Research Article

Comparison of Two Techniques of Robot-Aided Upper Limb Exercise Training After Stroke

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ABSTRACT

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Objective: This study examined whether incorporating progressive resistive training into robot-aided exercise training provides incremental benefits over active-assisted robot-aided exercise for the upper limb after stroke.

Design: A total of 47 individuals at least 1 yr poststroke were enrolled in this 6-wk training protocol. Paretic upper limb motor abilities were evaluated using clinical measures and a robot-based assessment to determine eligibility for robot-aided progressive resistive training at study entry. Subjects capable of participating in resistance training were randomized to receive either active-assisted robot-aided exercises or robot-aided progressive resistance training. Subjects who were incapable of participating in resistance training underwent active-assisted robotic therapy and were again screened for eligibility after 3 wks of robotic therapy. Those subjects capable of participating in resistance training at 3 wks were then randomized to receive either robot-aided resistance training or to continue with robot-aided active-assisted training.

Results: One subject withdrew due to unrelated medical issues, and data for the remaining 46 subjects were analyzed. Subjects in all groups showed improvement in measures of motor control (mean increase in Fugl-Meyer of 3.3; 95% confidence interval, 2.2–4.4) and maximal force (mean increase in maximal force of 3.5 N, $P = 0.027$) over the course of robot-aided exercise training. No differences in outcome measures were observed between the resistance training groups and the matched active-assisted training groups. Subjects' ability to perform the robotic task at the time of group assignment predicted the magnitude of the gain in motor control.

Conclusion: The incorporation of robot-aided progressive resistance exercises into a program of robot-aided exercise did not favorably or negatively affect the gains in motor control or strength associated with this training, though interpretation of these results is limited by sample size. Individuals with better motor control at baseline experienced greater increases in motor control with robotic training.

Key Words: Stroke, Robotics, Exercise Training, Resistance Training

Upper limb weakness after stroke is common and results in substantial disability. Motor outcomes after conventional treatment are poor, with 30–66% of individuals no longer able to use the paretic arm functionally.[1,2] It has been found that only 5% of individuals who receive intensive therapy for severe upper limb weakness poststroke regain functional use of the upper limb during the course of rehabilitation.[1] The need for effective rehabilitation for the paretic upper limb after stroke remains largely unmet.

Spontaneous recovery of motor function is very common after stroke, though recovery is often incomplete. Evidence that cortical reorganization underlies this recovery is now available through a variety of experimental techniques.[3–6] Exercise therapy has increasingly been recognized as an important and partially effective treatment for motor impairments after stroke. Studies of exercise to stimulate motor recovery have demonstrated changes in both metabolic activity and excitability in several areas of the cortex.[7–10] Based on this research, it seems that exercise can influence cortical reorganization.

Several approaches to providing upper limb exercise after stroke have been studied, including constraint-induced movement therapy[11–15] and robot-aided rehabilitation. Although constraint-induced movement therapy seems to be a promising therapy, it requires a significant level of residual motor function and is not feasible for individuals with more severe weakness after stroke. Alternative approaches are needed for this large population of individuals who are unable to achieve this threshold level of motor function at the initiation of therapy. Robotic exercise training has the capability to provide assisted exercises for individuals with severe weakness and resistive exercises for stroke survivors with greater motor abilities. Robotic therapy is capable of providing therapeutic exercise to stroke survivors with a broad range of motor impairments.

Robot-aided rehabilitation has been demonstrated to reduce upper limb motor impairment when provided early after stroke.[16–18] More recently, improved motor function in the limb segments exercised after robot-aided exercise has been shown in individuals with chronic stable deficits after stroke.[19,20] Robot-aided exercise can be provided using a variety of treatment paradigms, including passive movements, active assistive exercises, resistive exercises, and bimanual mirror-image exercises. Some robot-aided exercise protocols have incorporated resistive exercises as a component of a program consisting of several different types of exercise,[20] whereas others have not included any resistive component.[17] Previous robot-aided exercise studies have not attempted to determine which aspect of these treatment approaches is most effective.

