Effects of Compliant Coupling on Cooperative and Bimanual Task Performance

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Abstract: Coupled bimanual rehabilitation allows an individual with hemiparesis to use their sound arm to assist their impaired arm during rehabilitation. This method of self-rehabilitation could be used as a low-cost alternative for home rehabilitation, however, few studies have looked at the effects of coupling stiffness and symmetry mode on bimanual task performance. We have developed a compliant bimanual rehabilitation device (CBRD) that allows for the symmetry mode and stiffness of the coupling to be easily changed. Our results show the CBRD effectively couples the motions of two individuals in a task simulating hemiparesis, and that for some tasks, the symmetry mode and stiffness affect completion time. A stiffer coupling resulted in faster completion times and lower error. The device also reduced the completion time and error of bimanual tasks performed by healthy individuals.

Keywords: Terms—Home-based rehabilitation, low-cost therapy, stroke rehabiltation, self-rehabilitation, compliant coupling.

I. INTRODUCTION

Bimanual motions are those in which a person simultaneously moves both hands in a similar motion. This motion may be mirrored, in the same absolute direction, or symmetric in another reference frame. The natural symmetry of the human body and neural structures allows for easy duplication of these bimanual motions. For example, it is relatively easy to draw two circles or two squares at the same time, but it is much more difficult to draw a circle with one hand and a square with the other.

Since a stroke typically only affects one side of the body, the idea of bimanual rehabilitation is to physically couple the individual's arms, allowing the healthy arm to assist the impaired arm in making motions. Therefore, bimanual rehabilitaiton devices would allow patients to perform exercises that they typically would not be capable of without assistance. Because the assistive forces can be provided by the individual himself, rather than a therapist or powered robotic device, bimanual rehabilitation devices could provide a low cost alternative for home-based rehabilitation, allowing patients to self-rehabilitate more frequently over a longer period of time.

This paper presents the effects of a compliant bimanual coupling device on coordinating the hand motions of healthy individuals in an effort to better understand the properties of the device, its effect on coupling hand motion, and the best configuration(s) for rehabilitation.

II. BACKGROUND

The goal of upper limb rehabilitation following stroke is to improve the functional ability of the impaired arm and allow a person to use both hands in activities of daily living. Time spent training is one of the most important factors for functional recovery after stroke [1, 2]. However, the amount of time therapists are able to spend with patients is limited and current home-based methods are limited to higher functioning individuals. To increase access to rehabilitation and allow patients to spend more time practicing motions, several new rehabilitation methods have been developed in recent years.

A. Rehabilitation Methods

One of the oldest rehabilitation techniques still used is forced use of the paretic limb [3, 4]. One advantage of forced use is that the learning occurs during daily activities and can be used during home therapy, however its use is limited to relatively high functioning individuals. Recently a related technique, Constraint-Induced Movement Therapy [5], has shown promise for lower functioning individuals, although individuals must still initially be able to complete simple tasks. These techniques have been shown to aid in cortical re-mapping of neurons from damaged to functional brain cells [6].

The Bobath method [7] and proprioceptive neuromuscular facilitation technique [8], have been commonly used for stroke rehabilitation, however one

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disadvantage of therapist-assisted motions is that the therapist cannot know exactly how the patient intends to move his limb for a given task. Additionally, these techniques require significant effort from physical therapists and the time that each patient can spend with a therapist is limited.

Recently, robotic technologies have been developed to ease the burden of therapists and allow patients access to rehabilitation for longer and more frequent periods of time. One of the first robotic upper limb rehabilitation systems, the MIT-Manus [9], has been shown to improve upper limb function in several clinical trials [10]. Another device, the Assisted Rehabilitation and Measurement Guide has been shown to improve the function of those with stroke [11]. However it is not clear whether robotic methods produce greater benefits than conventional therapies when practiced for the same amount of time [12, 13].

Since time spent practicing is one of the most important factors in rehabilitation efficacy [14], several methods have been developed to allow patients to rehabilitate at home. The SMART system [15] monitors patient performance of daily tasks and rehabilitation exercises while providing a visual feedback system allowing therapists to provide instruction. Java Therapy [16] uses a commercially available force feedback joystick and a suite of online games to provide therapy and evaluation. Unitherapy uses a force feedback joystick and steering wheel and has shown benefits in clinical trials [17, 18]. An advantage of home based methods is that they allow patients to spread out the time spent exercising, thereby reducing the potential for fatigue. These home-based methods, however, are limited to relatively high motor function, as the devices used can only generate limited forces to interact with patients, and their workspaces are very limited.

