An Assessment of Robot-Assisted Bimanual Movements on Upper Limb Motor Coordination Following Stroke

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Abstract—Robot-assisted training is increasingly being investigated in upper limb rehabilitation for individuals with stroke. Many studies have suggested that an appropriate synchronization of voluntary motor commands and limb movement is critical for long-term efficacy. Bimanual training is one method for enhancing this synchronization or motor coordination. The purpose of the study was to evaluate the potential efficacy of bimanual robot-assisted movements by comparing the relative timing of muscle activation and forces to those generated during unimanual robot-assisted movement. A secondary goal was to compare bimanual robot-assisted movement to bimanual voluntary movement, where both limbs moved independently without robotics. Subjects performed reaching tasks while attached to one or two robotic manipulators. A predefined movement trajectory was prescribed during unimanual robot-assisted movement; in bimanual robot-assisted movement the paretic limb trajectory mirrored the nonparetic limb. Relative to unimanual movements, during bimanual movements the timing of muscle activation and initial interface forces was more similar to the nonparetic limb. However, there were limited differences in these measures between bimanual voluntary and bimanual robot-assisted movements. Bimanual robot-assisted movements resulted in superior motor coordination compared to unimanual movements and could be beneficial for individuals with a restricted movement range. Bimanual movements without robotics were just as efficacious and may be preferred for individuals who can generate movement without assistance.

Index Terms—Hemiparesis, motor control, robotics, upper limb.

I. INTRODUCTION

BILATERAL activation is a common technique to facilitate muscle activation on the paretic side [1]. Strategies involving concurrent activation of homologous muscles take advantage of inter-limb coupling that arises when simultaneous movements of the two limbs occur. During bilateral tasks there is a strong preference towards symmetry of the movement patterns, such that the limbs appear to be coupled together and controlled as a single functional unit [2]. This interlimb coupling can be exploited in populations with unilateral motor deficit if the impaired limb is able to be entrained to the nonimpaired [3]–[11]. However, recent long-term studies demonstrate that bimanual therapies are not always efficacious in the stroke population [12], [13], suggesting that further study is needed into which aspects of bimanual training are most critical for movement rehabilitation.

Another important factor for the rehabilitation of motor function following stroke is the provision of intact, appropriate proprioceptive input [14]. In people with hemiparesis who are unable to generate substantial motor output, there is a concomitant reduction in ascending afferent information. One way to enhance afferent flow is with assisted limb motion. Assisted movement therapies are commonly utilized both in the acute and chronic stages poststroke, and improvements in clinical measures have been documented in studies implementing long-term repetitive, robot-assisted movements of the upper limb [7], [15]–[17]. The integration of appropriately timed sensory input to cortical motor centers is critical to motor control and neural plasticity [18]–[21]. Techniques that facilitate the coordination of afferent information with motor commands may further the advances that have been made in movement rehabilitation. Several protocols have been developed using robot-assisted movement incorporated with aspects of voluntary control so as to optimize the coordination of efferent motor commands and actual movement. For example, force- or EMG-triggered initiation [22]–[24], constrained movement pathways [22], [24], and active assistance towards a target [25] have been implemented. Robot-assisted bilateral protocols, in which movement trajectories of the impaired limb are directed by the actual movements of the nonimpaired limb, also have been developed to facilitate training in people with stroke [7], [22], [26]. These protocols take advantage of the assisted movement capabilities of robotics and the intrinsic interlimb coupling characteristic of the motor control system, so that the subject’s voluntary motor commands are coordinated with the movements of the limb, as is the case in unimpaired reaching.

The coordination of voluntary motor commands, limb movements, and interface forces between the limb and the manipulator during bimanual movement have not been analyzed in detail in chronic stroke. Long-term studies implementing robotic training in stroke have shown muscle activation patterns and arm forces can be improved [27]. Characterizing these parameters during bimanual and robot-assisted movements is necessary for
assessing how each of these paradigms influences the relative timing of muscle activation and movement trajectories and may suggest the types of movement protocols that would be most beneficial for long-term rehabilitation programs.

