Robotic Unilateral and Bilateral Upper-Limb Movement Training for Stroke Survivors Afflicted by Chronic Hemiparesis

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***Abstract*— Stroke is the leading cause of long-term neurological disability and the principle reason for seeking rehabilitative services in the US. Learning based rehabilitation training enables independent mobility in the majority of patients post stroke, however, restoration of fine manipulation, motor function and task specific functions of the hemiplegic arm and hand is noted in fewer than 15% of the stroke patients. Brain plasticity is the innate mechanism enabling the recovery of motor skills through neurological reorganization of the brain as a response to limbs' manipulation. The objective of this research was to evaluate the therapeutic efficacy for the upper limbs with a dual arm exoskeleton system (EXO-UL7) using three different modalities: bilateral mirror image with symmetric movements of both arms, unilateral movement of the affected arm and standard care. Five hemiparetic subjects were randomly assigned to each therapy modality. An upper limb exoskeleton was used to provide bilateral and unilateral treatments. Standard care was provided by a licensed physical therapist. Subjects were evaluated before and after the interventions using 13 different clinical measures. Following these treatments all of the subjects demonstrated significant improved of their fine motor control and gross control across all the treatment modalities. Subjects exhibited significant improvements in range of motion of the shoulder, and improved muscle strength for bilateral training and standard care, but not for unilateral training. In conclusion, a synergetic approach in which robotic treatments (unilateral and bilateral depending on the level of the motor control) are supplemented by the standard of care may maximize the outcome of the motor control recover following stroke.**

Keywords— Robotic, Rehabilitation, Bilateral, Stroke

I. Introduction

Approximately 750,000 individuals suffer a stroke each year [1]. The majority of survivors experience hemiparesis and require rehabilitation. Over the last two decades it has become increasingly clear that the central nervous system has the potential to adapt and restore function despite impairments. However, this neural adaptive potential requires attended, repetitive, progressive training. Thus rehabilitation robotics has grown in popularity to assist patients in retraining. Notably, at the time of this writing none of these systems are a proven, or accepted alternative to traditional physical therapy with a trained therapist. For this reason, the robot/game interactions described in this paper are more accurately described as "movement training" with the goal of providing rehabilitation. Beyond being able to assist patients in moving their arms, robots provide a unique opportunity to interface these movements with therapy games in a virtual world.

With respect to motor function, many stroke survivors lose functions of the left or right side of their body. The robotic treatments being evaluated in this paper were intended to facilitate assisted movement training of the paretic left, or right, upper limb for chronic stroke survivors. Some have proposed that repetitive mirror symmetric bimanual movements might prime the stroke affected hemisphere/motor cortex for enhanced plasticity and motor learning. There is growing

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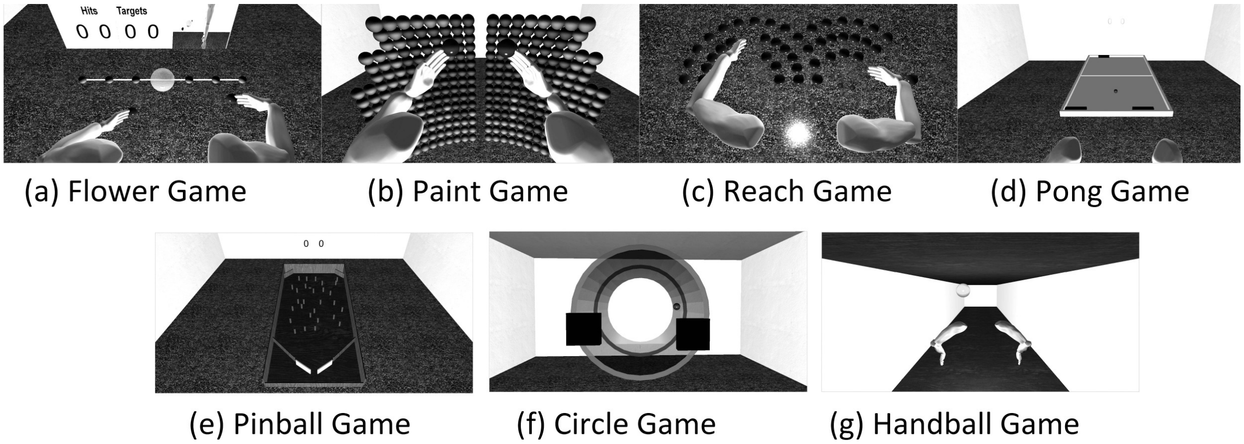