Generally, the optimal exercise regimen to improve motor function after stroke remains to be determined. The highly structured robot-aided exercise program provides an opportunity to test specific exercise strategies. Some previous evidence[21,22] suggests that progressive resistance (strength) training of the lower limbs may provide functional benefits, though there is little data on its effect on motor impairment per se. Data regarding the efficacy of upper limb resistive exercises after stroke are very limited and have examined finger strengthening rather than more proximal upper limb resistance training.[23,24] Our primary hypothesis was that incorporating progressive resistive exercises into robotic training would provide a greater improvement in motor control than robotic active-assisted training. A secondary hypothesis was that improvements in motor control associated with robot-aided training would be greatest in subjects with less severe motor impairments at baseline. This study was designed to evaluate the effects of incorporating resistive exercises into robotic training. Results of the overall effects of robotic training in a portion of these subjects has previously been reported.[19,25]

METHODS

A total of 47 subjects with a single previous stroke (either infarction or cerebral hemorrhage) between 1 and 5 yrs before study entry were enrolled. Subjects were required to have a residual hemiparesis, with average strength in the upper limb (measured at the shoulder and elbow flexors and extensors) between 2 and 4 on the Medical Research Council grading system.[26] All subjects were required to have concluded any conventional physical or occupational therapy before enrollment in this study and were instructed not to begin any new exercise treatments during their participation in the study. Subjects who were judged by the investigators to have severe cognitive, linguistic, or perceptual impairments that would prevent successful participation in the protocol were excluded, as were subjects with medical comorbidities likely to interfere with successful completion of the study (e.g., metastatic cancer). Subjects were recruited from a variety of sources, including advertisements, and outpatients at a rehabilitation hospital. One subject withdrew from the study due to unrelated medical issues. The results of the remaining 46 subjects who completed the training protocol are reported here. Table 1 provides demographic and clinical information for the study population.

All subjects underwent a battery of assessment tools performed by a single physical therapist not otherwise involved in the study and who was blinded to the patient's group assignment. Intrarater reliability testing was performed for the Fugl-Meyer ratings by the assessing thera-

TABLE 1
Subjects' characteristics and baseline scores by treatment group

	Group A	Group B	Comparison of Group A *vs.* B	Group C	Group D	Comparison of Group C *vs.* D	Group E	All Subjects
n	9	9		5	5		18	46
Age, yrs (SD, range)	53.3 (16.4, 19–78)	52.5 (14.4, 27–64)	$P = 0.9$	63.2 (13.3, 51–77)	59.4 (13.7, 43–75)	$P = 0.76$	60.2 (11.9, 41–79)	57.6 (13.6, 19–79)
Sex, *n* (% female)	3 (33)	3/9 (33)	$P = 0.61$	1 (20)	2 (40)	$P = 1.0$	6 (33)	15 (33)
Mean (SD) duration poststroke, mos	27.0 (12.7)	27.3 (11.4)	$P = 0.94$	29.4 (16.7)	26.7 (15.0)	$P = 0.82$	24.1 (12.0)	26.1 (12.4)
Mean (SD) baseline upper limb Fugl-Meyer score	38.0 (9.6)	35.3 (11.6)	$P = 0.67$	25.6 (2.4)	24.6 (7.9)	$P = 0.80$	20.7 (3.6)	27.9 (10.3)
Mean (SD) baseline upper limb modified Ashworth score	10.3 (5.8)	10.1 (4.9)	$P = 0.9$	13.1 (3.5)	12.1 (5.1)	$P = 0.73$	15.3 (4.1)	12.7 (5.1)
Mean (SE) peak force generated, N	34.9 (3.9)	34.4 (5.7)	$P = 0.9$	25.1 (3.4)	22.8 (5.1)	$P = 0.8$	20.9 (3.6)	27.0 (2.2)
No. (%) right-sided lesions	4 (44)	6 (67)	$P = 0.61$	1 (20)	3 (60)	$P = 0.52$	14 (78)	28 (61)

pist, with an intrarater correlation coefficient of 0.99. Serial assessments were performed before initiating the actual robot-aided exercise program. These were performed at study enrollment, after 2 wks, and after 4 wks to establish a reliable and stable baseline for motor function. Robotic therapy began after the completion of these assessments and continued for 6 wks, as detailed below. No conventional physical or occupational therapy was provided during the course of participation in the study.

