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ORIGINAL RESEARCH ARTICLE

Robot-Assisted Exercise for Hand Weakness After Stroke

A Pilot Study

ABSTRACT

Stein J, Bishop L, Gillen G, Helbok R: Robot-assisted exercise for hand weakness after stroke: a pilot study. Am J Phys Med Rehabil 2011;90:887–894.

Objective: Upper-limb paresis is a major source of disability in stroke survivors, and robotic device–aided exercise therapy is a promising approach to enhance motor abilities. Few robotic devices have been available to provide therapy to the fingers and hand. This study was designed to test a new robotic device for hand rehabilitation in stroke survivors.

Design: This is an open-label pilot study of 12 individuals with chronic moderate hemiparesis after stroke. Participants underwent a 6-wk training program using a hand robotic device. Participants received a total of 18 hrs of robotic therapy.

Results: Improvements were found in multiple measures of motor performance, including the Upper Extremity Fugl-Meyer test, the Motor Activity Log, the Manual Ability Measure–36, and the Jebsen Hand Function Test. All subjects tolerated the treatment well and no complications were observed.

Conclusions: Robotic therapy for hand paresis after stroke is safe and feasible, and further studies of efficacy are justified by these preliminary results.

Key Words: Stroke, Hemiparesis, Robotics, Rehabilitation

There are approximately 6.4 million stroke survivors in the United States, many of whom live with residual disability.[1] Hemiparesis is a substantial contributor to poststroke disability, and extensive resources are devoted to motor rehabilitation. Despite these efforts, outcomes for upper-limb function are frequently inadequate, leaving stroke survivors with very limited or no functional use of the upper limb.

Exercise therapy remains the mainstay of rehabilitation for hemiparesis after stroke. Repetitive task practice has been found useful in restoring some degree of motor performance after stroke, even in individuals with persistent hemiparesis.[2] Accompanying changes in the brain indicative of cortical plasticity have been demonstrated.[3] The use of robotic devices is appealing as a means of delivering well-defined repetitive exercises in a consistent fashion. Robotic devices also are suitable for use by individuals with more severe weakness who may not be able to complete conventional exercises without assistance. Robots also have the potential to provide a more labor-efficient exercise program that does not require as direct supervision by highly trained therapists. Ultimately, robotic therapy should allow patients to achieve larger overall doses of exercise treatment through the use of home-based or unsupervised robotic training.

The hand serves a unique and critical role in upper-limb function. Therapies focusing solely on the more proximal segments of the upper limb are unlikely to result in substantial improvements in actual upper-limb functional use. The development of robotic devices capable of providing exercise therapy for the hand is therefore an important milestone on the path to upper-limb functional restoration after stroke.

The use of visual displays can incorporate gaming or virtual reality as a means of making performance of the exercises more engaging for the patient. A variety of upper-limb robotic devices have been developed to provide robotic exercises for stroke survivors, and several of these are now available commercially. The results of training with these devices have been promising, although no conclusive evidence that they offer benefits exceeding that of human-delivered exercise exists.[4]

Few of these devices have specifically targeted the hand, and very limited data on the feasibility or efficacy of robotic hand rehabilitation exist. A pilot study of a prototype hand robot, the Hand and Wrist Robotic Device (HWARD), which does not permit individuated finger movements, has shown promising results, with improvement in multiple measures of upper-limb function and evidence that an active-assisted mode is more effective than a nonassistive mode.[5] The Hand Exoskeleton Rehabilitation Robot (HEXORR) is a prototype exoskeletal hand robot that assists digits 2–5 as a group and assists with grasping movements. It has been tested in a feasibility study of chronic stroke patients, with good tolerability and with individual subjects showing improved motor control.[6]

Devices that are commercially available include the Hand Mentor, a pneumatically actuated wrist/hand unit that has been found to provide improvements in certain aspects of quality-of-life when combined with a repetitive task practice program.[7] The InMotion Hand Robot, designed for grasping exercises, is available commercially, but there are no published reports on its efficacy thus