Fig. 1 Screen shots from the various games. Note, only the avatar arms are visible for visibility. Avatar arms are not visible in the Pinball and Circle games.

neurophysiological evidence for such an effect in chronic patients and healthy subjects [2]. The clinical framework of this research was to compare recovery using three different treatment modalities: two-armed mirror-imaged bilateral symmetric movement, single-armed unilateral movement, and conventional physical therapy (standard care) [3]. For unilateral games the subject's unaffected arm was unable to affect the outcome of the games being played. Therefore, the unilateral movement training could be regarded as an analog to constrain induced therapy [4].

II. METHODS

A. Standard Care

Subjects in the standard care group underwent treatments that were based on the principles of neuroplasticity. Treatments consisted of task oriented, repetitive training [5] [6]. Standard care involved using the upper limbs to perform tasks through various ranges of motion while maintaining different postures including sitting, standing, and supine positions. The goals of standard care were to maintain good postural alignment, reduce tone, and improve task performance. The standard care group abstained from all robotic motion training and all standard care was facilitated by a licensed physical therapist.

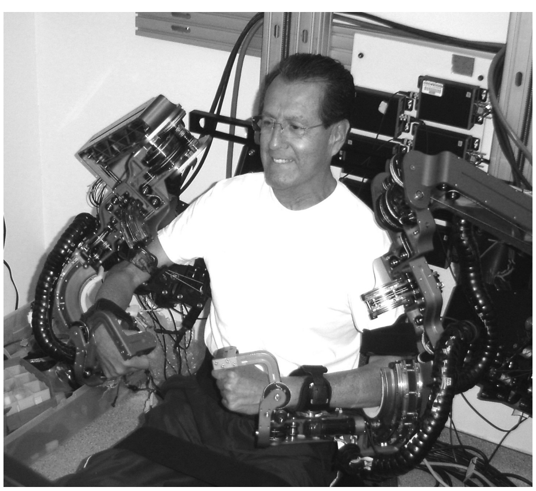

Fig. 2 The subject is pictured wearing the EXO.

B. Apparatus

The EXO-UL7 (EXO) used for this study is a robotic system that includes two exoskeleton arms for the upper limbs [7]. For bilateral training the least affected arm was the master, and the affected arm was the slave. PID control was used to reduce joint angle errors between the master arm and slave. For bilateral training, when a subject moved their unaffected arm the EXO provided mirror-image partial assistance for the affected arm [8]. The EXO provided “partial assistance” in the sense that the subject's paretic arm was never forced into a precise orientation that matched the unaffected arm. Instead, the paretic arm received a guiding push. The motors currents (i. e. joint torques) were limited in software. The EXO used gravity compensation to correct for its own weight, but not for the weight of the subject’s arm[s]. The EXO provided unilateral assistance for subjects to reach their targets in only one game, Flower.

The system recorded position, force, and torque information for each game. Joint position data for both arms was measured using optical encoders. Forces were recorded along orthogonal axes using ATI Mini40 transducers.

C. Games For Unilateral and Bilateral Treatments

The games were developed in C# using Microsoft Robotics Studio and are depicted in Fig. 1. Games were intended to maintain attention and motivate subjects to exercise their affected arm. Pong-style games involving a paddle and bouncing ball have been recommended as a good choice for motor deficit rehabilitation [9]. Accordingly, three games roughly fall into this category: Handball, Circle, Pinball, and Pong. All involved rebounding an incoming ball with a paddle of some kind.