B. Bimanual Rehabilitation

The idea of bimanual rehabilitation is that during rehabilitation, an individual attempts to simultaneously move both hands in a coordinated motion. It has been hypothesized by Burgar *et al*. that bimanual symmetric exercises will enhance recovery by stimulating the ipsilateral corticospinal pathways [19], which is similar to the hypothesis by Wolf *et al*. [20] that these therapies could target the ventromedial brain stem pathways. Unimanual and bimanual training have been shown to be similarly effective [21], however, the advantage of bimanual training is that it allows more severely impaired individuals to self-rehabilitate.

Bimanual motions typically occur in one of the symmetry modes shown in Figure **1**. In Joint Space Symmetry (JSS), the joints of the left and right arms move through the same motions, resulting in a hand motion that is mirrored about the sagittal plane. In Visual Symmetry (VS), both hands move in the same absolute direction in the visual reference frame. In Point Mirror Symmetry (PMS), the hand motions are mirrored about a point in space.

Many bimanual devices couple the motions of the hands allowing a patient to use his healthy arm to help guide the motion of his impaired arm. Some of these devices, including the Mirror Image Movement Enabler

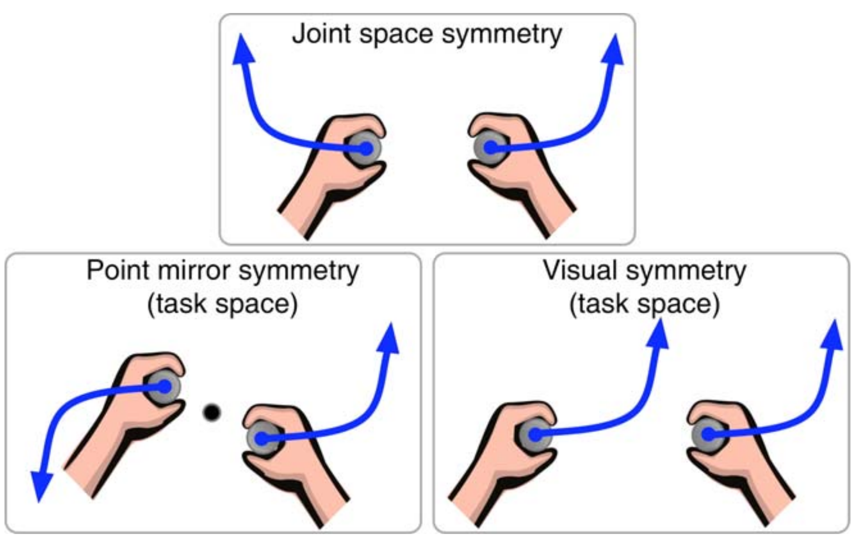

Figure 1: Three typical bimanual symmetry modes are Joint Space Symmetry (JSS) where the joint angles are mirrored, Visual Symmetry (VS) where the hands move through the same visual path, and Point Mirror Symmetry (PMS) where the hand motions are mirrored about a point in space.

(MIME) [19] and the BiManuTrack [22], use robotic devices to mirror the motion of the sound arm. Although these devices have been shown to be effective, due to cost and safety concerns, they are limited to hospital and clinical settings. Other devices such as the Reha-Slide [23] and ImAble system [24] physically couple the hand motions but do not provide assistive forces. The MOTOmed arm cycling device physically couples the hands in a cycling motion and has been shown to reduce arm spasticity [25]. The BATRAC allows patients to move their hands along a linear track in in-phase or out-of-phase motions [26] and has shown results similar to the dose matched therapeutic exercises [27].

The preceding devices have shown bimanual rehabilitation to be effective, but each only utilized one symmetry mode. However, for healthy individuals, certain bimanual motions are easier to duplicate in one symmetry mode than another [28, 29], indicating that the symmetry mode could affect bimianual rehabilitation efficacy. Additionally, these devices either used a rigid coupling, or no physical coupling between the hands. A completely rigid coupling allows an individual to entirely rely upon their sound arm for all motions [13, 30], whereas a coupling that is non-existent or too soft prevents individuals with low motor function from utilizing this training method. A compliant coupling would allow the sound arm to provide some assistance to the paretic limb without completely dominating the motion.

