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Monitoring Functional Arm Movement for Home-Based Therapy after Stroke

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Abstract—The goal of this project is to develop a means for individuals with stroke to practice arm movement therapy at home with remote monitoring. We previously developed a web-based system for repetitive movement training (Java Therapy). This paper describes a new input device for the system that measures and assists in naturalistic arm movement, as well as software enhancements. The new input device is an instrumented, adult-sized version of Wilmington Robotic Exoskeleton (WREX), which is a five degrees-of-freedom orthosis that counterbalances the weight of the arm using elastic bands. To test the ability of the new device (Training-WREX or "T-WREX") to measure and assist in functional arm movements, we measured five chronic stroke subjects' movement ability while wearing the orthosis without gravity balance compared to wearing the orthosis with gravity balance. T-WREX's gravity balance function improved a clinical measure of arm movement (Fugl-Meyer Score), range of motion of reaching movements, and accuracy of drawing movements. Coupled with an enhanced version of Java Therapy, T-WREX will thus provide a means to assist functional arm movement training at home, either over the Web in real-time, or stand-alone with periodic communication with a remote site.

Keywords— arm, motor control, movement, rehabilitation, stroke, telerehabilitation

I. INTRODUCTION

Each year in the U.S. over 400,000 people survive a stroke [1]. Approximately 80% of acute stroke survivors lose arm and hand movement skills [2]. Movement impairments are typically treated with intensive, hands-on physical and occupational therapy for several weeks after the initial injury. Unfortunately, due to economic pressures on the U.S. health care system, stroke patients are receiving less therapy and going home sooner. The ensuing home rehabilitation is often self-directed with little professional or quantitative feedback.

Even as formal therapy declines, a growing body of evidence suggests that both acute and chronic stroke survivors can improve movement ability with intensive, supervised training [3]. Thus, an important goal for rehabilitation engineering is to develop technology that allows the burgeoning U.S. stroke population to practice intensive movement training without the expense of a supervising therapist.

This paper discusses the development of a home-based, telerehabilitation system for improving functional arm movement recovery following stroke. The system extends previous work on a low-cost, highly accessible, web-based system for facilitating repetitive movement training, called "Java Therapy" (Fig. 1)[4]. The initial version of Java Therapy allowed users to log into a Web site, perform a customized program of therapeutic activities using a mouse or a joystick, and receive quantitative feedback of their rehabilitation progress. In preliminary studies of the system, we found that stroke subjects 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.

The goal of the present project is to develop an input device that allows a broader range of functional arm movements to be practiced and monitored. Toward this end, we modified an anti-gravity arm orthosis, the Wilmington Robotic Exoskeleton, to be used as a 3D input device for measuring and manipulating arm movement. This paper describes the modifications to WREX, software enhancements to Java Therapy, and initial testing of the system with five stroke subjects.

II. METHODOLOGY

A. WREX

WREX was originally designed to help children with weakened arms to perform activities of daily living, such as eating[5]. It uses elastic bands, wrapped around two four bar mechanisms, to counterbalance the arm. The counterbalance mechanism is similar to the one used in an architect's lamp.

WREX is a five degrees-of-freedom, backdriveable, passive device. It allows naturalistic movements across an estimated 66% of the normal workspace of the arm in the vertical plane and 72% in the horizontal plane. Thus, it is well suited for measuring functional arm movement. In addition, because it counterbalances the weight of the arm, it could potentially allow even a severely weakened stroke patient to practice functional arm movements at home, without the safety concerns raised by an active robotic device.

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 T-WREX (Training WREX) (Figure 1).

Figure 1. Training-WREX

B. T-WREX Design

Position Sensor Selection: We investigated a variety of position sensors for instrumenting T-WREX. We desired a sensing system that was affordable, small, robust, and accurate enough to allow measurement resolution of the tip of 1 cm, which corresponds to an angular resolution of about 0.3 degrees. In addition, we desired a sensor that did not require zeroing, so that home users of the system would not be required to execute any initialization procedures in order for the device to accurately measure their movement. Table 1 compares several position sensors that we considered. Contactless potentiometers by Midori America were chosen due to size, low weight, cost, life, and absolute position measurement. The potentiometers work on the Hall Effect principle. Because they are contact-less, they have an expected lifetime that is five times longer than a typical resistive type potentiometer.