The Fugl-Meyer scale is a widely used and well accepted scale of motor impairment after stroke, and the upper limb motor component was thus selected as the primary outcome measure for the study.[27] The properties of the Fugl-Meyer scale include construct validity and excellent interrater and intrarater reliability, but the minimal clinically important difference has not been clearly established.[28] Previous studies of upper limb exercise training after stroke have considered a 10% change in the Fugl-Meyer as clinically important.[15] The modified Ashworth scale[29] is a clinically-oriented assessment tool for spasticity, and is well suited to poststroke patients with upper limb impairments. The Motor Status Scale[30] has been used in previous studies of robot-aided exercise training[16–18] and was included as a secondary measure of motor impairment to allow comparison with previous studies. Manual muscle testing using the Medical Research Council Scale[26] was included as a secondary outcome measure of strength due to its familiarity to clinicians and widespread clinical application. Due to the insensitivity of this scale to small changes in strength and limitations in applying it to individuals with upper motor neuron lesions, this scale was supplemented by robotic measurements of strength. Robotic measurements of maximal isometric force were performed for four shoulder movements: Shoulder flexion, extension, abduction, and adduction. Subjects were seated and their arms were positioned during testing within the robot as shown in Figure 1. They were instructed to push (or pull) in the indicated direction as hard as possible for a brief interval (2–3 secs). Subjects were placed in approximately 30 degrees of forward flexion at the shoulder, 45 degrees of shoulder abduction, neutral shoulder rotation, and 45 degrees of elbow flexion for testing of abduction and adduction. Flexion and extension were tested with the shoulder in 30 degrees of forward flexion and neutral rotation and abduction, with the elbow at approximately 45 degrees of flexion. Rest periods of 10 secs were provided between each isometric effort. The maximum isometric force generated during the course of five trials was recorded and analyzed; submaximal force generated on the other trials was not included in the analysis.

All subjects received 6 wks of robot-aided exercise. Training was conducted three times each week for 1-hr sessions, for a total of 18 hrs of robot-aided exercise training per subject. During therapy, the subjects' paretic arm was supported by a molded wrist/hand orthosis that was attached to end-effector (handle) of the robot arm. All evaluation and training exercises consisted of reaching tasks in the horizontal plane that involved shoulder and elbow movements. Specifically, subjects were asked to move between a center target and eight peripheral targets arranged in a circular display. As they attempted to move the robot's handle toward designated targets, the computer screen in front of them provided visual feedback of the target location and movement of the robot handle (Fig. 1). Sixty repetitions of each "round" of moving to the set of eight targets were performed during each training session, and three rounds were performed with the robot inactive for the purposes of assessment. A total of 1,024 individual target-oriented movements were completed by subjects during each training session. A total of approximately 40 mins of each 1-hr session was spent performing robot-aided exercises, with the remainder of the session used for set-up and for several brief rest periods between training exercises. The therapist supervising the robotic therapy provided instructions and some general encouragement but no feedback regarding specific performance. Robot training was performed using the InMotion2 robot (Interactive Motion Technologies, Cambridge MA), a commercial version of the MIT-Manus robot that has been used in previous studies of upper limb rehabilitation after stroke.[16–19]

A robotic assessment of motor abilities was administered to all subjects at study entry. This assessment task, like the training task, consisted of reaching for each of eight virtual targets circumferentially surrounding the center target (Fig. 1). Subjects were eligible to engage in the resistance training protocol if they were capable of reaching each of the peripheral targets without robot assistance. These subjects were randomized to receive either robot-aided progressive resistance training (group A) or robot-aided active-assisted training (group B). Randomization in blocks of four was performed using a randomization table. Randomization for these subjects was performed after initial assessments were completed but before initiating therapy. Subjects who were ineligible for resistance training at study entry (i.e., unable to independently reach each peripheral target) were provided active-assisted training for 3 wks, with the expectation that some of these subjects would gain the ability to reach all targets. These subjects were reassessed after 3 wks of training, and those who were capable of reaching each of the targets at the 3-wk assessment were randomized to receive either robot-aided progressive resistance training for the final 3 wks of robotic training (group C) or continued robot-aided active-assisted training (group D). These subjects were similarly randomized in blocks of four using a randomization table. Subjects who remained incapable of reaching all

