Robotica (2003) volume 21, pp. 33–44. © 2003 Cambridge University Press
DOI: 10.1017/S0263574702004617 Printed in the United Kingdom

Robotic stroke therapy assistant

Richard M. Mahoney*, H. F. Machiel Van der Loos†, Peter S. Lum† and Chuck Burgar†

(Received in Final Form: October 4, 2002)

SUMMARY

The Rehabilitation Technologies Division of Applied Resources Corp. (RTD-ARC) has engaged in a Phase I effort to commercialize a robotic bi-manual therapy machine for use in stroke rehabilitation, in cooperation with the VA Rehabilitation R&D Center in Palo Alto. The robotic therapy device, called ARCMIME here in order to differentiate it from its clinical predecessor, has the potential to improve rehabilitation outcomes significantly for individuals who have upper limb impairments due to stroke and other brain injuries.

This paper describes design considerations and clinical outcomes with regards to the Phase I system. It was found that the kinematically simpler system adequately replicated the data outcomes of the more sophisticated PUMA-based experimental test rig.

KEYWORDS: Stroke therapy; ARCMIME; Rehabilitation; Robots.

I. INTRODUCTION

The VA Palo Alto R&D Research Center has been exploring bi-manual robotic stroke therapy system, called MIME, for over six years. This paper discusses a technology transfer initiative, the object of which was to create a commercially viable device that replicates the clinical outcomes of that system. The Phase I effort resulted in the construction and evaluation of a fully functioning alpha prototype of a pre-commercial robotic therapy machine, called ARCMIME.

Demographic trends indicate a significant increase in the already large population of individuals who have experienced a stroke. In addition, the inpatient rehabilitation length of stay following stroke has been shortening over the past 10 years. It is, therefore, critical to develop more efficient, scientifically-validated, interventions for the clinic and for post-clinic, home-based rehabilitation care. The combination of demographic trends, healthcare cost containment pressures and limitations in current clinical practice supports the commercial viability of ARCMIME (Figure 1).

Long term, a commercial system is expected to be able to provide the following advantages over current stroke therapy practice:

* Rehabilitation Technologies Division, Applied Resources Corp., 1275 Bloomfield Avenue, Fairfield, NJ 07004 (USA).
† Veterans Affairs Palo Alto Healthcare System, Rehabilitation Research and Development Center, and Department of Functional Restoration, Stanford University, Palo Alto, California (USA).

(i) *Augmentation of the clinical rehabilitation provided by a physical therapist*. ARCMIME will target achieving rehabilitation outcomes equivalent to those resulting from therapy performed by a Physical Therapist. As a clinical tool, ARCMIME will leverage therapist time, and become a cost-effective means to provide more rehabilitation for significantly less cost.

(ii) *Enhanced quantitative data to support rehabilitation decisions and progress review*. ARCMIME's sensing technology will provide quantitative information not currently available to therapists and physiatrists, to include ranges of motion, force profiles, movement efficiencies, and other indicators to be identified in future work.

(iii) *Improvements in the speed and quality of recovery from impairments caused by stroke*. It is expected that the uniform, systematic therapy techniques facilitated by ARCMIME will lead to advances in the under-



Fig. 1. The ARCMIME Phase I prototype, during a user trial.

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

standing of the effects of therapy on recovery from stroke, and eventually to new improved therapy techniques.

II. BACKGROUND

II.1. Increased prevalence of stroke

Each year 400,000 people in the United States survive strokes, and the total number of stroke survivors living in the US is quickly approaching three million.[1] The estimated associated cost for rehabilitation and lost revenue exceeds 7 billion per year.[2] Based on data from the Uniform Data System for Medical Rehabilitation, Granger *et al.*,[3] found that 76% of patients admitted for rehabilitation following stroke were over 65 years of age. The risk of stroke increases dramatically with chronological age, doubling with each decade after 55. Two-thirds of individuals affected with stroke and associated impairments are greater than 65 years of age. In this context it is important to appreciate that by the year 2025 one in five persons will be greater than sixty-five years of age.[4]

Stroke survivors represent the most common diagnostic impairment group on many rehab units and almost 40% of these persons have significant disability.[5–8] Over 80% of acute stroke survivors become hemiparetic, suffering from motor deficits on one side of the body while retaining almost normal function on the other side. The majority of victims recover less function in the upper limb than in the lower limb,[9–11] with approximately 50% of chronic stroke patients having arm impairment and thus requiring ongoing therapy to improve or at least maintain their level of arm function and health.

Persons with hemiparesis following stroke constitute the largest group of patients receiving rehabilitation services in this country.[12] In anticipation of the rehabilitative needs of the rapidly aging USA population, research efforts that lead to improved effectiveness of rehabilitative treatment of motor disability resulting from stroke are needed. With the dramatic reduction of inpatient rehabilitation length of stay following stroke, efficient and effective interventions have become critical.[13]

II.2. Current rehabilitation practice

A difficulty in assessing treatment strategies for patients with neurologic injury is the lack of accurate techniques to quantify the motor control impairment. Currently, clinical assessment of recovery of motor function is in terms of range of motion, strength, and evaluations of movement and coordination. There is wide agreement that quantitative measures are needed to aid in guiding treatment protocols, evaluating the efficacy of specific treatments, and charting the recovery process.[14]

II.2.1. Conventional therapy methods. Several different therapy techniques have been developed to address motor control impairments following stroke. Some techniques advocate resisted or assisted movements that facilitate activity in the paretic limb.[15] In contrast, some techniques emphasize movements and positions that inhibit abnormal muscle activity[16] or advocate practicing sub-components of functional tasks.[17] While the specific exercises vary from one method to another, a common thread is the application of external forces during volitional movement.

II.2.2. Bilateral therapy. Bilateral exercise is a potentially beneficial training paradigm, particularly early after stroke, when the central nervous system (CNS) may be undergoing plastic changes. There is recent evidence that recovery from hemiplegia is mediated by corticospinal ipsilateral pathways.[18,19] In addition, these same pathways appear to be active in bilateral movements. When normal subjects attempt to perform different movements with the upper limbs simultaneously, the kinematic patterns of one side appear in the movement of the other side.[20,21]

It is hypothesized that activity in corticospinal ipsilateral pathways are responsible for these bilateral interactions. Thus, a reasonable hypothesis is that bilateral symmetrical exercise early after the stroke will stimulate ipsilateral corticospinal pathways and enhance recovery. Along these same lines, Wolf *et al*. have postulated that bilateral therapies have the potential to target the ventromedial brain stem pathways that terminate bilaterally in the spinal cord.[22] They showed that a motor copy training technique using bilateral matching of the integrated EMG from homologous muscles improved upper limb function. Rathkolb *et al*. demonstrated improved paretic upper limb movements when preconditioned with mirror image bilateral movements and EMG feedback.[23]

II.2.3. Assessment of the movement impairment. There is considerable interest in developing quantitative measures of upper limb recovery after stroke that can be used to augment the existing subjective scales. In one study, performance in a simple Fitts tapping task was shown to correspond to the recovery curves of ADL scales.[24] Several studies have shown that tracking tasks can also be a sensitive measure of recovery, and advocate their use clinically.[25–27] Other measures that have been suggested are reaction and movement times of rapid untargeted elbow flexion,[28] and various parameters of reaching movements.[29–31]

All of these measures are more precise than existing subjective scales, and can continue to record improvement after subjective scales have reached a plateau. While all of the quantitative measures listed above are only useful after patients have regained significant function, the measurement of forces during assisted movements can be used in the initial flaccid stage and throughout recovery.