TABLE 1
SENSOR ANALYSIS

Sensor	Total Cost (5 dof)	Diameter (in.)	Zeroing Required	Max accuracy (°)	Comments
Shape-tape	$6,000	N/A	yes	variable	N/A due to large integral error.
Virtual Absolute Optical Encoder	$3,000	2	no	0.006	Large and heavy.
Precision Resistive potentiometer	$150	1.3	no	.02	Noisy, medium size, may wear.
Contactless-Magneto Resistive Potentiometer	$250	0.7	no	.025	Low noise, compact but limited range.

Mechanical Design: We desired T-WREX to accommodate adults of various sizes. The primary design changes that we made to the original WREX design were to increase the forearm and upper arm links to accommodate an adult's arm. All joint members were also increased in size to adapt to the increase of stress on the device. The elbow bracket depth was increased by two inches to allow room for the arm and a brace. The square adjustable telescopic members were switched to round SS-tubing to

decrease manufacturing costs while ensuring concentricity. The telescopic members allow for a large range of size adjustment that may accommodate upper arm lengths of 10-16.5in. Robust compact protective housings were designed to protect the pots from impact and use of custom designed split-clamp-shafts reduced the protrusion of the pots from the device. T-WREX was also designed to allow it to be flipped for use with both the left and right arm.

User Attachment: Our design criteria for the user attachment was that the attachment should be comfortable, hold the arm securely to the device, and allow a person with severe spastic hemiparesis to self-attach the arm to the device. The T-WREX uses the Elbow Ranger (dj Orthopedics, $70) to hold the arm. The Elbow Ranger has lower and upper arm cuffs that attach with Velcro that prevent the arm from slipping. The Elbow Ranger also has an elbow hinge with maximum and minimum range of motion settings that may be used as an added safety measure to limit the range of motion of the patient if needed. Use of an off the shelf brace reduced design cost, while ensuring a well-engineered, comfortable fit for the user.

Forward Kinematics: In order to use T-WREX as a three dimensional mouse, 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 [6]. The position of the tip of the forearm link p_t relative to a fixed reference frame located at the shoulder is:

$$p_t = e^{\hat{\xi}_1 \theta_1} e^{\hat{\xi}_2 \theta_2} e^{\hat{\xi}_3 \theta_3} e^{\hat{\xi}_4 \theta_4} e^{\hat{\xi}_5 \theta_5} e^{\hat{\xi}_6 \theta_6} M, \quad (1)$$

where the joint twists are

$$\xi_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \xi_2 = \begin{bmatrix} 0 \\ 5 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \xi_3 = \begin{bmatrix} 0 \\ -v-.5625 \\ -.73 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \xi_4 = \begin{bmatrix} 0 \\ -v-.5625 \\ -.73-ua \\ 1 \\ 0 \\ 0 \end{bmatrix}, \xi_5 = \begin{bmatrix} 1.743+ua \\ 1.25 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \xi_6 = \begin{bmatrix} -v-.5485 \\ 0 \\ 1.25 \\ 0 \\ -1 \\ 0 \end{bmatrix}$$

and

$$M = \begin{bmatrix} I_{3,3} & q_{t,0} \\ 0_{1,3} & 1 \end{bmatrix}, \quad q_{t,0} = \begin{bmatrix} -1+fa+tip \\ 4.491+ua \\ -v-.5485 \end{bmatrix}.$$

The initial location of the tip of the forearm is $q_{t,0}$, the angular displacements measured by the potentiometers are θ_i. The length of the upper arm is ua, the vertical displacement at the shoulder is v, the length of the forearm is fa, and the end effecter attachment length is tip. (All kinematic equations are in inches.)