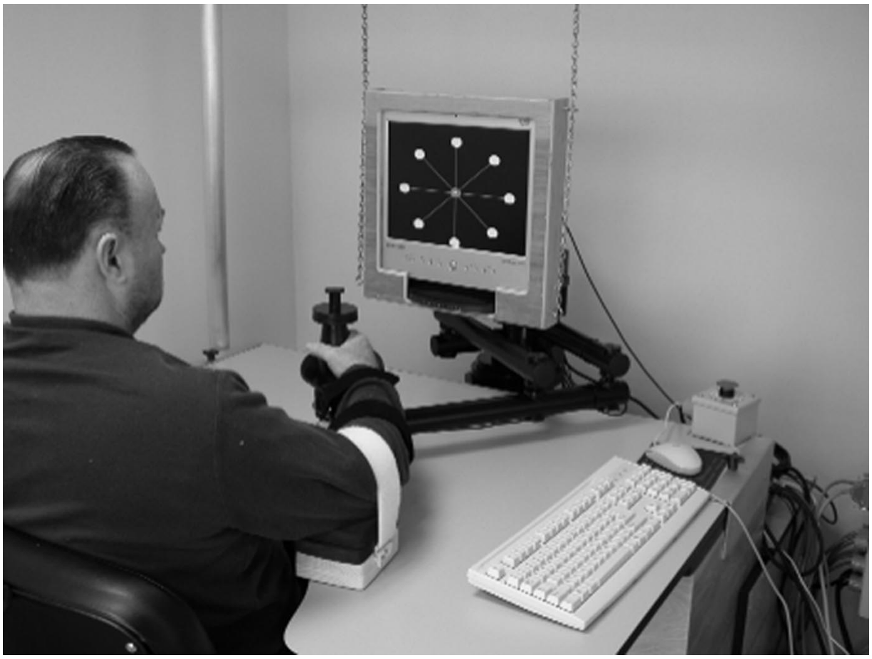

Figure 1: InMotion2 robot: a subject is shown performing robot-aided exercises. A cursor on the display corresponds to the position of the hand, and each target is highlighted sequentially as a goal for the subject to reach toward.

targets after 3 wks of active-assisted training were deemed incapable of participating in the resistance training protocol and were provided with active-assisted training for the remainder of the study (group E). The subject assignment algorithm is shown in the diagram in Figure 2. The intent of the design was to maximize the number of subjects randomized to receive robot-aided resistance training *vs.* active-assisted training. Due to the expected number of subjects who were not expected to meet the requirements for randomization at study entry (i.e., subjects incapable of reaching all targets), we designed the study with a second opportunity for testing and randomization after provision of 3 wks of active-assisted training. This design was intended to simulate a clinical approach, whereby a patient's exercise program is typically adjusted as his or her motor abilities improve. The design was also intended to result in comparable baseline motor abilities between the two primary treatment groups (A+C *vs.* B+D).

During active-assisted training, the robot provided assistance in reaching each target if the subject was unable to reach it independently. For subjects able to reach the target independently, the robot assisted with guidance to the target to improve the quality and efficiency of the movement and provided a tactile cue by nudging the arm toward the target.

The resistance training task was of the same form as the active-assisted task but with the robot programmed to provide resistance to the desired movement. The amount of resistance was determined and modified by a control algorithm that used robotic measures of the subject's muscle strength to increase or decrease the effort required to reach the targets. These measures were obtained at the end of each treatment session to determine the amount of force to be delivered by the robot during the next session. A maximum force of 28 N was provided by the robot as resistance during training exercises. The number of repetitions of the training task was the same in subjects receiving active-assisted training and those receiving resistance training. Over the course of therapy, subjects in each treatment group performed approximately 18,000 repetitive reaching movements with their paretic arm.

