

Robot-Assisted Movement Training Compared With Conventional Therapy Techniques for the Rehabilitation of Upper-Limb Motor Function After Stroke

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ABSTRACT. Lum PS, Burgar CG, Shor PC, Majmundar M, Van der Loos M. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. *Arch Phys Med Rehabil* 2002;83:952-9.

Objective: To compare the effects of robot-assisted movement training with conventional techniques for the rehabilitation of upper-limb motor function after stroke.

Design: Randomized controlled trial, 6-month follow-up.

Setting: A Department of Veterans Affairs rehabilitation research and development center.

Participants: Consecutive sample of 27 subjects with chronic hemiparesis (>6mo after cerebrovascular accident) randomly allocated to group.

Interventions: All subjects received twenty-four 1-hour sessions over 2 months. Subjects in the robot group practiced shoulder and elbow movements while assisted by a robot manipulator. Subjects in the control group received neurodevelopmental therapy (targeting proximal upper limb function) and 5 minutes of exposure to the robot in each session.

Main Outcome Measures: Fugl-Meyer assessment of motor impairment, FIM™ instrument, and biomechanic measures of strength and reaching kinematics. Clinical evaluations were performed by a therapist blinded to group assignments.

Results: Compared with the control group, the robot group had larger improvements in the proximal movement portion of the Fugl-Meyer test after 1 month of treatment ($P < .05$) and also after 2 months of treatment ($P < .05$). The robot group had larger gains in strength ($P < .02$) and larger increases in reach extent ($P < .01$) after 2 months of treatment. At the 6-month follow-up, the groups no longer differed in terms of the Fugl-Meyer test ($P > .30$); however, the robot group had larger improvements in the FIM ($P < .04$).

Conclusions: Compared with conventional treatment, robot-assisted movements had advantages in terms of clinical and biomechanical measures. Further research into the use of robotic manipulation for motor rehabilitation is justified.

Key Words: Arm; Cerebrovascular accident; Movement; Rehabilitation; Robotics; Therapy.

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WE REPORT THE RESULTS of a clinical trial comparing robot-assisted movement training with conventional techniques for motor rehabilitation of the upper limb after stroke. The robot-assistance is provided by a therapy system called mirror image movement enabler (MIME), in which a robot manipulator applies forces to the more affected forearm during goal-directed movements (fig 1). Efforts toward developing robotic treatments are motivated by the increasing public health burden associated with stroke-related disability¹ and the current emphasis on cost reduction in health care that has resulted in shorter inpatient rehabilitation length of stay.² These factors emphasize the need for optimal interventions for motor rehabilitation after stroke. Integration of robotic therapy into current practice could increase the efficiency and effectiveness of therapists by alleviating the labor-intensive aspects of physical rehabilitation and by enabling novel modes of exercise not currently available.

A key feature of MIME is that subjects at any impairment level can repetitively practice and complete stereotyped movement patterns. There is increasing evidence that active repetitive practice of movements can have a profound effect on recovery from brain injury. In animal models, active retraining coupled with pharmacologic agents can increase the rate of recovery from brain injury.³ Active retraining can also positively shape the cortical reorganization associated with motor recovery following brain injury.⁴ In chronic stroke subjects, constraint-induced therapy (CIT) can lead to substantial increases in use of the more affected limb in activities of daily living (ADLs).⁵⁻⁷ This therapy involves intensive repetitive exercise of the more affected limb coupled with constraint of the opposite limb and results in positive cortical reorganization in the motor cortex.⁸

In less severely impaired stroke subjects, simple repetitive exercise may be superior to other types of therapy. CIT has recently been shown to have advantages relative to neurodevelopmental treatment of equal intensity.⁹ Other studies have reported that repetitive practice of hand and finger movements against loads resulted in greater improvements in motor performance and functional scales than Bobath-based treatment,¹⁰ transcutaneous electric nerve stimulation,¹⁰ and supratherapeutic electric stimulation of hand and wrist muscles.¹¹ Parry et al¹² reported that additional treatment, in the form of repetitive practice of movements and functional activities with a trained assistant, was more effective than additional conventional

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treatment from a physical therapist that focused on teaching techniques and encouraging self-practice. Although they reported that neither of these additional treatments were effective in more severely impaired subjects, other studies have shown that highly repetitive and stereotyped movements can be effective in these subjects if the movements are facilitated by external forces applied to the limb¹³ or by neuromuscular stimulation.^{14,15}

