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Robotic upper-limb neurorehabilitation in chronic stroke patients

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Abstract—This pilot study tested the effectiveness of an intense, short-term upper-limb robotic therapy for improvement in motor outcomes among chronic stroke patients. We enrolled 30 subjects with upper-limb deficits due to stroke of at least 6 mo duration and with a Motor Power Assessment grade of 3 or less. Over 3 wk, 18 sessions of robot-assisted task-specific therapy were delivered with the use of a robotic exercise device that simulates a conventional therapy known as skateboard therapy. Primary outcome measures included reliable, validated impairment and disability measures of upper-limb motor function. Statistically significant improvements were observed for severely impaired participants when we compared baseline and posttreatment outcomes ($p < 0.05$). These results are important because they indicate that improvement is not limited to those with moderate impairments but is possible among severely impaired chronic stroke patients as well. Moderately and severely impaired patients in our study were able to tolerate a massed-practice therapy paradigm with intensive, frequent, and repetitive treatment. This information is useful in determining the optimal target population, intensity, and duration of robotic therapy and sample size for a planned larger trial.

Key words: elbow flexion, MIT-Manus, motor impairment, motor skills, neuromotor recovery, neurorehabilitation, outcome measures, rehabilitation, robot-assisted therapy, robotics, shoulder abduction, stroke, therapy.

INTRODUCTION

Stroke is a significant cause of disability among adults in the United States [1]. Although rehabilitation is available for acute stroke patients, few options exist for patients with moderate-to-severe chronic motor deficits due to stroke. This may be because of the majority of motor deficit recovery occurs within 6-months poststroke [2]. Research on task-specific massed-practice therapy (intensive therapy administered in a concentrated manner such as constraint-induced movement therapy [CIMT])

Abbreviations: CIMT = constraint-induced movement therapy, FM = Fugl-Meyer, MIT = Massachusetts Institute of Technology, VA = Department of Veterans Affairs.

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indicates that motor deficits that remain beyond post-acute rehabilitation may be in part due to learned nonuse and may be modifiable among subjects with mild-to-moderate upper-limb impairment [3–7]. Preliminary research also indicates that the intensity of training may be the most important component in CIMT for producing a treatment effect [6,8–9]. The generalizability of these results to chronic stroke patients with moderate-to-severe impairments is unclear.

To date, robot-assisted task-specific training has been administered with a less-intensive paradigm and has been associated with improved upper-limb motor scores for acute [10] and chronic stroke patients [11] with mild-to-moderate impairment and also for chronic [12] stroke patients in pilot studies with moderate-to-severe impairment. Our purpose was to obtain preliminary data for a controlled trial of the efficacy of upper-limb robotic therapy in patients with moderate-to-severe chronic deficits due to stroke by delivering a massed-practice intervention of half the duration and twice the intensity than has been previously reported with the MIT-Manus (Massachusetts Institute of Technology, Cambridge) [11–12].

METHODS

We have evaluated the efficacy of robot-assisted task-specific training among 30 volunteer subjects. Inclusion criteria were shoulder and elbow deficits due to stroke, stroke onset at least 6 months before enrollment, and a Motor Power Assessment grade of 3 or less for elbow flexion and shoulder abduction on the hemiplegic side [13]. Exclusion criteria were inability to give informed consent, contractures or orthopedic problems limiting the range of joint movement in the potential study arm, and visual loss such that the patient would not be able to see the test patterns on the monitor of the training apparatus.

Following their enrollment, we evaluated participants three times over 4 weeks to ensure stability of arm function. We used an average of the scores from all three evaluations to create baseline values and used repeated-measures analysis of variance to assess stability at baseline. Participants received 18 sessions of therapy delivered over 3 weeks: two sessions a day at 1 hour each, 3 days a week.

Therapy was delivered with InMotion2, a commercial version of the MIT-Manus, a robot developed at the Massachusetts Institute of Technology, Cambridge, specifically for upper-limb neurorehabilitation [14]. Each training session consisted of goal-directed planar-reaching tasks that focused on the shoulder and elbow of the impaired arm. Subjects reached for eight targets equally spaced around a center target in a circular pattern with their involved arm using a novel performance-based algorithm to control the robot [15] while visual feedback on target location and robot handle motion was provided on a computer screen. The InMotion2 robot is highly backdrivable [16], which allows the patient to express movement. If the patient was unable to reach the target, the robot guided the patient's hand to the target. Subjects moved from the center target and back for each task in a clockwise direction; 672 specific arm movements were completed for each therapy session. A performance-based algorithm automatically adjusted the time and amount of assistance to reach each target, with each movement lasting between 1.5 and 4.5 s. Subjects rested during a 1-hour break between the first and second session each day.