Data Acquisition: We desired an affordable method for acquiring data from T-WREX's position sensors. We selected the Personal Measurement Device (PMD, $110) by Measurement Computing. The PMD is a USB-based analog input device, with a software-triggered data transfer rate of 6 Hz per channel. A new version is available with software-triggered rates of 40 Hz per channel. The Java Therapy software communicates with the device through a custom built, dynamic link library.

Measurement Accuracy: To evaluate the measurement accuracy of T-WREX, we measured the ability of the device to measure known locations in space. A scale was placed near the vertical mid-plane of the workspace on a table near the end of the depth of range. Ten samples were taken at various point pairs whose distance was 25.4cm apart. The resolution for these movements was within ±0.38cm. Point pair distance was also determined with a resolution of ±0.49 cm for points located on a vertical disc placed in the approximate middle of the orthosis workspace.

C. Software Enhancements

The original version of the Java Therapy software (Java Therapy 1.0) required that users have an active connection with the Internet. To facilitate intensive use of the system by users with only a single phone line at home, we desired a version of the software that could be used without a live connection to the Internet, but that would still periodically transfer data to and from a central server, for interaction with a rehabilitation therapist. 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.

The end user interfaces of both versions are identical. 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. This version also periodically sends patients update information, containing the patients' usage data so that a therapist or researcher can view the data, provide feedback, and modify the therapy program.

Movement training games in Java Therapy 2.0 will follow a standard framework called "OpenJT". The use of OpenJT will allow Java Therapy 2.0 to be easily scaled to include or remove games. Template games will be provided, so that researchers with Java development knowledge can create their own games and submit them to the Java Therapy 2.0 system. These games will then be available through the website or automatically downloaded to the users' standalone systems. Using an administration tool, a researcher or therapist may assign these games to any user, and then access usage data for the games over the web.

Future Additions: The browser interface of Java Therapy 2.0 allows easy incorporation of media recording tools and playback. Incorporation of video recording and play-back of a patient while using T-WREX will be used to provide performance feedback to both the patient and their therapist in the near future. The PMD will also be upgraded to the newly released, faster, version.

D. Device Testing

Our initial testing of the device focused on evaluating the ability of T-WREX to measure and assist in functional arm movements. Specifically, we measured five chronic stroke subjects' movement ability within the orthosis without gravity balance compared to within the orthosis with gravity balance. In the gravity balance "off" condition, the weight of the orthosis itself was still counterbalanced with the elastic bands, but not the weight of the arm.

Five patients with a history of chronic stroke (> 3 months prior) and persistent motor deficits, but absence of cognitive deficits, neglect, and shoulder pain participated in the study. Baseline motor function in each patient was evaluated prior to using the device with the arm motor Fugl-Meyer Motor Score [7]. The arm motor Fugl-Meyer Score measures 33 tests of arm and hand movements, each on a three point scale, with score range from 0 (worst) to 66 (best). The subjects' Fugl-Meyer scores were and side of impairment was: 11 (r), 26 (r), 40 (r), 12 (l), and 25(l). Subjects were then seated with a shoulder harness to prevent torso movement. The subject's hand was placed in the padded orthopedic splint attached to T-WREX. Three types of movement tests were then performed with and without gravity balance, with the order of presentation of the two conditions randomized. The first test was a sub section of the arm motor Fugl-Meyer Motor Score consisting of 14 tasks that could be performed while in the orthosis, with scores therefore ranging from 0 (worst) to 28 (best). The second test assessed reaching movements. The subject reached to soft targets located at the boundary of the arm's passive workspace eight times. One target was placed in the workspace contralateral to the impaired arm and one ipsilateral. The subjects also reached upwards from the lap to the highest point possible eight times. The third test assessed drawing movements. The subject traced circle patterns (diameter of 17.8cm) presented on a transparent plastic disc in the vertical plane, centered in front of them, 4-5 fist lengths from the front of the shoulder. The subject was asked to hold their arm up to the start point with their "unimpaired" arm before starting each movement. Motor adaptation was assessed by repeating the pattern tracing tasks thirty times in intervals of ten with one minute breaks in between.
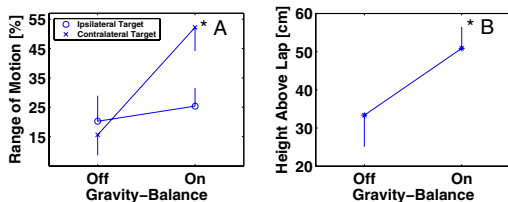
Figure 2: Effect of gravity balance on reaching movements. (A) Average reaching range of motion across subjects to targets with and with out gravity balance (distance traveled to target/total distance to target). (B) Average height reached above lap, with and without gravity balance. No short-term learning was observed across eight movement attempts. $*$ p < .05, paired t-test.
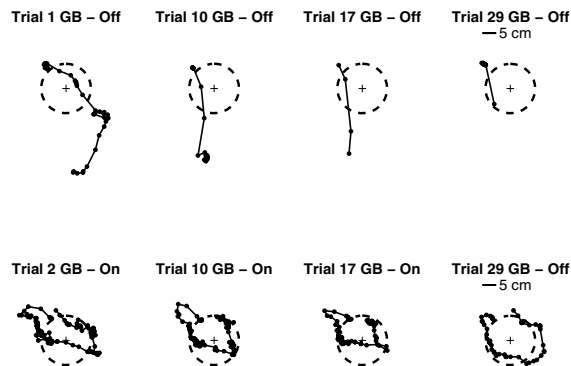

