptic devices, these anisotropies may be even more extreme, and they may need to be characterized per device or per user. Users in our study moved farther forward than backward. They also tilted farther right than left. Responses to some cues had notable biases. For four users, there was notable coupling between forward x and downward z motion in response to forward cues (Fig. 3). There was also a small amount of pitch when responding to roll cues. It is possible that by adjusting the end-effector actuation, pure roll could be isolated. Alternatively, this suggests it might be possible to provide some guidance for pitch. We hope to adapt the design or control to achieve pitch (radial/ulnar deviation) and y (side to side) cues.

B. Intuitive Direction Guidance

Even before the cues were explained in Part 2, users moved in the intended directions. (Fig. 4, before training). There was not a significant change in users' accuracy, delay time, or repeated cues after receiving the training in Part 2. This implies the ungrounded guidance cues are intuitive and could be applied without training in virtual environments or teleoperation tasks. Most users responded quickly to each haptic cue. Fast responders moved their hands while the haptic cue was still being applied, or shortly after it (Fig. 5(b)).

The mean delay for fast responders was 0.33s, which is on the order of the human reaction time to touch [25], implying that very little interpretation was needed. In contrast, slow responders waited for the end-effectors to return to the center point before moving their hand. They felt the cue, interpreted the cue, then responded. It could be helpful in future studies to compare each user's delay time to a standardized measure of reaction time. Interestingly, experience with haptic devices slightly increased delay (Fig. 5(c)). This may be because some experienced users were more concerned with performing well and acted more cautiously than novice users. This effect emphasizes the importance of including users with a range of experience in all haptics studies.

We did not vary cue magnitudes or speeds in this initial study, but we believe users' movements may be proportional to cue magnitude or duration as with the cutaneous guidance device in [19]. We will vary magnitude, speed, and direction in future studies with the goal of providing continuous closed-loop guidance. This seems especially promising for fast responders, who moved as if they were being pulled by an external force (starting and stopping in time with the end-effectors and reaching consistent peak magnitudes).

C. Variability Between Users

Holdable and wearable devices cannot enforce user motion like grounded devices can. Some differences are expected between users, as seen in Fig. 3. Psychometric tests on perception in different directions might clarify these differences and should be explored. However, users' responses to haptic guidance depend on perception, hand and wrist kinematics, and some user interpretation, making it difficult to fully explain their motion. Alternatively, it may be helpful to adapt guidance cues to each user by developing a model of the users' responses from data and scaling or rotating the cues for each user's trends.

VI. Conclusion

The holdable haptic device presented uses pantograph five-bar-linkages to displace the index finger and thumb. It provides intuitive guidance in 4-DOF without external grounding. The haptic cues did not require training to produce motion in each direction tested, and the cues could be discriminated easily. Application areas include teleoperation, virtual or augmented reality, and guidance in training simulations for manipulation tasks like surgery.

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