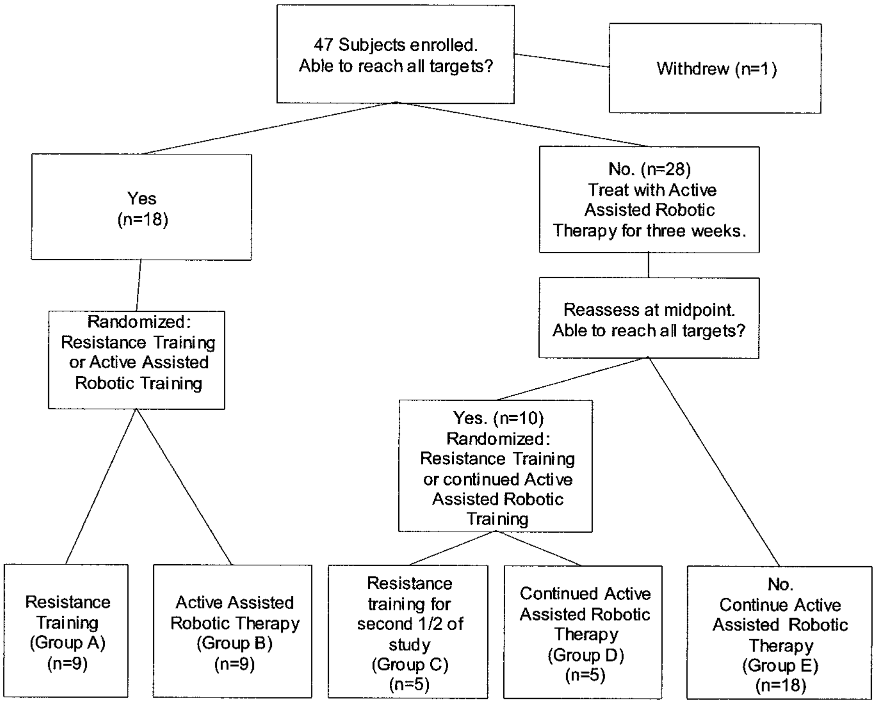

Figure 2: Subject treatment assignment algorithm and group definitions.

This study was approved by the institutional review boards at the participating institutions and conducted in accordance with their ethical standards.

Statistical Analysis. Student's t tests were used for pair-wise comparisons of Fugl-Meyer, Ashworth, and Motor Status Scale change scores between groups and for maximal isometric force generated. Simple linear regression was used to analyze differences in Fugl-Meyer change scores between different treatment assignment groups. Simple regression analysis was used to analyze the relationship between baseline Fugl-Meyer scores and change scores.

RESULTS

No significant difference in Fugl-Meyer change was found between subjects receiving resistance training for all or part of their training program (groups A and C, $n = 14$) and those qualifying for resistance training but randomized to receive standard robot-aided therapy (groups B and D, $n = 14$) ($P = 0.79$; 95% confidence interval, −3.7 to 2.86). Similarly, among subjects who qualified for resistance training at study entry, there was no significant difference in Fugl-Meyer change scores between those receiving resistance training (group A, $n = 9$) and those receiving standard active-assisted robotic therapy (group B, $n = 9$) ($P = 0.84$; 95% confidence interval, −4.1 to 4.9). Secondary outcomes measures did not reveal any significant differences between subjects receiving robot-aided resistance training and those receiving active-assisted training (Table 2).

Robotic treatment resulted in statistically significant reductions in motor impairment for the entire

TABLE 2

Comparison of progressive resistance training to active-assisted robotic training

	Group A, $n = 9$	Group B, $n = 9$	*P* Value	Groups A + C, $n = 14$	Groups B + D, $n = 14$	*P* Value
Change in modified Ashworth scale, mean (SD)	−1.5 (2.1)	−0.5 (1.8)	0.31	−1.4 (2.2)	0.0 (2.0)	0.09
Increase in Fugl-Meyer (upper limb) score, mean (SD)	5.2 (4.8)	4.8 (4.2)	0.84	4.0 (4.8)	4.4 (3.4)	0.79
Increase in Motor Status Scale (shoulder/elbow) score, mean (SD)	1.6 (2.9)	1.7 (0.9)	0.93	2.4 (2.6)	1.6 (1.1)	0.32
Increase in Motor Status Scale (wrist/hand) score, mean (SD)	1.2 (1.3)	1.3 (1.5)	0.91	1.6 (1.1)	1.3 (2.0)	0.62
Increase in manual muscle testing (Medical Research Council Scale) score, mean (SD)	2.4 (1.9)	2.1 (2.1)	0.73	2.2 (1.6)	1.6 (2.3)	0.63
Increase in peak force generated, Mean (SE)	2.01 (2.8)	6.51 (2.8)	0.10	6.4 (2.3)	4.2 (2.2)	0.47

study population (groups A–E), with a mean increase on the Fugl-Meyer Scale of 3.3 points (95% confidence interval, 2.2–4.4). Fugl-Meyer scores at the interim assessment after 3 wks of training were intermediate between admission and discharge scores (mean increase in Fugl-Meyer at interim assessment = 1.56).