Thus, it appears that unassisted repetitive movement is effective in persons who have the ability to complete at least a portion of the movements, but external assistance is required in more severely impaired subjects. These studies support the concept of a treatment technique that supports and assists repetitive and stereotyped movements in severely impaired subjects, progressively reduces assistance as the subject improves, and applies minimal assistance or even resistance to movement for mildly impaired subjects. Robotic devices can continuously and precisely provide this technique, potentially improving the quality of rehabilitative treatment after stroke. Positive results have been reported from the clinical testing of MIT-MANUS, a 2 degree-of-freedom robot manipulator that assists shoulder and elbow movement by moving the hand of the patient in the horizontal plane.¹⁶ Stroke patients interact actively or passively with MIT-MANUS, as visual, auditory, and tactile feedback is provided during goal-directed movements. When compared with controls who received only minimal exposure to the robot, subacute stroke patients who received 25 hours of robot exercise had greater gains in proximal arm strength, reduced motor impairment at the shoulder and elbow, and greater recovery of ADL function.¹⁶

Despite these encouraging results, many questions regarding robotic manipulation remain unanswered. The MIT-MANUS results showed that subacute patients who received robotic therapy in addition to their regular therapy improved more than patients who did not receive this added robot therapy. However, several meta-analyses have concluded that greater intensity of conventional therapy is also effective, resulting in decreased levels of impairment, disability,^{17,18} and reduced mortality.¹⁹ For robotic manipulation to gain clinical acceptance, it must first be shown that it offers advantages to conventional therapy or at least is no less effective than conventional therapy. The goal of the MIME study was to measure the effectiveness of a therapy program of robotic manipulation compared with an equally intensive program of conventional therapy techniques. We chose to use chronic subjects to minimize the confounding effects of spontaneous recovery and to maximize our chances of finding a significant result with a relatively small sample size. Preliminary reports of this study have appeared elsewhere.^{20,21}

METHODS

MIME System

Subjects were seated in a wheelchair in front of a height-adjustable table (fig 1). Straps and a contoured seat^a limited torso movement, and the affected limb was strapped to a forearm splint that restricted wrist and hand movement. A robot manipulator^b was attached to the splint and applied forces to the limb that would normally be provided by a therapist. The robot's 6 degrees of freedom allowed the forearm to be positioned within a large range of positions and orientations in 3-dimensional space. The forces and torques between the robot and the affected limb were measured by a 6-axis sensor^c (at .25N resolution).

We used 4 modes of robot-assisted movement, all patterned after exercises currently used in therapy. In passive mode, the

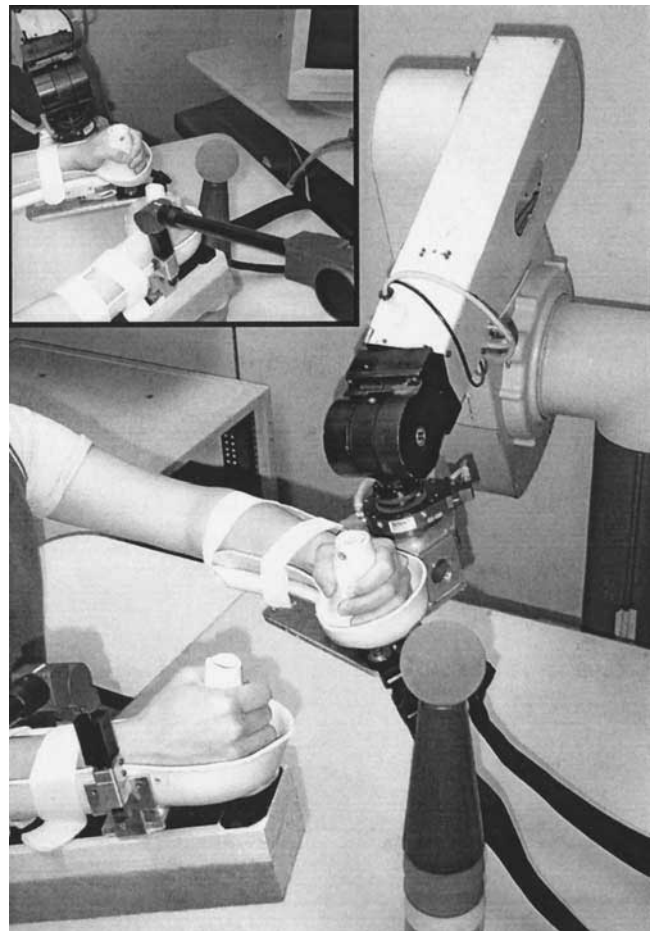


Fig 1. An individual performing bimanual robot-assisted training. Reprinted with permission.²²

subject relaxed as the robot moved the limb toward a target with a predetermined trajectory. In active-assisted mode, the subject triggered initiation of the movement with volitional force toward the target and worked with the robot as it moved the limb. In active-constrained mode, the robot provided a viscous resistance in the direction of the desired movement and spring-like forces in all other directions as the subject attempted to reach toward the target with maximal effort. In bimanual mode, the subject attempted bimanual mirror-image movements while the robot assisted the affected limb by continuously moving the affected forearm to the contralateral forearm's mirror-image position and orientation. During bimanual mode, the 2 forearms were kept in mirror-symmetry by a position digitizer^d (accuracy, <0.5mm), which measured the movement of the contralateral forearm and provided coordinates for the robot motion controller (1kHz update rate). The digitizer is capable of measuring arbitrary forearm trajectories with minimal resistance to movement (effective weight, <2N).

