# Virtual Reality-based System for Ankle Rehabilitation Post Stroke

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## Abstract

*The Rutgers Ankle is a compact Stewart-platform type robot used in ankle rehabilitation. It can measure displacements and apply forces/torques in six degrees of freedom. Two rehabilitation simulations resembling video games have been developed. One is an airplane flying exercise; the other is a boat navigation exercise. Both are executed with the ankle, using the Rutgers Ankle as a haptic joystick. To allow the patients to complete the routines, the simulations are customized to their abilities. Furthermore, the exercise complexity, as well as visual and haptic effects are set by the therapist, and can also be changed in real-time. A database stores exercise results and presents them in graph format remotely. Initial pilot trials with three chronic post-stroke individuals, of the above system were encouraging.*

## Keywords

*telerehabilitation, force feedback, ankle rehabilitation, Rutgers Ankle, virtual reality*

## Introduction

Lower extremity rehabilitation has followed other forms of training where VR has been used. These include orthopedic rehabilitation [2,3], post-stroke hand/arm rehabilitation [6,5], treatment of phobias [4], and cognitive assessment of children with attention deficits [8], among others.

Patients post-stroke receive rehabilitation therapy in the acute stage (a month or so) after the onset of the disease, followed by outpatient rehabilitation for several more months. Subsequently, they are considered in the "chronic phase" and little or no rehabilitation therapy is administered. The clinical motivation to apply VR-based post-stroke rehabilitation is the need for intensive and repetitive exercises, even if classical therapy ended. Such exercises have been shown to be effective in the chronic phase, potentially offering hope to millions of stroke survivors. For patients with ankle deficits, it is expected that exercising in VR will result in increased range of motion, torque output capability, as well as improved coordination and larger mechanical power output.

Virtual reality is ideal to create an engaging environment for patients to exercise in, repetitively, but without boredom. Furthermore, VR-based rehabilitation offers fine control over exercise parameters, and the ability to store data online, something uncommon in classical rehabilitation therapy.

The Human-Machine Interface Laboratory at Rutgers University, together with researchers from the University of Medicine and Dentistry of New Jersey (USA) has been working on such a system for several years. This paper presents the technical aspects of its use, including hardware, VR simulation exercises and patient database functionality. Preliminary findings from the most recent pilot clinical testing on three patients are also included.

## Hardware Setup

The rehabilitation system described in this paper consists of two Rutgers Ankle robots, a control interface, a host PC and a web monitoring system. The remote monitoring system was described elsewhere [1]. The Rutgers Ankle robot is a compact Stewart platform (shown in Figure 1a) designed to be attached to a user's foot and to provide 6 DOF force feedback. The two Rutgers Ankle platforms are mounted on a floor support and are connected to a single control interface through electrical and pneumatic lines.

The control interface has an imbedded Pentium board, which is performing all control and interfacing tasks. It also contains piezo control valves that regulate the pressure to the Rutgers Ankle double-action actuators, as well as a hard disk, display panel, and custom designed sensing boards.

**(a)** **(b)**

**Figure 1. The VR-based ankle rehabilitation system: (a) the rehabilitation system setup showing the PC monitor and the web-based monitoring display; (b) the Rutgers Ankle device detail; © Rutgers University 2002**

Low-level servo control software executed by the Pentium board in the control box, provides platform position and force control. The patient sits on an elevated chair (see Figure 1a) having the ankle strapped to one of the Rutgers Ankle platforms and facing the host PC monitor. The patient interacts with the virtual reality simulation running on the host PC using the Rutgers Ankle as a foot joystick. The control interface and the PC running the exercise simulations are exchanging data through a serial port in real time. These data consist of three position values, tree ankle orientation angles, thee forces and three torques applied on the mobile platform. The positions and orientations are computed by forward kinematics based on the displacement of six linear potentiometers mounted in parallel with the Rutgers Ankle pistons. The forces and torques are measured by a 6-DOF force and torque sensor mounted on the mobile platform and attached to the user's foot (the blue disk in Figure 1b).

## Rehabilitation Exercises

An important element of rehabilitation for patients post-stroke is the opportunity to produce many repetitions of the ankle movement or of the task that is being trained [7]. The Rutgers Ankle Rehabilitation System applies this principle to a game playing experience, which allows patients to exercise their ankle by reaching targets set in a virtual reality simulation.

The games implemented by the system are similar to vehicle driving arcade games, except that driving is done with the foot. Patients have to navigate through targets positioned on the route using the Rutgers Ankle. The ankle motions are recorded by the control interface and sent to the simulation running on the host PC.

In the first game patients have to fly an airplane through hoops (see Figure 2a). This is a refined version of a previously-reported airplane exercise developed by the authors [3]. In the second game patients navigate a boat on a seascape between pairs of buoys placed on top of incoming waves (see Figure 2b). Both exercises are designed to provide a similar type of training with some differences induced for simulation realism. While the airplane can take any route between two target hoops, the boat simulation places more constraints on the patients, since they are required to maintain contact with the sea surface in order to successfully clear a target. Maintaining contact with the water is most difficult at the top of waves, where the sudden change in the surface slope requires a quick change in the corresponding ankle orientation.


**(a) (b)**

**Figure 2. Virtual reality exercise simulations: (a) the airplane exercise; (b) the boat exercise © Rutgers University 2002**

The application screen layout is designed to provide patients and therapists with real-time performance feedback by using 2D graphics. On the blue band at the top of the screen the simulation displays the target accuracy score (targets cleared, missed, or hit) and the time left to exercise. On the right side of the screen is displayed the real time patient performance. Two sets of bar displays (one for angles and one for torques) fill up with color, which is proportional to the ratio between the target set for the corresponding motion and the current performance. Using these bars allows therapists to monitor the intensity and duration at which patients are exercising.