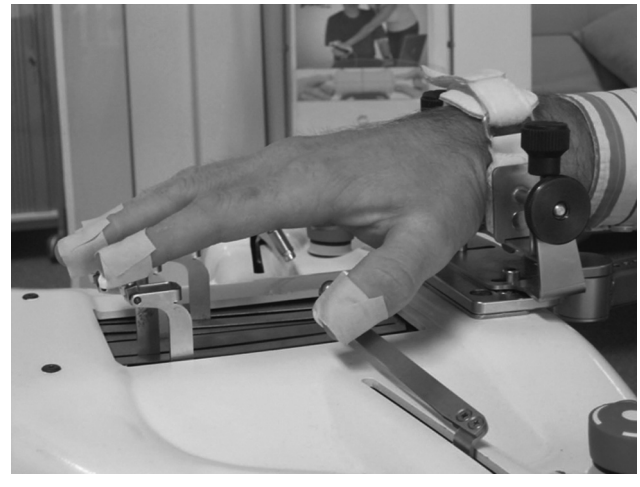

FIGURE 1 *Amadeo Robot showing attachment of fingers to device.*

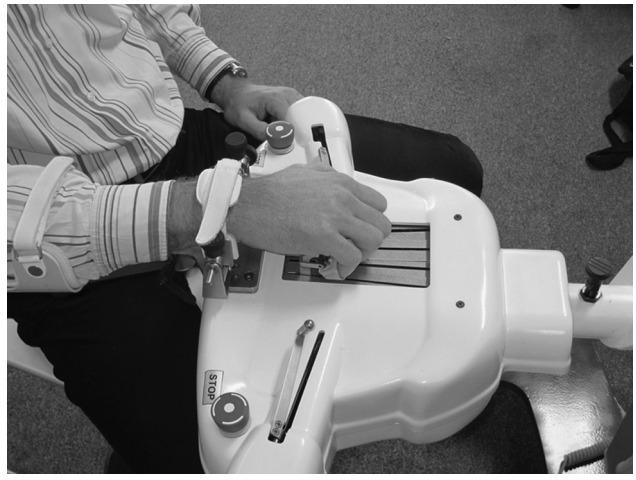

FIGURE 2 *Amadeo robotic device with fingers in flexion.*

far.[8] The CyberGrasp[9] provides individual fingers with force feedback, providing a haptic environment for virtual reality training. A recent review of hand robots found that although a substantial number of devices have been developed as prototypes, relatively few have yet undergone clinical testing with actual patients, and proof of efficacy remains to be established.[10]

The Amadeo hand robotic system (Tyromotion GmbH, Graz, Austria; Figs. 1 and 2) provides robot-assisted exercise for the finger flexors and extensors. This system provides a position-controlled active-assisted exercise mode, as well as isometric modes with visual feedback provided during computerized games emphasizing flexion and extension. There are no previous published reports of the use of this device for hand retraining after stroke.

We undertook this open-label pilot study to test the feasibility of treating hemiparetic stroke survivors using the Amadeo device and to obtain preliminary evidence of efficacy in restoring motor performance.

METHODS

Subjects were recruited through the use of a voluntary registry of stroke survivors maintained for clinical trials of stroke rehabilitation, as well as patients cared for at the Columbia University Medical Center. Inclusion criteria included a single stroke (hemorrhagic or ischemic) at least 6 mos before study entry, with confirmation by appropriate imaging studies (computed tomography or magnetic resonance imaging). Subjects were required to have at least trace finger flexion (1/5 on manual muscle testing using the Medical Research Council [MRC] scale) of at least three digits of the affected hand and to be reporting difficulty with activities of daily living using the affected hand and upper limb. Subjects were not receiving any physical or occupational therapy for the affected upper limb during the course of the study. Potential subjects with recent botulinum toxin injections within the previous 12 wks were excluded, and subjects were asked not to undergo these injections during their participation in this study.