Several redundant safety features were incorporated into the system. The software cut power to the robot if the error between the commanded and measured angles of the robot's joints exceeded a critical value. This would occur if the robot had encountered unexpectedly large resistance. A commercially available pneumatic device^e cut power to the robot when the torque applied to the forearm exceeded a critical value (20Nm). Straps limited the robot to a safe range of motion

(ROM). The experimenter always kept an emergency stop button nearby.

Participants

Subjects were included in the study if they had a diagnosis of a single cerebrovascular accident (CVA), were more than 6 months post-CVA, and had an obvious deficit in upper-limb motor function as a result of this CVA. Subjects had completed all formal outpatient therapy but continued with any home-based exercise regimen or community-based stroke programs they were enrolled in at the time of intake into the study. Subjects were excluded from the study if they exhibited any upper-extremity joint pain or ROM limitations that would limit their ability to complete the protocols. Subjects with any unstable cardiovascular, orthopedic, or neurologic conditions were also excluded. Cognitive impairments were screened with the Cognistat instrument,²³ and subjects were excluded if they were unable to cooperate with the study tasks. Thirty subjects were enrolled in the study.

Procedures

Once accepted into the study, subjects were randomly assigned to the robot or control group based on a list of random numbers. Over a 2-month period, both groups received twenty-four 1-hour treatment sessions held in the same treatment area and supervised by a single occupational therapist. Thus the 2 groups received equal intensity and duration of treatment. In each treatment session, robot group subjects received 50 minutes of robot-assisted movement, whereas control group subjects received 50 minutes of conventional treatment that targeted proximal upper-limb function that was based on neurodevelopmental therapy²⁴ (NDT). All subjects received 5 minutes of tone normalization and limb positioning at the beginning and end of each session. Subjects were not informed of the explicit goals of the clinical trial, only that the effectiveness of 2 treatments was being tested. All protocols were approved by the local institutional review committee and informed consent was obtained from all subjects.

Robot group protocol. In the robot group, emphasis was placed on targeted reaching movements that started close to the body and ended further away. Therefore, elbow extension was a component of all of these movements. Four point-to-point reaching directions were trained: forward medial (shoulder flexion, adduction), directly forward (shoulder flexion), forward lateral (shoulder flexion, abduction, external rotation), and directly lateral (abduction, external rotation). For each of these 4 directions, targets could be located at tabletop, shoulder, or eye level. These 12 targeted reaching movements formed a core set of movements. Subjects practiced some or all of these movements in each session (the eye level movements were usually only used for mildly impaired subjects). Each movement progressed from the easiest exercise modes (passive and bimanual) to the most challenging (active constrained). During active-constrained movements, feedback of the fraction of the movement completed or the time to complete 3 repetitions was used to track and motivate performance. Time permitting, tracing of circles and polygons and isolated elbow extension movements were practiced, all assisted by the robot. Movements were kept well within each subject's passive ROM. All subjects spent approximately 12 minutes in bimanual mode and 5 minutes in passive mode. A total of 20 minutes were spent in the active-assisted and active-constrained modes, with the ratio varying depending on the level of the subject. Lower-level subjects spent as much as 7 to 8 minutes in active-assisted mode, while higher-level subjects skipped directly to active-constrained mode.

Control group protocol. A typical control group session involved approximately 10 minutes of establishing a physical postural base of support coupled with assessing and facilitating the alignment of the shoulder. Approximately 35 minutes were devoted to graded application of the arm's use in functional leisure and self-care tasks. Emphasis was placed on the re-education of muscles using a sensorimotor approach to control motor output. Subjects needed to show ability to independently perform basic mass functional movements before progressing to more isolated advanced functional patterns. Progression within each movement was facilitated by increasing the number of repetitions, weight of item being handled, height at which tasks were done, and so on. The last 10 minutes were used for practice of the highest level task that was completed, with review, and additional assessment of the shoulder. Control subjects received exposure to the robot for 5 minutes within each session. The robot provided a moving target and subjects attempted to track the target with their hand or to stack cones on top of the robot end effector as it moved. Therapy was provided by an NDT-certified therapist with 9 years of experience in treating neurologically injured patients. Consultations regarding the subjects were held with another equally experienced therapist as needed.

Evaluations

Function. An occupational therapist blinded to group assignment tested all subjects with a battery of clinical evaluations immediately before the start of treatment, after 1 month of treatment, immediately posttreatment (at 2mo), and 6 months after the end of treatment. Motor and sensory impairment were assessed with the upper-limb portion of the Fugl-Meyer assessment.²⁵ Compared with the motor Fugl-Meyer, the sensory portion of the Fugl-Meyer is less commonly reported and involves assessment of light touch and proprioception at the arm, hand, and wrist. The validity and reliability of the Fugl-Meyer have been established.^{25,26} The Barthel Index^{27,28} and the self-care and transfers sections of the FIMTM instrument^{29,30} were used to measure improvements in basic ADLs. Both of these assessments have been used extensively in stroke studies, and both have been proven to be valid and reliable measures.