II.2.4. Semi-automated therapy systems. Although previous studies have failed to establish a clear benefit of any one type of conventional stroke therapy over others,[32–38] there is evidence that improved recovery can result from more therapy[39–43] and therapies which incorporate highly repetitive movement training.[44]

There is a growing interest in the therapeutic applications of robots.[45,46] One of the earliest papers to propose this

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

application was by Khalili and Zomlefer, who suggested that a two-joint robot system could be used for continuous passive motion and could be programmed to the particular needs of the patient.[47] Goodall *et al*. used two single degree-of-freedom (DOF) arms to stabilize sway in hemiparetic patients, and suggested the level of assistance could be withdrawn to encourage patients to relearn to balance on their own.[48] White *et al*. built a single DOF pneumatically powered orthotic device for elbow flexion that could be used for continuous passive motion, to measure patient strength and to assist elbow flexion.[49] Dirette *et al*. showed that a continuous passive motion (CPM) machine, when used regularly, can effectively reduce edema in the hands of flaccid hemiparetic patients.[50]

II.3. Robot-aided neuro-rehabilitation

Robot-aided stroke therapy techniques are actively being investigated at several research centers in the United States. Sometimes referred to as *rehabilitators*, robot therapy devices have significant potential to improve the recovery process for individuals with impairments resulting from stroke.

Robotic therapy provides a new form of active and passive mechanical movement that is programmable and augmented by force and position sensing. Research to date has shown that robotic therapy devices can be useful for treating stroke patients in both the chronic and post-acute stages.

The following list of advantages highlight the primary benefits of a robotic therapy device:

- Replicating therapy performed by physical therapists, including the rehabilitation outcomes of that therapy,
- Providing therapy outside of the clinical setting; Enable therapy to be performed at home.
- Maximizing a therapist's efficiency by supervising several patients at one time.
- Providing access to more therapy (which has been shown to improve outcomes).
- Providing access to diagnostic information not currently available.
- Leading to better understanding of stroke impairment and possibly improvements in therapy.
- Reducing clinical costs.

Robotic therapy lends itself to completely new paradigms for the practice of physical therapy. All of the following represent new opportunities in the clinical rehabilitation of stroke impairment:

- Active therapy programs that respond automatically to the client's progress;
- Computerized assessment and recommendations to augment the therapist's understanding of the impairment;
- Automated therapy routines that may be carried out remotely or in a networked scenario (leading to home-based or group therapy);
- Research leading to a fuller understanding of the underlying mechanisms of stroke.

II.4. MIME

The Rehabilitation Research and Development Center of the VA Palo Alto Healthcare System has been engaged in the study of a robotic therapy device, called MIME, for stroke rehabilitation. The MIME prototype and research results form the basis of the ARCMIME project, with the ultimate objective of a successful technology transfer to the marketplace.

II.4.1. Overview. The MIME studies at the Palo Alto VA introduced a new technique to quantify the impairment due to stroke. Abnormalities are being identified in the forces generated by paretic limbs during passive and active-assisted movements. EMG and force measurements are being employed to test hypotheses of the mechanisms of stroke impairment. Figure 2 shows the early MIME test bed, which consisted of a PUMA-260 manipulator on one side, and two instrumented mobile arm supports (troughs) for the two arms. This system was used to collect pilot data, prototype several clinical interventions[51] and develop quantitative measures of functions. Figure 3 shows an overview of the second MIME test bed, which consists of a PUMA 560 robot on one side, and a 6 DOF goniometer (Immersion Systems MicroScribe) on the other, each outfitted with a forearm trough for the subject's arms.[52–54]

The therapy regime consists of programmed and master/slave motions. In the programmed mode, the subject's forearm on the weaker side is comfortably strapped to a trough, with the hand gripping a vertical handle. The robot moves the trough carrying the arm through a slow, reaching motion path (passive ROM) several times to show the desired trajectory. A cone is placed on the table near the end-point as a visual clue. Then the subject's arm is brought back to the starting point, and the subject is asked to move to the endpoint cone.

However, using the force sensor, the computer will only allow the robot to move in the direction of the pre-taught trajectory, with a velocity proportional to the force applied (viscous behavior). If the subject generates no force in the appropriate direction, but rather backwards or sideways, the arm remains stationary. Each path is repeated several times, and then another of the 12 programmed trajectories is initiated.

In the bimanual master/slave mode, the same movement start and end points are used, but with the stronger arm, through the goniometer, providing the motion trajectories rather than the robot. Subjects are instructed to push with

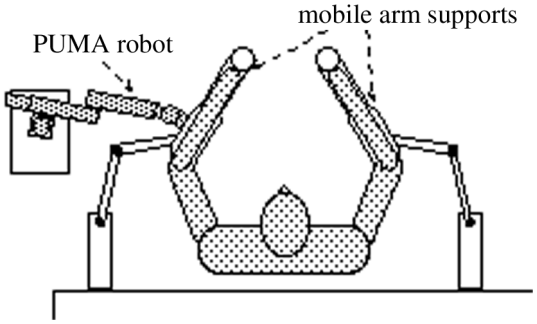


Fig. 2. Original test bed overview.

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

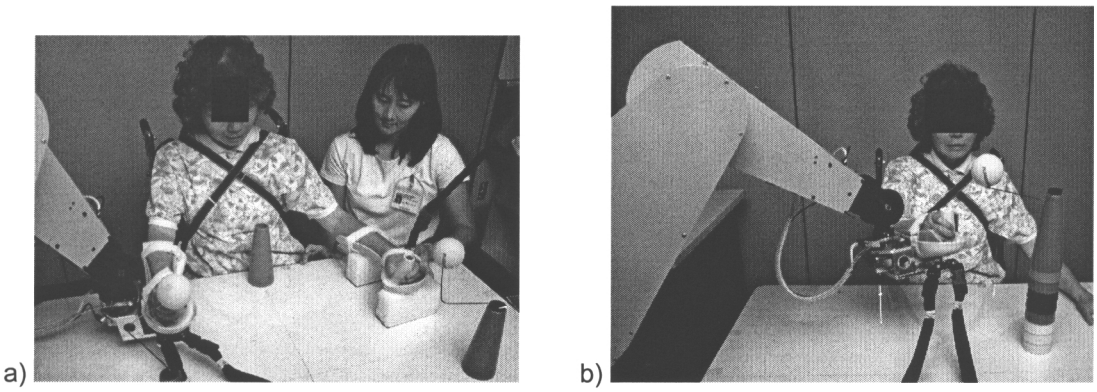


Fig. 3. Current MIME system being used to perform: a) master/slave therapy, and b) active constrained therapy.

the weaker hand in the direction of motion, with effort level measured by the force/torque sensor. The stronger side, attached only to the goniometer, feels no resistance.

Four modes of robot assistance are used:

passive mode: subject relaxes as the robot moves the limb in a predetermined pattern

active-assisted mode: subject triggers initiation of the movement with force toward the target and "works with the robot" as it moves the limb

active-constrained mode: robot provides a viscous resistance in the direction of movement and spring-like loads in all other directions

bimanual mode: subject attempts bimanual mirror-image movements while the 6-DOF goniometer measures movement of the contralateral limb and the robot moves the paretic limb to the mirror-image position with minimal delay

The bimanual master/slave mode of operation will offer unique therapeutic benefits. Subjects with flaccid hemiplegia can control and guide the manipulation therapy of the paretic limb by simply moving the strong limb. When subjects practice bilateral mirror-image movements with MIME, the master-slave control guarantees that the paretic limb is moved with the kinematics the subject intended, at least to the degree the subject is able to produce the desired movements with the stronger limb.