The purpose of this study was to quantify the influence of robot-assisted bimanual movement on the timing of muscle activity and limb–robot interface forces during arm reaching tasks performed by individuals with hemiparesis. Our first goal was to compare muscle activation patterns and movement characteristics of the paretic arm between unimanual robot-assisted movement and bimanual robot-assisted movement. During unimanual robot-assisted movement, the trajectory of the paretic limb is prescribed by a robot and subjects are asked to assist the movement. In contrast, during bimanual robot-assisted movement the trajectory of the paretic limb is prescribed by the self-initiated trajectory of the nonparetic limb. We hypothesized that the timing of muscle activation and force applied to the manipulator would match movement trajectories more appropriately in the bimanual condition. As the initiation of movement is voluntary in the bimanual condition and the same movement trajectories are achieved with each limb, the descending neural activity associated with the desired output of the paretic limb and the sensory information arising from the actual movement achieved by this limb would be congruent with a normal voluntary movement. This integration of sensory and motor information is critical for motor learning and an enhancement of the temporal aspects of integration may facilitate the motor recovery process.

Our second goal was to compare movement characteristics during bimanual robot-assisted movement to bimanual voluntary movement, where both limbs moved independently without robotics. The purpose was to evaluate the influence of the robot-assist mode on movement coordination. Robots can be expensive items of equipment and are not available to all people with stroke, so it is prudent to evaluate the benefits of equivalent movements without the use of robotic assistance. We hypothesized that movement trajectories and muscle activation would be superior during robot-assisted bimanual movements, where coupling of the robots would prescribe a more normal trajectory by the nonparetic arm, compared to bimanual voluntary movement.

II. METHODS

A. Overview

Subjects participated in two separate data collection sessions. In each session, they performed movements under three conditions: unimanual paretic limb, unimanual nonparetic limb, and bimanual. In the bimanual condition, the task was performed simultaneously in a mirror symmetric manner. In one session (voluntary movement), the movements of both limbs were initiated and controlled voluntarily. In the other session (robot-assisted movement), movement trajectories of the paretic limb were controlled by a robotic manipulator. Further details are provided in Section II-E.

B. Subjects

Fifteen people with poststroke hemiparesis (see Table I) volunteered to participate in the study. All subjects had suffered a single cerebrovascular accident at least 12 months previously and had residual unilateral deficits in upper limb function. The subjects were all able to activate arm muscles and move the robotic end-effector, although those with low function had restrictions in their active range of arm movement. We intentionally included these subjects to increase their movement distance using robotics. Subjects were excluded if they had any orthopaedic limitations of either upper limb, were unable to maintain grip on the robotic end-effector, or had any other neurological conditions. Informed written consent was obtained from all subjects prior to participation and the study was approved by the Northwestern University Institutional Review Board.

C. HapticMASTER Robot

The HapticMASTER (FCS Control Systems, The Netherlands) is a 3-degree-of-freedom admittance-controlled robotic manipulator with a control loop frequency of 2500 Hz [Fig. 1(a)]. It was used to provide measures of task performance for both data collection sessions through recordings of limb endpoint trajectories and force. It also was used to specify limb endpoint trajectories during robot-assisted movement.

Subjects were seated and comfortably restrained in an adjustable chair and secured with a harness to restrict trunk movements. Two robots were positioned in front of the subject [Fig. 1(b)]. Subjects grasped a ball mounted at the effector end of each robot. During active voluntary movement by the subject, the movement trajectory was determined by forces applied to the end-effector. During these protocols, the robot was programmed to behave as a gravity-compensated mass with a value of 3 kg. The accuracy of this simulation, quantified using a least-squares regression between the measured interface forces and the endpoint accelerations during random movements throughout the available workspace, was within 10% of the programmed 3 kg mass. An evaluation of the transfer functions [28] between the measured endpoint accelerations and forces indicated that the robot accurately simulated a pure mass for movements with frequency components less than approximately 8 Hz, well below those performed during the
Bessel filters with a lowpass cutoff frequency of 500 Hz. The EMG signals were anti-alias filtered with custom fifth-order filters at frequencies of 10 and 1000 Hz, respectively. Prior to sampling, the signals were amplified using a Bortec AMT-8 (Bortec Biomedical, Calgary, AB, Canada) with a position and force data acquisition from the robot, which occurred at the same rate.

