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The Rutgers Arm: An Upper-Extremity Rehabilitation System in Virtual Reality

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Abstract

Stroke is one of the leading causes of death and disability worldwide. Its prevalence calls for innovative rehabilitation methods for post-stroke patients. The Rutgers Arm is a novel arm rehabilitation system consisting of a special table, 3D tracker, custom forearm support, PC workstation, library of Java 3D VR exercises, clinical database module, and a tele-rehabilitation extension. The Rutgers Arm was tested on a chronic stroke subject, under local and tele-rehabilitation conditions, over five weeks of training. Case study results show improvements in arm motor control, shoulder range of motion, and (as illustrated by improvements in computerized measures and in Fugl-Meyer test scores). The tele-rehabilitation portion of training showed that exercise duration, level of difficulty and patient motivation, were maintained. A one-week-retention trial showed that most of the gains were maintained (or improved on) by the subject.

Keywords

Rutgers Arm, virtual reality, upper-extremity rehabilitation, stroke, rehabilitation exercises, tele-rehabilitation, ReCon, database, Java 3D, 3-D tracker.

INTRODUCTION

Stroke is considered the third leading cause of death and disability worldwide [1]. There are over 750,000 Americans who experience a new (or recurrent) stroke each year, causing upper and lower limb impairments and loss of function [15]. Economic pressures within the U.S. health care system lead these patients to return to their homes quite early after initial rehabilitation. Treatment is generally stopped after 6 to 9 months despite rehabilitation science evidence of the potential for improving motor function and recovery years after stroke [8,14].

The current acute rehabilitation interventions largely concentrate on the lower extremity, so that the patient will be mobile as soon as possible. Considerably less time is spent on encouraging arm and hand activities. With current rehabilitation methods it is estimated that between 30-66% of stroke survivors will not regain use of their affected arm [20]. Virtual Reality (VR) can address these needs by providing therapy through virtual games/exercises designed to motivate the patients and engage them in a period of intensive training. Virtual Reality-based rehabilitation can also improve the efficiency of a physical therapist by providing tools for better assessment and remote monitoring of multiple patients [4]. Tele-rehabilitation, a newer extension of virtual rehabilitation, will provide patients the ability to stay home and do the prescribed set of exercises under remote supervision [11].

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Several experimental virtual rehabilitation systems exist, for different limb segments affected by stroke. University of California Irvine developed a joystick-based system for wrist tele-rehabilitation [19]. Researchers at MIT used trackers and "teaching-by-example" simulations to remotely train a wide variety of functional 3D arm movements, for elbow, arm and wrist in patients post-stroke [9]. This paper is the first description of the Rutgers Arm [12] system that trains arm movement through a sequence of game-like exercises. The system also provides a tele-rehabilitation extension for future at-home use. This paper describes the initial system design, and results from a single case study. This research lead to subsequent system improvements, which are described in the concluding section.

EXPERIMENTAL SYSTEM

The Rutgers Arm (Figure 1*a*) consists of a PC (Pentium III dual processor workstation), a 3D tracker (Polhemus Fastrak [17]), a custom-designed low-friction table and armrest, Internet connection for tele-rehabilitation, and clinical database. The tracking system is used to track the patient's arm movements (wrist translation). A Posey [18] torso support attached to the chair prevents the patient from making compensatory trunk motions for actual shoulder flexion and abduction.

Custom-designed table

A computer table was retrofitted with a custom-designed tabletop for arm gravity support. It was designed so that the patient can extend either arm comfortably and swing it an angle of about 120 degrees. The patient seats facing one or the other of the long sides of the table, supporting the trained forearm on the tabletop. The Formica tabletop surface provides a low-friction support for arm 2D motion, helping the patient move without having to overcome large friction forces.