II.4.2. MIME outcomes. Extensive clinical trials have been carried out with the MIME system. The outcomes of those trials demonstrate the feasibility of the MIME approach and form a basis for the commercialization effort, the design of which is described herein.

The objective of the first MIME preliminary trials was to establish that the assistive forces during active-assisted movements accurately and reliably reflect the state of motor control recovery. Correlation was sought between aspects of each subject's force data and upper extremity Fugl-Meyer (FM) score. Preliminary data from 13 stroke subjects supported the hypothesis that performance during robotic assisted movements in terms of interaction forces correlates with the FM. The most descriptive parameter was the ability to generate a consistent force in the direction of movement, while eliminating forces in non-movement directions.

Clinical studies currently underway are examining the need for out-of-plane exercising. These studies will develop motion patterns and force strategies for effective upper extremity recovery in chronic and post-acute stroke subjects, and will allow the MIME project to plan for the use of the system during the acute recovery phase of stroke rehabilitation, in which the most dramatic functional improvements are anticipated. A three year clinical trial with chronic stroke subjects is nearing completion, and a four year study to evaluate MIME therapy for post-acute stroke subjects has just begun.

The most recent experimental program has focused on demonstrating the equivalence of the MIME therapy to conventional therapy for a chronic population. In a randomized, controlled, clinical trial, chronic stroke subjects (>6 months post-stroke) were randomly assigned to a robot or control group. Subjects were informed only that the objective of the study was to evaluate one of two treatment protocols, and were blinded to the fact that the robotic therapy was the experimental treatment. The therapist who performed the clinical evaluations was blinded to group assignments.

Both groups receive 24 one-hour sessions over two months. The robot group sessions include tabletop tracing of circles and polygons, and a series of 3-dimensional targeted reaching movements, all assisted by a Puma 560 robot arm. The control group sessions include Neuro-Developmental Therapy (NDT)-based therapy targeting upper limb function, and 5 min of exposure to the robot with target tracking tasks.

An occupational therapist blinded to group assignments evaluated the level of motor function in the paretic limb with the Fugl-Meyer exam[55] and the disability level of the subjects with the Barthel ADL scale[56–57] and the Functional Independence Measure (FIM).[58–59] The biomechanical evaluations include measures of isometric strength and free-reach kinematics. Electromyograms (EMG) are recorded from several shoulder and elbow muscles during these evaluations.

Data from a preliminary set of 11 robot group subjects and 10 control subjects who have completed the study shows that both the robot and control groups showed improvement in the upper limb portion of the Fugl-Meyer exam of motor function (Figure 4). There was a non-significant trend towards greater improvements in the robot

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

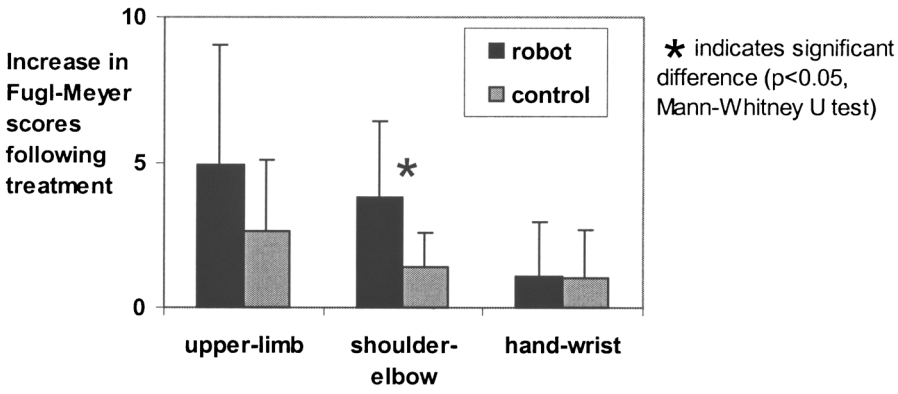


Fig. 4. Comparison of MIME and control therapy outcomes on Fugl-Meyer scale.

group compared to controls. When considering only the shoulder and elbow portions of the Fugl-Meyer exam, robot group improvements were significantly greater than control group improvements ($p<0.05$).

Robot-assisted movement promotes greater strength gains than conventional NDT-based therapy. In data from 9 robot-trained subjects and 9 controls, robot-trained subjects had significantly greater strength gains in 5 of 8 shoulder-elbow degrees of freedom ($p<0.05$) (Figure 5).

Robot group subjects often exhibited performance improvements in the training movements over the course of the 2 month treatment period. Decreased resistance to passive movement was common; while increased resistance was never observed. Improved performance of active-constrained movements under maximum effort instructions (move as fast as possible, or as far as possible) was indicated by increased positive work, efficiency, percent of movement completed, or average velocity (efficiency is defined as the positive work biased by the potential work that would have been done if the forces were directed perfectly toward the target). Improvements in some of these measures were observed in all subjects who have undergone robot-assisted training.

Although this data represents about 2/3 of the total number of target subjects for the study, the clinical outcomes of the MIME project so far provide a strong foundation for the development of the ARCMIME system described in this paper.

III. METHODOLOGIES

III.1. Specific aims of Phase I project

The purpose of the ARC SBIR Phase I research project was to demonstrate the commercial feasibility of the MIME therapy techniques described above. A design concept for a mechanically simple, yet functionally complete system was identified. The ARC SBIR Phase I activity included detailed design and construction of a fully functioning pre-commercial prototype. A clinical evaluation was designed to explore the ability of the prototype to replicate the therapy outcomes of the more sophisticated MIME test bed. Discussed below are the detailed design, manufacturing, and clinical evaluation results of this project.

III.2. System overview

In order to replicate the functionality of the MIME experimental system, ARCMIME is required to carry out the four control modes of the MIME system as described above. The system is also required to measure and log the variables listed in Table I.

Figure 6 is a CAD representation of the design generated for the first ARCMIME prototype from these specifications. Figure 1 shows the final manufactured system.

III.2.1. Mechanical system. The detailed design of ARC-MIME was carried out in ProEngineer. The ARCMIME

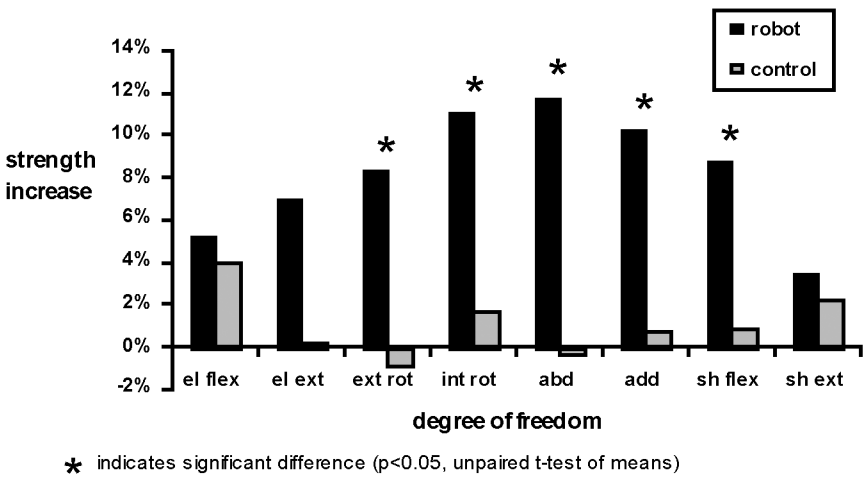


Fig. 5. Comparison of increases in strength between MIME therapy and control group.

