Simultaneous Perception of Forces and Motions Using Bimanual Interactions

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Abstract—When teaching physical skills, experts or robotic assistants commonly move a novice through a task. However, this guiding motion is only partially effective at portraying the full experience because the guided person is only performing the task passively and the guidance and task forces can become ambiguously intertwined. The interaction evaluated in this paper separates the task and guidance forces by guiding one hand so the user can actively recreate the motion with their other hand that receives task-related forces. This method is based on the ability of humans to easily move their hands through similar paths, such as drawing circles, compared to the difficulty of simultaneously drawing a square with one hand and a circle with the other. Several experiments were first performed to characterize the reference frames, interaction stiffnesses, and trajectories that humans can recreate. Visual Symmetry and Joint-Space Symmetry proved to be easier than Point Mirror Symmetry and participants' recreated motions typically lagged by approximately 50–100 ms. Based on these results, participants used bimanual guidance to identify the orientation of a hard rod embedded in a soft material. The results show that participants could identify the orientation of the rod equally well when working independently compared to being bimanually guided through a desired motion.

✦

1 INTRODUCTION

HUMANS have an inherent ability to synchronize the motions between both sides of their bodies. Note how difficult it is to simultaneously draw a circle with one hand and a square with the other, yet how easy it is to simultaneously draw a circle with each hand. One can even draw two circles in the same or opposite directions with relative ease. Here, we explore how these physical symmetries can be used to recreate the interaction another person had with an environment while experiencing task-related forces similar to the original experience (see Fig. 1). This method could be beneficial for training physical skills since it would allow the individual to actively recreate the motions [2] and would avoid the confusion between task and guidance forces [3], which typically occurs when both forces are applied to a single location. Another application is to separate cognitive and physical dominance. The cognitive dominance could be provided on one hand from an autopilot or robotic assistant and would guide the user who would have physical dominance on the system. This would prevent the guidance forces from directly interacting with the physical system.

Several reference frames can be used to recreate motion across the body (Fig. 2). A common reference frame is visual symmetry where the endpoint of each limb moves in the same absolute direction, such as when a person moves an object with both hands. Another frame is a mirror motion where the same efferent signal can be duplicated at a low level since the joints on each limb are identical, such as occurs when clapping. Point mirror symmetry occurs when an individual is rotating their hands about a common point, such as occurs when turning a steering wheel.

This paper examines the ability of humans to perceive a motion with one hand and recreate it with the other hand in three natural reference frames. Then, to separately dictate a guiding force and a task-specific force to an individual, experiments are performed where the guiding forces are applied to one hand and the task-specific forces are applied to the other hand that is recreating the motion. The goal is to generate the same motion and experience the same forces without feeling the coupled dynamics of the guidance forces. These experiments study performance with bimanual guidance in order to form a basis for bimanual training and rehabilitation methods but do not directly study learning effects.

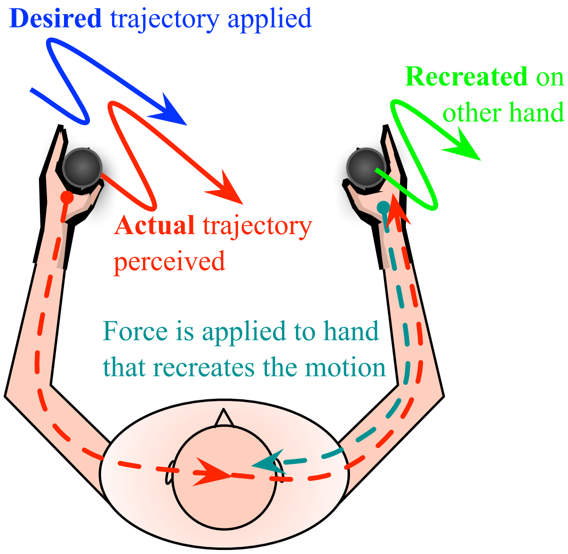

Fig. 1. Bimanual tracking allows an individual to follow a prerecorded path with one arm (left in figure) and recreate the path with the other arm (right in figure). The task is actively recreated while task and guidance forces are applied separately.

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Portions of this work have been published previously in [1].

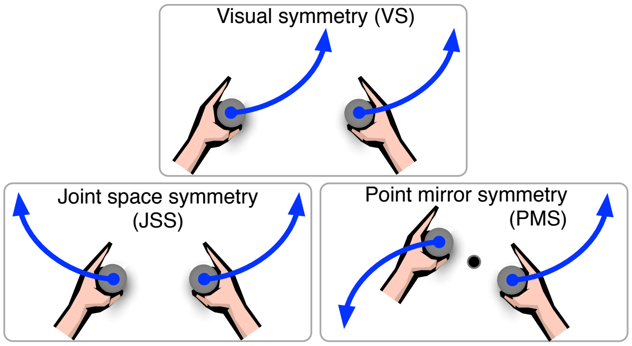

Fig. 2. The Bimanual symmetry modes tested here consist of Visual Symmetry (VS) where the hands move through the same visual path, Joint-Space Symmetry (JSS) where the joint angles are mirrored, and Point Mirror Symmetry (PMS) where the hand motions are mirrored about a point in space.

2 BACKGROUND

2.1 Coupled-Person Interactions

Many physical tasks are taught by an expert guiding a novice through the motions of the task. The motions are imparted to the novice and the novice is able to feel some of the resulting forces. However, the dynamics of the two people are coupled such that the motions are not exactly as intended and the forces are not as expected [4][5]. In a study with relatively simple dynamics, Glynn et al. [6] examined how two participants cooperatively moved a cursor through a virtual maze using both force and position control each with and without force feedback. They found that each member had difficulty separating the force feedback of the device from the other member's forces, an especially difficult issue for a pilot and co-pilot that are both trying to fly a plane [7].

A possibly detrimental issue during physical interaction is that the two individuals do not generate consistent forces. Two people cooperatively working on a target acquisition task will naturally specialize their forces such that one person takes on one role and the other takes on a complementary role [8]. Although for some interactions this is acceptable, such as cooperatively moving a large object, this altered dynamic is unacceptable in other situations, such as during rehabilitation where a physical therapist could unknowingly apply similar assistance forces over many trials and the patient would only learn to perform half of the task.