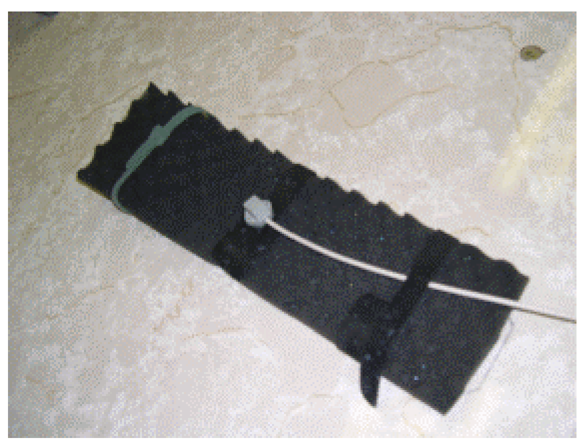
The Armrest

The custom armrest (Figure 1*b*) is a rectangular plastic platform, supported by 12 small Teflon cylinders. The Teflon cylinders reduce friction to help the patient move the arm comfortably over the tabletop surface. The armrest is padded with foam for comfort and has Velcro straps for proper fitting, regardless of individual anatomy. Extra foam is provided as support for the hand, in order to help keep the fingers extended. A tracker receiver is mounted on the strap near the wrist of the patient, since the wrist was chosen for tracking the arm movements during therapy.

The Rutgers Arm Tele-rehabilitation setup

The tele-rehabilitation system (Figure 2) uses the same setup as the local VR arm rehabilitation system, with additional devices to allow remote monitoring. The patient is monitored remotely by the therapist using a web camera and a speakerphone. The ReCon [13] media client software, developed collaboratively at Rutgers Human-Machine Interface Laboratory and UMDNJ Rivers Laboratory, is used to set up the connection between the patient's computer and the therapist's computer over the Internet.

(a)



(b)

Figure 1. The Rutgers Arm: a) system view (b) armrest detail. © 2005 Rutgers University.

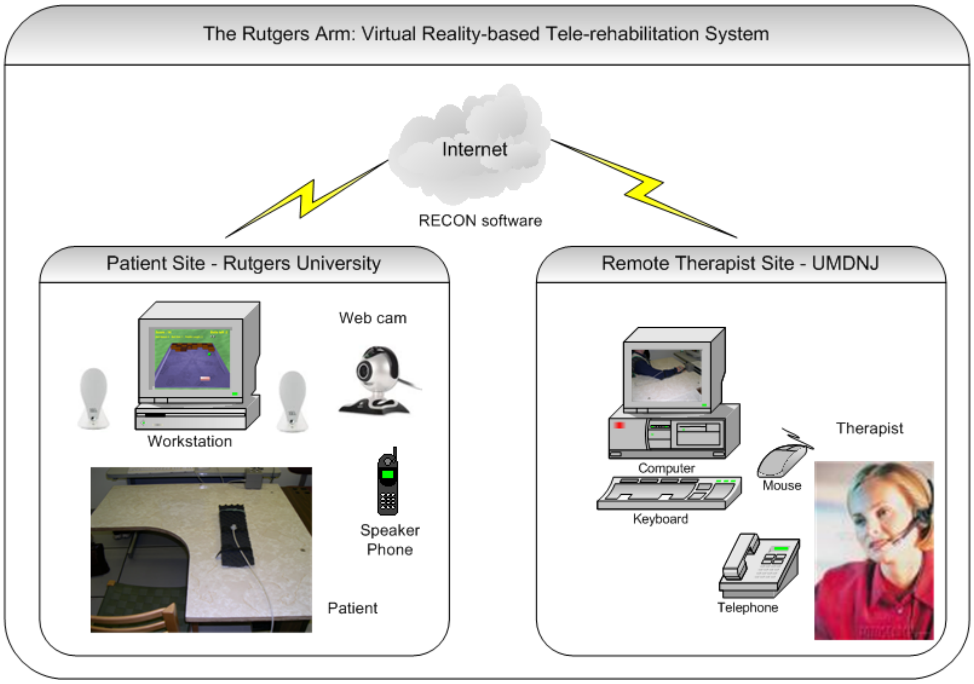


Figure 2.The Rutgers Arm tele-rehabilitation system setup. © 2005 Rutgers University

