Automating Arm Movement Training Following Severe Stroke: Functional Exercises With Quantitative Feedback in a Gravity-Reduced Environment

Robert J. Sanchez, Jiayin Liu, Sandhya Rao, Punit Shah, Robert Smith, Tariq Rahman, Steven C. Cramer, James E. Bobrow, and David J. Reinkensmeyer, *Member, IEEE*

***Abstract*—An important goal in rehabilitation engineering is to develop technology that allows individuals with severe motor impairment to practice arm movement without continuous supervision from a rehabilitation therapist. This paper describes the development of such a system, called Therapy WREX or ("T-WREX"). The system consists of an orthosis that assists in arm movement across a large workspace, a grip sensor that detects hand grip pressure, and software that simulates functional activities. The arm orthosis is an instrumented, adult-sized version of the Wilmington Robotic Exoskeleton (WREX), which is a five degrees-of-freedom mechanism that passively counterbalances the weight of the arm using elastic bands. After providing a detailed design description of T-WREX, this paper describes two pilot studies of the system's capabilities. The first study demonstrated that individuals with chronic stroke whose arm function is compromised in a normal gravity environment can perform reaching and drawing movements while using T-WREX. The second study demonstrated that exercising the affected arm of five people with chronic stroke with T-WREX over an eight week period improved unassisted movement ability (mean change in Fugl-Meyer score was 5 points ±2 SD; mean change in range of motion of reaching was 10%, $p < 0.001$). These results demonstrate the feasibility of automating upper-extremity rehabilitation therapy for people with severe stroke using passive gravity assistance, a grip sensor, and simple virtual reality software.**

***Index Terms*—Arm, motor control, movement, rehabilitation, stroke, telerehabilitation.**

I. INTRODUCTION

OVER 700 000 people in the United States survive a stroke each year [1]. Roughly half of stroke survivors experience chronic hemiparesis and approximately one quarter become dependent in activities of daily living [1]. Stroke survivors typically receive intensive, hands-on physical and occupational therapy to encourage motor recovery. However, due to economic pressures on the U.S. health care system, stroke patients are receiving less therapy and going home sooner [2]. Home rehabilitation is often self-directed with little professional or quantitative feedback.

Even as economic constraints limit the provision of rehabilitation services, a growing body of evidence suggests that both acute and chronic stroke survivors can improve movement ability with intensive, supervised training [3]–[7]. Thus, an important goal for rehabilitation engineering is to develop technology that allows stroke patients to practice intensive movement training without the expense of a supervising therapist [8].

Several researchers are addressing this goal by developing robotic devices that can assist in arm and hand movement therapy following stroke. Initial studies with MIT-MANUS [9], MIME [10], the ARM Guide [11], Gentle-S [12], and Rutgers Master II-ND [13] have been promising. Individuals with acute and chronic stroke who receive more therapy with a robotic device can recover more movement ability [9]–[12]. Matched amounts of robotic and conventional therapy produced comparable therapeutic benefits for people with a chronic stroke [10].

Despite these promising initial results, it still remains unclear as to whether the robotic features of these devices (i.e., the ability to apply programmable forces to the patient's limb), are important to improving movement recovery. That is, technology that allows patients to practice movement therapy without robotic actuation may also be effective in improving recovery [14], [15]. While nonrobotic devices are less useful for studying a broad range of interactive therapy techniques, they might ultimately be more practical because they avoid the expense and safety concerns associated with robotic actuators.

There is a long history of using nonrobotic technology in rehabilitation clinics to partially automate physical rehabilitation following stroke. Mobile arm supports, overhead slings, elastic bands, and weights allow patients to practice therapy semi-independently from therapists. However, these devices typically suffer from three key limitations: they can be difficult to adjust for different levels of impairment, their relevance to functional activities is indirect, and they provide little feedback to the patient or therapist about movement recovery.

This paper describes the development of a nonrobotic system for upper extremity movement training that addresses these limitations (Fig. 1). The system extends previous work on a low-cost, highly accessible, web-based system for facilitating repet-

---

Manuscript received June 21, 2005; revised May 17, 2006; accepted May 22, 2006. This work was supported in part by the Department of Education National Institute on Disability and Rehabilitation Research (NIDRR), H133E020732, as part of the Machines Assisting Recovery from Stroke (MARS) Rehabilitation Engineering Research Center (RERC) on Rehabilitation Robotics and Telemanipulation, and in part the University of California, Irvine, General Clinical Research Centers Program of the National Center for Research Resources, National Institutes of Health under Grant M01 RR000827-29.

R. J. Sanchez, J. Liu, S. Rao, P. Shah, R. Smith, J. E. Bobrow, and D. Reinkensmeyer are with the Department of Mechanical and Aerospace Engienering, University of California, Irvine, CA 92697-3975 USA (e-mail: dreinken@uci.edu).

T. Rahman is with the Computer Science and Mechanical Engineering Departments, University of Delaware, Newark, DE 19716 USA.

S. C. Cramer is with the Department of Neurology and Department of Anatomy and Neurobiology, University of California, Irvine CA 92697 USA.

Digital Object Identifier 10.1109/TNSRE.2006.881553

1534-4320/$20.00 © 2006 IEEE

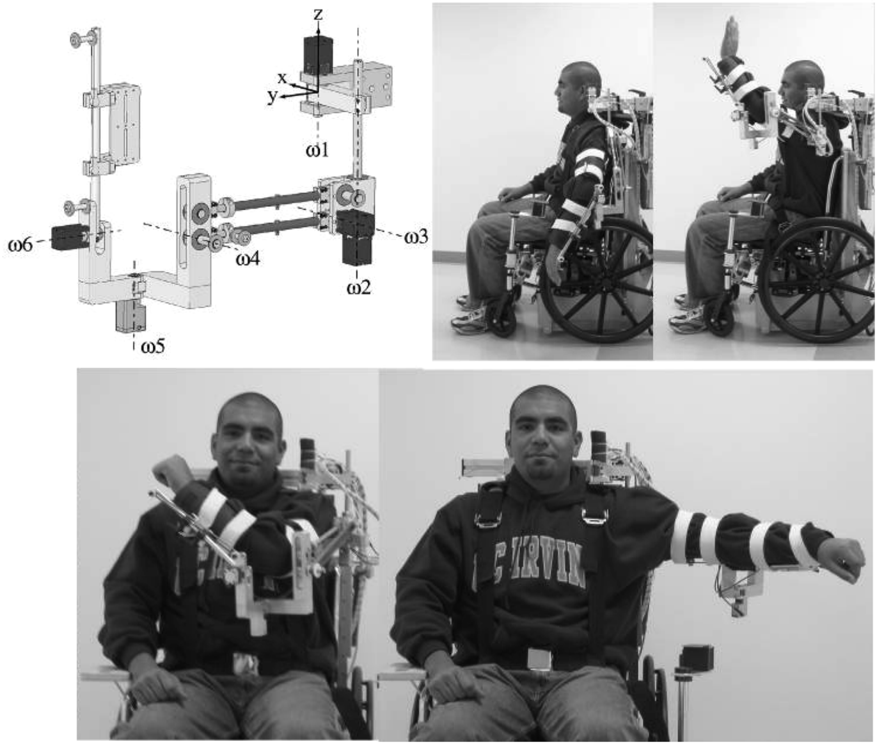


Fig. 1. Left: Computer model of T-WREX with labeled axes of rotation. Horizontal and vertical location of the device is adjusted for each subject with an extruded aluminum positioning system (not shown) so that the first axis ω_1 is above the head of the humerus. Subject's elbow is positioned above axis ω_5. Forearm is attached to the most distal link, which rotates around axis ω_6, using a forearm brace (not shown). Right and bottom: T-WREX range of motion in the up–down and left–right directions.

itive movement training, called "Java Therapy" [16]. The initial version of Java Therapy allowed users to log into a website, perform a customized program of therapeutic activities using a mouse or joystick, and receive quantitative feedback of their rehabilitation progress. In preliminary studies of the system, we found that people with a chronic stroke responded enthusiastically to the quantitative feedback provided by the system. However, the use of a standard mouse or joystick as the input device limited the functional relevance of the system.