E. Movement Tasks and Protocol

Subjects were required to perform two reaching tasks of differing difficulty. One was a constrained reach that limited movement to one axis, while the second was an unconstrained free-reaching task. In the starting position for both tasks the subject’s upper arm was vertical and the elbow at 90° with the forearm fully pronated [Fig. 1(c)]. Subjects made reaching movements toward a physical target that was an adjustable, pliable green disc (5 cm diameter). During the bimanual conditions, the target was placed on the paretic side and subjects were asked focus on the paretic arm but to make the same reaching movement with the nonparetic arm at the same time. Subjects were instructed to move their hand at a comfortable speed to touch the target. For Task 1 [Fig. 1(d)] the target was placed directly anterior to the hand just within the passive range of motion of the arm. Movement of the end-effector was restricted to the horizontal plane along a line from the starting position to the target position, i.e., subjects could not move the end-effector in the Y or Z directions. For Task 2 [Fig. 1(e)] the target was placed at head height approximately 10 cm anterior to the starting position to ensure that elbow extension was required to successfully reach the target. Movement of the end-effector was not restricted in any way.

Subjects performed 20 repetitions of each movement task in each of the three movement conditions (unimanual paretic, unimanual nonparetic, bimanual). At the start of each repetition, the robot end-effectors were held in a static position and then released for movement after a warning beep sounded. The subjects were allowed up to two practice trials to familiarize themselves with each task. In the voluntary movement session, movements of both manipulators were determined by voluntary activation. In the robot-assisted movement session, all movements of the paretic arm unimanual condition, a movement trajectory was specified and controlled by the robot. In the paretic arm unimanual condition, a movement trajectory was created from the start position to the target position and minimum-jerk velocity profile specified [29]. Peak velocity was approximately matched to that observed during the practice trials of the nonparetic arm. Subjects were asked to assist the robot in performing the movement task. In the bimanual condition, the robots were placed in the master–slave operation with movement of the paretic arm end-effector guided by the position of the nonparetic arm. Subjects were not told that the robots were functioning in the master–slave operation. In both data collection sessions, all movements of the nonparetic arm were performed voluntarily without robot-assistance. The order of data collection sessions, movement tasks, and movement conditions were all randomized between subjects. Rest breaks were provided as needed. Each data collection session was completed in less than 2 h.

F. Data Processing and Analysis

1) Robot Position and Force Data: Position and force data from the robots were bi-directionally filtered with a 10 Hz second-order lowpass Butterworth filter, resulting in zero resulting signals were sampled at 1250 Hz and synchronized with position and force data acquisition from the robot, which occurred at the same rate.

D. Electromyography

Electromyographic activity was recorded bilaterally from the anterior deltoid (AD), middle deltoid (MD), biceps brachii (BB), and the lateral head of the triceps brachii (TRI) muscles. Stand skin preparation was completed prior to the application of disposable dual electrodes (Noraxon USA Inc., AZ). EMG signals were amplified using a Bortec AMT-8 (Bortec Biomedical Ltd, Calgary, AB, Canada) with high- and low-pass cutoff frequencies of 10 and 1000 Hz, respectively. Prior to sampling, the EMG signals were anti-alias filtered with custom fifth-order Bessel filters with a lowpass cutoff frequency of 500 Hz. The
Fig. 2. Example force, position, and velocity profiles from individual subjects. Data are shown for the X movement direction for Task 1 and for the Z movement direction for Task 2. Each figure shows the individual trials along with the average (dark line). The dashed vertical line indicates movement onset. In A–C, the figure to the left shows movement profiles from the paretic limb in the unimanual (blue) and bimanual (red) movement conditions. In D, the figure to the left shows movement profiles from the paretic limb in the bimanual condition from the voluntary movement session (blue) and from the bimanual condition from the robot-assisted movement session (red). In A–D, the figure to the right shows the nonparetic arm in the unimanual condition (voluntary movement).

phase shift. For both movement tasks, analysis of position and force data was restricted to the primary movement direction (Task 1, X direction; Task 2, Z direction). Movement onset was defined as the first point at which movement velocity in the primary direction exceeded 0.05 cm/s. Movement end was defined as the first point at which movement velocity returned below 0.05 cm/s. In cases where the movement trajectory involved more than one submovement, i.e., the trajectory was discontinuous and movement velocity was below 0.05 cm/s on more than one occasion, movement end was defined as the point where velocity returned below 0.05 cm/s and was furthest from the start position. Movement distance was the difference in position along the primary axis of movement from movement start to end. Peak velocity was determined as the fastest tangential velocity achieved from movement start to end. Any trials that involved a movement time greater than two standard deviations above the mean were discarded from further analysis. This represented approximately 5% of all trials completed. From the remaining trials, measurements of average movement time, movement distance, and peak velocity were determined. To analyze the timing of voluntary activation in robot-assisted movement, the time of peak force in the paretic arm also was determined. These variables were compared between conditions using paired Student t-tests.