To better understand the effects of coupling stiffness and symmetry mode on bimanual task performance we developed the Compliant Bimanual Rehabilitation Device (CBRD). This device allows the hands to be coupled in JSS, VS, or PMS, with a wide range of coupling stiffnesses, from 100 N/m to 2000 N/m. In this paper we discuss the properties of this device, its ability to couple the motions of healthy individuals, and ramifications for bimanual rehabilitation.

III. COMPLIANT BIMANUAL REHABILITIATION DEVICE

A. Mechanism Design

We developed a device that physically couples two handles in a desired symmetry mode with an adjustable coupling stiffness. This device is shown in Figure **2**. By altering linkage attachment points within the assembly, the device can couple the handle motions in any of the symmetry modes shown in Figure **1**. The linkage may also be arranged to allow the handles to be positioned independently. The handles of the device are connected to the rigid coupling system by a compliant assembly that allows the stiffness of the coupling to be adjusted.

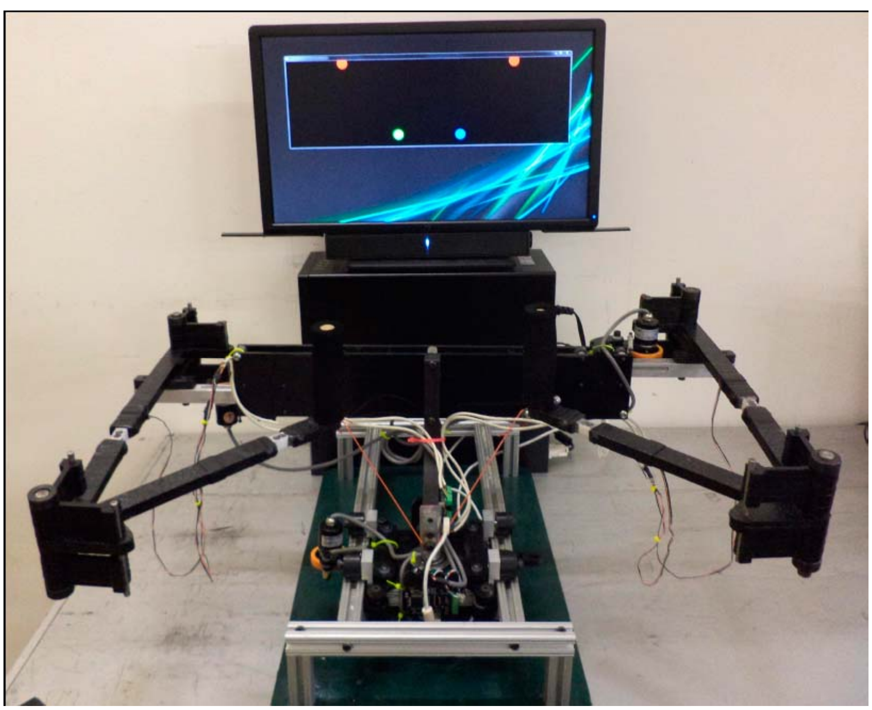

Figure 2: CBRD with haptic interaction game displayed. The left and right handles are displayed as blue and green circles, respectively, and the desired positions are displayed as red circles.