VIRTUAL REALITY GAMES

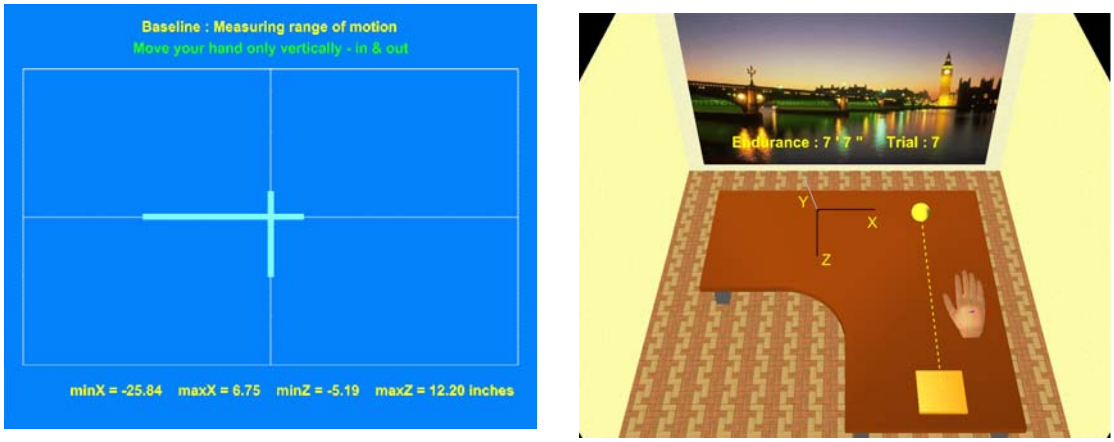
The Virtual Reality therapeutic games were created in our laboratory using Java3D [3]. This toolkit was chosen for its portability, rendering speed, cost (free), and other advantages over WTK [2]. The Windows 2000 operating system is used to run the entire simulation system. Based on the advice provided by the physical therapist researcher collaborating in this study two games were developed for training the movement of the arm/shoulder. This section explains the baseline exercise performed at the beginning of each VR therapy session and discusses the two VR games in detail.

Baselines

At the start of a new session, the patient's range of motion is measured using a baseline tool (Figure 3*a*). The patient's arm is placed at a calibration "home" position and the patient is instructed to perform an abduction/adduction (left-right) shoulder motion. During this time the patient is provided graphic feedback through a horizontal bar graph on the PC screen. The process is repeated for the flexion/extension (out-in)- directions. These ranges measured by the tracker are recorded in a file, and later used for mapping the real workspace to the virtual workspace and for positioning the objects in the VR scene.

The Pick-and-Place game

A simple virtual environment consisting of a room and a table (see Figure 3*b*) is displayed on the computer screen. The room was modeled in VRML and loaded in Java3D using VRML loader [16]. The 3DS Max authoring tool was used to model the virtual table (a proportional replica of the actual rehabilitation table) and to export it to VRML. A ball and a square target were placed on the table in different configurations. A virtual hand is mapped to the patient's wrist motion. The task is to pick up the ball and place it on the target by moving the hand on a specified trajectory, repeated for a specified number of trials. The patient is told not to rush, but to try to follow a prescribed dashed line trajectory the virtual table. When the virtual hand is in the proximity of the ball, a "pick-up" intelligent action is triggered (a well-known technique used when interacting with objects in the absence of a sensing glove). The ball then travels in the hand, until a release is triggered once the virtual hand is at the edge of the target box. Thus this game trains precision shoulder motor control, by emphasizing the need to follow the prescribed path. This is somewhat similar to work done at MIT [8,10], although in our case the patient



(a) (b)

Figure 3. Screen shots: (a) Baseline exercise – measuring the range of motion; (b) Pick-and-place game for shoulder flexion/extension with virtual world coordinate system shown.