Exclusion criteria include other neurologic disorders, such as Parkinson disease, a history of more than one stroke clinically, excessive spasticity (defined as a Modified Ashworth Scale score of 3 or greater, out of a maximum score of 4) at the wrist or finger flexors, uncontrolled hypertension, unstable coronary artery disease, contractures of the affected upper limb interfering with positioning in the device (e.g., shoulder or elbow), and contractures of any of the fingers of the affected hand greater than 10 degrees of flexion at any joint (metacarpophalangeal [MP], proximal [PIP] and distal [DIP] interphalangeal joints), impaired cognition defined by a Folstein Mini-Mental Status Examination score less than 24, or other medical conditions that might interfere with the subject's ability to complete the study. Subjects with severely impaired sensation in the affected hand (graded as 2 on the sensory item on the National Institutes of Health Stroke Scale) were excluded.

After undergoing baseline assessment, subjects received 1 hr of therapy with the device daily, 3 days/week for 6 consecutive weeks (a total of 18 sessions). Therapy sessions were conducted by an experienced physical therapist trained in the use of the device. Subjects were seated in a comfortable position, and the arm strapped into an adjustable stabilizing splint attached to the robotic device

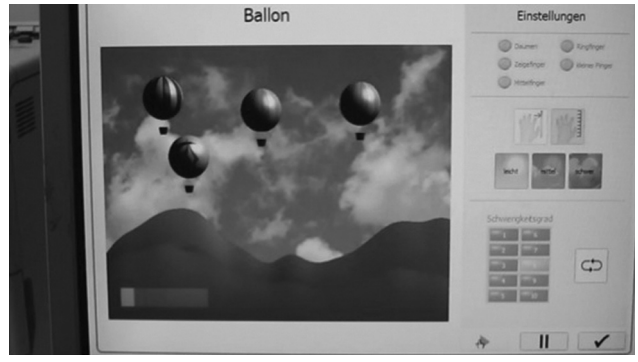

FIGURE 3 *Target avoidance task. Flexion causes the target balloon (second from the left in this figure) to move inferiorly, whereas extension causes it to move superiorly. Users are instructed to avoid making contact with the ground or other balloons.*

with the wrist in approximately neutral position and with the forearm pronated. A spring-loaded hinge attaches the wrist-stabilizing splint to the body of the device, allowing some degree of passive flexion and extension during use. The height of the device and the chair was adjusted to achieve an angle of approximately 30 degrees of flexion at the elbow. Each of the digits was attached to a robotically controlled slide using small permanent magnets taped to the distal phalanx of each finger.

Sessions included 20 mins of "Continuous Passive Motion Plus" mode, an active-assisted training mode wherein subjects were asked to assist the device to complete movements in both finger flexion and extension. This included both collective and sequential flexion and extension of the digits as well as flexion and extension of each digit individually. The device provided gradual flexion and extension of the fingers in rhythmic fashion in this mode, with the speed and extent of the excursions set by the supervising therapist. The user was encouraged to flex or extend his/her fingers in the same direction as moved by the device, with positive or negative visual feedback provided by a displayed "smiley face" indicating the degree of force exerted. This training mode provides constant (although therapist adjustable) speed and excursion distance, irrespective of the forces generated by the patient, thus providing an isokinetic exercise.

Visual feedback was also provided using two other games—one in which the flexion or extension isometric force exerted resulted in a proportional movement of a figure down or up in an obstacle avoidance task (Fig. 3) and the other in which a flexion or extension force resulted in leftward or rightward movement of a virtual figure in an attempt to reach a targeted position. The isometric digit contractions produced by the patient were sustained throughout each of the gaming modes (10 mins each game) and a 5-min rest period was offered between each game. After completion of the isometric game modes, each subject underwent an additional 20 mins of training with the Continuous Passive Motion Plus mode. Subjects were offered a 5-min rest period at the midpoint of each session (between the two games) if desired. Subject performance was monitored by the supervising physical therapist, and task difficulty was gradually increased throughout the course of the training. Manual incremental increases in task difficulty on the Continuous Passive Motion Plus mode were made every 2 wks, with increased active digit range of motion, and increased finger individuation. Automated increases in difficulty on isometric game modes were made by the device itself, requiring greater force generation and longer sustained forces for successful completion of the task, which occurred based on the successful completion of each difficulty level.