The method employed in this paper does not directly couple two people, but rather enables one person, a novice, to recreate the experiences of another person so he can learn the motions and feel of the task. Other methods of robot-mediated interaction have been classified [9]. These classifications include gross assistance, such as virtual fixtures [10], gross resistance, such as resisting the completion of the task or applying random noise [11], and temporally separated assistance, such as applying a force intermittently [12]. Another of their classifications is spatially separated assistance, which occurs when one hand receives a position input while the other hand recreates this motion and receives a force input. Powell and O'Malley's results show that using such a bimanual approach using two joysticks to recreate an expert's motions showed a lower overall workload compared to temporal separation and gross assistance [3]. Another version of spatially separated assistance is to apply the guiding force to the back of one's hand, but this was not conclusively shown to be better than practice [13].

2.2 Perception of Force

Research has shown that the human central nervous system is comprised of internal models that control the interactions between the body and its surroundings [14][15][16]. Some of these models are dedicated to predicting the outcome or anticipated force of the resulting impact from an individual's conscious action. This prediction is subtracted from the actual response, which results in an attenuation of the perception of the resulting action. The consistent attenuation of forces perceived causes a problem when a person is required to replicate a specific force; they consistently overestimate. This overestimation is evidence that "self-generated forces are perceived as weaker than externally generated forces of the same magnitude" [2]. This attenuation is part of an internal neural system and humans are generally unaware of it [14]. It has been shown that human's are so unaware of the effect that when individuals are asked to recreate the force felt on one hand with the other hand, the forces escalate quickly and consistently [2]. This attenuation of self-generated forces also explains why it is difficult to tickle oneself [17]. Thus, being led passively through a task will generate a different response than actively interacting with an object.

The origination of a force also has an impact on the perception of the force. Reed and Peshkin [8] describe a study where participants performed a task with a simulated partner that they either knew was not a human or that they thought was a human, but the human partner did not actually participate in any of the experiments, which can be thought of as a Haptic Turing Test [18]. At a conscious level, participants with a human visually present believed they were working with a human partner, but physically were not. The participant's performance changed based on the perception of who their partner was: participants were faster when they thought their partner was human and slower when they knew it was not human.

2.3 Bimanual Interaction

Humans are easily able to synchronize their limbs during many tasks, such as during walking, simultaneously drawing circles with both hands [19], and generally have a hard time performing uncorrelated tasks separately with each hand [20]. The motion of two hands can become more similar by using a mirror, which fools the brain into believing that it sees both hands moving identically [21]. It has also been demonstrated that motions generated simultaneously with both limbs can help an individual's ability to perform similar unimanual tasks [22].

Bimanual motions can also be used to enable self-rehabilitation where one arm guides the impaired arm through an external robotic coupling. The general idea of bimanual rehabilitation is that neither a physical therapist nor a robot is, or probably ever will be, able to determine the exact path a person wants his arm to move as well as the person can. When a patient moves both the impaired arm and the healthy arm at the same time, the same efferent signal is sent from the brain to the arms and, since the arms are constrained to move together, the proprioceptive feedback will be similar between the two sides of the brain [23][24]. Several devices have incorporated the idea of bimanual training where the two limbs mirror each other [25][26], but these bimanual rehabilitation studies used either a rigid coupling or no physical coupling for the impaired side hand. Those that used no physical coupling gave the participants a target or path to follow and assumed both hands could follow it similarly.

Compliance is known to affect the perception of an object in static and unimanual interactions [27][28], but few have examined how compliance affects the ability of an individual to follow a trajectory [1]. None of the bimanual studies have examined how well individuals can mirror a trajectory that is physically applied to one hand, nor is there an adequate description of the sensorimotor delay between hands. The delay associated with the ability to perceive a guidance force or motion on one hand and generate a non-reflexive action in the other hand could potentially affect how people perform bimanual motions, particularly in the presence of haptic or visual delays [29]. The next section examines these motions.

3 BIMANUAL TRACKING

The objective of this study was to understand an individual's ability to neurally couple the motions of one arm to the other in a bimanual tracking task. The experiments tested the effects of guiding path difficulty, guiding trajectory coupling stiffness, and symmetry mode. The three symmetry modes tested are shown in Fig. 2: Visual Symmetry (VS) is moving the hands in the same absolute direction; Joint-Space Symmetry (JSS) is mirroring the two hands about the midline of the person, and Point Mirror Symmetry (PMS) is rotating about a common arbitrary point. The guiding stiffnesses chosen were $50\,\mathrm{N/m}$, $200\,\mathrm{N/m}$, $500\,\mathrm{N/m}$ and $700\ \mathrm{N/m}$. The lower limit was set to be a very weak guiding motion and the upper limit was set to be a stiff, but not overpowering, guiding force. Three motions were tested: a chirp frequency, fixed frequencies (superimposed sinusoidal signals with different frequencies), and a step function. The procedures for these experiments are similar, so the general procedure is discussed once with variations explained for each specific experiment.

3.1 Procedure

Participants sat in front of two Phantom Omni force feedback devices and held an Omni stylus in each hand. To maximize the range of forces that the Omnis could provide, they were positioned facing the participant for VS and JSS, and back to back for PMS, as shown in Fig. 3. One Omni guided the user along a desired trajectory by applying a force of $F = k * (x_{desired} - x_{measured})$, where k is the virtual spring constant. The second Omni, held in the participant's other hand, only measured the recreated trajectory and did not provide any force. Motions in VS and JSS were restricted to the left-right axis, while motions in PMS were restricted to a forward-backward arc centered in between the two Omnis. Using the opposite hand, participants were instructed to simultaneously recreate the motion of the Omni that applied a guiding force.

All three symmetry modes were explained and demonstrated to the participant at the beginning of the experiment and reviewed again when switching between symmetries. VS was described to the participants as making motions in the same absolute direction. JSS was described as motions mirrored from left to right. PMS was described as motions centered about a point in between the Omnis.

Each unique combination of each parameter (e.g., symmetry type, spring constant) was tested once. The number of repetitions was limited to avoid participant fatigue. The presentation order was random. However, to avoid confusion with the symmetry modes, all tests involving a symmetry type were tested before moving to the next symmetry type. Participants were instructed to take a short break before starting each symmetry type. Each trial lasted approximately 23 seconds with an initial 1.5 second ramp up period.

Fig. 3. Omnis arranged for Point Mirror Symmetry.