Primary outcome measures included the upper-limb Motor Status Score [17], the Wolf Motor Function Test [18], the Motor Power Assessment [19], and the Fugl-Meyer (FM) Assessment upper-limb motor performance section [20]. An FM score of 15 or lower out of 66 defined impairment level as severe; otherwise, impairment level was defined as moderate. This was a clinically relevant division and was consistent with the level of joint action of patients; those having an FM score of 15 or below did not have any wrist or hand movement. Participants were evaluated for changes in motor function at the completion of the intervention and at 3 months postintervention. We used the Wilcoxon Signed Rank Test for paired data to evaluate differences in baseline and post-treatment outcomes and used SAS® (Statistical Analysis Software, Cary, North Carolina) to produce statistics [21].

The joint Department of Veterans Affairs and University of Maryland Institutional Review Board and the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects approved this study, and each patient gave written informed consent before enrollment.

RESULTS

Of the 30 subjects who enrolled, 27 completed the intervention and 22 returned for the 3-month evaluation. Reasons for dropout before study completion included

transportation difficulty (two subjects) and family emergency (one subject). Of the five subjects lost to follow-up, one had eye surgery, two lived out of the state and had transportation difficulty, and two were not available by telephone. No participant cited difficulty with the intervention or fatigue as a reason for dropout.

Of the 27 subjects who completed 3 weeks of treatment, 8 were classified as moderately impaired and 19 were severely impaired. The average FM score at baseline for the moderate group was 21.0, with a range from 16.0 to 29.3; average FM score for the severe group was 9.0, with a range from 4.0 to 13.7.

Subject characteristics are shown in **Table 1**. Data are shown as mean ± standard deviation. Twenty-one subjects were male and six were female and ages ranged from 42 to 79 years; the mean age was 54.6 ± 11.3 in the moderate group and 59.8 ± 9.5 in the severe group. All baseline measures were stable with the exception of an improvement of 3.63 ± 5.05 (p = 0.002) on the Motor Power Assessment in the severe group from the first to the third baseline evaluation.

All motor function scores at baseline and posttreatment are shown in **Table 2**. Those subjects with severe impairments showed significant improvement in FM shoulder and elbow scores (increase of 1.5 ± 1.8) and Motor Power Assessment scores (increase of 4.3 ± 6.4).

The improvement on the Motor Power Assessment in the moderate group approached statistical significance with an increase of 3.5 ± 5.1. Positive trends were observed on the FM shoulder and elbow (increase of 1.1 ± 1.8), and the Wolf Median Time (a reduction of –3.9 ± 10.7) in the moderate group; however, not none was statistically significant. Improvements on the Motor Status Score were not observed in either group. The Wolf Functional Ability measure indicated a small but significant improvement in the group with moderate impairment but not the group with severe impairment.

Motor function scores from posttreatment to 3-month follow-up are shown in **Table 3**. A statistically significant decrease in FM was observed among the moderate group; however, no significant changes were observed in the severe group. No adverse events associated with the intervention were reported during the study period.

Table 1.
Mean ± standard deviation for sex, age, and time since stroke for subjects with moderate and severe impairment levels.

Characteristic	Impairment Level	
	Moderate (n = 8)	Severe (n = 19)
Male	8 (100%)	13 (68%)
Age	54.6 ± 11.3	59.8 ± 9.5
Time Since Stroke (mo)	35.8 ± 19.0	53.9 ± 56.9
Affected Arm	3 R/5 L	10 R/9 L
Lost to Follow-Up	1 (13%)	4 (21%)

R = right, L = left.

DISCUSSION

Results of this evaluation of robot-assisted task-specific therapy among chronic stroke patients with moderate-to-severe upper-limb deficits show promising trends toward improvement of motor function. Our findings indicate that robotic task-specific massed-practice therapy produced a significant and measurable benefit in the short term among severely impaired patients. Similar trends were observed among moderately impaired patients but were not significant. These findings are important because they indicate that improvement in motor ability is not limited to those with mild impairment but is possible among moderately to severely impaired chronic stroke patients and also that intensive, repetitive treatment can be tolerated by groups with moderate-to-severe upper-limb impairment.

Our study used a massed-practice intervention of half the duration and twice the intensity than has been previously reported with the MIT-Manus [11–12], and we observed smaller improvements. Our subjects were more severely impaired than those on whom Fasoli et al. [11] reported (as indicated by their reported average FM scores at baseline of 28.15 ± 10.36) but were comparable with subjects on whom Ferraro et al. [12] reported. For moderately and severely impaired patients, they reported significant improvements on the FM and Motor Power Assessment that remained robust at the 3-month follow-up. Furthermore, the occurrence of multiple strokes was an exclusion criterion in those studies [11–12] and not in our study, which corresponds approximately to half of our patients.