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

Table I. Required variables for ARCMIME prototype.

Measured values (output data)
Position of limb with respect to origin
6 DOF force generated by impaired limb
Force generated by unimpaired limb in direction of motion
Velocity of limb
Set values (operator specified)
Angle between two links
Assist/resist torque from motor
Derived values (calculated from measured and set values)
Force directional error (comparison to unimpaired arm)
Positive work
Potential work (work if all forces and torques of impaired arm contributed to direction of motion)
Magnitude of force vector of impaired arm
Work efficiency (positive work/potential work)

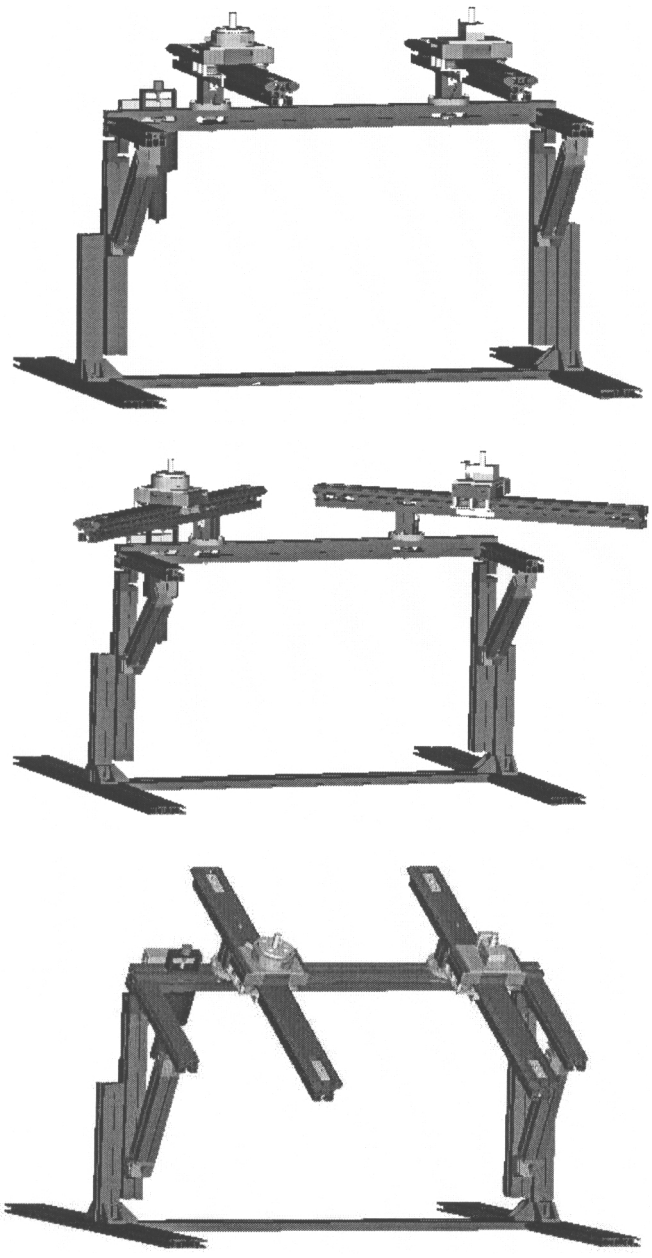


Fig. 6. CAD images of ARCMIME prototype, demonstrating possible adjustments with the system.

structure is composed of high precision aluminum extrusions and linear slides on which are mounted the arm supports. The system is designed to be manually reconfigured and adjusted. The pitch angle can be adjusted ±85° from horizontal. The two arms with the linear slides can be rotated 345° around their individual pivot points. Figure 6 shows ARCMIME in several different orientations. These mimic configurations of two MIME trajectories programmed on the PUMA-560 robot.

The ARCMIME prototype consists of the main system components as described in Table II.

III.2.2. Control software. The interface for ARCMIME is the same as the MIME software. The low-level hardware communication functions and other algorithms in the source code for the MIME system were modified as necessary for the ARCMIME hardware.

III.2.3. Safety features. In addition to meeting the functional requirements, a high priority was placed on incorporating an extensive set of safety features into the ARCMIME system. These features include:

E-Stop circuit,

Emergency shut-off switch,

Over-torque clutch,

Power amplifier malfunction electronics, and

Appropriate motor and gear train specifications to limit forces and speeds.

III.3. Clinical evaluation

The purpose of the clinical evaluation was to compare the operation of ARCMIME with that of the PUMA-560-based MIME system. The aim was to show that ARCMIME can replicate the movements of MIME and therefore can perform similar therapy interventions.

Four stroke subjects participated. All were more than 1 year post-stroke (3 right hemi, 1 left hemi). Two normal subjects participated (both PTs). Subjects were seated in a wheelchair in front of the ARCMIME system, and a chest strap was used to limit torso movement. Subjects' forearms were placed in the troughs, and the movement range adjusted to begin at a start point of 90° elbow flexion, neutral shoulder flexion and 20° abduction to an end point near full elbow extension. A handheld goniometer was used to measure these angles. Ten trials of each of the 4 main therapy modes were tested at each of two movement trajectories. To review, the therapy modes are:

Passive – subject relaxed and the system moved the arms back and forth;
Active-assisted – subject pushed with maximal effort with the paretic arm;
Active-constrained – subject pushed with maximal effort with the paretic arm;
Master/Slave – subjects pushed with both arms with maximal effort.

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

Table II. Major components of the ARCMIME prototype.

Component	Description
Rotary (Encoder) Potentiometer	The position of the arm troughs along the slides is measured by a precision potentiometer mounted on the motor shaft. The potentiometer signal is connected to an A-D converter on the data acquisition board in the control PC.
Motor	The motor is a coreless 24 Volt DC servo motor with a 43 : 1 planetary gearhead. The motor gearhead combination is capable of maximum torque of 15 Nm and a speed of 110 RPM.
Motor Controller	The PID controller in the PC's 1000 Hz interrupt service routine calculates the desired motor torque, which is sent by the D/A converter on the data acquisition board to the power amplifier in the external chassis.
One Degree of Freedom Linear Force Sensor	A one degree of freedom strain gage load cell is mounted on the base of the non-impaired arm support. The nominal maximum force range is ±.330 N.
Six Degree of Freedom Force Sensor	A six degree of freedom strain gage force/torque sensor (ATI Industrial Automation) is mounted under the other arm support. The sensing ranges are: F_x, $F_y \pm 330$ N, $F_z \pm 660$ N; Torque range ± 30 Nm
Clutch	The clutch, mounted between the motor gear head and the output sprocket, is a 24 Volt DC electro-mechanical crown tooth clutch with an override torque of 5.6 Nm.
Power Interrupt Circuit	The output of the E-Stop drives a *3PDT* relay coil via a properly-snubbed NPN Darlington switch on the E-stop circuit. This provision is included to inform the software of E-Stop status through the DIO input of data acquisition board.
Motor Current Monitor	The Motor servo amplifier has a current output monitor which is routed to an ADC input on the data acquisition board for verification.
Sensor (10V) Excitation Monitor	Presence of the 10V excitation voltage for the load cell and potentiometer is verified by a resistive matrix in the external chassis, and sent to an ADC input on the data acquisition board. This is included since failure of the 10V excitation would disable multiple sensors and confound software detection of over-speed and out-of range conditions.
Over- and Under-Voltage Sensing	Out-of-Range Operating Voltage from either of the two major power supplies is indicated by the front panel LEDs.
Servo-Fault Sensing	The *Advanced Motion Controls Corp.* Servo Amplifier has an output to signal when it is disabled due to a servo fault.
E-Stop Subsystem	The E-Stop subsystem, consisting of major hardware and software components, is a safety feature which causes an immediate shutdown of the DC motor, the servo amplifier, the clutch and clutch driver whenever certain conditions or triggers exist. Three classes of events result in the hardware being switched to an E-Stopped (Power-Interrupted) state: Manually-demanded E-Stop, induced either by a front-panel mushroom switch or by a foot-switch; Software-demanded E-Stop, induced by setting the E-Stop demand bit; Watchdog timer timeout, which results in an E-Stop if software execution fails to reset the watchdog timer in more than 100msec. In addition to the immediate power-down of the motor/servo and clutch devices, E-Stop operates four LED status indicators on the front-panel; E-Stop status is also signaled back to the software through the DIO, so software can arrange for a safe, smooth transition back to active operation when E-Stop de-asserts and power returns.