Our project goal was to develop an input device and software that allowed a broader range of functional arm movements to be practiced and monitored. We modified a passive antigravity arm orthosis, the Wilmington Robotic Exoskeleton (WREX[1]) [17], to be used as a three-dimensional (3-D) input device for measuring arm movement. We also developed a simple grip sensor and software that allows the system to be used to practice simulated functional movements that require coordinated arm and hand movement. This paper first provides a detailed design description of the modified arm orthosis coupled with the revised Java Therapy software. The paper then characterizes the ability of the counterbalancing function of the arm orthosis to improve arm movement ability of individuals with chronic stroke while wearing the device. Finally, this paper reports the results of a pilot study in which five individuals with chronic stroke exercised their affected arm for two months using the system.

II. METHODOLOGY

A. WREX

WREX was originally designed to help children with weakened arms to perform activities of daily living such as eating [17]. WREX is a five degrees-of-freedom, backdriveable mechanism that uses elastic bands wrapped around two four-bar linkages to counterbalance the arm. WREX allows naturalistic movements across an estimated 66% of the normal workspace of the arm in the vertical plane and 72% in the horizontal plane.

We have adapted WREX for use in movement training by stroke patients by making it larger, stronger, simpler to manufacture, and by instrumenting it with position sensors. We call the modified device, along with the enhanced version of software with which it is used, the T-WREX (Therapy WREX) System (Fig. 1).

B. T-WREX Design

1) Position Sensor Selection: We desired a sensing system that allowed measurement resolution of the tip of T-WREX within 1 cm for all axes, which corresponds to a required angular resolution at the orthosis joints of about 0.3°. In addition, we desired a sensor that did not require zeroing, so that users of the system would not be required to execute any initialization procedures in order for the device to accurately measure movement. Conductive plastic, compact rotary potentiometers (Midori America, CP-2FB(b)) met these requirements and were installed in protective aluminum housings at each non-redundant joint [18].

---

[1] WREX is not a robotic device even though it contains the term "robotic" in its acronym. This contradiction arose because the WREX development project started off as a powered orthosis project. However, the passive gravity balancing idea was soon conceived and worked well clinically. Thus, the robotic part of WREX was not pursued, although the name remained.

2) Mechanical Design Changes: The primary design changes that we made to the original WREX design were to increase the size of the forearm and upper arm links to accommodate an adult's arm, and the large, uncoordinated forces that individuals with strokes sometimes exert. The user's arm is now attached to the device using a commercial brace (Elbow Ranger, dj-Orthopedics), which has lower and upper arm cuffs that attach with Velcro. The new design can be flipped for use with the left or right arm by disassembling the device's elbow and forearm. The orthosis is attached at its shoulder to an extruded-aluminum stand that is mounted to a manual wheelchair. The left–right, up–down, and forward–backward position of the orthosis can be quickly adjusted then locked into place using hand cranks.

3) Forward Kinematics: In order to use T-WREX as a 3-D mouse for the computer interface, it was necessary to define the forward kinematic relationship between the measured joint angles and the user's hand position. We used the product of exponentials formation for the forward kinematics [19]. The position of the tip of the forearm link p relative to a fixed reference frame located at the shoulder is (Fig. 1)

$$p_t = e^{\hat{\xi}_1\theta_1} e^{\hat{\xi}_2\theta_2} e^{\hat{\xi}_3\theta_3} e^{\hat{\xi}_4\theta_4} e^{\hat{\xi}_5\theta_5} e^{\hat{\xi}_6\theta_6} M,$$

where the joint twists are

$$\xi_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 2.54 \end{bmatrix}, \quad \xi_2 = \begin{bmatrix} 0 \\ 9.93 \\ 0 \\ 0 \\ 0 \\ 2.54 \end{bmatrix}, \quad \xi_3 = \begin{bmatrix} 0 \\ v + 8.57 \\ 3.56 \\ -2.54 \\ 0 \\ 0 \end{bmatrix}$$

$$\xi_4 = \begin{bmatrix} 0 \\ -v - 8.57 \\ -3.56 - ua \\ 2.54 \\ 0 \\ 0 \end{bmatrix}, \quad \xi_5 = \begin{bmatrix} 6.86 + ua \\ -.23 \\ 0 \\ 0 \\ 0 \\ 2.54 \end{bmatrix}$$

$$\xi_6 = \begin{bmatrix} v + 8.57 \\ 0 \\ .23 \\ 0 \\ 2.54 \\ 0 \end{bmatrix}$$

and

$$M = \begin{bmatrix} I_{3,3} & q_{t,0} \\ 0_{1,3} & 1 \end{bmatrix}, \quad q_{t,0} = \begin{bmatrix} .23 \\ 13.86 + ua \\ -v - 21.96 + tip \end{bmatrix}.$$

The initial location of the tip of the forearm is $q_{t,0}$, the angular displacements measured by the potentiometers were θ_i. The length of the upper arm is ua, and the vertical displacement at the shoulder is v. (All kinematic equations are in cm.) The joint limits of the degrees-of-freedom labeled in Fig. 1 are: $\{-60, 220\}$, $\{-170, 90\}$, $\{-65, 65\}$, $\{-65, 65\}$, $\{-90, 90\}$, $\{-70, 120\}$ degrees, respectively, for the axes in ascending order, where Fig. 1 shows each joint position at 0°, and positive rotation for each joint is defined using the right hand rule with the thumb pointing toward the axes label (i.e., thumb pointing toward w_1, w_2, etc.).

4) Data Acquisition: Voltage signals are acquired from T-WREX's position sensors using a PCI data acquisition card (Measurement Computing, PCI-DAS6013). Data can be acquired at 66 Hz per channel through the software interface.

5) Measurement Accuracy: To evaluate the measurement accuracy of T-WREX, we measured the ability of the device to measure known locations in space, using a scale placed near the vertical midplane of the workspace on a table near the end of the depth of range, and a vertical disk in the middle of the workspace. The resolution for position measurement was within ±0.38 cm.

C. Grip Sensor

To incorporate hand grasp into therapy activities, we attached a custom-made, pressure-sensing, handgrip to the orthosis. The handgrip consists of a hydraulic bladder made of 2.54-cm-diameter marine grade polyolefin tubing, shrink-wrapped around PVC pipe ends connected via an aluminum rod that is tapped with a small bore hose fitting. Small diameter tubing connects the bladder to a pressure transducer (Viatran Corporation, 2476AHG, 0–50 PSIG) mounted at the back of the wheelchair. The sensor detects grasp pressures up to about 345 kN/m^2 (with a resolution of approximately 2.0 kN/m^2, or 2% of the peak maximum grip pressure of an average adult male, 110 kN/m^2 [20]).

D. Software Enhancements

The original version of the Java Therapy software (Java Therapy 1.0) required that users have an active connection with the internet. Java Therapy 2.0 is an ASP platform solution that stores and displays patient progress of T-WREX exercises in both web and standalone versions with an identical user interface. The web version is served through a server running IIS services and website hosting. This version is suitable for use by patients with high bandwidth Internet access or multiple phone lines. The standalone version is accomplished by the use of what is called a loop back to serve essentially the same version of the software, and does not require an Internet connection.

To use Java Therapy 2.0 the user must first log into a home page through Internet Explorer. Once the subject has logged into the system, the program displays a "To Do List" of games to choose from, with a required minimum number of repetitions per day to complete for each game.

Our criteria for selecting the Java Therapy 2.0 games were that they be functionally relevant and quantifiable with the T-WREX device. A summary page is displayed at the end of each game that shows the user their current score and how their score compares to their most recent attempt, and the mean of all of their previous attempts. In addition, although WREX measures five degrees-of-freedom of arm motion, we desired to use two-dimensional displays for the games, to avoid a requirement for 3-D virtual reality equipment, and to make the games as simple as possible to understand for the users. Therefore, for each game, we choose two degrees-of-freedom of the endpoint motion of WREX, and mapped it to the computer screen.