Three other games, Flower, Paint, and Reach were designed to provide static targets for subjects to reach. The intent of the static games were to provide constrained reaching tasks that are more amenable to data analysis [10]. More specifically, Flower

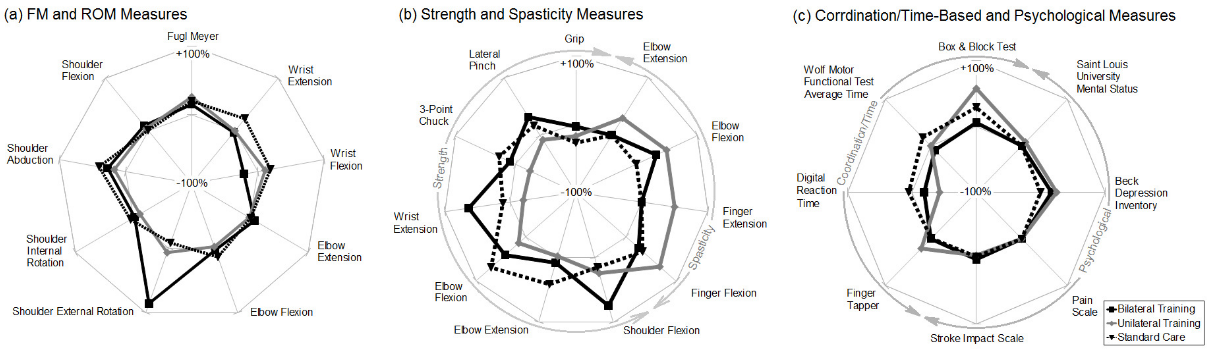

Figure 3 Percent improvement between before and after measures. Average or median points closer to the periphery of each spider graph indicates a more favorable outcome following a given treatment.

and Paint utilized fixed targets at known positions rather than moving targets. The Pong, Pinball, Circle, and Handball games were designed to engage the subjects as they exercised their paretic arm. A more detailed analysis of game design is available in [11].

As was mentioned earlier, the only unilateral game to include assistance was the flower game. In the unilateral Flower game the subjects were presented with spherical reaching targets – red balls. After the subjects touched the balls with their hands a new set of ball targets would appear with different ball positions. For each new target the EXO would provide a constant force that assisted the subject's arm to touch the target. This provided the sensation of the hands being attracted to the ball target.

D. *Subjects*

The research was approved by the University of California, San Francisco, Committee on Human Research. Subjects provided written consent prior to study participation. Subjects were assigned to participate in one of three treatments: 1. Bilateral motion training, 2. Unilateral motion training, 3. Standard care. Each group consisted of five randomly assigned subjects. Subjects ranged in age from 23 to 69 years old. Each treatment was 90-minutes in duration, occurring 2 days per week for 12 weeks. All subjects were at least 6 months post-stroke. Subjects were required to understand and follow instructions in English with a score of at least 18 on the Mini-Mental Status Examination. Subjects scored between 16 and 39 on the upper limb portion of the Fugl-Meyer assessment. These scores suggests that the subject has the ability to understand instructions, provide feedback, and have the necessary ROM, control, and strength to play the games. No brain imaging was performed and there were no experimental controls for the cause of brain injuries, in stroke survivors (hemorrhagic or ischemic).

Each subject was scheduled to participate in 12 sessions of treatments. Each session was 90 minutes in duration. Session intervals were approximately 1-6 days for 12 sessions. For each robotic motion training session subjects played 7 different games for 10 to 15 minutes each. Subjects played the games at their own pace. Therefore, game progress, or the number of repetitions completed, varied from subject to subject. Subjects were seated in a chair in front of a 50 in. flat screen monitor. A research assistant was seated to the subject's right side to provide instruction. Subjects were held in a neutral seating position with an elastic band restraint. The experimental setup is depicted in Fig. 2.

III. RESULTS

A. *Hypothesis Testing*

Hypothesis tests were used to compare various measures before and after the treatments. Generally speaking, non-parametric hypothesis tests for low sample sizes (such as this study) require an especially large difference to distinguish populations. Notwithstanding, for non-parametric data, there were no statistically significant differences between measures taken before and after the treatments.

Paired T-tests were performed for parametric measures for all groups before and after the treatments. Range of motion in the shoulder showed statistically significant differences (p-value < 0.05) for shoulder abduction and external rotation following bilateral movement training and standard care. A one-way ANOVA was then performed between the three treatment groups for both shoulder ROM measures. There was no significant difference between the three treatments for shoulder abduction and shoulder rotation ROM with $p = 0.43$ and 0.29 respectively. Therefore, while shoulder ROM appeared to improve significantly, there was still not a large enough of a difference between groups to resolve a differences between the three treatments.