Two movement trajectories were tested: (a) horizontal and straight forward, and (b) 30° elevation angle and straight forward.

The subject was then moved to the MIME system. The paretic limb was similarly strapped to the robot via a trough and the contralateral arm was placed in another trough that was attached to the 6-DOF goniometer. The start positions for the two trajectories were programmed to match the shoulder and elbow angles recorded with the subject in the ARCMIME system. The end positions were programmed to move the hand the same distance and direction as in the ARCMIME movements, and the forearm orientation at the end points was adjusted to be comfortable for the subject with the arm relaxed. The procedure was to rotate the trough

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

about the hand in three axes until there was minimal pressure at the contact surfaces between it and the forearm of the subject.

The 4 modes were repeated for the two trajectories, with ten trials per mode. The same instructions used for the ARCMIME system were given to the subjects on the MIME system.

IV. RESULTS

Figure 7 shows a typical data set from a stroke subject. The data shown is the time plot of the force generated by the paretic limb in the direction of motion (bold line) and the corresponding position of the limb (gray line).

In the passive mode (Figure 7a), the data from the two systems is very similar. The trajectories of the active-assisted mode (Figure 7b) are also similar, with the exception of a slight position lag for ARCMIME. This effect was seen throughout the study and was attributed to low gain settings in the software PID loop.

A comparison was made of the averages across all movements in each mode for each subject with the MIME and ARCMIME systems. Figures 8 and 9 show the average movement times for each subject. Some significant differences were apparent, which was expected given the extra lag in the ARCMIME system mentioned above. Across all subjects, there was no statistical difference between ARCMIME and MIME forces directed toward the target in either movement type (1 or 2), neglecting subject EL (2-way repeated measures ANOVA, categories of device (arcmime, mime) and subject (JP, SB, etc.). For several subjects, there are some statistically significant differences between average forces in the two systems (t-test of means, significance level of 0.05), in some cases.

Figure 10 shows the average force in the direction of motion for each subject. This measure is an indication of the ability of the individual to initiate movement in the direction of a target. Across all subjects, there was no statistical difference between ARCMIME and MIME forces directed toward the target in either movement type (1 or 2), (2-way repeated measures ANOVA, categories of device (arcmime, mime) and subject (JP, SB, etc.). Subject EL was neglected in this analysis because at the time of her test session, the

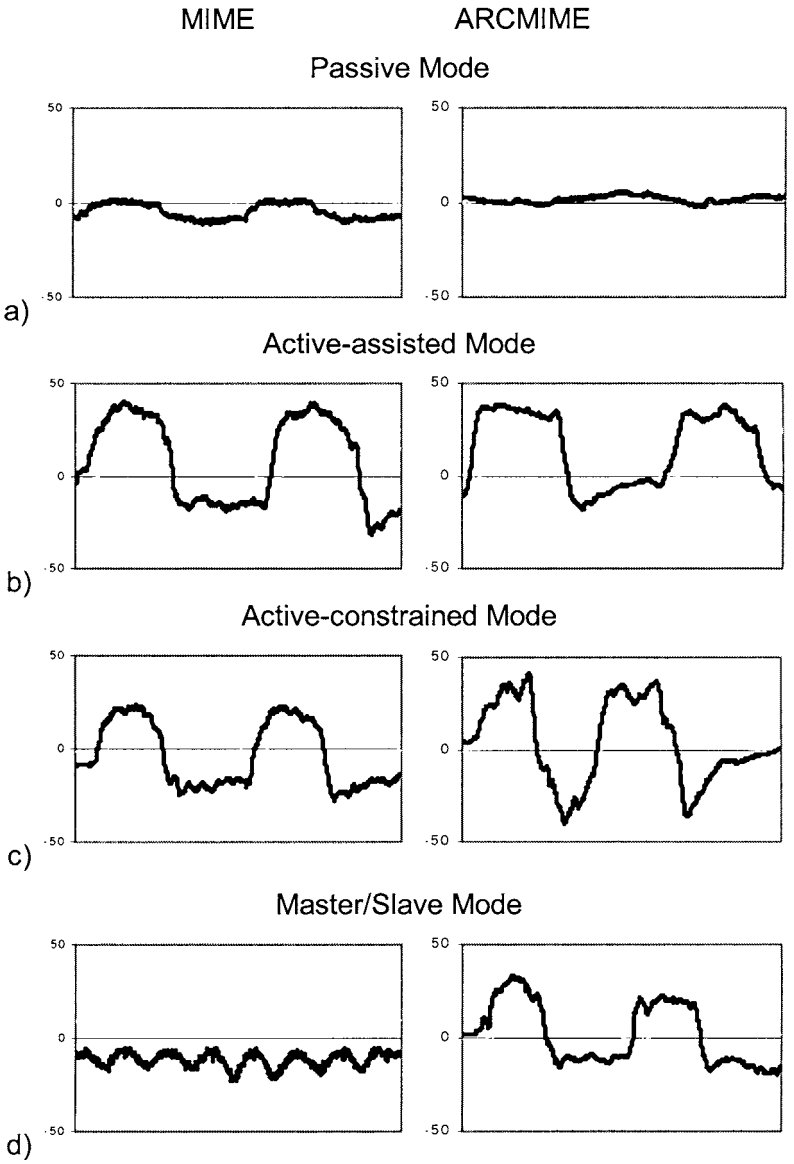


Fig. 7. Comparison of typical data sets for MIME and ARCMIME, across the four modes.

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

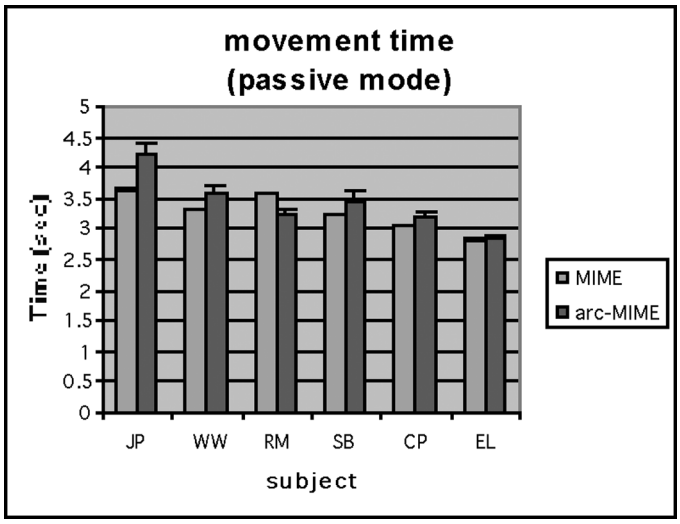


Fig. 8.