Our evaluations at 3 months posttreatment indicated no significant change from posttreatment evaluations, with the exception of the change observed on the FM in the moderately impaired group. Therefore, improvements observed immediately posttreatment did not appear to be lost at 3 months posttreatment in the severe group.

Table 2.
Mean ± standard deviation for motor function scores for moderately and severely impaired subjects at baseline and posttreatment.

Impairment Level	FM Shoulder/ Elbow*	FM Wrist/ Hand*	FM Total*	MSS Shoulder/ Elbow†	MSS Wrist/ Hand†	Motor Power Assessment‡	Wolf Median Time (s)	Wolf Functional Ability§
Moderate (*n* = 8)								
Baseline Average	21.0 ± 5.3	5.8 ± 9.4	26.9 ± 14.2	20.1 ± 4.4	6.3 ± 9.5	44.5 ± 8.0	39.1 ± 52.3	2.4 ± 0.9
Posttreatment	22.1 ± 5.3	6.3 ± 10.4	28.4 ± 15.1	20.9 ± 4.4	6.7 ± 10.9	48.3 ± 4.0	35.2 ± 52.6	2.6 ± 0.9
Difference	1.1 ± 1.8	0.4 ± 1.8	1.5 ± 2.6	0.7 ± 1.5	0.4 ± 1.5	3.5 ± 5.1	–3.9 ± 10.7	0.2 ± 0.2
	S = 7.0	S = 1.0	S = 8.5	S = 10.0	S = 1.0	S = 11.0	S = –5.5	S = 14.0
	p = 0.28	*p* = 0.88	*p* = 0.17	*p* = 0.20	*p* = 0.94	*p* = 0.06	*p* = 0.31	*p* = 0.02
Severe (*n* = 19)								
Baseline Average	9.0 ± 3.3	—	9.0 ± 3.3	9.8 ± 4.2	—	27.5 ± 13.2	120 ± 0.0	1.3 ± 0.2
Posttreatment	10.5 ± 3.0	—	10.5 ± 3.0	10.6 ± 3.8	—	31.7 ± 11.9	120 ± 0.0	1.2 ± 0.1
Difference	1.5 ± 1.8	—	1.5 ± 1.8	0.8 ± 2.3	—	4.3 ± 6.4	—	0.1 ± 0.1
	S = 70.5		S = 70.5	S = 36.0		S = 65.5		S = 13.0
	p = 0.003		*p* = 0.003	*p* = 0.16		*p* = 0.006		*p* = 0.13

Note: An increase in score indicates improvement in all scores except Wolf Median Time where a decrease in seconds indicates improvement.
*Fugl-Meyer (FM) score for shoulder and elbow, maximum = 36; FM score for wrist and hand, maximum = 30; and FM total score, maximum = 66.
†Motor Status Score (MSS) for shoulder and elbow, maximum = 40; MSS for wrist and hand, maximum = 26.
‡Motor Power Assessment score, maximum = 70.
§Wolf Median time, maximum = 120 s; Wolf Functional Ability score, maximum = 5.
S = value produced by SAS as Wilcoxon Signed Rank Test statistic.

Table 3.
Mean ± standard deviation for motor function scores for moderately and severely impaired subjects at posttreatment and 3-month follow-up.

Impairment Level	FM Shoulder/ Elbow*	FM Wrist/ Hand*	FM Total*	MSS Shoulder/ Elbow†	MSS Wrist/ Hand†	Motor Power Assessment‡	Wolf Median Time (s)	Wolf Functional Ability§
Moderate (*n* = 7)								
Posttreatment	23.1 ± 4.8	7.1 ± 10.9	30.3 ± 15.2	21.6 ± 4.2	7.6 ± 11.4	48.9 ± 3.9	37.4 ± 56.5	2.6 ± 0.9
Follow-Up	20.9 ± 5.3	7.0 ± 11.0	27.9 ± 15.9	20.9 ± 4.6	7.4 ± 11.3	49.6 ± 7.0	38.5 ± 55.9	2.6 ± 1.1
Difference	–2.3 ± 2.1	–0.1 ± 0.7	–2.4 ± 2.6	–0.7 ± 0.9	–0.2 ± 0.9	0.7 ± 5.7	1.1 ± 3.4	0.0 ± 0.36
	S = –2.5	S = –1.0	S = –12.0	S = –11.5	S = –2.0	S = 1.5	S = –1.0	S = 0.5
	p = 0.05	*p* = 1.0	*p* = 0.06	*p* = 0.06	*p* = 0.71	*p* = 0.86	*p* = 0.88	*p* = 0.98
Severe (*n* = 15)								
Posttreatment	10.9 ± 3.0	—	10.9 ± 3.0	11.1 ± 3.5	—	31.2 ± 12.3	120.0 ± 0.0	1.2 ± 0.1
Follow-Up	10.1 ± 2.6	—	10.4 ± 2.8	11.5 ± 3.4	—	30.7 ± 12.8	120.0 ± 0.0	1.3 ± 0.2
Difference	–0.7 ± 2.5	—	–0.7 ± 2.5	0.4 ± 2.1	—	–0.5 ± 5.2	—	0.1 ± 0.1
	S = –12.0		S = –12.0	S = 11.0		S = –3.5		S = 13.0
	p = 0.38		*p* = 0.38	*p* = 0.51		*p* = 0.79		*p* = 0.08