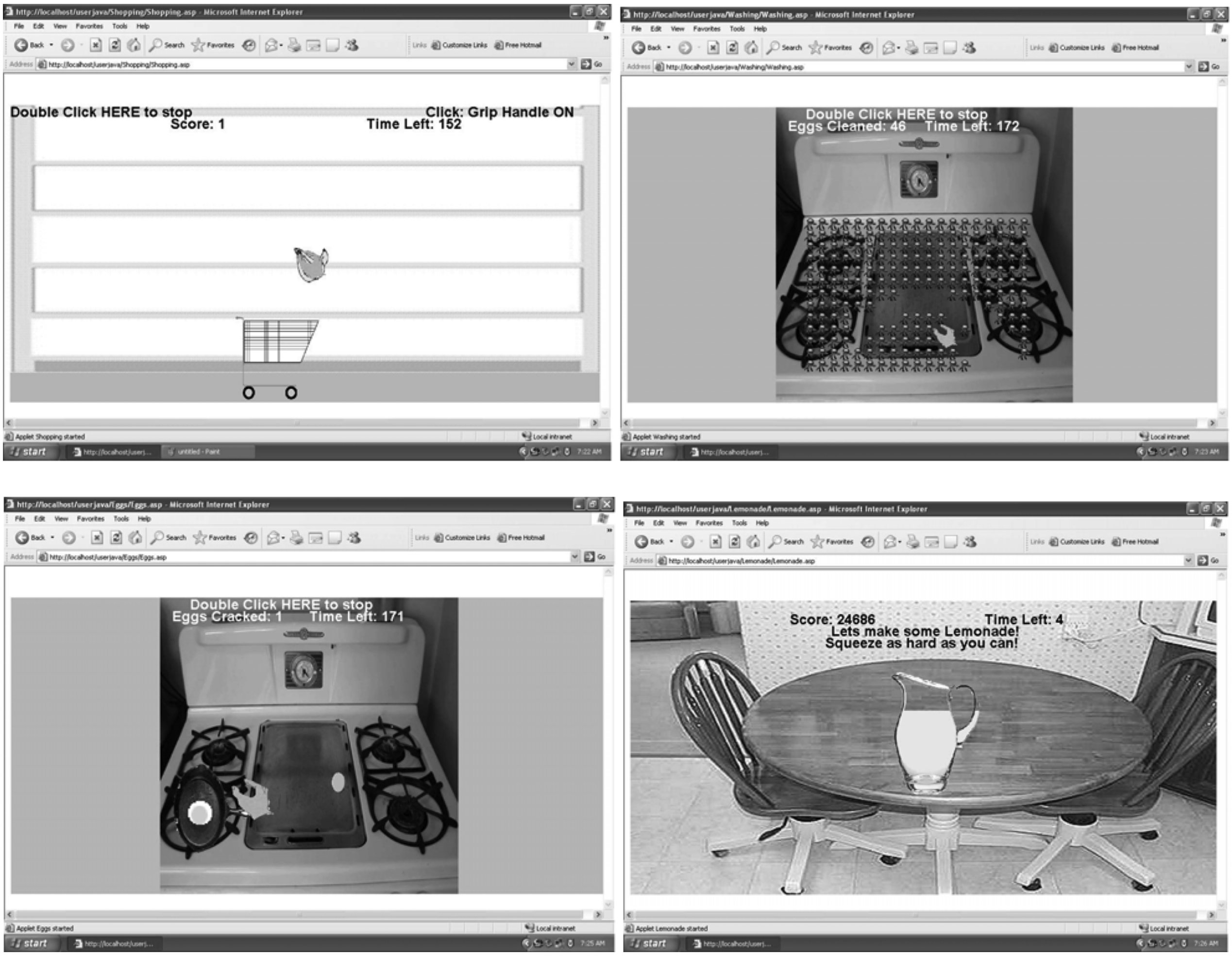


Fig. 2. Display screens for Java Therapy 2.0 games. Left to right: shopping, washing the stove, cracking eggs, and making lemonade.

Specifically, for some games, movement of the arm in a vertical plane controls cursor movement, while for others, movement of the arm in a horizontal plane controls cursor movement. The games and outcome scores are as follows (Fig. 2).

Shopping requires the user to move a hand cursor by moving the arm up, down, left and right to a common household item (e.g., a can of food) displayed on a picture of shelves, squeeze the handgrip above a threshold pressure to grab the object, move the item to the shopping cart, and release the handgrip to drop it in. This game primarily requires shoulder flexion/extension and shoulder horizontal abduction/adduction. The grasp function can be turned off if the subject is too weak to reliably pass the grip threshold. The grip threshold was typically chosen to be the smallest threshold above the noise level of the grip sensor, which was 2.0 kN/m^2, although the therapist could alter this parameter on a patient-specific basis. The shopping score that is displayed to the user following completion of the game is the number of items placed in the cart divided by the game duration.

Washing the Stove requires the user to move the arm across the horizontal plane to "clean away" an array of broken eggs spread across the stove. This game primarily requires elbow flexion/extension as well as shoulder flexion/extension and horizontal abduction/adduction. The score is the number of eggs cleared divided by the game duration.

Cracking Eggs requires the user to move their hand across the horizontal plane to the location of an egg displayed on the screen, and then squeeze the handgrip causing the egg to attach to the hand cursor. If the subject squeezes the handgrip with a pressure above a therapist-set threshold, then the egg breaks. The subject must then move the egg over a frying pan and squeeze with a force above a defined threshold to crack the egg into the pan. This game primarily requires shoulder flexion/extension and horizontal abduction/adduction. The game score is the number of eggs cracked in the pan divided by the game duration.

Washing the Arm requires the user to perform a washing-like motion across the upper segment of their unimpaired arm. The computer first prompts the user to move their impaired arm near their unimpaired shoulder and click the mouse with their unimpaired hand. The computer stores the selected location. The computer then prompts the user to move the impaired hand near the unimpaired-elbow and store the location. The user then practices making movements between the two points, mimicking washing their arm. The user must move to within 5 cm of the stored targets to consider the movement completed. This game primarily requires elbow flexion/extension. The computer screen shows the user a live video of himself as feedback, acquired from a low-cost digital camera mounted on the computer monitor, as well as a cartoon figure from which dirt disappears with each successful washing movement. The score is the number of completed movements divided by the game duration.

Eating is similar to Washing the Arm except the computer prompts the user to store one point near the mouth and one near the lap. The user then practices making movements between the two points, mimicking eating. This game requires shoulder and elbow movement. The computer screen shows the user real-time video acquired from the camera mounted on the computer monitor, as well as a plate from which food disappears gradually. The score is the number of completed movements divided by the game duration.

Making Lemonade requires the user to squeeze the handgrip as hard as possible for a chosen duration. The computer screen displays a pitcher of lemonade filling in proportion to the integrated pressure transducer voltage signal. The integrated pressure signal divided by the game duration is the score.

Ranging the Arm requires the user to move their arm as far up, down, left and right as possible. This game primarily requires shoulder flexion/extension and horizontal abduction/adduction The game shows the subject an aesthetic image that is uncovered in proportion to their range of horizontal and vertical range of motion. The score is the exposed area of the image divided by game duration.

E. Device Testing Methodology

We performed two studies of the system's capabilities with volunteers who had a chronic stroke. The subject selection criteria for both studies were a minimum of six months post stroke, no shoulder pain, ability to comprehend and communicate about the required tasks, and some degree of arm impairment (Fugl-Meyer Motor Score for the Upper Extremity [21] < 56 out of 66). The experiments were approved by the Institutional Review Board of the University of California at Irvine. For all experiments, the subjects were seated with a shoulder harness to prevent torso movement, and the subject's arm was placed in the padded orthopedic splint attached to T-WREX.