2) Electromyography: Due to the occurrence of noise, EMG data was discarded from three subjects in task 1, voluntary
movement session; from two subjects in task 2, voluntary movement session; and from one subject in both tasks of the robot-assisted session. In the remaining subjects, EMG data were rectified, time normalized from movement onset to offset, and averaged across trials to produce a mean activity profile for each movement condition. The individual activity profiles were amplitude normalized to the maximum level of activity recorded during each task. These profiles were then averaged across subjects to generate an average activity profile for each muscle and task. To analyze the timing of muscle activation, the onset of activity was determined for each subject as the first point to increase above three standard deviations of the premovement mean EMG activity in the same profile. The peak of EMG activity was determined to analyze the extent of muscle activation. Muscle activation onset and peak activity were compared between movement conditions using paired Student $t$-tests.

### RESULTS

A variety of movement and force trajectories were observed across the group. Fig. 2 shows example trajectory and force profiles from four subjects. Note that some subjects were applying force to the robotic end-effector prior to the start of movement while statically constrained in the starting position. In Fig. 2(a) (voluntary movement session, Task 1), the subject reached a greater distance, displayed a faster movement velocity, and had less kinematic variability in the bimanual compared to unimanual condition. In contrast to this, the subject in Fig. 2(b) displayed almost identical movement profiles in the unimanual and bimanual voluntary movement conditions. Fig. 2(c) shows data from the robot-assisted movement session. In this figure, it is evident that the timing of the force profile is more similar to the nonparetic arm during movement in the bimanual condition. In the unimanual condition, where a programmed movement trajectory was specified by the robot, the onset of the voluntary force is delayed in relation to the movement. Fig. 2(d) shows data from the bimanual movement conditions of the voluntary (blue) and robot-assisted movement conditions (red). This subject moved the same distance and achieved approximately the same peak velocity in the two bimanual conditions. However, the negative force throughout the majority of the robot-assisted tasks indicates that the arm was being dragged by the robotic end-effector in this condition.

We expected that the constrained reaching task (Task 1) would be easier for the subjects to perform; however, there was little difference in overall performance between the two tasks. Nevertheless, we present group results from both tasks below.

#### A. Comparison of Robot-Assisted Unimanual and Bimanual Movement

To address the first goal of the study, we compared performance of the paretic arm between robot-assisted unimanual movement, where a predetermined trajectory is specified by the robot, and robot-assisted bimanual movement, where the paretic limb trajectory is specified by the nonparetic limb. Group averaged movement profiles, force data, and muscle activity are shown in Figs. 3–5. In all movement trajectories, the timing of force and muscle activity in the nonparetic arm was assumed to be the most appropriate for the movements studied.

#### 1) Task 1: Inspection of the movement profiles in Fig. 3(a) and (b) indicates that the kinematics of the movement were similar in the two robot-assisted conditions, as was expected. Statistical analysis of the group data (Fig. 4) indicated that differences in the movement time ($P = 0.051$) and peak velocity ($P = 0.8$) did not reach statistical significance between unimanual and bimanual conditions; however, the total distance achieved by the paretic arm was slightly but significantly further in the bimanual condition ($P = 0.02$).

Although the movement trajectories were comparable between conditions, there were differences in the arm forces applied to the manipulator. The timing of force application in the initial stages of the movement appears more similar to the nonparetic arm in the bimanual robot-assisted condition [Fig. 3(c)]. This is consistent with the finding that the peak force occurred significantly earlier in the movement profile during bimanual $(19 \pm 7\%)$ compared to unimanual $(33 \pm 12\%)$ robot-assisted movement ($P = 0.005$). Peak force occurred at $16 \pm 3\%$ of the normalized movement time in the nonparetic arm. The force profile displays a large negative peak in the second half of the movement in the bimanual condition. This
indicates resistance to the movement prescribed by the manipulator and suggests that the arm was being dragged over the latter half.