Strength. Evaluation of strength in the more affected limb was performed on 2 occasions within the week preceding the start of treatment, and again on 2 occasions within the week immediately after the treatment period. Subjects were seated in a wheelchair in front of a table, and straps restrained torso movement. To measure shoulder and elbow strength, the forearm was strapped to a custom-reinforced splint that restricted wrist and hand movement. This splint was attached to the table through a 6-axis force/torque sensor (described previously). The elbow was flexed to 90°, and the shoulder was placed in 30° abduction, neutral flexion, and neutral rotation. Length measurements of the upper-limb segments were taken and used to estimate the location of the elbow and glenohumeral joint centers relative to the sensor. A simple algorithm based on these measurements converted the sensor data to the following joint torque values: elbow flexion and extension, shoulder flexion and extension, shoulder abduction and adduction, and shoulder internal and external rotation. These joint torques were continuously presented to the subject on a computer screen with bar graphs. For each of these 8 joint actions, 2 maximum voluntary contractions (MVCs) were performed. The experimenter first demonstrated the required torque by manually resisting the less affected limb and instructing the subject to "push against my hands." The hands were placed in standard positions, and the experimenter applied force in directions to encourage the activation of the target muscle

groups. The following instruction was given to the subject. "Now do the same action with your other arm. Push against the splint and move the line on the screen as high as possible. Hold for 2 seconds and relax." Verbal encouragement of the form "go, go, go" was given during the effort, but no additional instructions were given until the 20-second trial was over. No practice trials were given.

Reach. The extent of each subject's reach in the more affected arm was evaluated twice within the week preceding start of treatment, and again on 2 occasions within the week immediately after the treatment period. To measure reaching ability, the arm was strapped to a lightweight forearm splint. The stylus of the digitizer (described previously) was attached to the splint to measure the position and orientation of the hand in 3 dimensions. The subject started at a standard position and reached toward standardized targets. Targets were placed at locations that corresponded to the tabletop and shoulder level reaching directions used in the robot training. Targets were positioned far enough away from the subjects so that they could be touched only with nearly full extension of the limb in that direction. The repeatability of the target and start locations was made possible by a pegboard with a grid of holes, which was placed over the surface of the table. Subjects were given the following instruction: "Try to move your hand as close to the target as possible. Move at your own pace. When you feel you have gotten as close as you can, return to the start position." No further instructions were given. Two trials were performed for each target location. Data were collected at 200Hz and stored on computer for later analysis.

Data Reduction

To analyze the MVC data, the peak torque level achieved in each trial was calculated after a 0.5-second moving average filter was passed across the data. For each joint action, a subject's pretreatment strength level was taken to be the peak torque level achieved during all MVC trials for that joint action (trials from the 2 pretreatment evaluation sessions were grouped together). The same procedure was applied to get posttreatment strength levels. To compare strength gains across subjects of vastly different body types, a percentage gain in strength was obtained by normalizing each subject's raw strength gain with normative strength values. An estimate of normative strength for each subject was obtained from regressions on age, sex, and weight found in the literature.^{31,32} We chose to use normative data reported in the literature instead of measuring strength in the contralateral limb because of the possibility of strength losses ipsilateral to the CVA.³³

The reaching data were reduced in the following manner. For all reaching trials toward a particular target location, the minimum distance between the hand and the target was calculated. The smallest value (best performance) from all posttreatment trials was subtracted from the smallest value obtained from all pretreatment trials. This parameter was called the increase in reach extent toward that target for that subject.

Statistical Analysis

Baseline differences between groups were evaluated with Mann-Whitney *U* (continuous and ordinal data) and chi-square tests (categorical data). The motor Fugl-Meyer data were divided into proximal (shoulder and elbow movement, 36 points) and distal (hand and wrist movement, 24 points) portions for statistical analysis. All the clinical outcome data sets (proximal Fugl-Meyer, distal Fugl-Meyer, Barthel Index, FIM) passed the Kolmogorov-Smirnov test for normality. However, the gains in proximal Fugl-Meyer and FIM scores had large between-group differences in variance; both data sets failed the Levene test of

homogeneity of variance, which is an assumption of parametric analysis. The proximal Fugl-Meyer scores passed the Levene test after the variances were stabilized with a square-root transformation of the data. Analysis of transformed proximal Fugl-Meyer, distal Fugl-Meyer, and Barthel scores was done with a repeated-measures analysis of variance (ANOVA), with group (robot, control) entered as the between-subjects factor, and time of evaluation (pre-Tx, mid-Tx, post-Tx, follow-up) entered as the within-subjects factor. Significant effects in the repeated-measures ANOVA were further investigated with univariate analysis of covariance (ANCOVA) tests at each evaluation time, with pretreatment scores entered as a covariate. Entering the pretreatment scores as a covariate removed the data variance inherent in the subject pool's large range of pretreatment impairment and disability levels. Even after a square-root transformation, FIM scores failed the Levene test; therefore, nonparametric methods were used to analyze these data. The robust rank-order test³⁴ was used to detect differences between groups at each evaluation time. This test is similar to the more commonly used Mann-Whitney *U* test but does not make the assumption of homogeneity of variance.