The three types of motions were:

1) *Chirp frequency*: This trajectory consisted of a chirp frequency that increased linearly in frequency from 0 to 2.4 Hz over the course of the 23 second trial. It was performed twice for each combination of parameters. This trajectory was used to determine the general range of frequencies that can be followed accurately and was not meant to mimic a specific task.
2) *Harmonic and pseudo-random trajectories*: Based on the results of a preliminary experiment [30], three input trajectories were tested: a single frequency sine wave of 0.5 Hz, two superimposed frequencies of 0.9 & 1.3 Hz, and three superimposed frequencies of $0.6, 0.8,$ & 1.1 Hz. These fixed frequencies were chosen to provide a range of difficulties. The superimposed frequencies were selected to provide a pseudo-random path for the participant so that it would be more difficult to predict the trajectory. Most of the tasks that would be performed in training or during real-time interaction would follow a pseudo-random trajectory, like controlling an aircraft flight stick.
3) *Step function*: For this trajectory, each trial consisted of three steps away from the center point, and back, resulting in a total of six step motions. The direction of the step and delay between steps were randomized to prevent the participant from predicting the motions. This type of motion has similar applications as the pseudo-random trajectories, but occurs faster and, thus, limits pre-cueing [31].

3.2 Participants

This study was conducted at the University of South Florida with approval from the University's Institutional Review Board. Participants had limited to no experience using haptic feedback devices and none of them had any impairment that would limit their motion. One participant misunderstood the instructions for the experiment and performed the wrong symmetry mode on many of the trials, thus this participant's data was not analyzed. Eight participants performed the chirp frequency experiment: five were males, seven were right handed, age 21-24. Eleven participants performed the harmonic and pseudo-random trajectories experiment: eight were males, ten were right handed, age 21-26. Eleven participants performed the step function experiment: nine were males, all were right handed, age 21-56.

3.3 Data Analysis

Several metrics were compared for each combination of the *desired motion* (path the guiding Omni applied to the person), the *actual motion* (path of the hand holding the guided Omni), and the *recreated motion* (the path measured from the Omni that did not apply a force) as illustrated in Fig. 1. These combinations are, Desired-Actual (D-A), Desired-Recreated (D-R), and Actual-Recreated (A-R). D-A indicates how well the participant followed the desired path with their guided hand. D-R indicates how well the participant perceived the desired path and recreated it with their other hand. A-R indicates how well the participant coupled the motions between their hands. For consistent data analysis, the JSS motions were flipped ($x = -x$) so the positions would be directly comparable to the input.

To determine how well participants were following a chirp frequency, Total Lag and Average Lag were calculated for both A-R and D-R. The Total Lag was calculated by finding the lag at which the correlation was maximum between the input and output paths, which is essentially the phase lag between the two signals. Lower Total Lag indicates the participants were able to keep pace with the motion. Average Lag was calculated using a window two periods in width centered about the point at which the lag was being determined. A representative lag vs. time graph and metrics are shown in Fig. 4. The average of the absolute value of these windowed lags was calculated to determine the Average Lag for each trial. The absolute value was used to eliminate the participant receiving positive credit for producing negative lags as a result of lagging enough to be leading the next motion as occurs at approximately 21 seconds in Fig. 4. The maximum frequency that participants were able to obtain was typically in the 1.6 to 2.4 Hz range.

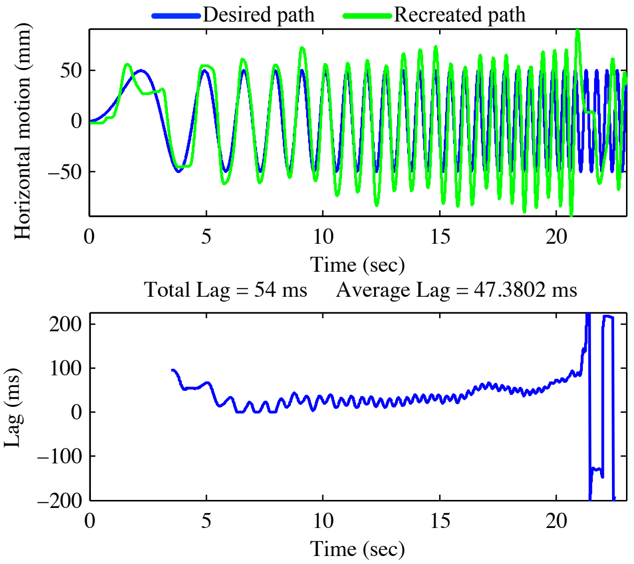

Fig. 4. Example of chirp frequency, which increased from 0 to 2.4 Hz. The top plot shows the desired path (dark blue), and the participant's recreated path (light green). The second plot shows the lag as a function of time. Performance metrics are shown in between.

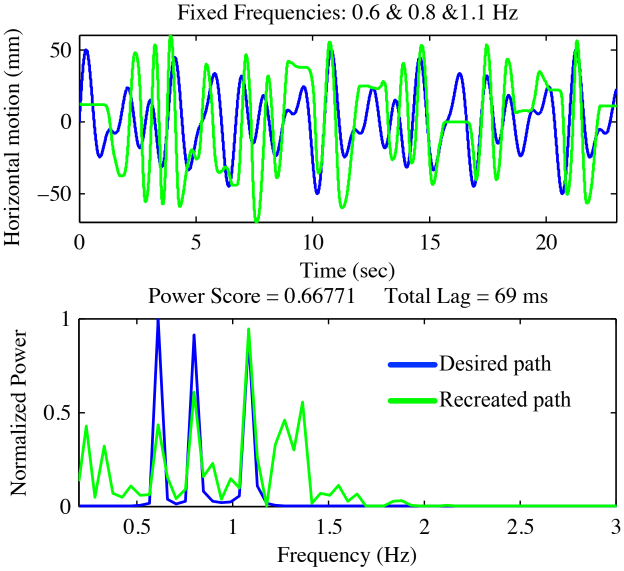

Fig. 5. Example of fixed frequency analysis. The top plot shows the desired path (dark blue) and the participant's recreated path (light green). The second plot shows a Fast Fourier Transform of the motion. The performance metrics are shown in between.