The percent-improvement for each measure is summarized in Fig. 3 in spider charts. The scales all range from -100% to +100%. Percent improvements are reported as average values for parametric data and median values for non-parametric data. Points that fall on the 0% line indicate that there is not an average, or median difference between measures taken before and after the treatment. Some measures, such as ROM, had a favorable result if the ROM went up. Other measures, such as spasticity, [3] indicated a favorable result if the measure goes down. Therefore, Fig. 3 depicts only improvements. As such, if the percent change was -41% (lower) for elbow flexion spasticity after bilateral motion training, the result is reported in Fig. 3 as a +41% improvement.

TABLE I
VARIOUS MEASURES OF IMPROVEMENT

Category	Test Name	Units	Description
Range of Motion	Fugl-Meyer Assessment	Ordinal	This assessment is not strictly a range of motion test and it also relates to quality of movement [12].
	Shoulder, elbow, and wrist	Degrees	The respective joints were measured with a plastic goniometer.
Strength	Grip	Newtons	Measured with a Jamar hand dynamometer (Lafayette Instrument Company, Lafayette, IN).
	Lateral Pinch	Newtons	Measured with a Microfet 2 hand dynamometer (Hoggan Health Industries, Draper UT).
	3-Point Chuck	Pounds	Measured with a hand Microfet 2 dynamometer.
	Wrist, elbow, and shoulder	Ordinal	Manual muscle test [13].
Coordination and Time Based	Average Wolf Time	Seconds	The Wolf Motor Function Test [14] typically measures the time to complete specific tasks. Rather than report the times for all tests, only the average of all tasks are reported here.
	Box and Block	Blocks/Minute	Number of blocks across a partition during a standard time [15].
	Finger Tapper	Taps/ Minute	Number of finger taps accomplished during a standard time [16].
	Digital Reaction Time	Milliseconds	How fast a subject can click on and off a stopwatch [17].
Psychological	Saint Louis University Mental Exam (SLUMS)	Ordinal	Measures for cognitive impairment that may have been caused by the CVA [18].
	Beck Depression Inventory (BDI)	Ordinal	A measure of depression [19].
	Pain Scale	Ordinal	A picture based self-assessment of pain used in clinics.

Included are the various tests that were conducted before and after each treatment.