Note: An increase in score indicates improvement in all scores except Wolf Median Time where a decrease in seconds indicates improvement.
*Fugl-Meyer (FM) score for shoulder and elbow, maximum = 36; FM score for wrist and hand, maximum = 30; and FM total score, maximum = 66.
†Motor Status Score (MSS) for shoulder and elbow, maximum = 40; MSS for wrist and hand, maximum = 26.
‡Motor Power Assessment score, maximum = 70.
§Wolf Median time, maximum = 120 s; Wolf Functional Ability score, maximum = 5.
S = value produced by SAS as Wilcoxon Signed Rank Test statistic.

Our study showed greater evidence for improvement in motor function for severely impaired subjects than for moderately impaired subjects. The reason for this distinction is unclear; however, the main factor that distinguished the two groups was sample size. Similar outcomes were observed between groups on the FM and Motor Power Assessment but more than twice the number of subjects was in the severe group compared with the moderate group.

Improvements measured with the Motor Status Score were not significant for moderately or severely impaired groups in these analyses. This finding is consistent with one other study in which no effect was observed on the Motor Status Score following robotic task-specific therapy in chronic stroke patients [12]. The Motor Status Score was developed as a sensitive indicator of change in motor function for acute stroke patients [17] but may need further validation as an appropriate measure for functional change in moderately to severely impaired chronic stroke patients.

Studies of repetitive task-specific interventions with a spaced-practice paradigm, such as repetitive bilateral arm training, and previous studies with the MIT-Manus have been associated with positive outcomes for chronic stroke patients with moderate [11,22] and severe [12] impairments. Previous studies of the MIT-Manus spaced treatments across 6 weeks compared with our intervention of 3 weeks. The observed improvements in these studies were substantially larger for moderately and severely impaired subjects than those observed in the present study [11–12]. The main factors that distinguished our study from these studies were the duration and intensity of the intervention.

Other massed-practice interventions, such as CIMT, have been successful among chronic stroke patients with moderate to mild impairment [3–4,6–7]. These studies suggest that task-specific treatment delivered in an intensive 2-week protocol could significantly improve motor function. Although our observed improvements were smaller than those from similar studies that used spaced practice, our findings indicate that patients were able to tolerate increased dose intensity. We did observe mild fatigue during the first 2 days of treatment and allowed for rest as needed. Beyond this, even the most severely impaired patients were able to tolerate the treatment intensity and repetitions in a session. We allowed for 1-hour rest breaks between treatment sessions; however, patients were usually ready to resume after only 30 minutes. Our experience should be interpreted carefully, but it is noteworthy that therapists may traditionally underestimate patient ability to tolerate intensive, frequent, or repetitive treatment.

This pilot study has several limitations. First, although we verified stability at baseline, we did not study a comparison group; therefore, we do not know how improvements observed in association with the study therapy compare with the absence of therapy. An effect of attention and motivation may be given to subjects by the supervising therapist. Second, our sample size was small; therefore, we are unclear as to whether the delivered treatment affected moderate and severe groups differently or whether we were unable to detect effects in the moderate group because of a smaller sample size. Also because of our small sample size in each group, we were unable to control for factors related to change in motor function other than level of severity.

CONCLUSIONS

Our intervention was half the duration and twice the intensity of previous studies of therapy delivered with the MIT-Manus [11–12]. Motor impairment scores demonstrated small but positive outcomes and treatment was well-received and tolerated by moderately and severely impaired subjects, which shows that robotic therapy may be useful for improving functional outcomes with a variety of time and intensity regimens. Researches should confirm these findings with a controlled trial and larger sample size to demonstrate the efficacy and cost-effectiveness of robot-assisted therapy in moderately and severely impaired chronic stroke patients.

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