Comparison of Reaching Kinematics During Mirror and Parallel Robot Assisted Movements

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Abstract. The use of robotic devices in rehabilitation allows therapists to administer the desired movement with the preferred level of assistance while expending minimum effort. Robotic devices have been used in recent years to enhance sensori-motor recovery of the impaired arm in persons with stroke. Despite recent recommendations for bimanual practice, robot-assisted bimanual activities are rarely explored and are limited to mirror image movements. We developed a novel parallel movement mode for the Mirror Image Movement Enabler robotic system and investigated trajectory error (TE) exhibited by healthy adults during parallel and mirror image motions to various target locations. TE values differed for parallel and mirror image motions and for certain target locations, suggesting the importance of considering these factors when developing robot-assisted bimanual activities.

Keywords. trajectory error, robotic devices, upper limbs

Introduction

Stroke is the leading cause of neurological disability in the United States[1]. Hemiparesis due to stroke is the primary cause of disability[2]. Most importantly, arm paresis is perceived as the primary cause of disability by individuals who have suffered stroke because of the limitations it creates in performing activities of daily living (ADL)[3]. Rehabilitation of the impaired limb/s is essential for improving motor function after stroke[4], yet only 30.7% of stroke survivors receive outpatient rehabilitation[5]. Therefore, effective therapy for upper-limb paresis must be addressed.

Approximately 80% of all stroke survivors suffer from upper limb paresis and only 18% of these individuals gain full motor recovery with conventional treatments in the year following stroke[6-8]. Thus, continued rehabilitation of the impaired limb/s is needed. Several studies indicate that with proper treatment, arm recovery can occur years after the stroke incident[3]. For example, repetitive, task specific training of the affected limb can result in significant motor recovery more than one year after the

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stroke incident[8]. Experiments show that robot-assisted training of the impaired arm can be as effective as unassisted repeated practice of the impaired arm [9, 10] and more effective than neuro-developmental therapy commonly used for motor recovery after stroke[11]. Furthermore, robotic rehabilitation systems offer increased efficiency, lower expenses, and new sensing capabilities to the therapist. Taken together, the recent successes and distinct advantages offered by robotic systems have garnered much attention.

Despite significant motor improvements reported after repeated practice of the impaired limb, recent neurophysiological evidence indicates greater benefits from bimanual practice[12]. These investigations report cortical reorganization in contralesional and ipsilesional brain hemispheres[12, 13] and enhanced inter-hemispheric activation[14] with bimanual practice. As a result, several robotic devices have been developed specifically for bimanual training, including the 6 degree-of-freedom Mirror Image Movement Enabler (MIME) system[11, 15], the 2 degree-of-freedom Bi-Manu-Track system[16, 17], and the 2 degree-of-freedom Bilateral Force-Induced Isokinetic Arm Movement Trainer (BFIAMT)[10]. These systems have achieved varying results. When added to conventional muscle tone normalization and range of motion exercises, resistive training with BFIAMT enhanced arm strength[18]. Bimanual mirror image training combined with unilateral arm practice with MIME led to improvements in the Fugl-Meyer scores of the proximal joints[11], while bimanual training alone using the MIME did not differ from conventional (neuro-developmental) treatments[19]. Training with Bi-Manu-Track, on the other hand, had no effects on the arm motor recovery even though it reduced wrist spasticity[16].

The abovementioned robotic systems deliver bimanual movements in a mirror image fashion and can operate in a master-slave mode where the movement of the impaired limb is directed by that of the unimpaired limb. When guided by the unimpaired limb, the affected arm experiences better joint coordination[10], so sensory afferent signals come from better coordinated movement patterns and further facilitate cortical reorganization[20]; however, use of mirror image movements alone can be criticized from the motor learning perspective. According to task specificity and variable practice principles, movements that resemble ADL and training protocols that involve a wide variety of activities result in better and more functional motor progress. To address this limitation, we developed a parallel mode for the MIME robotic system. It is reasonable to assume that parallel movements resemble more bimanual daily activities than mirror image motions (i.e., many reaching tasks) and can help attain a more variable practice for robot-assisted bimanual activities. The goal of the study was to compare the newly developed parallel movements to mirror image movements in healthy adults while reaching to various targets with the MIME robot. Findings can provide valuable knowledge for developing effective training regiments for stroke patients and other populations that can benefit from bimanual robot-assisted training.

1. Material and Methods

Figure 1 shows the experimental setup using the MIME system, which consisted of a PUMA-560 robot and a position digitizer.

Participants were seated in front of a low table with forearms placed in padded forearm splints at mid-position.