1) Study One—Effect of Gravity Balance On Static Positioning of the Arm and Voluntary Arm Movements: We quantified how well the gravity-balancing function of the orthosis worked by first measuring the forces required for a therapist to statically position the arm with and without gravity balance "on." In the gravity balance "on" condition, the combined weight of the subject's arm and orthosis was balanced by adding rubber bands to the orthosis until the arm "floated" in a default configuration. The default configuration was the elbow flexed to 90° and the shoulder flexed such that the forearm was parallel to the floor and the upper arm was parallel to the parasagittal plane. In the gravity balance "off" condition, the weight of the orthosis itself was counterbalanced with the elastic bands, but not the weight of the arm. For the static positioning tests, we measured the force required to hold the subject's relaxed arm at points throughout its workspace. Specifically, a physical therapist held the subject's arm at thirteen targets mounted on a test fixture that was placed at the workspace boundary (Fig. 3), with the order of presentation of the gravity balance "on" and "off" conditions randomized. The subject was instructed to attempt to relax the arm during testing. The shoulder of T-WREX was aligned with the center of the test fixture and placed 84 cm in front of it. The therapist held the subject's arm by grasping a six-axis force-torque sensor (ATI, Industrial Automation, FT-3293) that was mounted to the orthosis beneath the forearm brace. The sensor was sampled by the computer at 60 Hz. Both the impaired and unimpaired arms of each subject were tested using this protocol. The mean Fugl–Meyer score for the four subjects who participated in this experiment was 19.3 (± 6.5 SD).

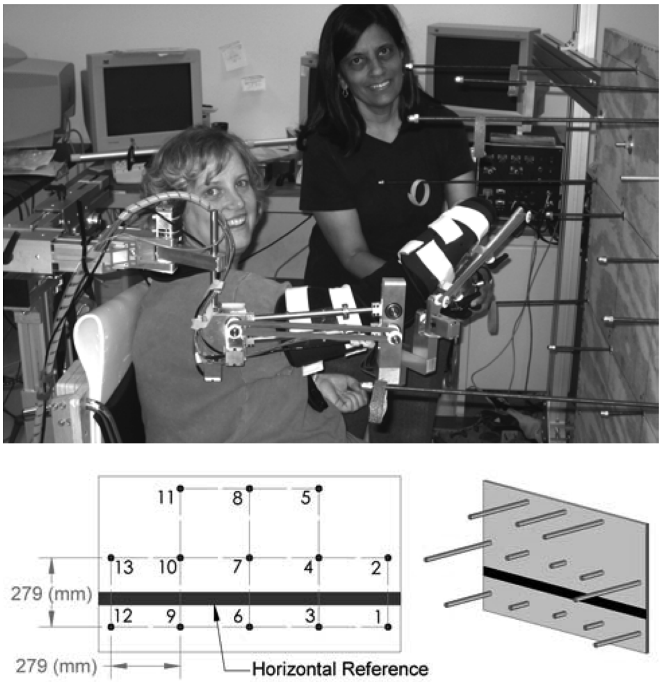


Fig. 3. Test fixture for measuring the force required to hold the arm in different positions when the orthosis provided gravity balance to the arm, and when it did not. While grasping the force-torque transducer, the therapist held the distal end of T-WREX to the tip of each rod that protruded from the fixture. "Horizontal Reference" indicates the vertical level at which the arm was placed when setting the number of rubber bands for the gravity counterbalance.

To quantify the effect of gravity balance on voluntary arm movements, we measured how well nine hemiparetic subjects could perform various arm movements while they wore the orthosis with and without gravity balance. The subjects' mean Fugl–Meyer score was 25.1 (± 13.9 SD). Three types of movement tests were performed, with the order of presentation of the gravity balance "on" and "off" conditions randomized. The first test was a subsection of the arm Fugl–Meyer score that could be performed while the subject's affected arm was in the orthosis. This modified Fugl–Meyer test measured fourteen tasks with a possible total score of twenty-eight. The second test assessed reaching movements. The subjects reached eight times to two targets located at the boundary of the arm's passive workspace, one on the ipsilateral side and one on the contralateral side, at the height of the subject's chest. The subjects also reached upwards from the lap to the highest possible point eight times. The third test assessed drawing movements. Four subjects traced a circular pattern (diameter of 17.8 cm) presented on a transparent plastic disc in the vertical plane, centered in front of them, five

TABLE I
SUBJECT CHARACTERISTICS AND FUNCTIONAL SCORES FOR THE PILOT TRAINING STUDY (STUDY TWO)

Subject No.	Age and Gender	Paretic Side	Years Post Stroke	Tone / Ashworth scale	Fugl Meyer (of 66)		Rancho-Level		Rancho-Tasks performed at next level		Box & Blocks		Mod. Box & Blocks	
			PRE	PRE	PRE	DELTA	PRE	DELTA	PRE	DELTA	PRE	DELTA	PRE	DELTA
1	72 F	Left	3	4	11	5	3	0	0	0	0	0	0	0
2	70 M	Left	6	4	19	5	2	1	1	0	0	0	0	0
3	43 F	Left	9	3	27	3	3	0	0	0	0	0	19	0
4	44 F	Right	4	3	20	8	3	0	0	0	0	1	15	7
5†	72 M	Right	11	3	32	4	3	0	0	2	0	0	0	0
AVG	60.2		6.6	3.4	21.8	5.0*	2.8	0.2	0.2	0.4	0.0	0.2	6.8	1.4
STD	15.2		3.4	0.5	8.0	1.9	0.4	0.4	0.4	0.9	0.0	0.4	9.4	3.1

DELTA is the difference of the post evaluation to the pre evaluation. † Completed 15 of the 24 sessions. * One sided t-test, $p = 0.002$.

fist widths from the front of the affected shoulder. Each subject was asked to hold their arm up to the start point with their unimpaired arm before starting each movement. The subjects repeated the circle tracing task 30 times in intervals of ten with 1 min rests in between each interval.

2) Data Analysis: Data from the left arm was flipped in a mirror-symmetric fashion so that all data was analyzed in a right arm coordinate frame. Paired, one-sided t-tests with a significance level of 0.05 were used to determine whether the static positioning force from the force ranging test, the subset of the Fugl–Meyer score, the range of motion to the targets, and the maximum vertical reach changed with gravity balance.

The data from the circle tracing task was analyzed by calculating three measures of the success in achieving the task. The *Radius Error* was computed as the difference between the actual and the desired radius for each point sampled during tracing. *Circularity* was computed as the standard deviation of the *Radius Error*. The *Circle Percentage Completed* was computed by dividing the circle into 64 sectors, then computing the percentage of sectors in which at least one sampled point occurred. A paired, one-sided t-test comparing gravity balance "on" to "off" across all thirty reaching trials was conducted for each subject to determine improvement in the subjects' ability to trace circles for each of the three success measures.

3) Study Two—Effect of Gravity-assisted Movement Training On Arm Motor Recovery: The second study was designed as a pilot study to test the feasibility of using the T-WREX system as a tool for retraining arm movement after chronic stroke. We tested the hypothesis that repetitive movement training with T-WREX over a two month period would improve the ability of people with chronic hemiparetic stroke to move their arm and hand. Five hemiparetic subjects were enrolled in the study (Table I), all of whom had severe arm and hand impairment.

4) Training Protocol: The five subjects practiced movement training with the orthosis for 45 min, three times per week, for eight consecutive weeks. One subject completed only 15 instead of 24 training sessions for personal reasons not related to the study. In each training session, a physical therapist or research assistant assisted the subjects to place their affected arm in the orthosis. The setup time, including time to adjust the number of rubber bands for the appropriate counterbalance, was typically 3 min. The subjects then used the Java Therapy 2.0 software to complete the seven therapy games three times per session. The duration of all games was 3 min, except for the "*Making Lemonade*" and "*Ranging the Arm*" games, which lasted 15 s and 1 min, respectively. The therapist or the research assistant provided occasional verbal cueing or manual assistance to the subjects as they played the games during the first week. By the second week of therapy sessions, subjects seldom required manual assistance or verbal cueing during the 45 min Java Therapy session.

5) Weight-support Progression: Subjects experienced a decreasing amount of weight support for their arms throughout the study, in order to encourage them to learn to move without weight support. For the first two weeks, the number of rubber bands chosen was such that it balanced the arm in the default configuration used in study one. For weeks three and four, 20% of the rubber bands were removed. For weeks five and six, another 20% of the rubber bands were removed. Rubber bands were not removed for weeks seven and eight due to the difficulty the subjects experienced performing the tasks with the existing 40% reduction in gravity balance.