Differences between the unimanual and bimanual conditions were also evident in the EMG data. Group averaged profiles are shown in the top half of Fig. 5. The timing of muscle activation was significantly closer to the onset of movement for the prime mover, AD, in the bimanual robot-assisted condition ($P < 0.001$). Muscle activation onset was also slightly but significantly earlier in the TRI ($P = 0.03$). In the second half of the movement, the level of activation appears lower in the bimanual condition for the TRI, AD, and MD muscles. The difference in peak activity was significant for the TRI ($P = 0.03$) but not the AD or MD (both $P = 0.1$). This is a further reflection that, in some subjects, the paretic arm may not have actively participated in the latter half of the movement.

2) Task 2: For Task 2, movement time ($P = 0.5$), peak velocity ($P = 0.6$), and movement distance ($P = 0.3$) were not significantly different between unimanual and bimanual conditions (Fig. 4). Profiles of kinematic data [Fig. 3(d) and (e)] indicate a similar movement trajectory in the unimanual and bimanual conditions; however, the timing of the force profile is closer to the nonparetic arm in the bimanual condition. Again, the timing of peak force was significantly earlier, and closer to the nonparetic arm ($14 \pm 2\%$ of normalized movement time), in the bimanual condition (unimanual $= 29 \pm 8\%$; bimanual $= 19 \pm 11\%; P = 0.02$). The large proportion of time showing negative force in both conditions [Fig. 3(f)] indicates that the paretic limb was dragged by the manipulator for most of the movement, most likely due to the fact that this anti-gravity task was more difficult for most subjects.

Similar to Task 1, there were differences in onset of muscle activation between the two robot-assisted conditions (Fig. 5, lower half). In all four muscles, the onset of muscle activity in the unimanual condition approximates the onset of movement, rather than prior to movement onset, as evident in the nonparetic arm and in the bimanual condition. Statistical analyses revealed a significantly earlier onset of activation in all muscles in the bimanual condition (all $P < 0.04$). In contrast to Task 1, the level of muscle activation is similar between the two conditions over the remainder of the movement. There were no differences in peak EMG activity for any of the four muscles (all $P > 0.09$).
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3) Correlations With Functional Ability: To determine if the subject’s functional ability influenced their performance in the bimanual robot-assisted condition, we correlated the Fugl–Meyer score with the difference in force onset time between the unimanual and bimanual conditions. Thus, this analysis determined if lower or higher functioning individuals improve their force timing more in the bimanual movement condition. We chose this variable as it was significantly improved in the bimanual movement condition compared to unimanual. For both Task 1 and Task 2 the correlation with Fugl–Meyer score was not significant (Task 1, Pearson $r = -0.08$, $P = 0.8$; Task 2, Pearson $r = 0.38$, $P = 0.2$).

B. Comparison of Voluntary and Robot-Assisted Bimanual Movement

To address the second goal of the study, we compared performance of the paretic arm between voluntary bimanual movement, where both limbs are moved independently, and robot-assisted bimanual movement, where the trajectory of the paretic limb is specified by the nonparetic limb.

1) Task 1: There were no differences in movement time or peak velocity between conditions for Task 1 (both $P = 0.7$; Fig. 4); however, the movement distance was larger in the robot-assisted condition ($P < 0.001$). This is evident in the group averaged movement profiles shown in Fig. 6. The force profiles indicate much more appropriate amplitude of forces applied to the end-effector in the voluntary condition and less variation between subjects. The relative timing of peak force was not significantly different between the two conditions (robot assisted; voluntary $= 19 \pm 7\%$; voluntary $= 16 \pm 6\%$; $P = 0.4$).

Muscle activity profiles shown in Fig. 7 (top row) indicate similar timing of muscle activity between the two conditions. There were no significant differences in the onset of muscle activation in any of the four muscles (all $P > 0.2$). Comparisons of the amplitude of muscle activity were not made because the data were collected on two separate days.

2) Task 2: There were no significant differences in movement time or movement distance between the two conditions in Task 2 (both $P = 0.2$). The higher peak velocity in the voluntary movement condition approached significance ($P = 0.051$). The movement profiles shown in Fig. 6(d) and (e) confirm similar kinematic aspects of movement for the two conditions. The
relative timing of peak force was not significantly different between the two bimanual conditions (Fig. 6(f); robot-assisted = 19±11%; voluntary = 14±3%; \( P = 0.2 \)).