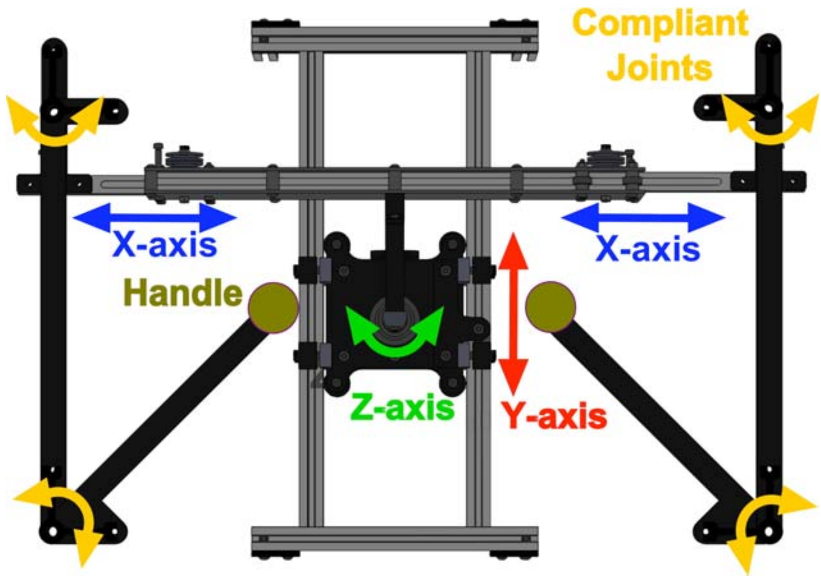

Figure 3: CBRD Joints. The Z-axis is locked for VS and JSS, the Y-axis is locked for PMS, and the X-axes are coupled.

As shown in Figure **3**, the coupling system consists of a mechanism with three prismatic and one revolute joints. The first prismatic joint, referred to as the Y-axis joint, connects the device base to a slider that supports the rest of the device; this joint allows for a forward-backward motion as is necessary for JSS and VS. A set screw is used to lock out this motion for PMS. The second joint, referred to as the Z-axis joint, is revolute and allows for the rotation necessary for PMS. A locking mechanism prevents the joint from rotating when JSS or VS are desired. The final two joints allow for side to side motion in JSS and VS and radial motion in PMS. These final two joints, referred to as the X-axes, are coupled by a cable system, as shown in Figure **4**. With one arrangement of the cables and pulleys, the handles move in opposite directions, as is necessary for JSS and PMS. With a different arrangement, the handles move in the same absolute direction, as is necessary for VS. The joint angles and positions are monitored by optical rotary encoders.

A compliant assembly connects each handle to the coupling system and provides a restoring spring force towards the rest position of the handle. This assembly consists of a two DOF mechanism, for which the motion is restricted by custom torsion springs applied to the joints between the links. The stiffness of the restoring spring force may be adjusted by changing these torsion springs. The compliant handle assembly is designed to allow a maximum deflection of 75 mm at the handle. Shear load cells measure the forces in the links. From the load cell readings, given a known joint stiffness, the handle position is calculated.

In JSS and VS, each handle has a workspace that is 330 mm deep and 431 mm wide, starting 124 mm from the centerline. The PMS workspace is an annulus with an inner radius of 124 mm and an outer radius of 555 mm. The total cost for the prototype materials, including sensors and interface hardware, was approximately $700.

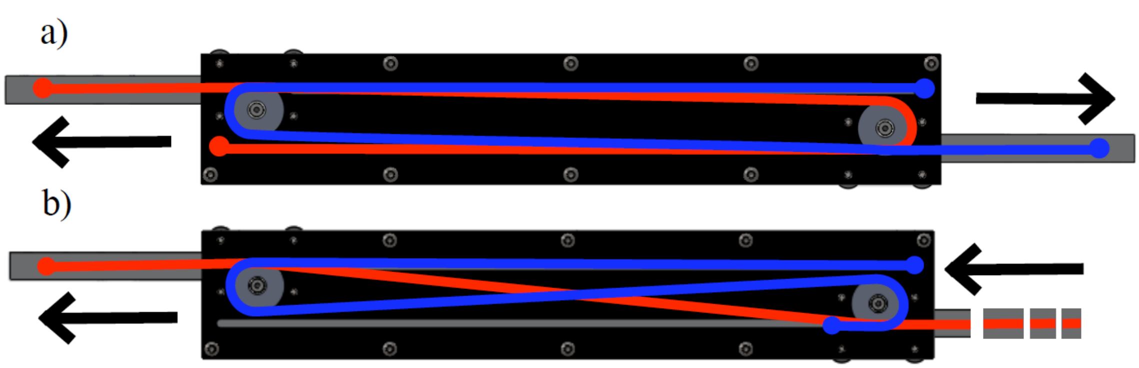

Figure 4: A schematic of the cable arrangements viewed from the backside for (**a**) Joint Space and Point Mirror Symmetries and (**b**) Visual Symmetry.

B. Display and Interaction Game

As shown in Figure **2**, the desired and actual handle positions are displayed on a screen located above and slightly behind the device. The visual area is 132 mm tall and 442 mm wide. The physical displacements are therefore scaled down by a factor of 2.5:1 on the visual display. The handles and desired positions were represented as colored circles 16 mm in diameter. For the studies presented here, the task that participants were asked to complete consisted of matching the handle position(s) with a series of randomly generated desired positions. Each trial consisted of eighteen segments, corresponding to different displayed positions. A segment would end when the handle position(s) was within 5mm of the desired position(s). After a brief delay, a new segment would begin with a different desired position. If the handle position(s) did not match the desired position(s) within 15 seconds, the segment would end automatically.