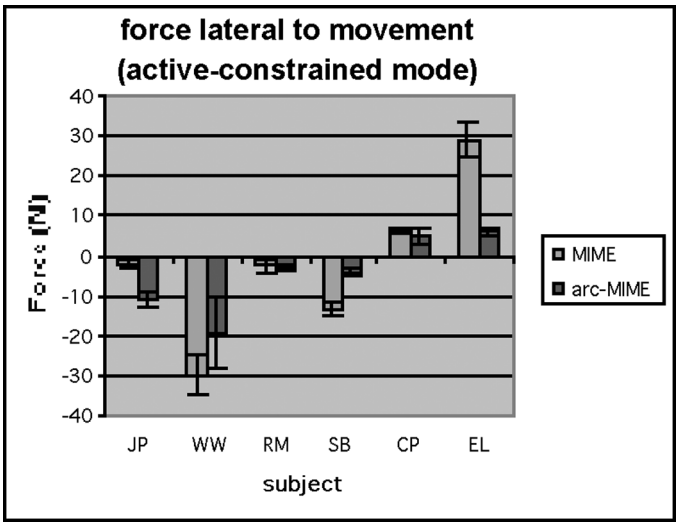


Fig. 11.

ARCMIME was not adjusted properly allowing her to overpower the system prematurely. For several subjects, there were some statistically significant within-subject differences between average forces in the two systems (t-test of means, significance level of 0.05), in some cases. Nevertheless, the similarities in the forces between systems are significant given the substantial differences in the kinematic design of each system.

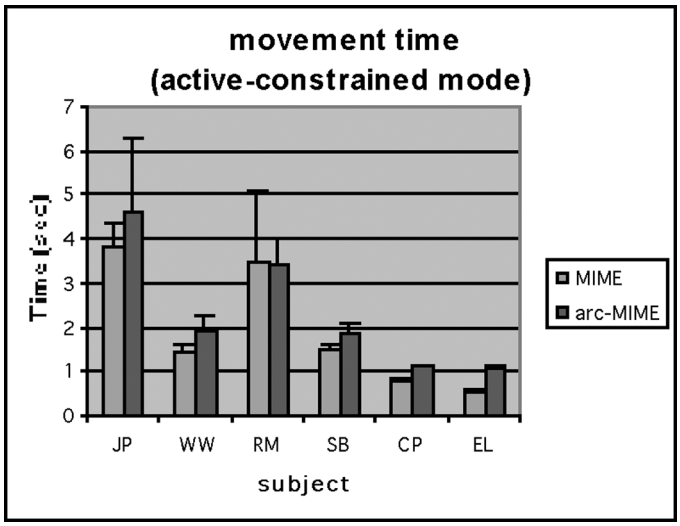


Fig. 9.

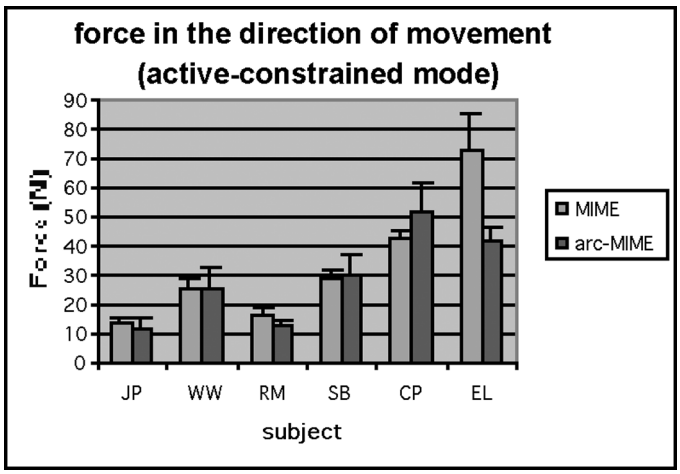


Fig. 10.

Figure 11 shows the average forces for each subject lateral to the desired movement direction. Again, the forces are similar in magnitude, and, importantly, in direction for the trials carried out. The same statistical analysis was applied to forces lateral to the target and significant differences were found for both movement types.

In addition to the measured data, other information regarding the performance of ARCMIME was obtained through interviews with the subjects and project staff.

The subject feedback was generally neutral. Some of the subjects preferred the original MIME system and some preferred ARCMIME. None of the responses were particularly strong and the data shows that each subject performed about the same on each system.

The project staff who administered the trials were very pleased with the operation of ARCMIME. Personal interviews showed that the project staff felt that the ARCMIME system seemed safer, and, therefore, there was less anxiety about the safety of the subject while running the trials. ARCMIME was also considered to be easier to use. It took less than three minutes to set up for each subject.

V. DISCUSSION

V.1. Results

In summary, the correlation between the results for the MIME and ARCMIME systems provides strong support for the potential of ARCMIME to replicate the therapy treatments carried out thus far in the MIME studies. Several observations can be made based on the differences found.

The lag exhibited in the ARCMIME trajectories provided an interesting result that warrants further examination. It appears that the slower response of the ARCMIME controller caused the paretic limb to engage at a greater level in the motion. For example, in the active constrained

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

mode (Figure 7c), higher forces were generated by the paretic limb during the motion. In the master/slave mode (Figure 7d), ARCMIME exhibited a more apparent lag than MIME, and resulted in a significant change in the interaction of the paretic arm.

Figure 7d, on the MIME side, shows 7 movements to the target position, and the force curve indicates that the paretic arm was lagging the system as it was carried along. In ARCMIME, however, only two movements to the target are shown for the same time period, and considerable involvement of the paretic limb is indicated by the force plot. This result is considered a significant finding and an advantage resulting from evaluation of the ARCMIME system.

This difference in lateral force magnitude (shown in Figure 11) can be attributed to variations in the geometry of the two systems. ARCMIME does not constrain rotation of the forearm about the hand in the vertical axis, while the MIME system does.

V.2. Future work

Future work will include specification and construction of a second generation prototype. Emphasis in the phase II design effort will be on improving aesthetics and functionality of both the mechanical system and the user interface with regards to ultimate use in a clinical environment, improving manufacturability, and reducing cost. Clinical trials will take place to measure the effects of an intensive program of robot-assisted therapy for stroke outpatients who are less than three months post-stroke.

Future clinical evaluation will target the population of individuals who are post-acute because they represent the initial market for ARCMIME. Pressures in the delivery of rehabilitation services are shortening the amount of therapy an individual receives after incurring a stroke. These patients typically receive limited therapy, although they are still typically recovering arm function. ARCMIME has the potential to make the therapy more cost-effective and either cause insurance companies to extend the amount of therapy sessions they will support, or make the therapy financially accessible to the consumer out of pocket.

Further, effort will be made to demonstrate the advantages of the unique measurements of stroke impairment provided by ARCMIME. A complete analysis of a range of parameters, both directly measured and derived, will take place with respect to existing scales of ADL proficiency. Review of the measures will be carried out with clinical personnel to identify those that may improve clinical practice.

V.3. Commercial potential

The commercial potential for ARCMIME is based on its potential to provide access to better treatment and better rehabilitation practices. Commercial opportunities will become available as benefits to individuals with impairments due to stroke are shown to have a quicker or greater recovery through use of the device under development here. In addition, many chronic patients cannot afford and do not receive reimbursement for therapy after a cutoff date, but would like to continue their therapy. Having a reasonably affordable, efficacious device in a clinic or gym would make this possible.