The EMG activity profiles shown in Fig. 7 (bottom row) again indicate similar patterns of activation in all four muscles for the two bimanual movement conditions. Statistical analyses revealed that the onset of activity in the TRI was significantly earlier in the voluntary movement condition (\( P = 0.02 \)). There were no differences in activation onset in the remaining three muscles (all \( P > 0.05 \)).

IV. DISCUSSION

The first goal of this study was to compare muscle activation and force generation in the paretic arm between a unimanual robot-assisted condition and a bimanual robot-assisted condition where movement was specified by the nonparetic arm. Force and EMG profiles indicated that the initial muscle activation was more synchronized with limb motion during bimanual, robot-assisted movement, although there was evidence the paretic limb was not actively contributing beyond the initial force generation phase in the bimanual condition of Task 1. The second goal of the study was to determine differences in motor control of the paretic arm during bimanual movements performed either voluntarily or with robot-assistance from the nonparetic arm. Force and muscle activation profiles were similar in voluntary and robot-assisted bimanual movement, even though robot assistance allowed subjects to move a greater distance in one of the tasks. Under our assumption that the timing of muscle activation is a critical outcome measure, these results suggest that bimanual robot-assisted movement training could provide additional therapeutic benefits beyond those reported for unimanual robot-assisted training when applied over the long-term. These benefits, however, may not be greater than those that can be obtained using voluntary bimanual therapies without robot assist, provided that the individuals have the capacity to perform the specified movements. Thus, the benefits of bimanual movements appear to be independent of the control strategy adopted (robot-assisted or voluntary).

A. Robot-Assisted Unimanual and Bimanual Movement

At movement initiation, there was greater muscle activity in the prime movers and the timing of force profiles was closer to the nonparetic arm in bimanual robot-assisted movement compared to unimanual robot-assisted movement. Therefore, although the kinematics of the movements performed were comparable in the robot-assisted conditions, muscle activity and the timing of initial force generation were more similar to the nonparetic arm in bimanual robot-assisted movement, rather than when movement was initiated and specified by the robotic manipulator. This suggests that muscle activation timing was more appropriately linked to actual movement of the paretic arm in the bimanual condition, at least in the initial stages of the movements that were evaluated in this study.

The use of robotic manipulators for assisted-movement interventions affords the ability to generate repeatable, controlled, and highly specific movement trajectories that a therapist may not be able to provide manually. The ability of sensory information to modulate the excitability of cortical motor regions has been well documented [30]–[36]. This capacity of induced limb motion to invoke plasticity of motor regions is highly relevant for populations with movement deficits following neurological impairment, and may account for the traditional use of assisted-movement therapy as a treatment intervention in populations with hemiparesis [37]. However, a common limitation of robot-assisted movement is that movement initiation and timing is governed externally. The force- and EMG-triggered robotic assistance modes of robotic systems such as the MIME [16], ARM Guide [38], and MIT-Manus [39] function to overcome this limitation by ensuring the user initiates the appropriate movement prior to robotic assistance. Similarly, an advantage of the coupled master-slave mode offered by the HapticMASTER manipulators is that the user is in control of the spatial and temporal characteristics of the training movements applied to the paretic limb. Indeed, the force and EMG profiles during bimanual robot-assisted movement indicated closer temporal matching of applied forces to the actual movement trajectory. This likely arises due to the tight temporal and spatial coupling of motor commands between the two upper limbs [2], [40]–[43]. This inherent coupling means that the advantages afforded by robot-assisted movement can be augmented by the potential neural benefits of bilateral activation of the two cortical hemispheres [44].

Appropriate timing of neural inputs is crucial for neural plasticity and rehabilitation. Long-term potentiation and depression-like (LTP, LTD) mechanisms are postulated to account for use-dependent cortical plasticity in the motor cortex [45]–[47]. The induction of LTP and LTD is critically dependent on spike timing [48], [49]. Studies in humans pairing peripheral nerve stimulation with cortical stimulation have demonstrated that the excitability of corticomotor pathways can be up- or down-regulated based on the timing between cortical and peripheral stimuli [20], [21], [50]. Therefore, to strengthen appropriate motor control pathways it is important to temporally match afferent input signals with the generation of descending efferent motor commands. The results of our study indicate that assisted movement involving the nonparetic limb may provide a further method of appropriate temporal matching. Importantly, such techniques do not have to involve expensive robotic devices but may make use of simple mechanical coupling mechanisms between the two limbs [10].