All subjects reported stable motor function before study enrollment, consistent with a population of stroke survivors more than 6 mos after stroke and without ongoing physical or occupational therapy. Subjects underwent a reassessment

TABLE 1 Subject characteristics

	Subjects (N = 12)
Male/female	9/3
Age, mean (SD), yrs	53 (14)
Duration poststroke, mean (SD), mos	66 (100)
Range	6–378
Right-/left-handed	12/0
Side of hemiparesis, right/left	8/4
Baseline score of the Upper Extremity component of the Fugl-Meyer test, mean (range)	37.9 (23–52)

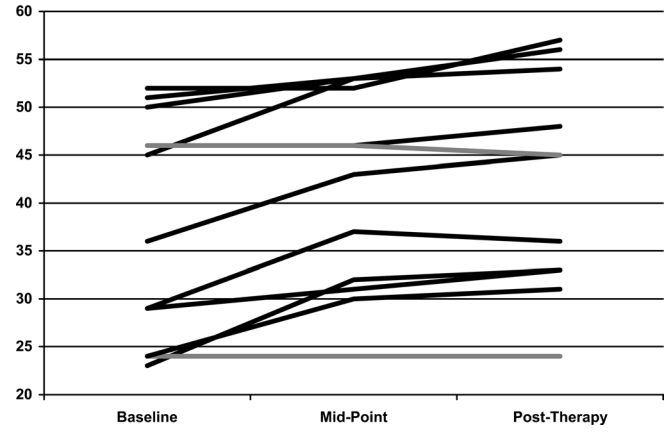

FIGURE 4 *Individual-subject Upper Extremity Fugl-Meyer scores. The scores of subjects with improvement are shown in darker shade; those without improvement or decline in score are shown in lighter shade. Range of possible scores, 0–66.*

of motor abilities at the midpoint of the training period and again at the conclusion. All scales were measured by an experienced occupational therapist familiar with the administration and scoring of these instruments who was not involved in the administration of the robotic therapy.

The primary outcome measure for this study was the Upper Extremity component of the Fugl-Meyer (UEFM).[11] Secondary outcome measures included the Motor Activity Log,[12] including both the amount of use and the quality of use scales, the nine-hole peg test,[13] the Manual Ability Measure–36,[14] the Jebsen Hand Function Test,[15] and the Stroke Impact Scale–16.[16]

Total active range of motion (TAM) was measured manually using a standard goniometer. The TAM score was calculated by subtracting the total extension deficits of finger joints from the total finger joint flexion of the same digit. Goniometric measurements were taken at each of the metacarpal phalangeal (MCP) joint, PIP, and DIP. The following formula was used to calculate TAM for each digit: TAM = (MCP + PIP + DIP flexion) − (MCP + PIP + DIP extension deficit).[17]

Maximal isometric force in flexion and extension was measured for each finger using the capabilities of the device, as well as for the summated forces of all of the fingers. Each of the subject's fingers was attached to an individual force sensor/actuator (used both for training and measurement; Fig. 1), and the subjects were instructed to first extend their fingers as forcefully as possible. After a brief rest, they were then asked to flex their fingers as forcefully as possible. Total force was obtained by summating the forces generated at each finger in the flexion and extension directions, respectively.

Primary and secondary outcome measures were analyzed using paired *t* tests of baseline values compared with values at the completion of treatment. Results were considered significant at a $P < 0.05$.

TABLE 2 Outcome measures before and after therapy

	Baseline, mean (SD)	Conclusion, mean (SD)	Change, mean (SD)	*P*
Upper Extremity component of the Fugl-Meyer test (instrument range, 0–66)	37.9 (11.1)	43 (10.8)	5.08 (3.38)	0.0004
Motor Activity Log—Amount of Use (instrument range, 0–5)	1.26 (0.90)	1.86 (1.16)	0.60 (0.47)	0.001
Motor Activity Log—Quality of Use (instrument range, 0–5)	1.34 (0.86)	1.81 (0.99)	0.47 (0.44)	0.004
Manual Ability Measure–36 (instrument range, 0 to 144)	103 (20)	112 (15)	8.7 (10.7)	0.02
Jebsen Hand Function, secs (instrument maximum of 1050)	701.5 (371.1)	649 (397)	52.4 (52.4)	0.007
Stroke Impact Scale–16 (instrument range 0–80)	67.6 (7.3)	69.4 (6.0)	1.8 (5.8)	0.31