The demographic data showing an increase in individuals who have incurred a stroke, and the related fact that the population of elderly persons in the United States will increase dramatically, support the need for devices that will result in better therapy, and ultimately in greater functional ability.

In the long term, opportunities exist for extending this technology and developing more modular therapy devices that may be used by clients at home. The use of internet technology and computer-mediated evaluations will provide more individualized and detailed data gathering, therapy and evaluation.[60]

VI. CONCLUSION

The results of the Phase I project described here support ARCMIME as a viable robotic stroke therapy device. The clinical evaluation results showed that ARCMIME is capable of replicating the movements and data of subjects with neurological impairment – with a system that is considerably simper in design, ease of use, and safety. In conjunction with fundamental research outcomes being generated by our MIME collaborators, support for the potential long term benefits of the ARCMIME are positive.

ACKNOWLEDGEMENTS

Support for this work was provided through the following: NIH Phase I SBIR, Grant 1 R43 HD37301–01, 1999; VA Rehabilitation Research Service Grant B2056-RA and Pilot Grant B1846PA: "Mechanically Assisted Upper Limb Movement for Assessment and Therapy", 1997–2000.

The authors would like to thank the subjects who took part in the clinical evaluation, and gratefully acknowledge the participation in this work of Peggy Shor OTR, Craig Wunderly, Aman Siffeti, Chris Hardy, and Dan Zuckerman.

References

1. M. Goldstein, "The decade of the brain: challenge and opportunities in stroke research," *Stroke* **21**, p. 373 (1990).
2. F. D. Weinfield, "The national survey of stroke," *Stroke* **12**(suppl. 1) (1981).
3. C. V. Granger, B. B. Hamilton and R. C. Fiedler, "Discharge outcome after stroke rehabilitation," *Stroke* **23**(7), 978–982 (1992).
4. J. Siegel, *Aging into the 21st Century* (National Aging Information Center, Bethesda, MD, under contract number HHS-100-95-0017, Administration on Aging, U.S. Department of Health and Human Services, http://pr.aoa.dhhs.gov/aoa/stats/aging21/) (1996).
5. N. E. Mayo, "Epidemiology and recovery," *Phys. Med. Rehabil.: State of the Art Reviews* **7**(1), 1–25 (1993).
6. M. Stineman and C. Granger, "Epidemiology of stroke-related disability and rehabilitation outcome," *Phys. Med. Rehabil. North Am.* **2**, p. 457 (1991).
7. P. A. Wolf, A. J. Belanger and R. B. D'Agostion, "Management of risk factors," *Neurol. Clin.* **10**(1), 177–191 (1992).
8. M. L. Dombovy and P. Bach-y-Rita, "Clinical observations on recovery from stroke," **In:** (Waxman S. G., editor) *Advances in Neurology*, Functional Recovery in Neurological Disease (New York: Raven Press, 1988) **Vol. 47**, pp. 265–276.
9. R. Schneider and J. C. Gautier, "Leg weakness due to stroke. Site of lesions, weakness patterns and causes," *Brain* (England) **117**(Pt 2), 347–54 (1994).

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

10. P. W. Duncan, L. B. Goldstein, R. D. Horner, P. B. Landsman, G. P. Samsa and D. B. Matchar. "Similar motor recovery of upper and lower extremities after stroke," *Stroke* (U.S.) **25**(6), 1181–1188 (1994).
11. T. S. Olsen, "Arm and leg paresis as outcome predictors in stroke rehabilitation," *Stroke* (United States) **21**(2), 247–251 (1990).
12. K. J. Ottenbacher and S. Jannell, "The results of clinical trials in stroke rehabilitation research," *Arch. Neurol.* **50**(1), 37–44 (1993).
13. Frost and Sullivan (Research Company), *U.S. Rehabilitation Equipment and Product Markets – Market Overview, Total Market, Diathermy, Electrotherapy, and Continuous Passive Motion Markets* (Dialog Corporation, April, 1996).
14. *Post-Stroke Rehabilitation. Clinical Practice Guideline* (US Department of Health and Human Services. AHCPR Publication no. 95-0662, 1995).
15. S. Brunnstrom, *Movement Therapy in Hemiplegia* (Harper and Row, London, 1970).
16. B. Bobath, *Adult Hemiplegia Evaluation and Treatment*, 2nd Edition (Heinneman, London, 1978).
17. J. H. Carr and R. B. Shepherd, *A Motor Relearning Program for Stroke*, 2nd edition (Oxford: Butterworth-Heinemann, 1992).
18. F. Chollet, V. DiPiero, R. J. Wise, D. J. Brooks, R. J. Dolan and R. D. Frackowiak, "The functional anatomy of motor recovery after stroke in humans: a study with positive emission tomography," *Annals of Neurology* **29**(1), 63–71 (1991).
19. C. M. Fisher, "Concerning the mechanism of recovery in stroke hemiplegia," *Canadian Journal of Neurological Sciences* **19**(1), 57–63 (1992).
20. R. G. Marteniuk, C. L. MacKenzie and D. M. Baba, "Bimanual movement control: information processing and interaction effects," *The Quarterly Journal of Experimental Psychology* **36A**, p. 335 (1984).
21. S. P. Swinnen, D. E. Young, C. B. Walter and D. J. Serrien, "Control of asymmetrical bimanual movements," *Experimental Brain Research* **85**, 163–173 (1991).
22. S. L. Wolf, D. E. LeCraw and L. A. Barton, "Comparison of motor copy and targeted biofeedback training techniques for restitution of upper extremity function among patients with neurologic disorders," *Physical Therapy* **69**(9), 719–735 (1989).
23. O. Rathkolb, S. T. Baykoushev and V. Baykousheva, "Myobiofeedback in motor reeducation of wrist and fingers after hemispherial stroke," *Electromyogr. Clin. Neurophysiol.* **30**, 89–92 (1990).
24. A. Turton and C. Fraser, "The use of a simple aiming task to measure recovery following stroke," *Physiotherapy Practice* **3**, 117–125 (1987).
25. R. D. Jones and I. M. Donaldson, "Measurement of integrated sensory-motor function following brain damage by a computerized preview tracking task," *Int. Rehab. Med.* **3**, 71–83 (1981).
26. M. E. Halaney and J. R. Carey, "Tracking ability of hemiparetic and healthy subjects," *Physical Therapy* **69**, 342–348 (1989).
27. L. H. DeSouza, R. Langton Hewer, P. A. Lynn, S. Miller and G. A. L. Reed, "Assessment of recovery of arm control in hemiplegic stroke patients. 2. Comparison of arm function tests and pursuit tracking in relation to clinical recovery," *Int. Rehab. Med.* **2**, 10–16 (1980).
28. R. Dickstein, S. Hocherman, G. Amdor and T. Pillar, "Reaction and movement times in patients with hemiparesis for unilateral and bilateral elbow flexion," *Physical Therapy* **73**(6), 374–385 (1993).
29. A. M. Wing, S. Lough, A. Turton, C. Fraser and J. R. Jenner, "Recovery of elbow function in voluntary positioning of the hand following hemiplegia due to stroke," *Journal of Neurology, Neurosurgery and Psychiatry* **53**(2), 126–134 (1990).
30. S. Lough, "Visual control of arm movement in the stroke patient," *International Journal of Rehabilitation Research* **10**(4 suppl. 5), 113–119 (1987).
31. C. A. Trombly, "Observations of improvement of reaching in five subjects with left hemiparesis," *Journal of Neurology, Neurosurgery and Psychiatry* **56**, 40–45 (1993).
32. M. K. Logigian, M. A. Samuels, J. Falconer and R. Zagar, "Clinical exercise trial for stroke patients," *Arch. Phys. Med. Rehabil.* **64**, 364–367 (1983).
33. J. V. Basmajian, C. A. Gowland, A. J. Finlayson, A. L. Hall, L. R. Swanson, P. W. Stratford, J. E. Trotter and M. E. Brandstater, "Stroke treatment: comparison of integrated behavioral physical therapy vs traditional physical therapy programs," *Arch. Phys. Med. Rehabil.* **68**, 267–272 (1987).
34. R. C. Wagenaar, O. G. Meijer, P. van Wieringen, D. J. Kuik, G. J. Hazenberg, J. Lindeboom, F. Wichers, F. Rijswijk, "The functional recovery of stroke: a comparison between neurodevelopmental treatment and the Brunnstrom method," *Scand. J. Rehab. Med.* **22**, 1–8 (1990).
35. S. L. Wolf, D. E. LeCraw and L. A. Barton, "Comparison of motor copy and targeted biofeedback training techniques for restitution of upper extremity function among patients with neurologic disorders," *Physical Therapy* **69**(9), 719–735 (1989).
36. J. P. Lord and K. Hall, "Neuromuscular re-education versus traditional programs for stroke rehabilitation," *Arch. Phys. Med. Rehabil.* **67**(2), 88–91 (1986).
37. R. Dickstein, S. Hocherman, T. Pillar and R. Shaham, "Stroke rehabilitation. Three exercise therapy approaches," *Physical Therapy* **66**(8), 1233–1238 (1986).
38. P. H. Stern, F. McDowell, J. M. Miller and M. Robinson, "Effects of facilitation exercise techniques in stroke rehabilitation," *Arch. Phys. Med. Rehabil.* **51**(9), 526–531 (1970).
39. A. Sunderland, D. J. Tinson, E. L. Bradley, D. Fletcher, R. Langton Hewer and D. T. Wade, "Enhanced physical therapy improves recovery of arm function after stroke. A randomized controlled trial," *J. Neurology Neurosurgery and Psych.* **55**, 530–535 (1992).
40. R. S. Stevens, N. R. Ambler and M. D. Warren, "A randomized controlled trial of a stroke rehabilitation ward," *Age and Aging* **13**(2), 65–75 (1984).
41. M. E. Smith, W. M. Garraway, D. L. Smith, A. J. Akhtar, "Therapy impact on functional outcome in a controlled trial of stroke rehabilitation," *Archives of Physical Medicine and Rehabilitation* **63**(1), p. 21 (1982).
42. M. Dam, P. Tonin, S. Casson, M. Ermani, G. Pizzolato, V. Iaia and L. Battistin, "The effects of long-term rehabilitation therapy on poststroke hemiplegic patients," *Stroke* **24**(8), 1186–1191 (1993).
43. D. S. Smith, E. Goldenberg, A. Ashburn, G. Kinsella, K. Sheikh, P. J. Brennan, T. W. Meade, D. W. Zutshi, J. D. Perry and J. S. Reeback, "Remedial therapy after stroke: randomized controlled trial," *Br. Med. J.* **282**, 517–520 (1981).
44. C. Butefisch, H. Hummelsheim, P. Denzler and K. H. Mauritz, "Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand," *Journal of the Neurological Sciences* **130**, 59–68 (1995).
45. R. F. Erlandson, "Applications of robotic/mechatronic systems in special education, rehabilitation therapy, and vocational training: A paradigm shift," *IEEE Trans. on Rehab. Eng.* **3**(1), 22–34 (1995).
46. D. J. Reinkensmeyer, J. P. A. Dewald and W. Z. Rymer, "Robotic devices for physical rehabilitation of stroke patients: Fundamental requirements, target therapeutic techniques, and preliminary designs," *Technology and Disability* **5**, 205–215 (1996).
47. D. Khalili and M. Zomlefer, "An intelligent robotic system for rehabilitation of joints and estimation of body segment parameters," *IEEE Transactions on Biomedical Engineering* **35**(2), 138–146 (1988).
48. R. M. Goodall, D. J. Pratt, C. T. Rogers and C. M. Murray-Leslie, "Enhancing postural stability in hemiplegics using