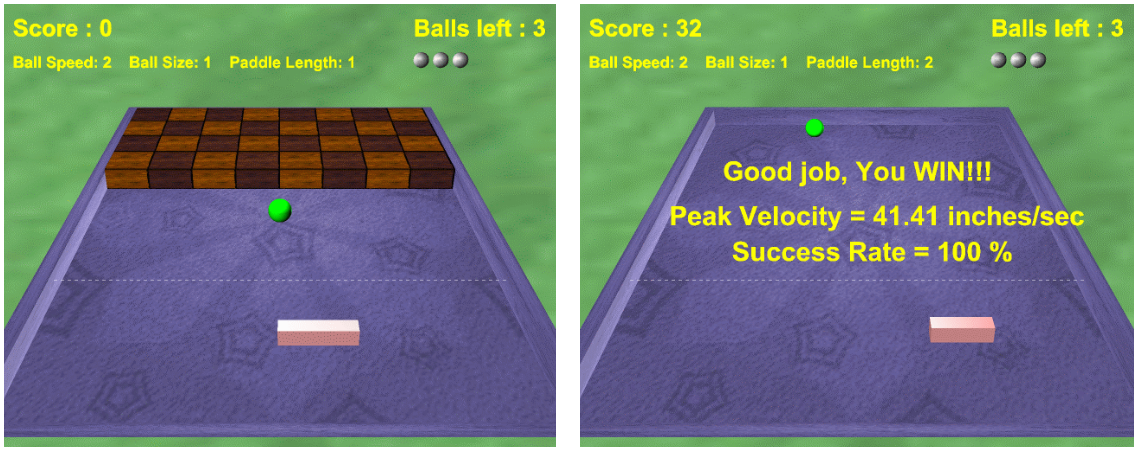
actually sees a ball avatar and there is no "expert" object motion example displayed on screen.

Three configurations (horizontal, vertical and diagonal) were programmed for ball and box placements. In the "horizontal" configuration, the ball and the target box are placed such that the patient has to move the shoulder in the abduction/adduction direction. Similarly, in the "vertical" configuration, the patient uses shoulder flexion/extension to complete the task. The "diagonal" configuration requires the patient to move in a natural clockwise/counter clockwise circumduction of the shoulder joint. The ideal path dashed line was calculated for every trial in each configuration and displayed on the virtual table. The length of the path in all the three configurations is derived from the baseline, an adaptive algorithm automatically increases the length of the path, as the patient's shoulder range of motion improves.

While the patient is playing the game, the simulation transparently measures and stores several parameters in the database: time taken to complete the exercise, distance traveled by the wrist, and errors between the ideal path and the path taken by the patient. The patient's immersion in the virtual rehabilitation environment is increased through several modes of feedback. Each trial displays the trial number, and the total distance that the wrist moves (as a measure of endurance), overlaid on a pleasant image at the distant wall of the virtual room. The patient receives continuous on-going feedback regarding their hand path from the time the ball is picked up until it is dropped. Auditory feedback is provided to make the game more engaging and motivating. A congratulatory sound (applause) is played when the patient completes an exercise.

Breakout3D game

An exercise to improve hand-eye coordination and reaction time (speed of arm movement) was designed in the form of a "Breakout3D" game (Figure 4*a*). This is an adaptation of the well-known "Breakout" video arcade game [6], but was programmed from the ground-up in our laboratory. The virtual environment consists of a ball, a paddle and a number of blocks placed on a game board. The task is to destroy all the blocks with the number of balls available. A prismatic paddle is used to bounce the ball in the desired direction, as well as to stop it from rolling off the game board on the side closest to the patient. A total of four balls are provided for the patient to complete the game. The position of the paddle is mapped based on the extents of the patient's shoulder motion obtained in the baseline. The score consists of the number of blocks destroyed at a given time and is displayed on the screen after the game is over. Difficulty levels may be set by changing the ball size, the ball speed, the paddle length, or the block size. Smaller ball sizes, higher ball speeds, smaller paddle lengths and smaller block sizes are the characteristic of more difficult games. Changing the block size also changes the number of blocks that have to be destroyed.



(a) **(b)**

Figure 4. Screen shots: (a) Breakout3D game setup; (b) User feedback message displayed after successful completion of the game. © 2005 Rutgers University.

When the ball collides with a block, the block explodes (following a QuadParticles system model [5]) and disappears from the table. The ball bounces off of other blocks when there are multiple-block collisions. Ideally, whenever the ball hits a block, that block should be destroyed. However, in order to increase the amount of patient shoulder movement, it was decided that a ball should only destroy one block for every bounce off the paddle. In this way, consecutive ball-block collisions will destroy only the first block. The process is repeated after a new collision with the paddle.