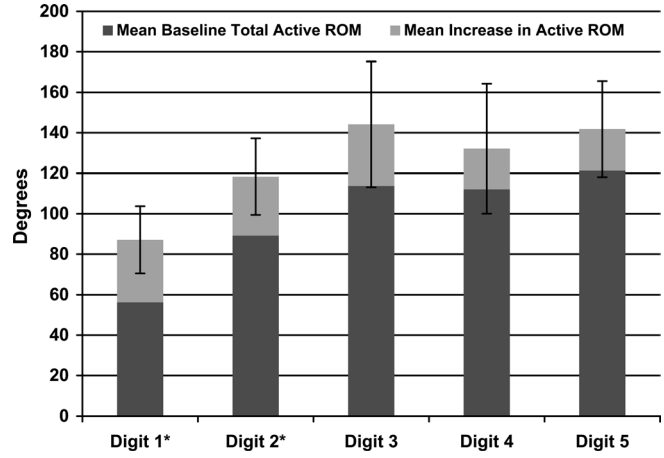

FIGURE 5 *Change in active ROM. SEM bars show 95% confidence intervals for the change in total active ROM. ROM indicates range of motion. *Change is statistically significant (P < 0.05).*

This study was approved by the institutional review board at the host institution, and informed consent was obtained from all participants.

RESULTS

Twelve subjects were enrolled in this study; all completed the training program, and no complications of robotic therapy were observed. Subject characteristics are provided in Table 1.

All subjects had some degree of spasticity in the wrist or hand, with a Modified Ashworth Scale score of at least 1. Six of the subjects had a Modified Ashworth Scale score of 2 at either the wrist or finger flexors, but no subjects were enrolled with scores of 3 or higher.

The UEFM scores improved from a mean (SD) of 37.9 (11.1) to 43 (10.8) from baseline to the conclusion of therapy (P = 0.0004). Individual-subject UEFM scores are shown in Figure 4. Previous studies of upper-limb robot-assisted rehabilitation have divided the UEFM into two components based on the limb segments tested—a "Shoulder/Elbow" component (maximum score of 42), and a "Wrist/Hand" component (maximum score of 24).[18] Subjects in our study showed mean improvements of 3.0 points in the UEFM Shoulder/Elbow component (P = 0.005) and 2.1 points in the UEFM Wrist/Hand component (P = 0.01), representing improvements of 12% and 17%, respectively.

Significant improvements were seen in the Motor Activity Log (both the amount of use, and the quality of use), the Manual Ability Measure–36, and the Jebsen Hand Function Test (Table 2). No change was seen in the Stroke Impact Scale–16 (Table 2).

The nine-hole peg test proved difficult for most subjects to perform, with 7 of 12 subjects unable to place any of the pegs at baseline. None of these seven subjects showed any improvement on this measure at the conclusion of training. Three subjects placed four to five pegs at baseline; all improved to eight or nine pegs by study end. The two subjects capable of placing all nine pegs at baseline were able to perform the 9-peg placement faster at the conclusion of treatment, with a reduction in time required of 36 secs and 49 secs, respectively, compared with baseline.

Total active range of motion increased for all digits, but this increase only achieved statistical significance for digits 1 and 2 (Fig. 5).

With the exception of maximal extension force for digit 1, which increased from a mean of 0.15 (0.28) to 0.44 (0.42) lbs (P = 0.013), force data generally failed to demonstrate any statistically significant change in maximal isometric finger flexion or extension force for any of the individual digits from baseline to completion of the training program or for the summated forces for all of the fingers. Generally, a trend for small increases in maximal extension force and small decreases in flexion force was observed but did not achieve statistical significance.

DISCUSSION

This pilot study found that individuals with chronic hemiparesis after stroke were able to successfully train with the Amadeo robotic device and demonstrated improvements in multiple measures of motor performance during the course of a 6-wk program consisting of a total of 18 hrs of robot-assisted therapy.