Analysis of strength changes was performed with a multivariate analysis of variance (MANOVA) using treatment group (robot, control) as the between-subjects factor, and joint action (8 unique actions) as the within-subjects factor. The Wilks λ statistic was used to test the null hypothesis that there was no difference between groups in terms of strength gains when considering all 8 joint actions together. The Wilks λ is analogous to the *F* statistic used to test the null hypothesis in univariate ANOVA. The MANOVA method was used because the 8 strength measurements were likely to correlate. Several muscles of the shoulder and elbow contribute to more than 1 of the tested joint actions (ie, biceps contributes to both shoulder flexion and elbow flexion strength). Similarly, performance improvements in the 8 reaching movements are also likely to correlate (ie, elbow extension is a component of all 8 movements). Therefore, analysis of increases in reach extent paralleled the analysis of strength data with movement type (8 unique types) replacing joint action as the within-subjects factor. Data from high-level subjects who touched all targets during the pretreatment evaluations were not included in the analysis because no measurable improvement in reach extent was possible. On a few occasions, subjects could touch some targets, but not others during the pretreatment evaluation. To include data from these subjects in the MANOVA analysis, data for targets that were touched were handled with the Expectation Maximization method.³⁵ Follow-up testing of between-group differences in each of the dependent variables was performed with univariate ANOVA.

RESULTS

Thirty subjects were enrolled into the study. Two subjects dropped out during the intervention period because of medical complications unrelated to the study, and 1 subject's data were not included in the analysis when it was learned that her hemiparesis was not caused by a CVA. Thus, data from 27 subjects were analyzed. One subject could not be located for the 6-month follow-up. There were no significant baseline differences between groups in terms of age, months post-CVA, sensory impairment, cognitive level, side of lesion, or any of the clinical outcome measures (table 1). Significantly more men were randomized to the robot group ($P=.04$), but we have no reason to believe that this biased the results. To further investigate balance between groups in terms of impairment level, subjects were categorized as severe (Fugl-Meyer <20), moderate ($20 \leq$ Fugl-Meyer <40), or mildly impaired (Fugl-

Table 1: Baseline Characteristics

	Robot (n=13)	Control (n=14)	Test	P
Age	63.2±3.6	65.9±2.4	U	.45
Months post-CVA	30.2±6.2	28.8±6.3	U	.73
Sex				
Male	12	8	χ^2	.04*
Female	1	6		
Side of Lesion				
Right	9	10	χ^2	.90
Left	4	4		
Sensation (max score, 12)	8.9±1.1	9.5±1.0	U	.98
Cognistat (max score, 84)	74.9±2.2	76.6±2.1	U	.53
Fugl-Meyer (max score, 66)	24.8±4.5	26.6±4.7	U	.73
Barthel Index (max score, 100)	90.8±2.6	84.8±3.3	U	.23
FIM (max score, 63)	54.5±2.1	52.0±2.2	U	.37

NOTE. Values are mean ± standard error of the mean (SEM) or n.

Abbreviations: U, Mann-Whitney U test for 2 independent samples; FIM, FIM self-care and transfers sections.

* $P < .05$.

Meyer ≥ 40). The severe:moderate:mild distribution was 7:3:3 in the robot group and 7:3:4 in the control group. These 2 distributions were not significantly different ($P = .95$, χ^2 test).

Evaluations

Function. Table 2 summarizes the clinical outcomes. Repeated-measures ANOVA revealed that, in general, subjects improved significantly in both the proximal ($P < .001$) and distal ($P < .001$) portions of the Fugl-Meyer test as a result of the interventions (time effect). Trend analysis on the proximal Fugl-Meyer test revealed a significant group-by-time quadratic interaction ($P < .03$), indicating a different pattern of improvement between groups. The plot of average gains in the proximal Fugl-Meyer test for each group at each time point reveals the nature of this quadratic interaction (fig 2). Univariate ANCOVA tests showed that the robot group had significantly greater improvements compared with the control group after 1 month of treatment ($P < .05$) and after 2 months of treatment

($P < .05$), but there was no difference between groups at the 6-month follow-up ($P > .30$). The group by time interaction was not significant in the distal Fugl-Meyer test ($P > .50$). No significant effects were present in the Barthel Index. Nonparametric analysis of FIM scores with the robust rank-order test resulted in no group differences after 1 month ($P > .999$) or after 2 months of treatment ($P > .20$). However, the robot group had significantly greater gains in FIM scores at the 6-month follow-up ($P < .04$).