IV. Two Participant Study

We conducted two studies. The first was a two participant study designed to mimic the hemiparesis resulting from stroke. One participant acted as the guide, representing the healthy arm interacting with the device. This participant controlled the handle motions and was tasked with matching the desired position. The other participant passively followed this motion, mimicking paralysis of the arm. Spasticity was not considered in this study.

A. Procedure

In this study, two individuals stood in front of the device and each held one handle in a way similar to the way it would be held by a person with stroke during rehabilitation. The participant on the left held the left handle and the participant on the right held the right handle. For each trial, the desired and handle positions were only shown to one participant; this person was defined as the guiding participant, and his goal was to match the handle position to the desired position. The second participant was asked to close his eyes, or use a blindfold and follow the motions that he felt. A curtain between the participants prevented the guiding participant from observing the motion of the following participant. He could only see his side of the device and the computer screen.

The participants completed two types of tasks with the handles coupled in different symmetry modes and with different coupling stiffnesses between the handles. Only JSS and VS were tested; PMS was excluded to limit the total study time to 1 hr to reduce the possibility of participant fatigue and because earlier studies demonstrated that PMS results in less coordinated bimanual motions [31]. The coupling stiffnesses tested were 110 N/m and 380 N/m. A stiffness between 50 N/m and 200 N/m has been shown to be a transition region for the accuracy of path perception [31], thus the lower stiffness level was chosen in this range. The 380 N/m stiffness was selected because it is the highest stiffness possible while maintaining the same compliant workspace area as the 110 N/m stiffness; higher stiffnesses are possible, but would change the maximum allowable deflection.

In one task, hereafter referred to as Two Person-Guiding Visible (2P-GV), the guiding participant's goal was simply to move his handle to the desired position and only his handle and desired position were displayed. In the other task, hereafter referred to as Two Person-Following Visible (2P-FV), the guiding participant was asked to move the following participant's handle into the desired position; both handle positions and the following participant's desired position were displayed. Both handle positions were displayed to make it easier for the guiding participant to understand the coupling, i.e. in JSS when his handle moves left the following handle moves right, but forward and backward motions remain unchanged.

Each trial tested a unique combination of symmetry mode, stiffness, and task type, as well as which participant acted as the guide. The order of the task types, and guiding sides was randomized, however, to avoid confusing the participants and reduce the delay time from moving the curtain and blindfold, each participant completed both task types before switching the guiding and following participant. Similarly the presentation order of symmetry modes and stiffnesses were randomized, however, all of the trials for one stiffness were done before changing the stiffness, and for a given stiffness, all of the trials for one symmetry mode were done together. Twelve participants performed this study with Institutional Review Board (IRB) approval: nine were male, all were right handed, age 21-61 years old.

B. Analysis

To quantify performance during a trial, the average completion time and the average coupled position error were analyzed. The average completion time for a trial was determined by calculating the average segment time, from the display of a desired position or positions to the matching of the handle position(s) with the desired position(s), and averaging these segment times for each trial. The average coupled position error was the average, for a trial, of the distance between the right handle position and the projected symmetric position of the left handle at the end of each segment. The projected symmetric position of the left handle was determined by mirroring the position of the handle for JSS or adding 679 mm to the left handle position for VS.

For statistical analysis, we conducted an analysis of variance (ANOVA) to analyze the effects of symmetry mode, coupling stiffness or condition, task type and guiding side on the average completion time and average coupling position error. 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.

For the two participant study, the two tasks are inherently different, i.e. controlling the handle directly vs. moving the other handle through the coupling of the device. We therefore performed our analysis for each type of task individually, as well as for both tasks combined.

C. Results

For both tasks combined, an analysis of the average completion time showed statistically significant results between symmetry modes ($F_{1,95}$ = 9.38, p = 0.003), coupling stiffnesses ($F_{1,95}$ = 5.75, p = 0.02) and task types ($F_{1,95}$ = 149.67, p < 0.001). Post hoc analysis showed that the completion time was lower for VS mode, for the 380 N/m stiffness, and for the 2P-GV task. The completion times for the symmetry modes and tasks are shown in Figure **5**. The average completion time for 2P-GV was 2.6 s, and the average completion time for 2P-FV was 5.4 s.