6) Outcome Measures: Subject's movement ability was evaluated before and after the eight-week movement training program using four clinical tests: the Fugl–Meyer Motor Assessment for the Upper Extremity [21], the Rancho Functional Test for The Hemiplegic /Paretic Upper Extremity [22], the Box and Blocks Test for Manual Dexterity [23], and a modified version of the Blocks and Box test in which the subjects attempt to move their arm back and forth across a divider without picking up blocks.

Subject's movement ability was also evaluated using several quantitative measures at each therapy session. The subjects' grip strength was tested at the beginning and end of each training session. Grip strength was tested using a hydraulic hand dynamometer (Jamar, 5030J1) while the subject was seated, with the arm supported on their lap. The subjects' ability to reach to a target in 3-D space without any arm support, and to reach across a table top with arm support to a target, were also tested before each training session using a three degrees-of-freedom lightweight robot arm (PHANToM 3.0 SensAble Technologies, Inc., Woburn, MA) with a customized orthopedic hand-splint interface. The subjects' arm pain was assessed by asking the subjects to define the pain intensity on a scale from one to ten,

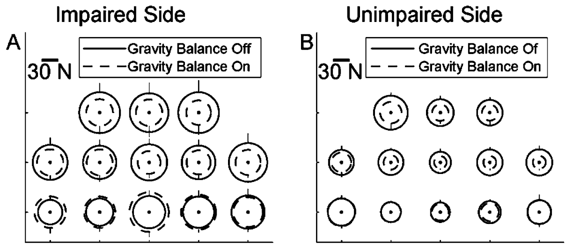


Fig. 4. Mean effect of gravity balance across four subjects. Circle radius is the magnitude of force required to hold the subjects' arms at the test fixture locations shown in Fig. 3. Vertical bars indicate one standard deviation across subjects. (A) Impaired arm. (B) Unimpaired arm.

with one being no pain and ten being severe pain. Blood pressure and pulse rate were measured before and after each training session.

7) Data Analysis: Changes in the clinical scores post-training compared to pretraining were analyzed using paired t-tests for each subject. The percent of reaching range was calculated by first subtracting out the baseline range (distance moved on first day) and then dividing by the distance from the start point to the target. Linear regression was used to determine if there was a significant change in the percentage range of motion of supported, unsupported reaching, and grip strength, as a function of training sessions. The average change in these measures across training was estimated using the slope of the best-fit line.

Changes in game scores with training were analyzed for three games only (Shopping, Ranging the Arm and Cleaning the Stove) due to a data storage error with the other two games. The scores for these games were normalized to a scale of 0 to 1 by dividing the scores by the score of an unimpaired user, and then averaged to obtain a single score. Linear regression was used to determine if there was a significant change in the normalized game score for the four-week period during which the gravity balance was held at a fixed level of 60%.

III. RESULTS

A. Study One: Effect of Gravity Balance On Static Positioning of the Arm and Voluntary Arm Movements

We first measured the force required to hold the arm in different positions when the orthosis provided gravity balance to the arm, and when it did not. The magnitude of force required to hold the arm at the boundary of its workspace was significantly smaller with gravity balance "on" than with it "off," for all of the unimpaired arms and three of the impaired arms of the four subjects tested (t-test across thirteen targets, $p < 0.04$ for each subject, Fig. 4). The gravity balance function was more effective for workspace locations above the horizontal reference shown in Fig. 3, and ineffective for those locations below it (Fig. 4). When we compared the force required to hold the impaired arm with that required to hold the unimpaired arm, a significantly greater force of 9.6 N ($\pm$4.6 SD) was required for the impaired arm, consistent with increased tone (paired t-test across subjects, $p < 0.001$).

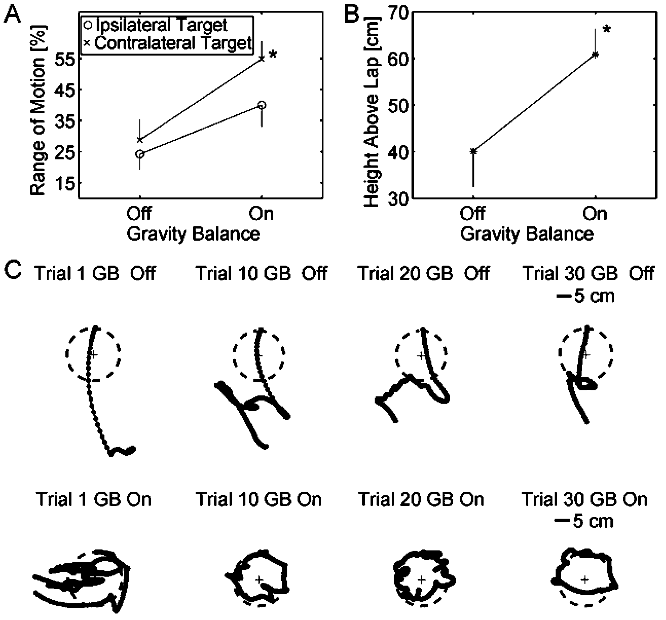


Fig. 5. Effect of gravity balance on reaching movements for nine subjects A) Average reaching range of motion across subjects to targets with and without gravity balance (distance traveled to target/total distance to target). (* paired t-test, $p < 0.05$). B) Average height reached above lap, with and without gravity balance. (* paired t-test, $p < 0.05$). C) Example data from one subject as she attempted to trace a circle 30 times, without gravity balance (top four panels) and with gravity balance (bottom four panels).

The subjects moved more effectively with the gravity balance "on." The mean modified Fugl–Meyer score with gravity-balance was 12.1 ($\pm$6.2 SD) and without gravity-balance was 11.3 ($\pm$6.3 SD), a difference that neared significance (paired, one-sided t-test, $p = 0.055$). Gravity balance significantly improved reaching to the contralateral target (paired, one-sided t-test, $p = 0.038$), but not to the ipsilateral target [$p = 0.071$, Fig. 5(a)]. Gravity balance significantly improved the vertical reaching range of motion [$p = 0.008$, Fig. 5(b)]. Finally, gravity balance significantly improved the ability of the subjects to draw circles for those subjects who could not draw them without assistance [Fig. 5(c)], and improved the quality of the drawn circles for those who were able to draw a circle (paired t-test for each subject, $p < 0.05$, Table II).

B. Study Two: Effect of Gravity-Assisted Movement Training On Arm Movement Ability

The five subjects who participated in the two month therapy program significantly improved their arm movement ability as measured by the Fugl–Meyer score (one sided t-test, $p = 0.002$, Table I). The mean improvement was 5 points ($\pm$1.87 SD). The improvement in the Fugl–Meyer Score was primarily due to improvements in subscores related to shoulder movement (Table III). No significant improvements were seen for the three functional tests: the Rancho Functional Test, the Box and Blocks test, or the modified Box and Blocks test.

At each therapy session, we measured the subject's grip strength, ability to reach to a target, self-rating of pain, and vital signs. Grip strength significantly increased for two of the five subjects over 24 therapy sessions (linear regression, $p < 0.05$, Table IV). Three of the subjects significantly improved the distance that they could reach away from their body both with

TABLE II
MEASURES OF ABILITY TO TRACE A CIRCLE WITH AND WITHOUT GRAVITY BALANCE (GB)

Subjects Fugl-Meyer	Mean radius error area		Mean radius error p-value	Circularity measure area		Circularity p-value	% Circle completed area		% Circle completed p-value
	GB-Off	GB-On		GB-Off	GB-On		GB-Off	GB-On	
19	15.00	3.43	0.001*	34.50	14.80	0.001*	100.00	100.00	1.000
20	47.00	13.20	0.001*	97.30	18.20	0.001*	32.69	100.00	0.001*
18	29.80	21.60	0.006*	40.10	30.20	0.001*	80.69	100.00	0.001*
54	3.04	2.28	0.002*	11.40	8.69	0.008*	100.00	100.00	1.000

* Paired, one sided t-test comparing GB “on” to “off” across 30 trials, $p < 0.05$.