Figure 1. A picture of the experiment set up. Right-handed participants were seated in front of a target array and placed their arms in forearm splints. The right splint was attached to the Puma-560 robot (Stäubli Unimation, Inc.). Optical encoders in each of the robot's six joints allowed monitoring of the position and orientation of the splint, while a six-axis force-torque sensor (resolution 0.25N) on the end of the robot measured any forces and torques applied. The left splint was attached to the position digitizer (MicroScribe-3DLX, Immersion Corp.), which could measure arbitrary trajectories for the left forearm while applying minimal resistance to movement.

Splints were supplemented with pen-like extensions to allow for precision reaching to targets. A software controller monitored the trajectory of the left arm and commanded the robot to produce corresponding positions and orientations in the right arm. For the purpose of this experiment, two modes were used: a mirror image mode (pre-existing) and a novel parallel mode. In mirror mode, the robot continuously moved the right arm to the mirror image position of the left. In parallel mode, the robot moved the right arm in the same direction as the left.

Healthy right-handed participants were recruited to take part in this study. All the participants signed consent forms approved by the Institutional Review Board of each participating individual. All participants performed simple reaching exercises with the MIME robot. Targets were ping-pong balls arranged as a vertical six-by-three array and instrumented with blinking LEDs. The three rows indicated upper, middle, and lower reaching points and the six columns allowed bimanual parallel reach to the right and left and bimanual mirror reach to inner and outer targets (Figure 2). Each session consisted of performing 48 reaching trials at a comfortable speed. For all trials, the MIME system operated in the master-slave mode where the left arm was attached to the digitizer and was therefore the leading arm. Participants performed unilateral, parallel, and mirror image reaching movement in separate training sessions. The first training session was for familiarization purposes and involved unilateral reaching with the left arm. Thereafter, half of the participants performed the parallel and mirror image tasks on sessions two and three respectively, while the remaining performed these tasks in the opposite session order. All training sessions were completed in three consecutive days. This design allowed all the participants to perform parallel and mirror movements while accounting for practice order. The participants were instructed to reach to the illuminated target pairs presented in a random order as accurately as possible at their comfortable speed.

Data were sampled from the MIME at approximately 110 Hz. Trajectory error (TE) was selected as the primary measure of interest. This measure represents the difference between the performed and the desired trajectories. For reaching movements

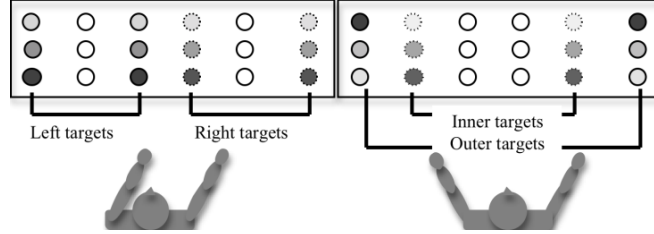the most natural trajectory is a straight path[21].

Figure 2. The schema of the vertical target array used for the reaching task and the associated reaching pattern. Six target pairs were illuminated for parallel (left panel) and mirror (right panel) conditions in random order and are depicted in different patterns. For the parallel condition participants reached to right or left target pairs at upper, middle and lower rows. For the mirror condition participants reached to outer or inner target pairs at the three rows.

Hence for current calculations the desired trajectory was taken to be the straight line between the starting and end points of the reaching movement. Since only the reaching portion of the task was goal oriented, analysis did not include the return path to the starting position. In addition, since the bilateral mode of MIME operates in a master-slave fashion, paths were analyzed for the left arm only. For each trial, the position at the beginning of the movement was set to $\vec{p}(t_i) = (0,0,0)$, and the direction of the straight-line path $\hat{u}_{des}$ was calculated by

$$\hat{u}_{des} = \frac{\vec{p}(t_f)}{\left\|\vec{p}(t_f)\right\|}$$

(1)

where $\hat{u}$ is a unit vector, $\vec{p}$ is the trajectory of the left forearm, t_i is the time at the beginning of the movement, and t_f is the time at the end of the movement. The error in trajectory for each point in time was then determined by taking the component of the position vector that was perpendicular to $\hat{u}_{des}$,

$$\vec{\theta}(t) = \vec{p}(t) - (\vec{p}(t) \cdot \hat{u}_{des})\hat{u}_{des}$$

(2)

The final TE was the magnitude of this error value summed over the length of the trial and normalized over the total distance and duration of the movement to account for differences in reaching distance and speed across participants where N is the number of samples between t_i and t_f.

$$TE = \frac{\sum_{t=t_i}^{t_f} \left\|\vec{\theta}(t)\right\|}{N \sum_{t=t_i}^{t_f-1} \left\|\vec{p}(t+1) - \vec{p}(t)\right\|}$$

(3)

Normality of the data was confirmed using a quantile-quantile plot. Repeated measures ANOVA with the main factors of condition (two: parallel, mirror) and target (six: two in each row) and repeated factor of trial was used for data analysis. Kenward

Rodgers adjusted degrees of freedom was used to account for the small sample size. Tukeys post hoc analysis was conducted when appropriate. Alpha was set at 0.05.