We selected individuals with residual finger flexion of at least trace movements in three or more

digits in an effort to identify a population likely to tolerate and benefit from the intervention. The range of UEFM scores is indicative of moderate levels of motor impairment, and the most severely impaired individuals with hemiplegia were not included in this study. It remains unknown, therefore, whether this type of therapy would be beneficial for individuals without volitional finger flexion after stroke. We also enrolled subjects with chronic deficits after stroke, with duration poststroke of up to 13 yrs. The capacity to respond to this or other therapies may decline in time poststroke, and we may have studied a suboptimal population from this perspective. Nonetheless, the population targeted encompasses a broad range of motor impairment and suggests that this therapy may be useful for a substantial portion of hemiparetic stroke survivors.

The open-label, uncontrolled nature of this pilot study limits the ability to make any definitive statements regarding efficacy or to compare this therapy with other promising upper-limb exercise training programs. Nonetheless, the results of this pilot study are encouraging and justify further study on the efficacy of this device in larger controlled trials.

The magnitude of the improvements in motor function seen in this study are similar to those found in other studies of chronic hemiparetic individuals receiving comparable doses of robot-assisted motor retraining using devices that target more proximal muscles[19] and to those seen with other training techniques.[20] The finding that training one portion of the upper limb (the hand, in our case), results in improvements in motor impairment in other portions of the upper limb (Shoulder/Elbow portion of UEFM in our study) is consistent with other studies that have shown similar generalization of training benefits beyond the segment or segments trained.[21] The mechanisms underlying this phenomenon are speculative at this time. Possibilities include a more generalized activation of the sensorimotor cortex during upper-limb training that facilitates plasticity of the cortex controlling other portions of the limb or, perhaps, the possibility that increased use of the entire limb resulting from focal training and improved motor control results secondarily in more diffuse training effects. In addition, the durability of the improvements seen in this study is unknown, and more definitive studies will require longer-term follow-up assessments.

The improvements in measures of motor control and performance are in contrast with the small, statistically insignificant changes seen in maximal force generation. This suggests that the clinical benefits observed are more likely caused by changes in motor control than by the strengthening effects of the training. The suggestion of small reductions in flexion force coupled with improvements in extension force raise the possibility that any changes in maximal force generation may be resulting in part or entirely from reductions in finger flexor spasticity. Although we did not measure spasticity after training, this should be examined in future studies to clarify this issue.

The Amadeo provides each finger with a single degree of freedom using an actuated linear slide and thus provides training of a simulated grasping activity. It does not provide specific training in other functionally important hand movements, such as a lateral pinch or finger pincer grasp. Whether robotic devices that provide multiple movement directions and a greater number of degrees of freedom would provide greater therapeutic benefits is unknown at this time.

Combining robotic training at multiple sites in the upper limb using a set of modules targeting different limb segments (e.g., the shoulder, elbow flexors and extensors, wrist, and hand) is conceptually appealing as a means of increasing the magnitude of the improvements in motor impairment. Despite the intuitive appeal of this approach, a previous study failed to demonstrate larger gains in UEFM with a combination of multiple upper-limb robotic modules.[4] The reasons for this failure remain unclear. One possibility is that there are fundamental limits on the amount of motor performance/plasticity that is achievable using exercise therapy after stroke, whereby adding more extensive training fails to provide incremental benefit. The benefits of robot-assisted training may be contingent on particular patient characteristics, such as severity level, although this has not yet been conclusively established. Another possibility is that the design of the individual robotic modules may not yet be optimally effective and that improvements in robotic technology may expand the range of achievable motor improvements. Lastly, the modular approach to training may be inferior to an integrated approach incorporating multiple limb segments, although previous studies have not demonstrated superiority of this integrated approach.[21]

Further clinical tests of novel robotic devices such as this one, both as individual therapies and in combination with modules directed at other limb segments are needed to answer these questions. Moreover, combining robotic therapy with other techniques to enhance brain plasticity, such as noninvasive brain stimulation, is an appealing strategy

that requires empiric testing. Other strategies to enhance the magnitude of the clinical effect might include providing robotic therapy earlier poststroke, when plasticity may be more robust, or providing training programs of greater duration or intensity.

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