Analysis of the average coupled position error for both tasks combined showed statistically significant results between symmetry modes ($F_{1,95}$ = 5.22, p < 0.03) and coupling stiffnesses ($F_{1,95}$ = 309, p < 0.001). Post hoc analysis showed that the error was smaller for JSS than VS, 51 mm and 56 mm, respectively, and that the error was lower for the 380 N/m stiffness than for the 110 N/m stiffness.

For the 2P-GV task alone, analysis of the average completion time did not show statistically significant results between symmetry modes or coupling stiffnesses. However, analysis of the average coupled position error showed statistically significant results between coupling stiffnesses ($F_{1,47}$ = 133.6, p < 0.001). Post hoc analysis showed that the average error was lower for the 380 N/m stiffness.

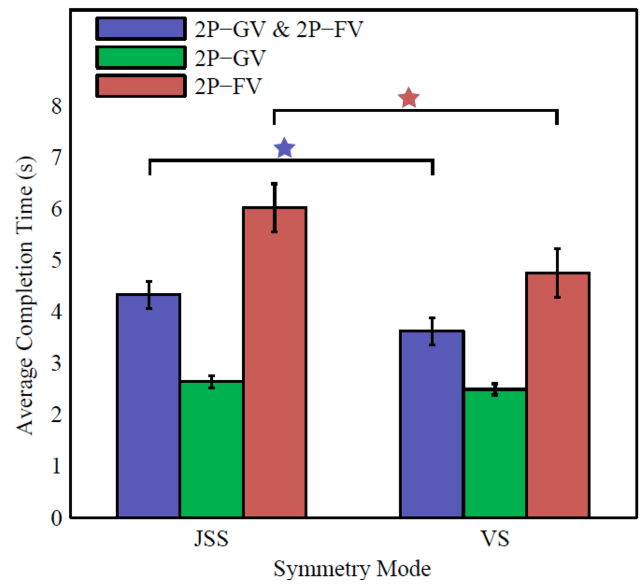

Figure 5: Results of average completion time analysis for Two Participant Study. Error bars represent 95% confidence interval. Stars indicate results that are statistically significant, but too close to be obvious from the graph.

For the 2P-FV task, analysis of the average completion time showed statistically significant results between symmetry modes ($F_{1,47}$ = 9.79, p = 0.004). Post hoc analysis showed that the average completion time was lower for VS than for JSS. Analysis of the coupled position error showed statistically significant results between coupling stiffnesses ($F_{1,47}$ = 175.35, p < 0.001). Again, post hoc analysis showed that the average error was lower for the 380 N/m stiffness.

V. SINGLE PARTICIPANT STUDY

The purpose of the second, single participant, study was to analyze how a single user interacts with the device and to analyze its effect on coupling the motions of a healthy individual.

A. Procedure

In the single participant study, one participant stood in front of the device and held both handles. The desired and handle position(s) were displayed and the goal was to match the handle position(s) to the desired position(s) as quickly as possible. The participants completed three types of tasks, in both VS and JSS symmetry modes, either with the handles physically coupled in the desired symmetry mode or with them uncoupled. JSS and VS symmetry modes were also compared. For consistency, a coupling stiffness of 380 N/m was used when the handles were coupled.

For the physically coupled trials, the device was locked in the desired symmetry mode. For the uncoupled trials, neither the Y nor Z-axis joints were locked, and the X-axes uncoupled, allowing the handles to be positioned independently, anywhere in the device workspace, however, they were dynamically coupled by inertia and friction, and the handles would still twist by the same angle about the Z-axis. In the uncoupled trials, participants were instructed to move their hand motions in the desired symmetry mode.

One task was similar to the two participant study. In this task, hereafter referred to as One Person-Single Visible (1P-SV), the participant's goal was to match one handle position to a desired position as quickly as possible, while simultaneously moving the other handle in the desired symmetry mode. In another task, referred to as One Person-Both Visible (1P-BV), the handle and desired positions were displayed for both the left and right handles, and the participant's goal was to match both handle positions to both desired positions. The desired positions were consistent with the symmetry mode being tested.