In this game, the emphasis is on speed of arm movement and arm-eye coordination, rather than on control of a precise trajectory. Hence the peak velocity of the wrist is measured in real time and stored in the clinical database. This peak velocity is decomposed into four peak translation velocities (left-to-right, right-to-left, in-to-out, and out-to-in motions). These are indicative of the shoulder velocities for abduction, adduction, flexion and extension, respectively. The total distance covered by the wrist movement is also measured along with the time taken for the completion of the whole game. At the end of the game, the Euclidean peak velocity along with the game success rate, are displayed as feedback to the patient (see Figure 4*b*). The success rate is the ratio of total number of blocks destroyed to the total number of blocks available at the beginning of that game. In each training session the Breakout3D is played several times, interspaced with the pick-and-place game for more variety of training.

PILOT STUDY

A pilot study to test the Rutgers Arm system was conducted with a 56-year-old male (Figure 5) who had a right hemiparesis secondary to a left middle cerebral artery infarct sustained 17 months prior to the study. He showed limited return in his upper extremity, with active movement predominantly in the shoulder region. He was ambulating independently using a cane and was independent in all activities of daily living, including driving.

The first part of the patient trials consisted of twelve sessions, one each on Mondays, Wednesdays, and Fridays. Three physical therapists took turns supervising the training, while keeping a fixed order during the week. The training protocol was therapist-driven based upon patient improvement. It was found that the initial number of pick-and-place trials (10) was suboptimal. Therefore the number trials increased to 20 from Session 2 onwards. During the second week of the study, a 5 min break was introduced after the first 30 minutes of exercising so that the subject could increase his total exercise time without undue fatigue. To compensate for two sessions lost during the second week of the study (patient absence and software problems) two additional sessions were performed

Figure 5. A stroke patient performing the pick-and-place exercise © 2005 Rutgers University

on the fifth week of the trial. In addition to the VR measures for evaluating the patient's progress, a Fugl-Meyer test [7] was conducted before and after the twelve-sessions of local therapy.

The tele-rehabilitation study was conducted for one week, immediately following the end of training under local rehabilitation conditions. The subject started with the same set of exercises done on the twelfth session of local VR rehabilitation. Two Breakout3D games were added for sessions 14 and 15. A one-week retention session (session 16) was then conducted to test the retention of the subject's gains.

RESULTS AND DISCUSSION

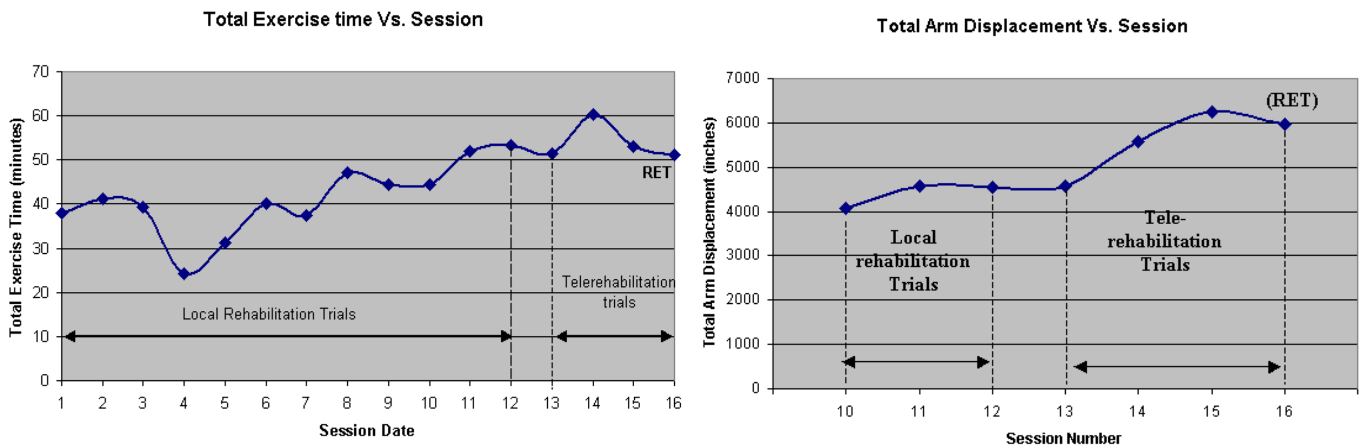
The subject had limited range of motion in shoulder flexion at the beginning of the trials. As the subject underwent more VR therapy sessions, he was able to move his wrist further out on the table surface. It is interesting to note that training in a tele-rehabilitation environment did not diminish this subject's performance as he was not only able to maintain the shoulder flexion/extension range of motion, but also improve compared to the last four local rehabilitation trials. Table 1 shows a comparison of the performance variables between sessions 2, 12 and 15.