We performed a Fast Fourier transform to analyze the frequencies that were apparent in the recreated motions for fixed-frequency inputs; an example is shown in Fig. 5. Two metrics were used to determine how well the participants followed the given path: Total Lag and Power Score. The Total Lag was calculated the same as it was for the chirp frequency paths. The Power Score for each input frequency of interest was determined according to

$$S = \begin{cases} 0, & P < 0.2 * I \\ \frac{P/I - 0.2}{0.7}, & 0.2 * I < P < 0.9 * I \\ 1, & 0.9 * I < P < 1.1 * I \\ \frac{1.1 - P/I}{1.8} + 1, & 1.1 * I < P < 2I \\ 0.5, & P > 2I, \end{cases} \tag{1}$$

where S is the Power Score, P is the output power, and I is input power. If the power of the output frequency was within $10\,\%$ of the input power, the participant was successfully following and awarded a score of 1. If the output power was less than $20\,\%$ of the input power, the participant was considered to not be following that frequency, and awarded a score of 0. The participant's score was scaled linearly between these points. The participant's score was penalized for producing a larger amplitude response than the input, varying linearly from a score of 1 at $110\,\%$ to 0.5 at $200\,\%$. We used this scaling to determine the score so that neither random motions nor motions larger than the input would get weighted too heavily. When the input consisted of multiple frequencies, the average of the Power Scores was used.

To determine how well participants were able to coordinate step like motions, the time constant for each of the steps in a trial was determined and averaged. The D-R time constant was calculated as the average time constant of the recreated motion. To determine the A-R time constant, the average time constant of the actual path of the participant's guided hand was subtracted from the D-R time constant. A representative step response plot can be seen in Fig. 6.

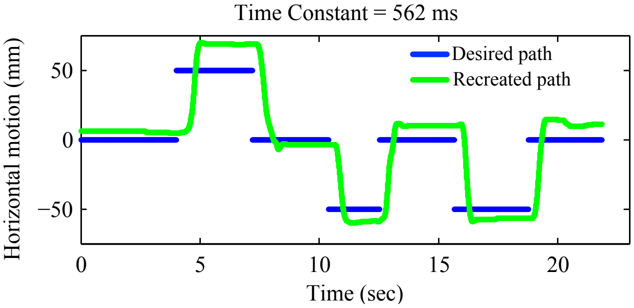

Fig. 6. Example step response: dark blue is the desired path and light green is the recreated path.

For statistical analysis, we conducted an analysis of variance (ANOVA) to analyze the effects of virtual spring stiffness, symmetry mode, and input frequency on the Total Lag, Average Lag, Power Score, and time constant for all path comparison combinations. When the ANOVA yielded significant results, we used Tukey's honestly significant difference test. We used an alpha of 0.05 for all statistical tests. Error bars in all plots represent the $95\,\%$ confidence interval and statistical significance is indicated by a '*'.

3.4 Results

3.4.1 *Chirp Frequency*

The Average Lag for the chirp frequencies showed statistically significant results between symmetry modes ($F_{2,179} = 14.56$, $p < .001$ A-R, $F_{2,179} = 17.46$, $p < .001$ D-R) and between virtual spring stiffnesses ($F_{3,179} = 11.29$, $p < .001$ D-R), as shown in Fig. 7. Post hoc analysis of the D-R Average Lag showed all three of the symmetry modes to be statistically significantly different. JSS had the lowest lag between desired and recreated motions, followed by VS and then PMS. Post hoc analysis of the A-R Average Lag showed that JSS produced a smaller delay between the motions of the participants' hands, while there were no statistically significant differences between PMS and VS.

Post hoc analysis of the D-R Average Lag for different guiding stiffnesses (Fig. 7) showed that participants lagged more for the $50\,\mathrm{N/m}$ spring stiffness. The guiding stiffness did not affect the A-R Average Lag, which suggests that the arm motions were coupled equally at each frequency regardless of the participant's ability to perceive the desired motion.

The Total Lag for the chirp frequencies also showed statistically significant results between symmetry modes ($F_{2,179} = 18.64$, $p < .001$ A-R, $F_{2,179} = 7.99$,

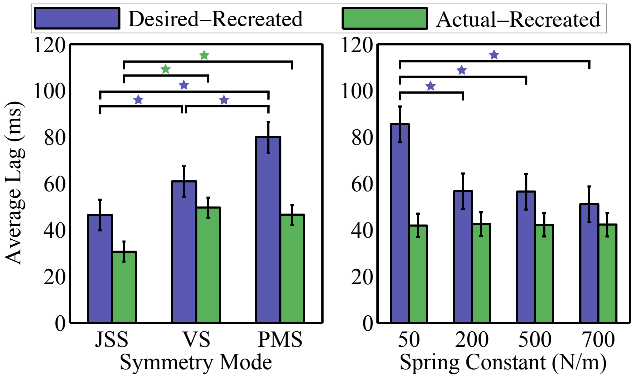

Fig. 7. When following a chirp frequency, the symmetry mode affects both D-R and A-R, but the stiffness only affects D-R.

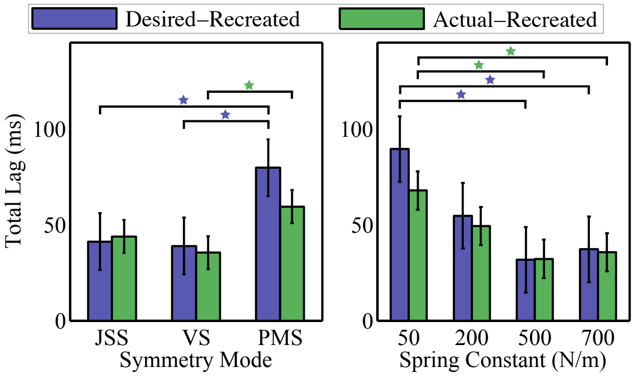

Fig. 8. When following a harmonic or pseudo random trajectory, the symmetry mode and stiffness affect the Total Lag for both D-R and A-R.

$p < .001$ D-R). Post hoc analysis of the D-R Total Lag as a function of symmetry mode showed that participants had a larger lag between the desired and recreated motions in PMS, as compared to VS and JSS. VS was not distinguishable from JSS.