Strength. Strength data from 25 subjects were available for analysis (data from 2 subjects were lost due to technical difficulties). In this reduced subject pool, there were no baseline group differences in age, months since CVA, side of lesion, impairment, or disability ($P > .16$). The MANOVA on strength changes found that the robot group had significantly greater improvements in proximal arm strength than the control group after 2 months of treatment ($P < .02$, Wilks λ). Univariate ANOVA tests of individual joint actions showed that robot group strength gains were significantly greater than control group gains in elbow extension, abduction, adduction, and shoulder flexion ($P < .05$) (fig 3). There were trends in favor of the robot group in external rotation, internal rotation, and shoulder extension.

Reach. Reaching data from 19 subjects were available for analysis (data from 5 subjects were lost due to technical difficulties, 3 subjects touched all targets during the pretreatment evaluations). In this reduced subject pool, there were no baseline group differences in age, months post-CVA, side of lesion, impairment, or disability ($P > .21$). The MANOVA showed that the robot group had significantly greater improvements in reach extent compared with the control group after 2 months of treatment ($P < .01$, Wilks λ). Univariate ANOVA tests of individual movements showed that robot group improvements were significantly greater than control group improvements in 6 of 8 movements ($P < .05$), with trends in favor of the robot group in the other 2 movements (fig 4).

Analysis

Pearson correlation coefficients were calculated between improvement in the main outcome measures and several factors that could influence the effectiveness of the treatments (pre-Tx sensation level, Cognistat, months since CVA, pre-Tx Fugl-Meyer score). In both groups, pre-Tx Fugl-Meyer scores positively correlated with strength gains (averaged over the 8 joint

Table 2: Average Gains in Scores From Clinical Outcomes

	Robot (n=13)	Control (n=14)	P†
Fugl-Meyer (proximal)			
After 1mo of Tx	2.2±0.8	0.5±0.2	.043*
After 2mo of Tx	3.3±0.7	1.6±0.3	.044*
6-mo follow-up	3.6±1.0	2.8±0.8	.379
Fugl-Meyer (distal)			
After 1mo of Tx	1.2±0.4	1.1±0.4	—
After 2mo of Tx	1.4±0.5	1.5±0.5	—
6-mo follow-up	1.3±0.4	2.0±0.6	—
Barthel Index			
After 1mo of Tx	0.0±0.0	0.0±0.0	—
After 2mo of Tx	1.2±1.2	0.0±0.0	—
6-mo follow-up	2.1±1.3	0.4±0.4	—
FIM			
After 1mo of Tx	0.0±0.0	0.0±0.0	.999
After 2mo of Tx	0.2±0.2	0.0±0.0	.215
6-mo follow-up	2.5±1.2	0.1±0.1	.039*

NOTE. Values are mean ± SEM.

* $P < .05$.

† Univariate ANCOVA test used on proximal Fugl-Meyer data (after the square-root transformation). Robust rank-order test used on the FIM data.

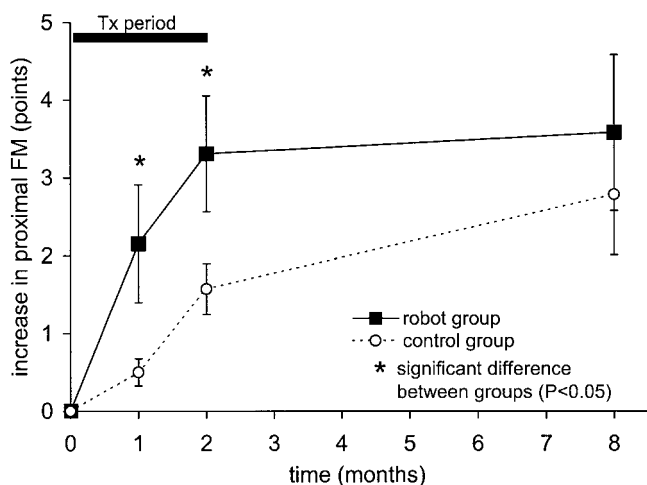


Fig 2. Average change in proximal Fugl-Meyer (FM) score for the robot and control groups. After a significant group-by-time effect was found in the repeated-measures ANOVA, univariate ANCOVA at each time point revealed significant differences between groups at 1 and 2 months after the start of treatment but no group difference at the 6-month follow-up. Error bars are SEM.

actions, $P < .02$ for the control group, $P < .01$ for the robot group). In the control group, subjects with better sensory and cognitive function appeared to be more responsive to the treatment. In controls, sensation level positively correlated with gains in strength ($P < .05$) and reach extent (averaged over the 8 movements, $P < .01$); Cognistat scores correlated with strength gain ($P < .03$).