For the third task, referred to as One Person-Distorted Positions (1P-DP), again, both left and right handle and desired positions were displayed, however the desired positions were distorted from their symmetric locations, by a factor of 1:1.5. The participant's goal was to match both handle positions to the desired positions. This task was intended to test the ability of the device to transmit forces and to mimic the decreased perceptional ability of individuals with stroke.

Each unique combination of symmetry mode, coupling condition, and task type was completed twice; 1P-SV was completed once with the left handle and desired positions visible, and once with the right handle and desired positions visible. Similarly, 1P-DP was completed once with the larger, distorted positions on each side. As the 1P-BV task is identical on both sides, it was completed twice.

The overall order of the symmetry mode, coupling condition, task type, and visible/distorted side was randomized. However, due to time constraints all of the trials for one symmetry mode were completed before changing the symmetry mode and for each symmetry mode all of the trials for a given coupling condition were completed before adding/removing the coupling. If the first trial of a symmetry mode was 1P-SV, with the handles uncoupled, i.e. the participant has no visual or haptic representation of how to move their hands in that symmetry, then the participant was allowed to practice in the symmetry mode until they understood the correct way to couple his motions. Seven participants performed this study with IRB approval, six were male, all were right handed, age 21-29.

B. Analysis

The analysis was performed in the same way that it was for the two participant study, as discussed in Section IV-B. For the single participant study, the analysis of the average completion time was performed both with the data of the three tasks individually as well as with the data combined. However, the coupled position error was only analyzed for the 1P-SV task since for the other two tasks the correct final positions were displayed, therefore the coupled position error would be close to zero.

C. Results

For the combined analysis of the three tasks and both coupling conditions, the average completion time showed statistically significant results between coupling conditions ($F_{1,167}$ = 6.54, p = 0.01) and task types ($F_{2,167}$ = 48.95, p < 0.001). Post hoc analysis showed that the tasks were completed faster when the device coupled the hand motions. The results also showed that 1P-SV was completed faster than 1P-BV, which was faster than 1P-DP. The average completion times for 1P-SV, 1P-BV, and 1P-DP were 2.2 s, 2.8 s and 3.2 s, respectively.

For the 1P-SV task and both coupling conditions, analysis of the average completion time showed statistically significant results between coupling conditions ($F_{1,55}$ = 20.52, p < 0.001). Post hoc analysis showed that the task was completed faster with the handles coupled (Figure **6**).

For the 1P-BV task and both coupling conditions, analysis of the average completion time showed statistically significant results between coupling conditions ($F_{1,55}$ = 49.23, p < 0.001). Post hoc analysis showed that the task was completed faster when the handles were coupled (Figure **6**).

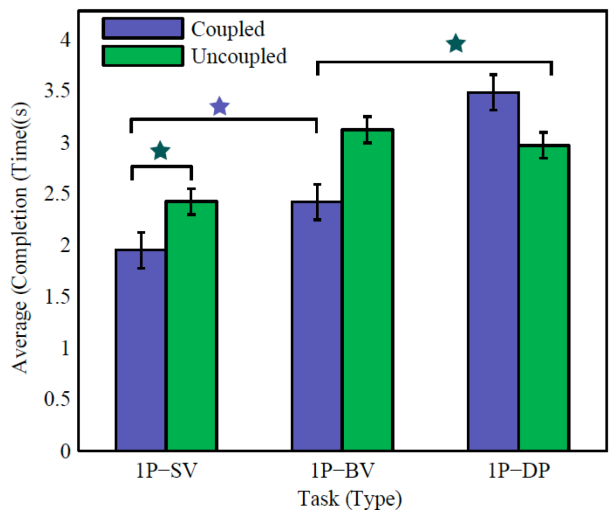

Figure 6: Results of average completion time analysis for Single Participant Study. Error bars represent 95% confidence interval. Stars indicate results that are statistically significant, but too close to be obvious from the graph.

For the 1P-DP task and both coupling conditions, analysis of the average completion time showed statistically significant results between symmetry modes ($F_{1,55}$ = 4.07, p = 0.05) and coupling conditions ($F_{1,55}$ = 11.26, p = 0.002). Post hoc analysis showed that the task was completed faster when the handles were uncoupled (Figure **6**) and that JSS was completed faster than VS. Analysis of the completion time for the uncoupled 1P-DP task showed statistically significant differences between symmetry modes ($F_{1,27}$ = 14.74, p = 0.001). Post hoc analysis showed that the task was completed faster in JSS than in VS. Analysis of the completion time for the coupled 1P-DP task did not show statistically significant results.