3.4.2 Harmonic and Pseudo Random Trajectories

The Total Lag showed statistically significant differences for the symmetry modes ($F_{2,378} = 5.43$, $p < .005$ A-R, $F_{2,378} = 6.51$, $p < .005$ D-R), virtual spring stiffnesses ($F_{3,378} = 7.14$, $p < .001$ A-R,$F_{3,378,} = 6.29$, $p < .001$ D-R), and trajectory types ($F_{2,378} = 39.83$, $p < .001$ A-R, $F_{2,378} = 15.76$, $p < .001$ D-R), as shown in Fig. 8. A lower Total Lag indicates that participants were more accurately keeping pace with the motions. Post hoc analysis of the D-R Total Lag showed that the participants' recreated motions lagged the desired motion significantly more in the PMS than the other two. Post hoc analysis of the A-R Total Lag showed that participants had a larger delay between their coupled motions in PMS than VS, but that neither mode was statistically significantly different from JSS.

Post hoc analysis of the D-R Total Lag (Fig. 8), demonstrates that participants' recreated motions lagged the desired motion more when the guiding stiffness was $50\,\mathrm{N/m}$ compared to when the stiffness was $500\,\mathrm{N/m}$ or $700\,\mathrm{N/m}$. Post hoc analysis of the A-R Total Lag also showed that participants had a larger delay between their coupled motions when the guiding stiffness was $50\,\mathrm{N/m}$ compared to when the stiffness was $500\,\mathrm{N/m}$ or $700\,\mathrm{N/m}$.

For both the D-R and A-R Total Lag, participants' recreated motions lagged both the desired motion and actual motion of their other hand less when the trajectory was the simple harmonic input. The D-R Total Lags of the pseudo random frequencies averaged approximately $70\,\mathrm{ms}$ and were generally in the 50 - $100\,\mathrm{ms}$ range.

For the Power Score, statistically significant results were found between symmetries ($F_{2,378} = 17.13$, $p < .001$ D-R), between virtual spring stiffnesses ($F_{3,378} = 9.5$, $p < .001$ D-R), and between trajectory paths ($F_{2,378} = 81.91$, $p < .001$ A-R, $F_{2,378} = 125.22$, $p < .001$ D-R). The D-R Power Score post hoc tests showed results similar to symmetry and guiding stiffnesses for the D-R Total Lag with the chirp trajectory. No statistical difference was seen between symmetry modes nor between guiding stiffnesses in the A-R Power Score. The A-R and D-R Power Score for the different trajectory paths showed that the single $0.5\,\mathrm{Hz}$ frequency trajectory was easier to follow and reproduce compared to the double ($0.9\,\&\,1.3\,\mathrm{Hz}$) and triple ($0.6, 0.8\,\&\,1.1$) superimposed frequencies.

3.4.3 Step Response

The time constant resulting from the step input showed statistically significant results between symmetry modes ($F_{2,116} = 8.30$, $p < .001$ A-R, $F_{2,116} = 14.92$, $p < .001$ D-R) and virtual spring stiffnesses ($F_{3,116} = 3.36$, $p < .05$ A-R), as shown in Fig. 9. Post hoc analysis of the D-R time constant showed that participants recreated the desired step motion faster in VS than JSS or PMS. Post hoc analysis of the A-R time constant showed that the step was recreated faster in VS and PMS, indicating that while the step motion is perceived and recreated much faster in VS, the time required to match the motion of the guided hand with the other hand in PMS is comparable to that in VS.

Post hoc analysis shows that the A-R time constant (Fig. 9) was lower for the $50\,\mathrm{N/m}$ guiding stiffness than the more stiff guiding spring constants. This difference was statistically significantly different between the $50\,\mathrm{N/m}$ stiffness and the $700\,\mathrm{N/m}$ stiffness, however, no statistical significance was seen between the $50\,\mathrm{N/m}$ and the other stiffnesses. The lower A-R time constant for $50\,\mathrm{N/m}$ stiffness is a result of the participant taking longer to match the actual position of their guided hand to the desired position, while not significantly increasing the time required to recreate the motion in their task hand.

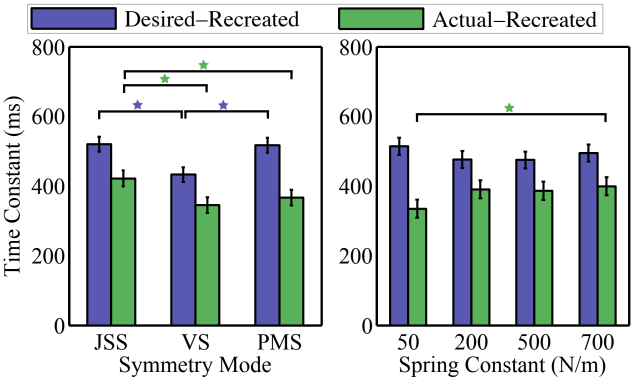

Fig. 9. For a step input trajectory, the symmetry mode affects the Time Constant for both D-R and A-R, but the stiffness only affects A-R.

3.5 Discussion

Different symmetry modes can be duplicated better at different speeds. JSS resulted in the lowest delay between the desired and recreated motions for chirp frequencies and also resulted in a lower delay between the motions of both hands (Fig. 7). This suggest that JSS may enable better duplication of motions when the task is fast, such as clapping one's hands. This result may be caused by the physical symmetry inherent in JSS that is most noticeable at the higher frequencies towards the end of the chirp trials. JSS provides equal and opposite motions whereas fast motions in VS often result in the torso of the body moving in the opposite direction as the hands to cancel out the generated torque about the body's center of rotation.

Motions were recreated less accurately and with more delay in PMS for both the chirp and fixed frequencies. This was in agreement with what the majority of participants verbally reported regarding the difficulty of each symmetry set. Although some daily tasks involve PMS motions, these tasks often have an external constraint, such as a steering wheel, so generating the exact same path on each hand is not as important as it is for tasks such as carrying an object. One explanation for the lack of accurate recreation of the trajectory in the presence of an external constraint is that humans can push in alternative directions that are biomechanically easier while generating a resultant force along the constraint [32]. The resultant force would be in the desired PMS motion. In contrast, when moving an object, the two hands push slightly inward [33], generating a force in JSS, but the motion occurs in VS. This cooperative motion between the hands in JSS/VS requires more coordinated motion between the hands than PMS typically does.

The Total Lag for fixed frequencies demonstrate that the lag between the desired and recreated motions was small for simple harmonic trajectories and relatively large for the pseudo random motions. For simple harmonic inputs, the delays were on the order of $10\,\mathrm{ms}$. This small delay indicates that participants were likely predicting or adapting to the upcoming motions rather than sensing and recreating them. The superimposed frequencies are pseudo random and are relatively difficult to predict, thus they lagged further behind. The D-R Total Lags of these pseudo random frequencies were generally in the $50\text{-}100\,\mathrm{ms}$ range and can be thought of as the overall sensorimotor delay associated with perceiving the unknown motion and recreating the action.