The total session duration minus rest periods (total *exercise* time) as well as total wrist movement per session can be used as a measure of endurance of the subject's shoulder motion. These are graphed in Figure 6. The total exercise time was kept at about 40 minutes at the beginning of training and was gradually increased to almost 55 minutes by session 12 (a 38% increase). The total wrist translation motion in each session (which in turn reflects the shoulder motion) had a 39% increase over the first four weeks of local therapy. This went up to 90% improvement by session 15 (end of tele-rehabilitation).

Figure 7 shows a comparison between the path bundles generated by the patient in session 2 and session 12. It can be observed that the wrist paths from session 12 have become more uniform and compact. This is indicative of better shoulder flexion/extension motor control and coordination by the end of the four-week local training.

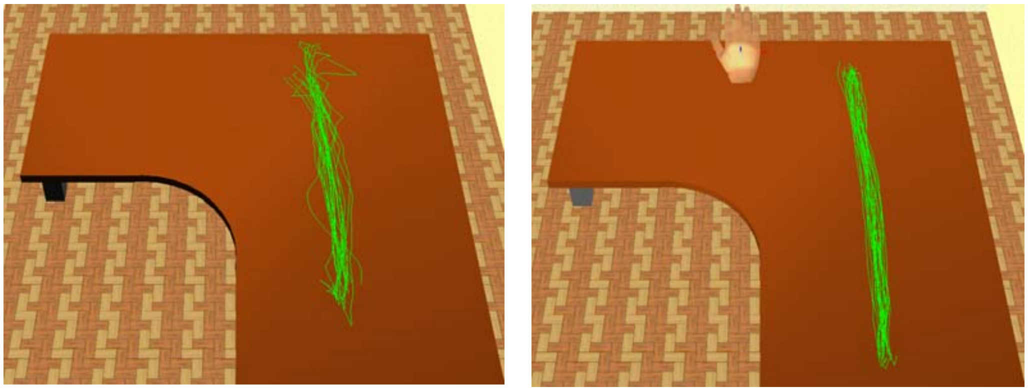
Table 1. A comparison of the performance variables between sessions 2, 12 and 15.

Variable	Session 2 (local)	Session 12 (local)	Session 15 (tele-rehab)	Change (%) session 2 vs. 12	Change (%) session 2 vs. 15
Shoulder flexion/extension baseline range	15.89 inches	20.09 inches	24.24 inches	26% increase	52% increase
Total exercise time	41.28 minutes	53.39 minutes	53 minutes	29% increase	28% increase
Total wrist displacement	3281 inches	4572 inches	6238 inches	39% increase	90% increase
Average Peak Euclid. velocity	17.1 inches/sec.	26.07 inches/sec.	29.24 inches/sec.	52% increase	71% increase
Fugl-Meyer Test scores	UE Score 22 ROM 17/24	UE Score 29 ROM 21/24	-	32% increase 24% increase	-



a) b)

Figure 6. The subject's progress: a) total exercise time vs. session; b) total wrist displacement vs. session © 2005 Rutgers University.



a) b)

Figure 7. Paths followed by the subject during the pick-and-place task using shoulder flexion/extension: a) in session 2; b) in session 12. © 2005 Rutgers University.

CONCLUSIONS AND FUTURE WORK

This initial study that trained one subject, in the chronic phase post-stroke under local and tele-rehabilitation conditions using the Rutgers Arm showed encouraging results. The system was subsequently modified to increase its functionality. Exercise simulations were upgraded to support left-arm affected patients. The flat tabletop was redesigned, with an extra capability to tilt (pitch and roll) in controlled increments. This will enable us to gradually increase the difficulty of the exercises by having the patient move their arm against gravity. A database graphing utility previously developed at Human-Machine Interface Lab still needs to be integrated with the patient database for easy web-based access and analysis of outcomes. Additionally, a more sophisticated tele-rehabilitation system is planned. New patient trials are planned. Subsequently, we will redesign the system with the goal of reducing overall cost.

ACKNOWLEDGEMENTS
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