Subject groups were similar at baseline when compared with matched groups (A *vs.* B, C *vs.* D) (Table 1). Baseline motor performance as measured by the Fugl-Meyer was significantly greater in groups A and B when compared with groups C and D (36.7 *vs.* 25.1, *P* = 0.003). Groups C and D were similarly less impaired on the Fugl-Meyer than group E (25.1 *vs.* 20.7, *P* = 0.017). Compliance with the training protocol was very good, with one subject who did not complete the study and one subject who missed one robot training session.

Maximum force generation analysis revealed similar results for flexion, extension, abduction, and adduction. Accordingly, these four values were collapsed into an average score for further analysis. Maximum force generation increased significantly for all subjects from admission (mean = 25.0 N, SE = 1.2) to the interim measurement after 3 wks of training (27.6 N, SE = 1.3) (*P* = 0.0004) and from admission to the completion of the training (27.9 N, SE = 1.4) (*P* = 0.0077). No significant differences were seen between the interim assessment and the completion of training. All treatment groups experienced comparable changes in strength, and no significant difference in maximum force was seen for groups receiving robot-aided progressive resistive training when compared with control groups receiving robot-aided active-assisted training. A possible trend is present (*P* = 0.10) suggesting that group B (who received active-assisted training throughout) had a greater improvement in strength than group A (resistance training throughout), though no comparable trend was seen in manual muscle testing. This trend is in contrast with a nonsignificant trend in the opposite direction when comparing groups C and D. These apparent trends are no longer evident when combining all subjects receiving resistance training (A+C) to those receiving active-assisted training (B+D), consistent with no overall difference between resistance and active-assisted training. This observed "trend" seems due to variation present because of the small sample size in the individual groups rather than because of a meaningful difference between the groups.

The study design segregated subjects into groups based on ability to complete a motor task consisting of reaching each of the virtual targets using the robot. Subjects with the highest motor function based on this task (groups A and B) showed the greatest increase in Fugl-Meyer scores with robotic training (mean = 5.0, SD = 4.4), subjects with intermediate motor function (groups C and D) showed intermediate increases in Fugl-Meyer scores (mean = 2.8, SD 3.2), and subjects with the lowest motor function (group E) showed the smallest increase in Fugl-Meyer scores (mean = 1.8, SD 2.9). The difference between groups A+B when compared with group E was statistically significant on regression analysis (*P* = 0.01), though the difference between groups C+D when compared with groups A+B or group E did not achieve statistical significance. A trend was found suggesting a relationship between baseline Fugl-Meyer scores and the Fugl-Meyer change scores, but this did not achieve statistical significance (*P* = 0.18). Linear regression revealed no relationship between age and Fugl-Meyer change scores (*P* = 0.7).

DISCUSSION

We did not find any differences in motor function gains between the two forms of robot-aided exercise studied. Subjects receiving robot-aided progressive resistance training and those receiving active-assisted robotic treatment showed comparable improvements in motor function and maximal force generation. Due to the exploratory nature of this study, enrollment was limited to 46 subjects. Given the number of statistical comparisons performed in our analysis, a much larger sample size would have been required to exclude a type II error with certainty. For this reason, these results must be regarded as preliminary. The possibility that a larger sample would have resulted in the identification of a significant advantage to one treatment or the other has not been definitively excluded.

The Motor Status score was used as a secondary outcome measures of motor function, with results comparable with the Fugl-Meyer—improvement was observed for the entire study population, but no difference was observed between groups. The modified Ashworth scale showed a nonsignificant trend favoring the resistance training groups, suggesting that the resistive training protocol might have some value in reducing spasticity. Further studies are needed to further explore this possibility.

Robot-aided exercise training is feasible for patients with a broad range of impairment severity and seems beneficial both early after stroke[16–18] and for individuals with late effects of stroke.[19–20] Its feasibility for individuals with more severe motor deficits represents a unique feature of this therapeutic approach. Although robot-aided exercise represents a promising therapeutic approach to individuals with weakness after stroke,[16–20] the magnitude of the increases in motor function, as measured by the Fugl-Meyer scale, remain modest overall. The future development of robots capable of providing assisted exercise to the wrist and hand may enhance the magnitude of the increases in motor function seen with this treatment modality.

We did not formally assess subject impressions of the robotic training. Some subjects reported that the robotic tasks were interesting and challenging, whereas others found the training boring. No subjects withdrew due to any complications or dissatisfaction with robotic training.