The guiding stiffness does not significantly affect the ability to recreate step type desired motions, but the guiding stiffness does affect the delay between the two hands even though the stiffness does not directly affect the coordinated movement. This effect could be the result of the participants perceiving the desired direction based on the step force applied and then responding by simultaneously coordinating the motions of both hands as they reach the desired position with their guided hand. Although the step input can be thought of as a fast motion, it can also be thought of as a single piece of information informing the individual about which direction to move, much like moving one's hands to catch a basketball. VS may be slightly faster at these types of motion since they are more common even though VS and JSS can track the harmonic motions equally well.

A larger guiding stiffness resulted in better duplication of the motions between the hands. Fixed frequency and chirp frequency desired motions are recreated less accurately, and with a larger delay, when the guiding spring stiffness is $50\,\mathrm{N/m}$, as shown in Figs. 7 and 8. This is not surprising since stronger forces are easier to discern than weaker forces. However, for the fixed frequency motions, the $50\,\mathrm{N/m}$ stiffness also resulted in a larger delay between the motions of both hands. The stiffness of the guiding force affected the coordination between the participants' hands.

The stiffness results may have implications for bimanual rehabilitation for stroke. To be effective for training, the bimanual coupling should allow an appropriate assistance force, which will ensure the motor commands are duplicated. If the coupling is too rigid, the sound limb may exert all the effort and the paretic limb could simply follow passively, but if the coupling is too soft, the paretic limb could not receive any assistance from the sound limb and may not be able to perform the task. Current bimanual rehabilitation methods use either no connection or a completely rigid connection. An intermediate stiffness would likely balance the assistance force against the need for the individual to generate some of the motion with the paretic arm and could be adjusted gradually throughout the rehabilitation.

4 DELAYED FORCE PLAYBACK

Any incongruent delay associated with perceiving the motion on one hand and generating the motion on the other will result in an incorrect stiffness discrimination and can make a task significantly more difficult [29]. It is well known that a haptic delay can cause a virtual object to feel softer [34][35]; this experiment aimed to test whether a haptic delay could compensate for the sensorimotor delay associated with perceiving and recreating the motion from another individual who has used the device extensively, referred to below as the expert. Since there is a delay of approximately $50-100\,\mathrm{ms}$ between the desired motion of the guiding Omni and the recreated motion of the following hand, as determined in Sec. 3, a reasonable hypothesis is that delaying the application of the task forces from the respective guidance forces would improve the perception of the bimanually separated assistance task.

Although VS and JSS were demonstrated to be better for different tasks, we will focus on only performing them in VS since the tasks performed here are performed in the vertical direction and VS and JSS have the exact same motions when moving vertically. Additionally, in a related set of preliminary experiments, VS and JSS were tested with eyes open and closed to evaluate the effects of internal (JSS) or external (VS) reference frames. Malabet et al. [30] showed that VS with eyes open was statistically significantly better than JSS with eyes closed.

4.1 Procedure

The interaction of an expert with a horizontal plane of stiffness $500\,\mathrm{N/m}$ was recorded. The expert was familiar with the task design and had ample experience with the task. The expert started approximately $9\,\mathrm{cm}$ above the plane and penetrated $5\,\mathrm{cm}$ below it before returning to the initial position and was restricted to a vertical motion along the z-axis. The expert's vertical position and the plane reaction forces were recorded over the course of this 5 second task.

Novice participants then recreated this interaction using bimanually separated assistance. Participants sat in front of two Omnis located $40\,\mathrm{cm}$ apart (approximately shoulder width) and held an Omni stylus in each hand. Participants were instructed to simultaneously recreate the motion of their left hand with their right hand, while paying attention to the task-specific forces they felt with their right hand. To guide the participant's left hand position, a guidance force (F_g) was applied based on

$$F_g(x, y, z) = k * \{P_d(x, y, z) - P_m(x, y, z)\}, \qquad (2)$$

where P_d and P_m are the desired and measured position, respectively, and k is $500\,\mathrm{N/m}$. The participant's left hand was guided through the same motion as the expert, while their right hand experienced the task forces that the expert felt under several delays: $0\,\mathrm{ms}$, $50\,\mathrm{ms}$, $100\,\mathrm{ms}$, $200\,\mathrm{ms}$, and $300\,\mathrm{ms}$. The participant conducted a series of trials to determine which value of force playback delay felt most realistic (i.e., more like interacting with a virtual plane). Prior to performing the task, participants were first allowed to familiarize themselves with the concept of virtual objects by interacting with a static virtual cube.

A trial consisted of a pair of interactions, the first with one value of delay and the second with a different value. The participant was asked which one felt more realistic. Each pair of delays was presented four times for each participant, twice with the lower delay first and twice with the larger delay first. Additionally, two trials for each delay were conducted in which both the first and second delay were identical. The order of all delay pairs was randomized for each participant. Participants were allowed to repeat a pair once, if desired. To prevent the participants from visually observing the vertical motion, they were asked to close their eyes or use a blindfold.

4.2 Participants

Four participants, all were male, all were right handed, age 18-29, performed this study with IRB approval.

4.3 Results

The values in Table 1 show which pairwise comparison felt more realistic. The number listed indicates the percentage of all trials that participants selected the delay listed along the top of the table compared to the corresponding delay listed along the left column of the table. For example, participants reported that a $100\,\mathrm{ms}$ delay felt more realistic than a $0\,\mathrm{ms}$ delay $69\,\%$ of the time, and a $100\,\mathrm{ms}$ delay felt more realistic than a $50\,\mathrm{ms}$ delay $31\,\%$ of the time. Values that are at least twice their converse are bolded. For example, while $100\,\mathrm{ms}$ delay felt more realistic than a $0\,\mathrm{ms}$ delay $69\,\%$ of the time, a $0\,\mathrm{ms}$ delay was reported as more realistic only $13\,\%$ of the time. Participants could also state that they felt the same, thus the symmetric values do not always add up to $100\,\%$. On average, participants reported two different delays as feeling equally realistic $22\,\%$ of the time, while reporting pairs

TABLE 1
Results of Pairwise Delay Study

	Percentage the delay felt more realistic				
Delay	0 ms	50 ms	100 ms	200 ms	300 ms
0 ms		38 %	**69 %**	31 %	31 %
50 ms	31 %		31 %	19 %	13 %
100 ms	13 %	56 %		19 %	6 %
200 ms	50 %	**63 %**	**63 %**		31 %
300 ms	31 %	**81 %**	**69 %**	38 %	
Average	31 %	59 %	58 %	27 %	20 %

with the same delay as feeling equally realistic 29 % of the time, indicating that they had some difficulty in small differences.