Figure 3: Effect of gravity balance on tracing movement for one subject. The subject attempted to trace a circle 30 times, without gravity balance (top four panels) and with gravity balance (bottom four panels). The panels show example trials throughout the 30 trials.

III. RESULTS

The score on the subset of arm motor Fugl-Meyer testing without gravity-balance was 9.0 (+/- 6.2SD) and with gravity-balance was 10.4 (+/- 6.5 SD). The change in Fugl-Meyer was marginally significant (p = .054) for a one-sided, paired t-test comparing the change to zero. Gravity balance significantly improved reaching to the contralateral target, but not to the ipsilateral target (Fig. 2A). Gravity balance significantly improved vertical reaching range of motion (Fig. 2B). Fig. 3 shows an example of circle tracing movements for one subject with and without gravity-balance. This subject was unable to trace the circle without gravity balance. However, with gravity balance the subject could trace the circle. Tracing accuracy improved with practice (Fig. 3).

IV. DISCUSSION

These results demonstrate the ability of T-WREX to measure and assist in functional arm movements across a large workspace of the arm. T-WREX's gravity balance function improved a clinical measure of arm movement, range of motion of reaching movements, and accuracy of drawing movements. The small improvements in the Fugl-Meyer score were due to improvements from an inability to perform a sub-task (score 0) to partial completion (score 1). This result highlights the "threshold" nature of gravity: i.e. it requires a threshold amount of strength to move against

gravity. For the reaching movements, only the movements to the ipsilateral target did not improve significantly. This is likely because these movements require shoulder external rotation, and the subjects had increased passive stiffness and spasticity of internal rotators. Achieving a full range of arm movement will likely require an active robotic device. We also showed an example for which gravity balance improved one subject's ability to draw a circle. Gravity balance appeared to unmask a latent motor learning capability that was not apparent with gravitational loading.

When asked if T-WREX "seemed scary or daunting," all subjects responded that they felt comfortable and safe while using the device. All subjects were pleased with their experience and asked to participate in future studies.

V. CONCLUSION

T-WREX provides a means to measure and safely assist in naturalistic arm movement. The manufacturing and parts cost for the system is currently about $4000. Coupled with Java Therapy 2.0, T-WREX will provide a means to practice and monitor functional arm movement training from home, either over the Web in real-time, or stand-alone with periodic communication with a remote site. By providing gradable levels of assistance and quantitative feedback of progress at home and to the clinic, we hope to increase access to and improve functional outcomes of arm therapy after stroke.

ACKNOWLEDGMENT

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