2. Results

Ten right-handed participants with an average age of 23.3 ± 2.7 years successfully completed eight repetitions for each target pair presented in random order (48 trials in each training session). Training did not result in any significant changes in the calculated TE values across trials; however, there was a significant main effects for condition ($F_{1,818} = 192.17$, $P < 0.0001$): TE was significantly larger for the parallel condition than the mirror image condition. There was also a significant effect of target ($F_{5,818} = 44.51$, $P < 0.0001$) where upper-row target pairs had smaller TE values. The significant condition x target interaction ($F_{5,818} = 40.59$, $P < 0.0001$) clarified the main effect findings and is presented in Figure 3. Based on the interaction, TE values were smaller for the mirror image condition when compared to the corresponding target rows in the parallel condition. This difference was not always significant. Lower right targets in the parallel condition had the largest TE values.

3. Discussion

Trajectory error is a scalar measure that is commonly used to represent the kinematic error of point-to-point movements. When performing goal directed reaching tasks, motor commands that yield the smallest kinematic error are the most optimal and are preferred by the central nervous system (CNS)[22]. Another central preference is for the two limbs to operate in spatial symmetry and in an in-phase relationship (i.e. both arms in abduction or adduction at a specific point of time) during bimanual activities [23]. This predominance is observed in healthy older adults and those affected by stroke[24]. In-phase movements are less demanding on the CNS[25] and are therefore easier to maintain, more stable[24], less variable[26], and more accurate[27] than out-of-phase movements (i.e., parallel). The in-phase relationship present for the mirror condition, together with the smaller TE values for this motion regardless of the target location, indicate better performance for mirror-type motion and further support previous findings. It should be noted that there is evidence that out-of-phase movements can be mastered with repeated practice[28]. For our experiments, trajectory-error values did not change with training for the parallel and mirror conditions, indicating the potential need for longer practice. The effect of target location on reaching kinematics was also evident from the current findings. Targets at the upper level had the smallest TE values for both parallel and mirror conditions and TE was largest for the lower right target pairs in the parallel condition (Fig 3). The upper targets were at eye-level for most participants, so it is tempting to assume this is the reason behind the smaller TE for upper targets; however, previous findings suggest that the most influential factor in goal oriented reaching is the "target laterality," the side to which reaching must occur[29]. Therefore, placing targets at eye-level is not necessarily advantageous[30]. The exact visuo-spatial integration processes are unknown and other factors such as eye dominance[31], which can further affect reaching kinematics, were not accounted for in this study. Hence, no specific

conclusions can be drawn for the differences across the presented targets, and further research is required to clarify the current findings.
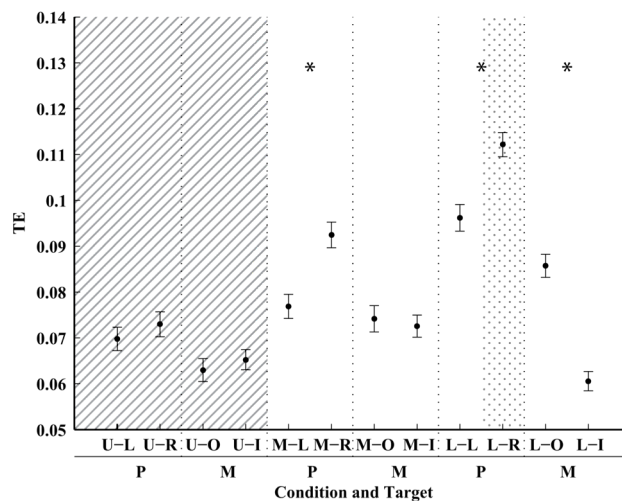

Figure 3. Mean trajectory error (TE) values are presented for the condition x target interaction. Values are ordered by row (upper (U), middle (M), lower (L)), followed by the target pairs (left (L) and right (R) for the parallel condition (P), and outer (O) and inner (I) for the mirror (M) condition). Asterisks indicate significant differences between TE values for target pairs in the same row and condition. The TE values were smallest for the upper targets of both conditions (dashed area) and largest for the lower-right target pair in the parallel condition (dotted area). Error bars represent the standard error.

In conclusion, results from the current investigation indicate the importance of considering the movement pattern and the target location when developing bimanual efficient training protocols. Protocols similar to that used in this study can be implemented prior to training to determine individual characteristics and customize training type and duration accordingly.

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