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press

externally applied forces," *Int. J. of Rehab. Research* (suppl. 5) **10**(4), 132–140 (1987).
49. C. J. White, A. M. Scneider and W. K. Brogan Jr., "Robotic orthosis for stroke patient rehabilitation," *Proc 15th Annual Int Conf IEEE Eng Med Biol* (San Diego, 1993) pp. 1272–1273.
50. D. Dirette and J. Hinojosa, "Effects of continuous passive motion on the edematous hands of two persons with flaccid hemiplegia," *American Journal of Occupational Therapy* **48**(5), 403–409 (1994).
51. P. S. Lum, C. G. Burgar, D. Kenney and H. F. M. Van der Loos, "Quantification of force abnormalities during passive and active-assisted upper-limb reaching movements in post-stroke hemiparesis," *IEEE Transactions Biomedical Engineering* **46**, 652–662 (June, 1999).
52. P. S. Lum, H. F. M. Van der Loos, P. Shor and C. G. Burgar, "A robotic system for upper-limb exercises to promote recovery of motor function following stroke," *Proc. 6th International Conference on Rehabilitation Robotics*, Palo Alto, CA (July, 1999) p. 235.
53. C. G. Burgar, P. S. Lum, M. Shor and H. F. M. Van der Loos, "Rehabilitation of upper limb dysfunction in chronic hemiplegia: Robot-assisted movements vs.conventional therapy," *Arch. Phys. Med. Rehabil.* **80**(9), p. 1121 (1999).
54. C. G. Burgar, P. S. Lum, H. F. M. Van der Loos and M. Shor, "The Evolution of Robots for Rehabilitation Therapy: The Palo Alto VA/Stanford Experience," *J. Rehabil. Research and Development* (In press).
55. A. Fugl-Meyer et al., "The post-stroke hemiplegic patient: A method of evaluation of physical performance," *Scand. J. Rehabil. Med.* **7**, 13–31 (1975).
56. D. T. Wade and C. Collin, "The Barthel ADL Index: a standard measure of physical disability?," *Int. Disabil. Stud.* **10**(2), 64–67 (1988).
57. G. E. Gresham, T. F. Phillips and M. L. Labi, "ADL status in stroke: relative merits of three standard indexes," *Arch. Phys. Med. Rehabil.* **61**(8), 355–358 (1980).
58. B. B. Hamilton, C. V. Granger, F. S. Sherwin, M. Zielezny and J. S. Tashman, "A uniform national data system for medical rehabilitation," **In:** (Fuhrer, M. J., editor). *Rehabilitation Outcomes: Analysis and Measurement* (Baltimore: Brookes, 1987) pp. 137–147 .
59. B. B. Hamilton, J. A. Laughlin, R. C. Fiedler and C. V. Granger, "Interrater reliability of the 7-level functional independence measure (FIM)," *Scand. J. Rehabil. Med.* **26**(3), 115–119 (September, 1994).
60. D. J. Reinkensmeyer, C. T. Pang, J. A. Nessler, C. C. Painter, "Java Therapy: Web-based robotic rehabilitation. Integration of Assistive Technology in the Information Age," *Proceedings 7th International Conference on Rehabilitation Robotics*, Institut National des Télécommunication (INT), Evry, France, IOS Press, Amsterdam (April 25–27, 2001) pp. 66–71.

https://doi.org/10.1017/S0263574702004617 Published online by Cambridge University Press