DISCUSSION

Compared with conventional treatment of equal intensity and duration, a program of robot-assisted movements had advantages after 2 months of treatment in terms of decreasing impairment, improving strength, and increasing reach extent. However, it remains to be determined if robot-assisted movement has unique therapeutic aspects that cannot be provided by

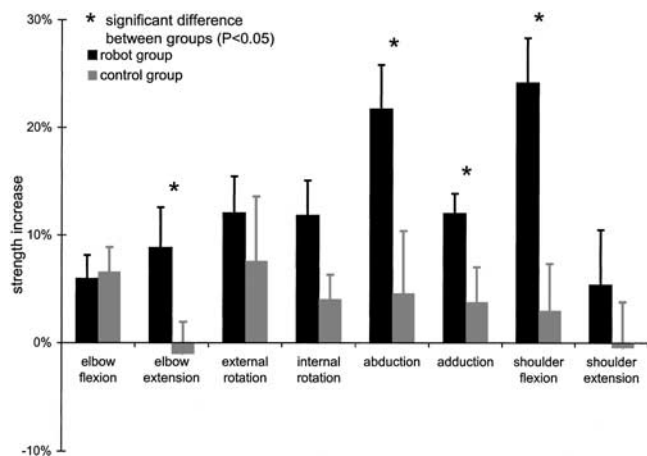


Fig 3. Average strength gains in 8 shoulder and elbow joint actions after 2 months of treatment. After a significant group effect was found in the MANOVA (all actions considered together), ANOVA of each joint action revealed significant differences between groups in 4 of 8 joint actions. Error bars are SEM.

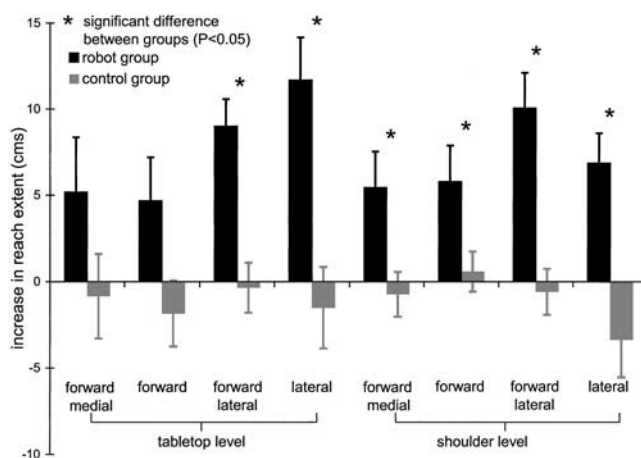


Fig 4. Average increase in reach extent (cm) toward 8 different targets after 2 months of treatment. After a significant group effect was found in the MANOVA (all 8 movements considered together), ANOVA of each movement revealed significant group differences in 6 of 8 movements. Error bars are SEM.

a human therapist. All of the MIME training modes can be performed in some fashion with the therapist performing the functions of the robot, and we have no evidence that the robot group would have outperformed the control group if the 2 treatments were matched in terms of content (eg, movement types, modes of assistance, repetitions). In fact, some of the significant differences between groups can be explained by differences in the content of the 2 treatments. Greater strength gains in the robot group could have been due to the active-constrained mode, which is a form of maximal-effort resistance exercise. This type of exercise was not performed in the control group. These strength gains could have been the basis for the robot group's greater improvements in reach extent and Fugl-Meyer scores after 2 months of treatment. However, our results do suggest that the current content of conventional therapy is not optimal, at least for chronic subjects. More emphasis could be placed on repetitive practice of movements, and the use of maximal effort during these movements should be considered. Moreover, we have shown that these repetitive movements are effective if facilitated by a robotic system.

When comparing rates of improvement in the proximal Fugl-Meyer test, the robot group increased at a rate that was 4 times greater than the control group in the first month (see fig 2). Improvement continued in the second month, but the rate was similar in both groups. This suggests that the enhanced effects of this particular robot therapy protocol were apparent only in the first month of treatment. Again, this finding might be explained by the content of the 2 interventions. Subjects had already received a considerable amount of conventional therapy by the time they were enrolled into the study. Thus the full benefits of conventional therapy may have already been realized. In fact, the criterion for stopping conventional therapy is often a plateau in response to that treatment. In contrast, subjects were not likely to have experienced the type of training delivered in the robot group before entry into the study. It is possible that some aspects of the lost motor function (eg, weakness) did not recover to their full potential during the conventional therapy that subjects received before entry into the study, but did respond to the robotic therapy during the study. This hypothesis might explain the greater rate of improvement in the robot group compared with the control group in the first month but not the second month.