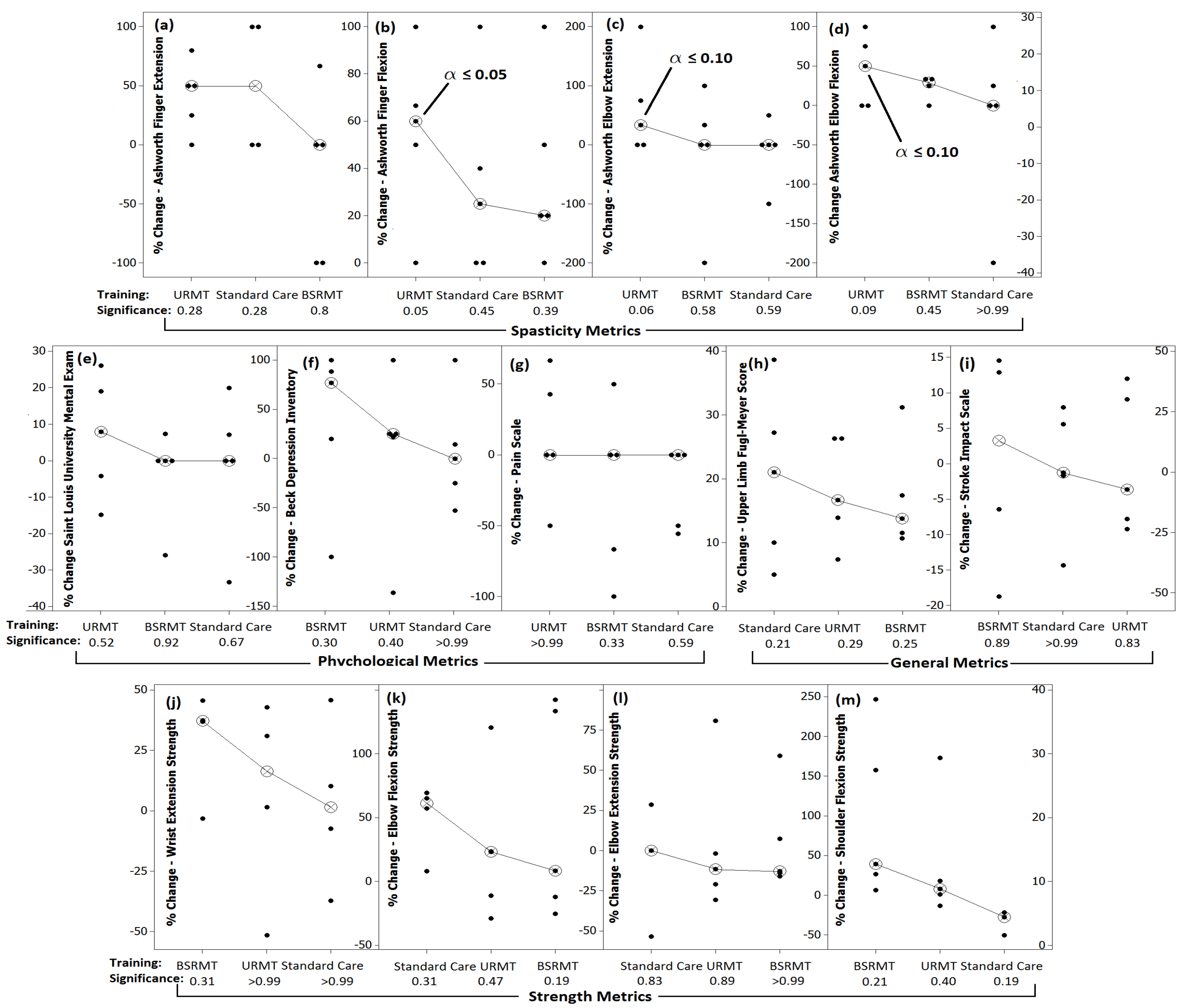

Figure 4 Individual value plots of clinical measures for non-parametric data. Individual values represent percent *improvements* as measured before and after the intervention. Also depicted are significant (p ≤ 0.05), or marginally significant (p ≤ 0.10) changes as determined by a Wilcoxon test. Connecting lines attach median values. Note, for cases where a decrease in a metric is regarded as an improvement the individual values are given positive, and vice-a-versa.