TABLE III
IMPROVEMENT IN FUGL-MEYER SCORE AS A FUNCTION OF JOINT AT WHICH IMPROVEMENT OCCURRED AND NATURE OF SCORING CHANGE

	Elbow (%)	Shoulder (%)	Total (%)
0-1	17	26	43
1-2	17	35	52
0-2	4	0	4
Total (%)	38	61	

A change from 0–1 indicates a change from unable to perform movement to able to perform partially, and a change from 1 to 2 is a change from performs partially to performs fully[21].

and without support (Table IV). The mean percent improvement in unsupported reach extent, as calculated from the linear regression in Fig. 6(a), was 9%, which amounted to a 3.3 cm increase on average. There were no significant changes in the pain score, pulse rate, or blood pressure across the training program, or when these measures were compared before and after each training session.

The subjects improved the scores they achieved on the games during the last four weeks of training, when the level of gravity balance was held fixed at 60%. The mean, normalized, game score across three games increased significantly by 5.6% (Fig. 6(b), linear regression, $R^2 = 0.564, p = 0.005$).

IV. DISCUSSION

The force of gravity severely limits arm movement ability for many invididuals with stroke. To allow people with stroke to practice arm movement training, we instrumented a gravity-balancing orthosis, coupled a pressure sensing handgrip with the orthosis, and developed simple virtual reality software that simulates functional movement tasks and provides quantitative feedback of performance.

Study One demonstrated that individuals with stroke who have not practiced moving their arm in a coordinated manner for several years can quickly relearn to control their arm movement given some support against gravity with this system. For example, the subjects were able to trace a circle in the vertical plane with gravity support even though their ability to do this was severely limited without gravity support. Gravity-balance also improved reaching range of motion.

The results of *Study Two* further demonstrated that this latent ability to coordinate arm movement can be enhanced with repetitive training with the T-WREX system, resulting in improvements in unsupported arm movement ability. Subjects who practiced with T-WREX over an eight week period improved their movement ability as quantified by the Fugl–Meyer score, hand grasp strength, as well as unsupported and supported reaching range of motion. They achieved these improvements with approximately six minutes of direct contact with a rehabilitation therapist, focused on donning or doffing the device, and 45 min of repetitive movement training with T-WREX.

These results demonstrate the safety and feasibility of automating functional, upper-extremity rehabilitation therapy for patients with chronic stroke using passive gravity assistance and a grip sensor to execute a sequence of simulated, daily tasks. We will first discuss the significance of these results in relationship to other attempts to automate movement training after stroke and then discuss directions for future research.

A. Comparison With Other Attempts To Automate Movement Training

The approach we adopted in this study to automate movement training is different from previous clinical and robotic approaches in several ways. It is different from the clinical use of devices such as arm skateboards, overhead slings, and mobile arm supports primarily due to the use of an instrumented orthosis with a large, 3-D workspace. The use of an instrumented device makes it possible to provide quantitative feedback to the patient and therapist about movement recovery, and also engages the user in simple virtual reality games oriented towards improving functional activities. The large workspace makes a greater range of movement possible than with standard clinical devices.

This approach is different from recent attempts to use robotic devices to automate therapy because it uses a passive device that does not generate power. The system can be manufactured at substantially less cost than an equivalent actuated system. Although preliminary testing of robotic devices has shown that they too can be safe [10], [24], [25], the T-WREX system has an obvious safety advantage compared with robotic approaches because it is fundamentally incapable of moving on its own. This advantage may be especially significant if the technology is to be used for home based therapy. Kinematically, the device allows a substantially larger range of motion than previous robotic devices, including feeding and washing motions, contributing to

TABLE IV
REGRESSION ANALYSIS OF SUPPORTED AND UNSUPPORTED REACHING RANGE OF MOTION, AND HAND GRIP STRENGTH, ACROSS TRAINING SESSIONS

Subject	Supported Table Reaching Range			Free Reaching Range				Hand Grip Strength				
	Change in Distance Reached (mm)	R^2	p-value	Change in Distance Reached (mm)	Change in Distance Reached (%)	R^2	p-value	Initial Grip Strength	Change in Grip (kgF)	% Change	R^2	p-value
1	64	0.09	0.200	11.12	3.05	0.05	0.332	1	1.95	195.00	0.06	0.245
2	123	0.47	0.001*	-4.26	-1.17	0.01	0.651	2	3.26	163.00	0.15	0.065
3	35	0.25	0.029	76.10	20.88	0.35	0.006*	1	2.68	268.00	0.33	0.003*
4	124	0.74	0.001*	45.19	12.4	0.21	0.042*	6	-0.16	-2.67	0.00	0.906
5†	-13	0.09	0.359	32.95	9.04	0.21	0.034*	15	5.996	39.97	0.64	0.001*
AVG	66.6**			32.2**	8.8**				2.7**	132.7**		
STD	58.8			31.1	8.5				2.2	111.8		

† completed 15 of the 24 sessions. * significant regression, $p < 0.05$. ** One sided t-test, comparing change to zero, across all therapy sessions, $p < 0.05$.

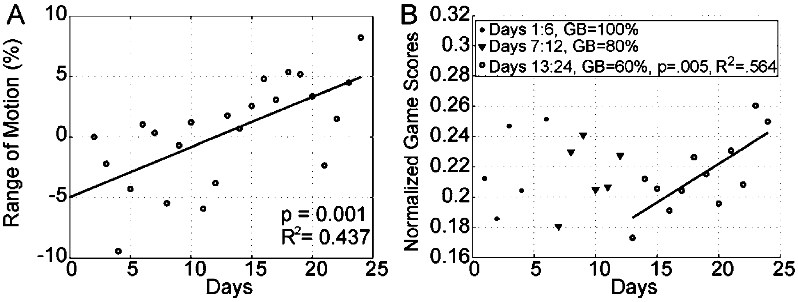


Fig. 6. Mean range of motion of unsupported reaching and normalized game scores across the 24 training sessions (Study Two). A) Mean percent range of motion across four subjects and three trials. Percent range of motion was calculated by subtracting the mean distance traveled on the first day from the daily movements, then dividing the difference by the mean distance between the start point and target. B) Ensemble average of normalized game scores (possible range 0–1) for three games (shopping, ranging the arm, and cleaning the stove) across the four subjects who completed all eight weeks of movement training.

its ability to facilitate functional movements. The incorporation of a simple hand grasp sensor with an arm supporting mechanism is unique to our knowledge, and again contributes to the ability of the system to facilitate functional movement.

On the other hand, the system is more costly than standard clinical assistive devices because of its mechanical complexity, and use of sensors and a computer. The system is also less flexible than robotic approaches because it is limited in the pattern of assistive force that it can apply. T-WREX can only apply fixed levels of gravity support, defined by the number of elastic bands attached to the device. Further, the gravity support mechanism is only partially effective in counterbalancing the arm. The device also does not compensate for subject-specific variations in muscle tone. Further, the device does not allow changes in forearm supination or pronation away from the initial forearm orientation, or the full range of shoulder internal and external rotation.

The system is also different from the recently-developed Auto-Cite system, which consists of a computer-adjustable workspace with sensorized tasks for automating constraint-induced therapy [15]. Auto-Cite focuses on hand manipulation tasks suitable for less impaired stroke patients and does not provide assistive support to the arm. The system we developed is targeted at patients with moderate to severe stroke, as it allows individuals with only a small amount of arm and hand movement ability to engage in simulated functional activities.

The clinical viability of this approach will depend in large part on the system's effectiveness in facilitating movement gains. Training with T-WREX for eight weeks did not improve the subject's functional movement ability according to the scales used here. The lack of improvement in the functional scales is likely due to a floor effect in these scales: i.e., these scales are insensitive to small changes in movement ability when the starting ability level is low. The five point mean improvement in the impairment-measuring Fugl–Meyer score, on the other hand, was comparable to improvements seen in patients with a similar degree of deficits with the MIT-MANUS (4.2 additional points with robot therapy) [9], MIME (3.4 point gain with robot therapy, 1.6 point gain with conventional therapy) [10], and GENTLE/s (4 point gain with robot therapy) [12]. The majority of improvement in the Fugl–Meyer Score was seen in the shoulder (61% increase) as compared to the elbow (38% increase) (Table III), similar to the improvements seen with the robot therapy group and conventional therapy control group in the MIME study (Robot: Shoulder—65%, elbow—35%; Control: Shoulder—69%, elbow—31%) [10], and the robot therapy group in the GENTLE/s study (Shoulder—55%, elbow—45%) [12]. This relatively greater improvement in shoulder movement could be due to an inherent proximal-to-distal pattern of recovery, or to a greater emphasis on shoulder-related exercises due to the selection of the training games. Incorporating games that encourage practice of isolated elbow movement is an important direction for future research.