The force profiles during both conditions of robot-assisted movement showed areas of negative force. The application of negative force during movement indicates resistance applied to the robotic end-effector and suggests that, rather than pushing along the movement trajectory, the subjects’ upper limb was dragged by the manipulator. This was particularly evident in the second half of bimanual robot-assisted movement during Task 1. This may be due to difficulty generating elbow extension forces in this posture [51], if subjects did not focus on their impaired arm to the same extent during the bimanual condition as during the unimanual condition for this phase of the movement. Lum et al. [12], who did not detect any beneficial effects of bimanual robot-assisted therapy compared to unilateral robot-assisted therapy following a four-week intervention, suggested that unilateral training may result in a more focused effort and greater concentration on the paretic limb. The benefits, or
otherwise, of bimanual therapy remain a contentious issue. Further intervention studies with matched tasks between unimanual and bimanual conditions, and that control for attention, effort, and task complexity are required. We suggest that instructions to users and the level of engagement of their paretic limb are critical to the efficacy of bimanual-based robotic therapies.

B. Bimanual Voluntary and Robot-Assisted Movement

Bimanual robotic or mechanically-coupled devices may not be available to many populations of stroke survivors. We provided a direct examination of whether bimanual voluntary movement, where the two limbs moved independently, elicited similar movement characteristics to bimanual robot-assisted movement. Analysis of movement kinematics indicated that a further distance was reached in robot-assisted movement, but this was only significant for Task 1. The remaining movement characteristics, including movement velocity, muscle activity profiles, and the timing of force production, were similar for the two bimanual movement conditions. This indicates that our population of subjects was able to generate comparable movement characteristics during independent bimanual movement. This outcome does not support our hypothesis and suggests that independent bimanual training may provide similar benefits to bimanual robotic training if applied over the long-term. It is important to note that most of our subjects demonstrated moderate impairments of the upper limb according to stratification criteria proposed by Kwakkel et al. [52]. The comparability of voluntary and robot-assisted movement characteristics may not generalize to more severely impaired individuals who show more marked deficits in movement ability of the paretic arm, or to movement tasks that are more difficult for stroke-impaired individuals to perform.

C. Clinical Applications of Robotic and Bimanual Training

Robot-assisted bimanual movements appeared to provide an advantage over unimanual robot-assisted movement in terms of more appropriate timing of afferent and efferent neural information at movement initiation. Therefore, in terms of long-term application of robot-assisted training, coupled active-passive bimanual training, in which active movement of one limb generates passive movement in the other, may provide a treatment effect that is superior to unimanual, assisted-movement training. Importantly, subjects should be encouraged to actively involve their impaired arm during robot-assisted therapies to ensure activation of appropriate muscles throughout the movement. Reports from some subjects in this study indicated that they did not realize that movement in their paretic arm during the bimanual robot-assisted condition was generated by their nonparetic arm. This shows that such coupled robotic interventions are acceptable to subjects and result in natural feelings of movement control. Further support for the use of coupled active–passive bimanual therapies is provided by a recent four-week intervention study [10]. This study, which documented a beneficial effect of active–passive bilateral training, suggested the synchronous afferent input arising from the two upper limbs was able to prime the motor system and facilitate recovery.

Robot-assisted movement can generate movement trajectories that may not be achievable by voluntary movement. Therefore, although our correlational analyses showed that improvements in the timing of force application were independent of functional ability scores, robot-assisted interventions would appear beneficial for lower functioning individuals who have limited range of voluntary movement or who are unsuitable for other rehabilitation interventions that are targeted to the upper quartile of movement ability [12], [53]. Given reports from previous studies that bimanual therapies are more efficacious in lowering functioning individuals [9], [13], bimanual robot-assisted therapies may prove a superior intervention than unilateral robot-assisted therapies for individuals with severe movement impairments. The force profiles obtained in our study show that it would be important to monitor and provide feedback on forces generated by the paretic arm during movement to ensure that it is actively participating in the prescribed movement [54]. The similar, or even superior, movement characteristics displayed during voluntary bimanual movement suggest that bimanual training without robotics may be efficacious on its own. It is suggested that bimanual training without robotics should target individuals who have a larger active range of motion and can generate suitable movement trajectories without the assistance of a robotic manipulator.

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Authors’ photographs and biographies not available at the time of publication.