For the 1P-SV task and both coupling conditions, analysis of the coupled position error showed statistically significant results between symmetry modes ($F_{1,47}$ = 11.86, p = 0.001) and coupling conditions ($F_{1,55}$ = 41.41, p < 0.001). Post hoc analysis showed that the error was smaller in JSS than in VS, and when the handles were coupled.

For the coupled 1P-SV task, analysis of the coupled position error showed statistically significant results between symmetry modes ($F_{1,23}$ = 51.45, p < 0.001). Post hoc analysis showed that the error was smaller for JSS than VS. For the uncoupled 1P-SV task, the error did not show statistically significant results between symmetry modes.

VI. DISCUSSION

As shown in Figure **5**, for the two participant experiment with both tasks combined, the average completion time was lower for 2P-GV task. This is consistant with the idea that with a compliant coupling, it is easier to control the position of the handle that the guide is holding. Additionally, for 2P-FV in JSS, the guiding participant must account for the mirrored motion while completing the task. For the 2P-GV, the completion time was comparable between symmetry modes. This makes sense because from the perspective of the participants, the task is the same and only coupling through the device changes.

The average coupled position error for both tasks combined did show that the error was smaller for JSS than VS, 51 mm and 56 mm, respectively. The difference is likely a result of minor differences in the accuracy of the coupling in the different symmetry modes. Ideally the error for both symmetry modes should be comparable, and smaller than it currently is. Reducing the friction in the joints could reduce this error.

The average completion time for 2P-FV was lower for VS mode. In VS, the guiding participant moves his handle in the same direction as he wants the displayed position of the following handle to move, whereas in JSS he must account for the mirrored motion of the displayed handle position. It may therefore be beneficial for rehab to display the actual and desired positions of both handles so that patient can intuitively understand the motions required of both hands rather than needing to think about which way they should move their sound arm to assist. Requiring a patient to match both handle positions simultaneously could also be used to ensure that the patient does not overcompensate with his sound arm, but rather is forced to make symmetric motions.

Unsurprisingly, for both the 2P-GV and 2P-FV tasks, the average coupled position error was lower for the 380 N/m stiffness than for the 110 N/m stiffness. With the stiffer coupling, the friction in the joints is overcome with a smaller deflection of the handles, and the participant has better control over the dynamics of the system.

For the single participant study, the average completion time showed that both the 1P-SV and 1P-BV tasks were completed faster when the device coupled the hand motions, as shown in Figure **6**. This indicates that physically coupling the hands through the device improves bimanual task performance. The figure also shows that the average completion time for 1P-SV uncoupled is comparable to 1P-BV coupled, this shows that coupling motions through the CBRD can reduce the difficulty of matching two visually displayed positions to that of matching only one.

For the 1P-DP task, the average completion time was lower when the handles were uncoupled. This makes sense because when the handles are coupled for this task, the participant must fight against the device to move the handles to the distorted desired positions. The forces required to reach the desired positions ranged from 0-45 N.

For the 1P-SV task and both coupling conditions, the coupled position error was smaller in JSS than in VS. This is consistent with the results seen for the two participant task. The coupled position error for 1P-SV was also lower when the handles were coupled, indicating that the CBRD is better at symmetrically coupling motions than an individual is without assistance.

VII. CONCLUSIONS AND FUTURE WORK

Preliminary results, with a small number of healthy subjects, have shown that the CBRD can couple the motions of two healthy individuals in a task that simulates hemiparesis. Because it was more difficult to complete a task in which the following handle was moved in a mirrored motion, it may be beneficial during bimanual rehabilitation to display the desired positions of both handles. Tasks were completed faster when the coupling stiffness was higher.

The CBRD also improves bimanual task performance of healthy individuals, indicating that it could be an effective rehabilitation method. The device can also reduce the difficulty of a two position matching task so that it is comparable to that in which only one position match is required.

To improve coupling performance of the CBRD and make it suitable for testing with individuals with stroke we plan to reduce the friction in the prismatic joints, optimize the stiffness ellipse of the compliant handle assembly, and add a dynamic arm rest with a means to secure an individual’s impaired arm to the compliant handle assembly.

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