Practice with T-WREX also improved quantitative measures of upper extremity movement ability. Three subjects improved their ability to reach to a target with and without support. The gain in free reaching range of motion was approximately 3 cm on average, with one subject achieving a 7.6 cm gain (Table IV). Reaching in free space away from the body requires substantial shoulder strength because the center of mass of the arm moves away from the body during such movements, producing a large moment at the shoulder. The gains in shoulder subscores for the Fugl–Meyer score are thus consistent with the observed gain in reaching range of motion. Subjects in the MIME study also improved their reaching range of motion by an average of 5 cm.

Two subjects significantly improved their hand grasp strength by 270% (2.7 kgF) and 40% (6.0 kgF), respectively. Subjects who underwent movement training with the MIT-MANUS device did not significantly improve their hand function over the control group suggesting that motor gains are specific to the limb segments exercised. The present results indicate that arm movement training can be integrated with hand movement training, producing benefits for both the arm and hand.

None of the daily measures, including hand grasp strength, reaching range of motion, and the game scores, appeared to have reached a plateau during the training program. This suggests that additional improvement may have been possible with continued training. Defining the limits to the level of recovery possible with intensive practice is an important direction for future research.

Exit interviews with the subjects indicated that they increased their use of their affected side in some activities of daily living. Two subjects began carrying items such as laundry or bags with their affected side following training. Another subject noted that increased range of motion enabled her to turn on and off a light switch with the affected side. On a scale from 1 to 5, 1 being the least enjoyable, 5 being well satisfied, the subjects on average rated their enjoyment of using the device with a score of 4.3. A common criticism from the subjects was that the device should be refined to allow supination and pronation of the forearm.

B. Directions For Future Research

These pilot study results indicate that the T-WREX training system can produce measurable benefits in arm movement ability of chronic stroke patients. Therefore, a larger clinical test of the device is warranted. Goals for clinical testing will include defining the relative effectiveness of T-WREX compared to standard clinical approaches, unassisted exercise, and recent robotic approaches. At the mechanical design level, the ability of T-WREX to counterbalance the arm across a wider workspace could be improved. Incorporating forearm supination and pronation along with shoulder internal and external rotation would allow the device to assist in even more naturalistic arm movements. We are also developing an actuated version of T-WREX named Pneumatic-WREX (Pneu-WREX) [26] that will facilitate the study of a wider range of movement training techniques than fixed support against gravity. Using T-WREX as the base for Pneu-WREX will make it possible to increase the force range of Pneu-WREX, since the gravity assistance function can be used to lift the weight of the actuators, rather than using some of the actuator capacity itself to achieve this requirement.

V. CONCLUSION

The initial testing with the T-WREX system reported here demonstrates its ability to measure and safely assist in naturalistic arm movement. By using a passive arm support, simple virtual reality software, and a hand grasp sensor, the T-WREX system provides a means to practice and monitor arm movement training. Users of the device currently require about 3 min of assistance to don or doff the device, but even these relatively brief requirements for assistance might be eliminated with refinement of the user attachment interface. The device could allow a therapist to supervise several patients at a time for group therapy sessions, or possibly be used at home since it requires only minor assistance from a caregiver to use. The device's ability to provide gradable levels of assistance make it well suited to customized training programs. Its ability to provide quantitative feedback of progress make it well suited for motivating motor training, and for off-line monitoring of patient compliance and progress by a skilled rehabilitation therapist.

REFERENCES

[1] American Stroke Association, 2005 [Online]. Available: http://www.strokeassociation.org/

[2] K. J. Ottenbacher, P. M. Smith, S. B. Illig, R. T. Linn, G. V. Ostir, and C. V. Granger, "Trends in length of stay, living setting, functional outcome, and mortality following medical rehabilitation," *JAMA*, vol. 292, pp. 1687–95, 2004.

[3] J. van der Lee, I. Snels, H. Beckerman, G. Lankhorst, R. Wagenaar, and L. Bouter, "Exercise therapy for arm function in stroke patients: A systematic review of randomized controlled trial," *Clin. Rehabil.*, vol. 15, pp. 20–31, 2001.

[4] E. Taub, G. Uswatte, and R. Pidikiti, "Constraint-induced movement therapy: A new family of techniques with broad application to physical rehabilitation—A clinical review," *J. Rehabil. Res. Develop.*, vol. 36, pp. 237–51, 1999.

[5] J. Liepert, H. Bauder, W. Miltner, E. Taub, and C. Weiller, "Treatment-induced cortical reorganization after stroke in humans," *Stroke*, vol. 31, pp. 1210–6, 2000.

[6] C. Butefisch, H. Hummelsheim, P. Denzler, and K. Mauritz, "Repetitive training of isolated movement improves the outcome of motor rehabilitation of the centrally paretic hand," *J. Neurolog. Sci.*, vol. 130, pp. 59–68, 1995.

[7] N. Byl, J. Roderick, O. Mohamed, M. Hanny, J. Kotler, A. Smith, M. Tang, and G. Abrams, "Effectiveness of sensory and motor rehabilitation of the upper limb following the principles of neuroplasticity: Patients stable poststroke," *Neurorehabil. Neural Repair*, vol. 17, pp. 176–91, 2003.

[8] D. Reinkensmeyer, J. Emken, and S. Cramer, "Robotics, motor learning, and neurologic recovery," *Annu. Rev. Biomed. Eng.*, vol. 6, pp. 497–525, 2004.

[9] H. I. Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans. Rehabil. Eng.*, vol. 6, no. 1, pp. 75–87, Mar. 1998.

[10] P. S. Lum, C. G. Burgar, P. C. Shor, M. Majmundar, and M. Van der Loos, "Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper limb motor function following stroke," *Arch. Phys. Med. Rehabil.*, vol. 83, pp. 952–9, 2002.

[11] D. J. Reinkensmeyer, L. E. Kahn, M. Averbuch, A. N. McKenna-Cole, B. D. Schmit, and W. Z. Rymer, "Understanding and treating arm movement impairment after chronic brain injury: Progress with the arm guide," *J. Rehabil. Res. Develop.*, vol. 37, no. 6, pp. 653–662.

[12] S. Coote, E. K. Stokes, B. T. Murphy, and W. Harwin, "The effect of GENTLE/s Robot mediated therapy on upper extremity function post stroke," presented at the Int. Conf. Rehabil. Robotics, Seoul, Korea, May 21–26, 2003.

[13] A. S. Merians, D. Jack, R. Boian, M. Tremaine, G. C. Burdea, S. V. Adamovich, M. Recce, and H. Poizner, "Virtual reality-augmented rehabilitation for patients following stroke," *Phys. Ther.*, vol. 82, pp. 898–915, 2002.

[14] L. E. Kahn, M. L. Zygman, W. Z. Rymer, and D. J. Reinkensmeyer, "Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: A randomized controlled pilot study," *J. Neuroeng. Rehabil.*, vol. 3, no. 12, 2006.

[15] P. S. Lum, E. Taub, D. Schwandt, M. Postman, P. Hardin, and G. Uswatte, "Automated constraint-induced therapy extension (AutoCite) for movement deficits after stroke," *J. Rehabil. Res. Develop.*, vol. 41, pp. 249–258, 2004.

[16] D. Reinkensmeyer, C. Pang, J. Nessler, and C. Painter, "Web-based telerehabilitation for the upper-extremity after stroke," *IEEE Trans. Neural Sci. Rehabil. Eng.*, vol. 10, no. 2, pp. 1–7, Jun. 2002.

[17] T. Rahman, W. Sample, R. Seliktar, M. Alexander, and M. Scavina, "A body-powered functional upper limb orthosis," *J. Rehabil. Res. Develop.*, vol. 37, pp. 675–80, 2000.