In the 6-month period after the end of treatment, the robot group maintained the gains made during treatment, whereas the control group continued to improve to the point that the 2 groups did not differ significantly at the 6-month follow-up (see fig 2). This finding suggests that conventional techniques may have a larger impact on individual home-based exercise programs than robotic treatment. This explanation is all the more plausible when considering that 1 goal of conventional treatment is to instruct patients to exercise properly on their own. Although many of the exercises performed by the control group could easily be performed at home, it might have been difficult or impossible for subjects to integrate the exercises performed during robotic treatment into their home-based programs. Because significant improvements occurred as a result of conventional NDT treatment, future studies should consider using a control group that receives matched intensity of conventional treatment instead of a control group that receives no therapy.

The robot group's improvement in FIM scores in the 6-month period after the end of treatment was unexpected. The inability to significantly affect disability is often reported in the literature. In a comprehensive review of 165 studies, Wagenaar and Meijer³⁶ concluded that experimental treatments in persons with hemiparesis from CVA often have effects on the parameters specifically trained, but that transfer to ADLs was minimal. However, our result was consistent with the MIT-MANUS clinical studies, in which robotic therapy in the subacute poststroke phase was found to positively affect disability levels.¹⁶ Nevertheless, this result should be viewed with caution, especially because the robot group did not show improvements in the proximal Fugl-Meyer test over this same 6-month period, and the FIM instrument does not penalize subjects who perform activities using compensation with the less affected limb. Future studies should consider the Motor Activity Log,⁵⁻⁹ which assesses the actual amount of use of the more affected limb in ADLs and the quality of movement. It would also have been useful to determine if the group differences at the 6-month point were retained 1 year after the treatment.

There was clear evidence of treatment specificity in the robot group. The robot treatment focused on the shoulder and elbow while the wrist and hand were splinted. As a result, the robot group had significantly greater improvements in their proximal Fugl-Meyer scores relative to the control group, but the change in distal Fugl-Meyer scores was no different between groups. There was also evidence of treatment specificity in the strength measurements. Relative to the control group, the robot group had significantly greater strength improvements in joint actions that received focused training (shoulder flexion, abduction, adduction, elbow extension). In contrast, strength gains in joint actions that were of secondary focus (elbow flexion, shoulder extension, internal rotation) were not significantly different between groups.

Our results are encouraging considering that many of the potential advantages of robot therapy were not implemented in this study's protocol. First, because robot-assisted movements can be performed with minimal or no supervision, higher intensity of therapy, beyond 3 hours a week, can be provided without requiring increased amounts of 1-on-1 attention from therapists. Second, movement trajectories of arbitrary shapes can be created and customized for each subject. Third, subject performance during training might be improved by immediate visual feedback of the forces the affected limb was producing. Fourth, integration of robot-assisted movement into regular treatment may further enhance its effectiveness. For example, the therapist might apply hands-on postural cues while the subject is performing robot-assisted tasks. Fifth, in the present

study, the robot-assisted movements were well within the subject's passive ROM. As safety measures improve, subjects will be allowed to work within their entire passive ROM. Sixth, several studies have investigated the use of force and kinematic measures during robotic treatment to quantify motor impairments more precisely,³⁷⁻³⁹ potentially providing the clinician with improved ability to assess patient progress.

The bimanual mode of robot-assistance is unique to MIME. In this mode, subjects attempt bimanual mirror-image movements while the limbs are maintained in mirror-image symmetry by the robot, which assists the affected limb by continuously moving the affected forearm to the contralateral forearm's mirror-image position and orientation. Conceptually, this type of robotic assistance is supported by a recent pilot study⁴⁰ with chronic subjects, which used a mirror placed in the vertical parasagittal plane during bimanual symmetrical movements to provide feedback to the patient in the form of visual images of a properly moving affected limb. The investigators found that subjects trained in this way had substantially greater improvements in limb movement than a control group in which the mirror was replaced by transparent plastic. They hypothesized that the proper visual input substitutes for lost proprioceptive input and recruits the premotor cortex into the rehabilitation process. They based this hypothesis on the fact that the premotor cortex is highly responsive to visual input,⁴¹ contributes to descending corticospinal tracts, and is involved in bimanual movements.⁴² This result supports the use of MIME's bimanual mode, which provides both visual and proprioceptive feedback of a properly moving limb in phase with the attempted movements.

CONCLUSION

Our results and the results from MIT-MANUS offer evidence supporting further research into robotic manipulation for poststroke therapy. Although MIME has many similarities with MIT-MANUS, several features distinguish the 2 systems. MIT-MANUS can be programmed to interact with the patient with low impedance, giving it a soft, compliant feel during movements in the horizontal plane. On the other hand, MIME can completely control both the position and orientation of the forearm in space and can accommodate a large range of complex 3-dimensional movement patterns. MIME's novel bimanual mode allows subjects at any impairment level to practice and complete mirror-image bimanual movements. Future research should identify what features are essential to the efficacy of robotic manipulation. Integration of robotic manipulation into current practice holds the promise of improving the quality of physical rehabilitation, alleviating its labor-intensive aspects, and increasing the efficiency of therapists.

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