A delay of 50 ms or 100 ms felt most realistic and, thus, would likely be most beneficial in a bimanual force playback task. The delays that felt most realistic agree with the experiments performed in Sec. 3. Thus, the midpoint was chosen as the delay for the next experiment on actively recreating and simultaneously feeling an expert's interactions during a task.

5 OBJECT DISCRIMINATION

The objective of this experiment was to determine if an individual could recreate another person's interaction with an environment via guidance forces while simultaneously perceiving information about the resulting task forces using the bimanual method demonstrated in Fig. 1. The task chosen to demonstrate this method was to identify the direction of a stiff rod inside a soft medium, which is a palpation task commonly performed to find calcified arteries. This task was based on the virtual version of a rod orientation task performed by Gwilliam et al. [36]. This identification task was chosen since it has an identifiable object to use as a metric, the object has minimal dynamics, and this same interaction can be compared to other haptic interaction methods [36]. Also, this task does not require guidance to perform, so the performance with and without guidance can be compared. It is not expected that this method will produce better identification than manual exploration, rather, we aim to determine if one can perform similarly while following another person's interactions. Many other unimanual interaction tasks can likely be performed using this bimanual guidance method.

5.1 Procedure

Participants sat in front of two Omnis located 40 cm apart (approximately shoulder width) and held an Omni stylus in each hand. The Omni in the participant's left hand conveyed the desired position, while the Omni in the participant's right hand conveyed the task forces. To guide the participant's left hand position, a guidance force (F_g) was applied based on (2) where P_d and P_m are the desired and measured position, respectively, and k is 500 N/m. The desired position of the left hand was based on a prerecorded interaction of an expert performing the task. Participants were instructed to simultaneously recreate the motion of their left hand with their right hand, while paying attention to the task forces they felt with their right hand. The vertical reaction force applied to the participant's right hand was modeled as

$$F(z) = -[k_{base} + k_{rod} * cos\{(\pi/W) * q\}] * z, \quad (3)$$

where k_{base} is the stiffness of the base material (100 N/m), k_{rod} is the stiffness of the rod (900 N/m), W is the width of the rod (3 cm), q is the horizontal distance between the stylus and the centerline of the rod, and z is the vertical displacement below the surface of the plane. The plane was restricted to a circle, 15 cm in diameter. The rod was orientated at one of four angles: 0°, 45°, 90°, or 135° (Fig. 10).

An expert, who was familiar with the task design and had ample experience with the task, was presented with the task of identifying the angle of the rod by repeatedly poking the plane. Once the angle was identified, the expert would verify the angle by poking several locations along the length of the rod and exploring areas around the rod. These identification trials lasted 30 seconds and each rod angle was explored once by two expert users. Both expert users were able to confidently identify the rod within approximately 10 seconds with the remainder of the time spent continuing to explore. The expert's vertical position and the plane reaction forces were recorded for playback to novices.

Novice participants then recreated this interaction. The participant's left (position) hand was guided through the same motion as the expert, while his right (task) hand experienced the task forces in one of three ways: force playback with no delay, force playback with a 76 ms delay, and real-time object interaction. Force playback with and without delay exerted a force on the user's task hand identical to the force applied by the expert. For the force playback with 76 ms delay, the position conveyed to the position hand was advanced 76 ms ahead of the force exerted on the task hand. For the real-time object interaction case, the task force portrayed to the participant was simply the reaction force based on (3) using the current position of the user's right hand. The force playback delay was determined from the pairwise delay experiment (Table 1) to be 76 ms, since the benefits were similar between the 50 ms and 100 ms delays and is similar to the lag for pseudo random motions.

Based on preliminary experiments, the three dimensional task was difficult for participants to both pay attention to the 3D task forces applied to their hand and coordinate their 3D motions, therefore their task hand was also guided in the horizontal (x,y) plane by a force based on the difference between the measured

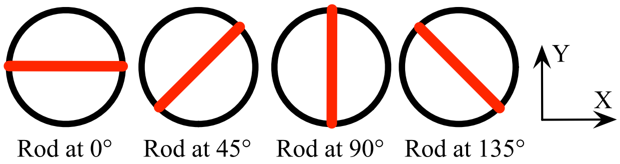

Fig. 10. Possible virtual rod orientations for the stiffness discrimination task.

position of the task hand and the desired position as

$$F(x,y) = k * \{P_d(x,y) - P_m(x,y)\}, \tag{4}$$

where k is $500\,\mathrm{N/m}$, but the user generated the z motion with guidance only from the opposite hand.

Participants were first allowed to familiarize themselves with virtual objects and bimanual interactions by conducting a few warm up tasks, including exploring the plane surface with the rod randomly oriented, both freely, and bimanually guided. This was followed by a few trials of the experiments in Sec. 3 using VS to provide some practice in coordinating bimanual motions and a few trials of the delayed force playback experiment to provide them with experience coordinating bimanual motions while feeling a force applied to their task hand.

After this initial familiarization task, each participant conducted a series of trials consisting of unique combinations of each of the three task interaction types, the four rod angles, and the two expert recordings. The order of these combinations was randomized. Based on the fundamental difference between force playback modes and real-time object interaction, all of the real-time object interaction combinations were presented either at the beginning or the end, chosen randomly, and balanced among all participants.

Based on the guiding and task forces the participant felt during the guided interaction, they were asked to identify the angle at which the rod was located by rotating a physical bar, placed below the Omni, and centered in the same horizontal position as the virtual bar. This bar was of similar shape and size to the virtual rod. The bar could freely rotate on a fixed surface with angle markings from $0°$ to $180°$. The participant reported the angle of the rod by turning the bar to the angle at which they felt the virtual rod and reading the angle from the surface below the bar.