In addition to potential value as a therapy in its own right, robot-aided exercises provides a unique platform for testing specific exercise therapies in a carefully controlled setting. Due to its design, the InMotion2 robot provides a programmable, highly structured exercise program. This allows the manipulation of individual variables in the exercise program, such as intensity and number of repetitions, and provides an opportunity to define which elements of an exercise program are beneficial and which are without specific benefit or may even be harmful.

These results are consistent with previous studies of upper limb nonrobotic strengthening exercise programs that have failed to demonstrate functional benefits[23,24,31] and in contrast to studies showing benefits in the lower limbs with this type of training.[21,22,31] This may reflect the very different functional demands for the upper and lower limbs. The weight-bearing tasks of the lower limbs may be more dependent on strength, and ameliorating the loss of strength resulting from stroke may therefore be functionally beneficial. Studies of the impact of lower limb progressive resistive training on motor control are lacking, and thus, it remains unclear if the benefits observed are due merely to increased strength or if underlying motor control has been affected. For the upper limbs, most functional tasks are highly dependent on distal fine motor control and less dependent on strength. Therapeutic approaches to improve distal fine motor control are needed.

Our finding that the ability to reach each of the targets without robot assist predicts the magnitude of the gains in motor control is intriguing. It suggests that the benefits of exercise therapy are greater for individuals with better motor control at baseline. This finding emphasizes the need for better therapies for the most severely impaired individuals. Although robotic therapy is feasible for a broad range of impairments, it seems less effective for the most severe impairments. Despite this observation, assisted exercise, such as robotic therapy, is likely to be the only practical technique for providing exercise for patients with severe paresis because techniques such as constraint-induced movement therapy are not feasible for these individuals. Further studies are needed to determine if more intensive or prolonged robotic therapy can overcome these baseline differences or if there is a limit to the amount of motor improvement possible based on the severity of the initial motor deficits. It also suggests that robotic therapy may be beneficial for individuals with deficits judged too mild to participate in this study.

Modest increases in maximum force generation were seen in subjects undergoing robotic training (13.7% from baseline to study completion). The absence of any difference between groups receiving robot-aided progressive resistance training and those receiving active-assisted training suggests that the resistive training did not play a significant role in improving strength or that the training stimulus was not optimal in terms of intensity, sets, repetitions, or duration of training. Our results suggest that active-assisted exercises may be as effective as progressive resistive exercises for increasing force generation in the impaired upper limb after stroke.

The gains in force generation primarily occurred during the first 3 wks of training, without further significant increases during the second 3 wks of training. This is in contrast to the Fugl-Meyer scale results for motor impairment, in which the improvements observed were evenly distributed between the first and second 3 wks of training. We speculate that this reflects differential effects of our training protocol on distinct neural mechanisms for motor force and motor control, but further investigation is required to elucidate this hypothesis.

Measurements of muscle hypertonicity using the Ashworth scale did not reveal any difference between subjects receiving robot-aided progressive resistance training and those receiving active-assisted training, though a reduction in spasticity was seen for study subjects overall. This provides further support for the observation that resistance training does not exacerbate spasticity in hemiparetic stroke survivors.[32,33]

Other limitations of this study include the relatively modest amount of resistance provided by the robot due to safety considerations. Limitations in the force and acceleration provided by the robot are important safety features that are a unique aspect of this robot's design.[34] Due to the unique nature of robot-assisted exercise training, we did not use a percentage of each subject's maximal voluntary force generated to establish a resistance training program. Accordingly, our results should not be compared with conventional (nonrobot aided) progressive resistance exercise programs. Although it is possible that larger resistive forces may provide significant benefits, it is unlikely that most stroke patients with deficits comparable with our patient population could overcome substantially larger resistive forces.

Another limitation of this study is that functional use of the impaired upper limb for activities of daily living was not directly measured, as change in motor impairment served as the primary outcome measure in this study. Subjects informally reported that they thought their functional use of the upper limb was somewhat improved after robot-aided training. Better quantitative measures of actual functional use in the community setting are needed to accurately measure effects of robotic exercise therapy on functional use.

Many questions regarding the optimal robot-assisted exercise regimen remain unanswered at this time. Further studies are needed to determine the optimal intensity of exercise poststroke and the optimal duration. Techniques to enhance the simulation of functional activities during robotic training may also be of benefit.

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