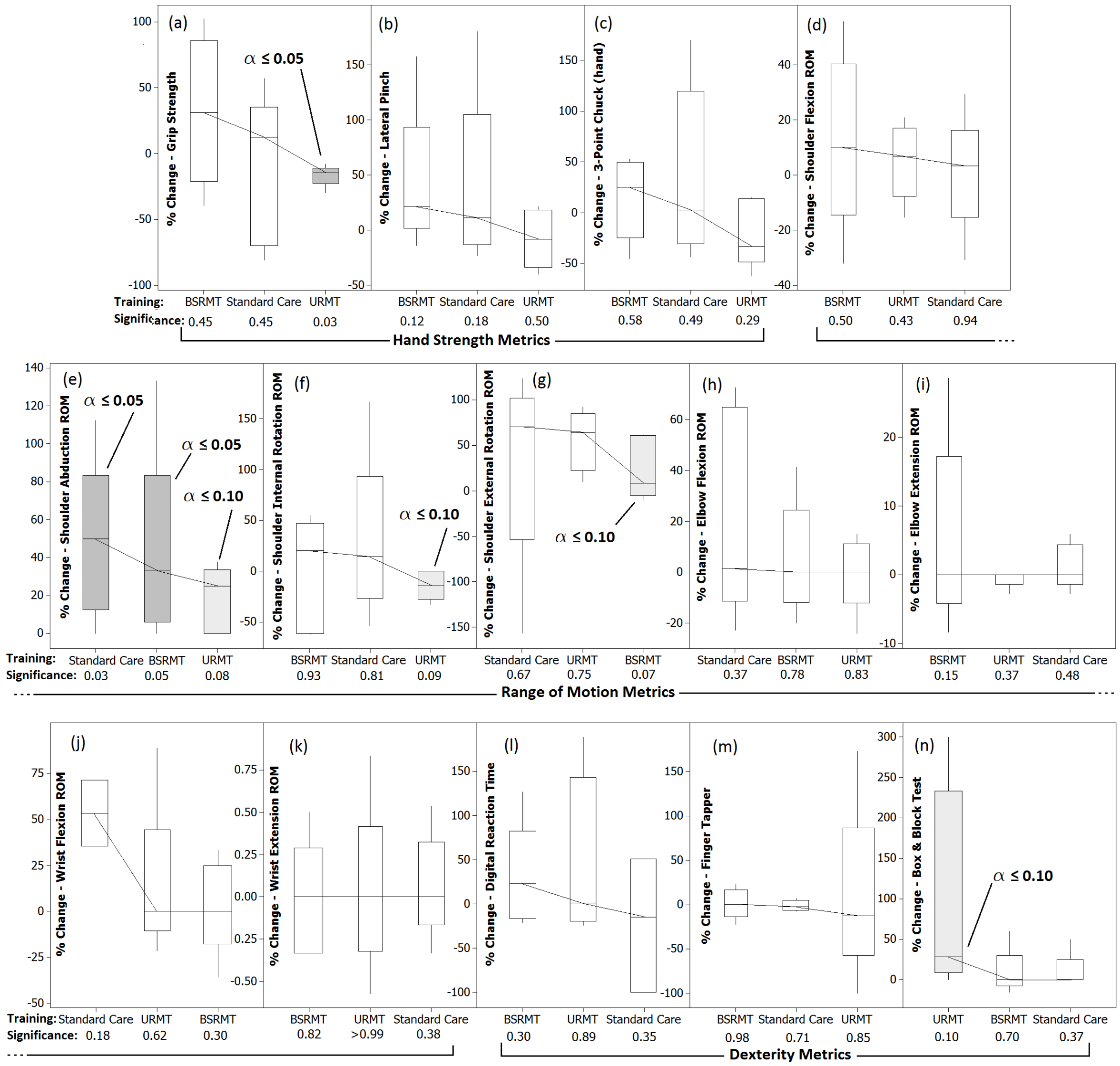

Figure 5 Box plots of clinical measures for parametric data. Individual values represent percent *improvements* as measured before and after the intervention. Also depicted are significant ($p \leq 0.05$), or marginally significant ($p \leq 0.10$) changes as determined by a paired t-test. Connecting lines attach mean values.

Consistent with the hypothesis tests, notice that there was an improvement for all treatments in terms of shoulder abduction ROM. Conversely, the ROM for shoulder external rotation was improved following robotic motion training but diminished after standard care. A graphical summary of all non-parametric data is provided in Fig. 4. A summary of all parametric data is provided in Fig. 5.

IV. DISCUSSION

Twenty-eight different metrics were considered in this paper. Of those various metrics, only ROM in the shoulder showed significant differences. In particular, bilateral symmetric motion training appeared to improve ROM in the shoulder. These results have two implications. The first implication is that robotic motion training seems to have been more effective for the shoulder than the wrist and elbow. An explanation for this effect requires a more detailed analysis of the kinematic data collected by the EXO and is outside the scope of this paper [8] [11].

The second implication of these results is that robotic bilateral therapy might be more effective than unilateral therapy. Indeed, while both therapy regimes resulted in a slight improvement for ROM of the shoulder, only bilateral movement training resulted in a statistically significant improvement. Some have proposed bilateral training as a therapeutic approach [20]. The arguments for bilateral training often have neurological justifications. It has been shown that a different region of the brain is involved in symmetric motion. If this region of the brain is undamaged by a Cerebral Vascular Accident (CVA) it is believed that symmetric therapy might promote neural plasticity in the undamaged region, thus leading to improved therapeutic outcomes.

Another explanation for more favorable outcomes of bilateral versus unilateral movement training could relate to the type of assistance being provided. For unilateral subjects, only the Flower Game provided assistance for the subjects to reach their targets. The other games typically involved unstructured play that involved a moving ball. Because the targets were often moving, the required arm trajectory and speeds of unilateral subjects were indeterminate. Therefore, unilateral subjects had no assistance other than gravity compensation for all but the Flower game. However, for the bilateral treatments the subject's affected arm was compelled to move symmetrically with the unaffected arm. In this way the robot provided assistance for every game. Additionally, that assistance was also consistent with the natural movements that a given subject chooses to make with their unaffected arm. Therefore, the improved outcomes of the bilateral treatment group over the unilateral treatment group might instead be related to the greater amount of partial assistance provided by the robot.

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