To determine how well participants could identify the rod without guidance, they also conducted two trials for each rod angle in which they were not guided and were free to explore and identify the rod angle based on the real-time object forces. These trials were identical to the task originally performed by the expert. These trials were conducted either before or after, randomly determined, the bimanual interaction trials to prevent the participants from receiving training in between the bimanual trials.

5.2 Participants

Six participants performed this study with IRB approval: five were males, all were right handed, age 21-25.

5.3 Results

For every trial conducted by each participant, we determined the absolute error between the actual angle of the virtual rod and the angle reported by the participant. We then conducted an ANOVA to analyze the effects of interaction type, actual rod angle, and guiding expert. When the ANOVA yielded significant results, we used Tukey's honestly significant difference test with an alpha of 0.05.

The absolute angle error as a function of interaction type was statistically significant ($F_{3,179} = 5.44$, $p < .005$) and the results of this analysis are shown in Fig. 11. The free interaction is better than force playback both with and without delay and the real-time object interaction is significantly better than the delayed force playback, but not the force playback without delay.

A subset of participants also performed an additional set of real-time interaction trials where the virtual rod was rotated $90°$ from that which the expert identified. For example, if the expert was presented with and identified a rod at $45°$, then the participant would be guided through the motions used to determine the angle of the rod at $45°$, however, the rod in their real-time interaction would be at $135°$. The participants' performance when being guided with an incongruent rod angle was significantly poorer than when the correct guiding paths for the angles were applied.

5.4 Discussion

The participants were able to perceive the orientation of the rod similarly between the real-time object interaction and the free interaction, and they were similar to the non-experienced users in Gwilliam et al.'s study with both haptic and graphical force feedback [36]. In the real-time object interaction, the participants were following the guided motions, but were experiencing task-related forces based on their own motions. Although this interaction does not provide the exact same experience as the expert originally had, it does provide the benefits of allowing the user to actively generate a path similar to the expert and it provides task forces directly relevant to their motions. Since there was no detriment in performance, this method could possibly be used to teach strategies that other users have employed in performing this task, but further research is needed to evaluate the learning effects.

Although the results of Sec. 4 showed that a delay in recreating the desired motions of 50–$100\,\mathrm{ms}$ and delays of 50 and 100 ms felt more realistic, the bimanual performance with a delayed task force was very similar to the non-delayed task force. One of the issues confounding this delayed playback is that the sensorimotor delay between hands is not constant for different motions, as demonstrated in Sec. 3.4.1. One possible solution is to use a similar delay, but scaled based on the speed of the motion. The chirp trajectory experiment suggests that the lag changes

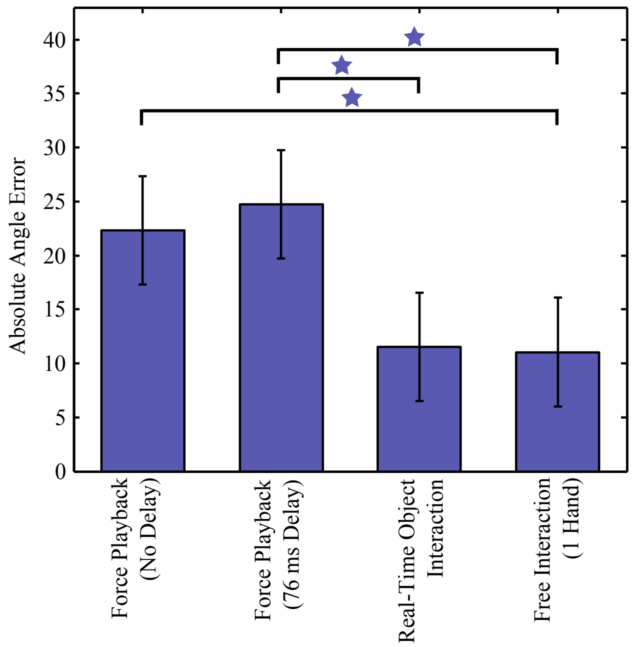

Fig. 11. Results of absolute angle error vs interaction type analysis for step functions.

based on the speed of the motion for rhythmic tasks. A more accurate model of the delay between the hands may increase the performance of the force playback method, which would enable the use of this method in dynamic tasks.

Possible applications for this method include dental and surgical training simulators. Current simulators can convey the guiding motion of an instructor and high frequency interaction forces [37]. A bimanual trainer would allow the trajectory of the instructor to be displayed on one hand while the interaction forces are displayed on the other. In general, tasks that are inherently bimanual are not well suited to be performed using this method since the task and guidance forces could not be divided between the two arms. However, this method could be applied to tasks that traditionally require two hands, such as driving by only using one hand for the training and then performing the task again with both hands.

6 CONCLUSIONS AND FUTURE WORK

This paper examined the stiffness and symmetry modes that can be recreated bimanually and demonstrated one task in which bimanual guidance can separate the task and guidance forces. The participants could identify the orientation of the rod equally well when using the bimanually guided method as they could when generating the desired motions themselves. These results indicate that this method may allow one to recreate the physical interactions of another person in other circumstances. One of the general goals of human-human and human-robot interaction is to assist a person in learning a skill. The specific motions of a task vary from person to person, but there are gross overall motions and strategies for tasks that could likely be taught to a person using this method.

Since many applications of haptic guidance also have a visual component and JSS and PMS motions are not consistent in the visual frame, the best way to provide visual guidance during a bimanual haptic tracking task should be studied. One possibility is providing visual guidance for both hands and another is only providing visual guidance for the hand recreating the motions and receiving task forces. In the second case, the visual display could be offset to the side recreating the motions, which would allow the participant to more closely associate the motions of the task hand with the visual guidance.

There are a range of tasks that need to be tested to demonstrate generalizability of this method, particularly in dynamic environments. Many tasks, such as swinging a tennis racquet and reaching for an object, consist of feedforward step-like motions as opposed to feedback received during the motion [38]. This bimanual method may help in teaching these ballistic motions, but it would likely require additional haptic guidance to teach when to start the motion [39]. Dynamic environments typically have objects that move when touched, so any variation in motion or force would change the recreated environment relative to the original interaction. As opposed to using prerecorded forces, as tested here, this bimanual guidance scheme could be adapted to provide guidance from an expert in real time. The expert would be able to react to the changing environment and indicate the direction the novice should move. The indication could either be through direct interaction to the novice's guided hand or through a master-slave interface. The novice would then recreate the motion and feel the task forces in the other hand in the same way presented here.

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