[18] R. Sanchez, P. Shah, J. Liu, S. Rao, R. Smith, S. Cramer, T. Rahman, J. E. Bobrow, and D. Reinkensmeyer, "Monitoring functional arm movement for home-based therapy after stroke," in *Proc. 2004 IEEE Eng. Med. Biol. Soc. Meeting*, San Francisco, CA, Sep. 1–5, 2004, pp. 4787–4790.

[19] R. M. Murray, Z. Li, and S. S. Sastry, *A Mathematical Introduction to Robotic Manipulation*. Boca Raton, FL: CRC, 1994.

[20] R. Gurram, G. J. Gouw, and S. Rakheja, "Grip pressure distribution under static and dynamic loading," *Exp. Mechanics*, vol. 33, pp. 169–173, 1993.

[21] A. R. Fugl-Meyer, L. Jaasko, I. Leyman, S. Olsson, and S. Steglind, "The post-stroke hemiplegic patient. 1. A method for evaluation of physical performance," *Scand. J. Rehabil. Med.*, vol. 7, pp. 13–31, 1975.

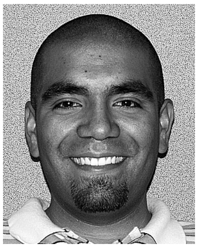
[22] D. Wilson, L. Baker, and J. Craddock, *PROTOCOL-Funtional test for the hemiplegic/paretic upper extremity*. Downey, CA: Rancho Los Amigos, 1984.

[23] V. Mathiowetz, G. Volland, N. Kashman, and K. Weber, "Adult norms for the box and block test of manual dexterity," *Amer. J. Occup Therapy*, vol. 39, pp. 386–91, 1985.

[24] H. I. Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans. Rehabil. Eng.*, vol. 6, no. 3, pp. 75–87, Sep. 1998.

[25] L. E. Kahn, M. Averbuch, W. Z. Rymer, and D. J. Reinkensmeyer, "Comparison of robot-assisted reaching to free reaching in promoting recovery from chronic stroke," in *Integration of Assistive Technology in the Information Age*, M. Mokhtari, Ed. Amsterdam, The Netherlands: IOS Press, 2000, pp. 39–44.

[26] R. Sanchez, E. Wolbrecht, R. Smith, J. Liu, S. Rao, S. Cramer, T. Rahman, J. Bobrow, and D. J. Reinkensmeyer, "A pneumatic robot for re-training arm movement after stroke: Rationale and mechanical design," in *Proc. 2005 IEEE Int. Conf. Rehabil. Robot.*, Chicago, IL, Jun. 1, , pp. 500–504.



Robert J. Sanchez received the B.S. degree in mechanical and aerospace engineering from Loyola Marymount University, Los Angeles, in 2000, and the M.S. and Ph.D. degrees in mechanical and aerospace engineering from the University of California, Irvine, in 2002 and 2005, respectively.

He has been an Instructor for a computer-aided design course at the University of California, Irvine. Currently, he is Senior Research Engineer at Alcon Laboratories, Inc., developing surgical tools for ophthalmology.

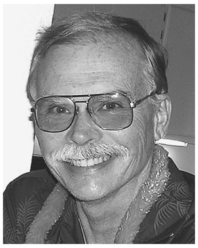
Jiayin Liu received with the B.S. degree in industrial engineering from Tsinghua University, Beijing, China, in 2001, and the M.S. and Ph.D. degrees in mechanical and aerospace engineering from the University of California, Irvine, in 2002 and 2006, respectively.

She is currently a Mechanical Engineer with the Aubrey Group.

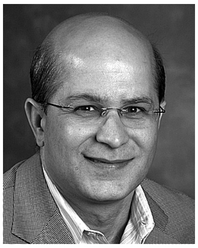
Sandhya Rao is a licensed Physical Therapist with over 20 years experience in rehabilitation care and management. She is currently with the University of California, Irvine Medical Center in the acute rehabilitation setting. She is also the Team Physical Therapist for the Neuromuscular Disease Clinic at the University of California, Irvine.

Punit Shah received the B.S. degree in computer science from the University of California, Irvine, in 2003. He is currently working toward the M.S. degree in information technology with a concentration in software engineering at Harvard University, Cambridge, MA.

He is hemiparetic and joined the T-WREX project to help better the lives of those with similar mobility impairments. He has worked for such Fortune 50 companies as Hewlett Packard and Microsoft and is now partner at Skyy Consulting, a software consulting firm in Santa Monica, CA.



Robert Smith is a Development Technician in the Department of Mechanical and Aerospace Engineering, at the University of California, Irvine. He has worked for 40 years in mechanical and aerospace industry and research. At one time, the speed record for both piston and jet engine aircraft were held by machines he helped to build.



Tariq Rahman received the Ph.D. degree from Drexel University, Philadelphia, PA, in 1990. He then joined the Alfred I. duPont Hospital for Children, Wilmington, DE, as a Postdoctoral Fellow working on assessment of rehabilitation robotics and incorporated prosthetic ideas of extended physiological proprioception into rehabilitation robotics.

He is currently Senior Research Engineer at the Alfred I Dupont duPont Hospital for Children and Head of the Pediatric Engineering Research Laboratory. He also holds the position of Research Associate Professor in the School for Biomedical Engineering, Drexel University. He has published extensively in the area of rehabilitation engineering on issues relating to tremor reduction, robotics, and orthotics. He has served as the chair of RESNA's Special Interest Group in Robotics and Mechatronics. He organized and chaired the Fourth International Conference on Rehabilitation Robotics (ICORR) in 1994, held at the duPont Hospital, and organized the RESNA research symposium on robotics in 1997, in Pittsburgh PA. He is the past chair of the International Steering Committee of ICORR. He holds five patents related to technology for people with disabilities.

Steven C. Cramer received the B.A. degree in neurobiology (with highest honors) from the University of California, Berkeley, and the M.D. degree from the University of Southern California, Los Angeles. He completed a residency in internal medicine at the University of California, Los Angeles, Center for Health Sciences. This was followed by a neurology residency and a fellowship in cerebrovascular disease at the Massachusetts General Hospital, Boston. During his fellowship, he trained in functional MRI under Dr. B. Rosen and stroke recovery under Dr. S.

Finklestein. He also studied clinical investigation, earning a Masters of Medical Science from Harvard Medical School, Boston.

Currently, he is an Assistant Professor in the Department of Neurology, the University of California, Irvine. He is board certified in both internal medicine and neurology. His research interests include changes in brain function that underlie recovery from neurologic disease.

James E. Bobrow received the B.S. degree in mechanical engineering from California State University, Long Beach, in 1977, the M.S. degree in engineering mechanics from the University of California, Los Angeles (UCLA), in 1979, and the Ph.D. degree, also from UCLA, in 1983. His Ph.D. thesis was on the optimal control of robotic manipulators.

He is a Professor of Mechanical and Aerospace Engineering at the University of California, Irvine. After graduate school, he was a Senior Programmer Analyst at McDonnell Douglas Automation Company, where he developed CAM software for the Unigraphics system. In 1984, he joined the University of California, Irvine (UCI), as an Assistant Professor. While at UCI, his research interests have included optimal control and motion planning for robots, design of pneumatic actuators and sensors for automation systems, robots for rehabilitation, and machine learning systems. HE has also been a Visiting Professor in Computer Science at Stanford University, and in Mechanical Engineering at the Massachusetts Institute of Technology, and he has created robots and automation devices for several startup companies, including Robomedica, Inc., and Cobra Technologies. He serves on the Engineering Steering Committee for Robomedica, Inc., and he has served on the program committees or organizing committees of the leading conferences in control systems and robotics.

David J. Reinkensmeyer (M'93) received the B.S. degree in electrical engineering from the Massachusetts Institute of Technology, Cambridge, in 1988, and the M.S. and Ph.D. degrees in electrical engineering from the University of California, Berkeley, 1991, and 1993, respectively.

He was a Research Associate at the Rehabilitation Institute of Chicago and Northwestern University Medical School from 1994 to 1997. He is currently an Associate Professor in the Department of Mechanical and Aerospace Engineering and the Department of Biomedical Engineering at the University of California, Irvine. His research interests are in neuromuscular control, motor learning, robotics, and neurorehabilitation.