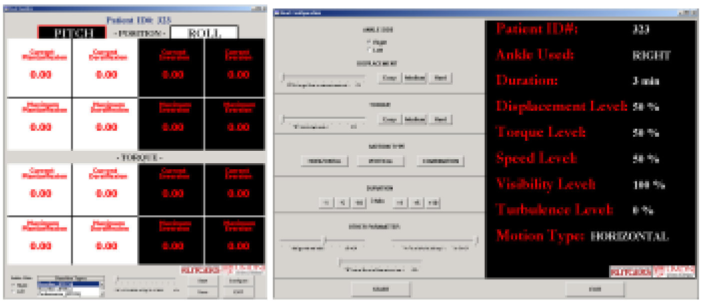
The vehicle (airplane or boat) moves automatically along the Z-axis of the simulation (into the screen), at a constant speed selected by the therapist. The up and down motions of the vehicle are mapped to the patient's pitch orientation, while the left and right motions are mapped to the ankle roll orientation. The yaw angle is not used as an input parameter because the patients found it difficult to isolate the yaw motion from their ankle roll motion. The targets are placed equidistantly along the Z-axis and are displaced in the XY plane in one of the following nine positions: center, N, NE, E, SE, S, SW, W, NW. To reduce the virtual environment complexity, a limited number of targets are shown at any one time. As the vehicle passes a target, the target is "repositioned" at the end of the visible target queue.

At the beginning of each rehabilitation session the patient's maximum motion range and force output capacity are measured using a baseline application (shown in Figure 3a). These values are used to scale the patient's motion during the exercise to match the target placement. This method ensures that any patient can play the game regardless of how large or small their (initial) ankle range is.

Upon completing the baseline stage therapists can configure an exercise by setting the training parameters (see Figure 3b). The configurable parameters are: exercise duration, displacement level, torque level, target sequence, vehicle speed, visibility, and air/water turbulence. The displacement level parameter selects the percentage of the maximum range (measured by the baseline) that the patient needs to achieve in order to reach the targets. The torque level parameter defines the platform stiffness as a percentage of hardware-imposed limits. The speed of the vehicle is measured in targets passed every second. The speed parameter is a percentage of the maximum vehicle speed (currently set at 0.4 targets/second by the simulation).

Depending on a particular patient's rehabilitation needs, therapists select the target sequence based on the ankle motions and impairments that need to be rehabilitated. The pitch motion is trained by placing the targets in the vertical plane only (North and South locations), while the horizontal placement (East and West locations) corresponds to the roll motion. Non-planar target placement (N-E, S-W, N-W, S-E) requires diagonal ankle motions. Complementary motions (N/S, E/W, NE/SW, etc.) are selected in consecutive positions. For more difficult motions (especially diagonal ones) a neutral target is placed between complementary positions, to give the patient more time to change their ankle orientation. The airplane exercise supports any of the above target sequences. The boat exercise supports only a limited set of target sequences due to the constraints imposed by the targets (buoys) sitting on the waves.

To increase the realism of the simulation and to keep patients challenged and interested, the therapist can modify the weather conditions (such as visibility and turbulence). The visibility parameter selects the level of fog in the scene on a 0% (clear visibility) to 100% (completely fogged) range. The fog thickness is mapped linearly to the number of visible targets, so that a visibility level of 50% shows only half of the targets at any one time.




**(a)** **(b)**

**Figure 3. Exercise customizing environment: (a) the baseline screen; (b) the exercise configuration screen for therapist-set parameters. © Rutgers University 2002**

The turbulence parameter controls the level of weather effects (windy, stormy, etc.). As the turbulence level is increased between 0% and 100%, the sky darkens and the light in the scene is dimmed. For turbulence levels above 50%, lightning and thunder effects are introduced in the simulation (see Figure 4). The Rutgers Ankle is programmed to do lateral swaying motions at a frequency proportional with the turbulence level. This acts as a haptic disturbance, which the patient has to overcome in order to successfully navigate in the scene.

Beside the parameters described above, therapists can enable or disable the haptic feedback of the Rutgers Ankle or can choose to ignore certain motion aspects of the patient's ankle. For example, in an exercise training the pitch motion (vertical target arrangement) the system can ignore the ankle's roll motion's keeping the vehicle on track, while the patient concentrates solely on moving the ankle up and down. This method is consistent with rehabilitation principles of limiting the degrees of freedom that a patient has to control in order to achieve a given motion.

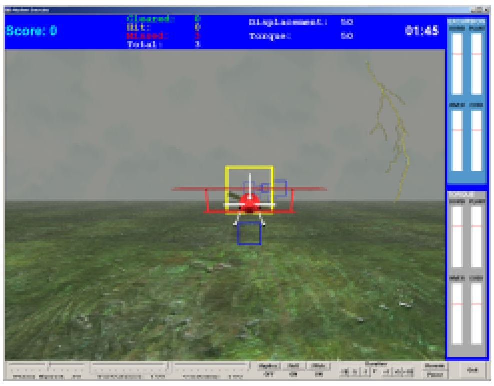



**Figure 4. Airplane exercise simulation during stormy weather. © Rutgers University 2002**

## Data Collection, Storage and Access

The data collected and stored by the system can be divided into three categories: "raw data," "events," and "performances." The raw data comes from the Rutgers Ankle sensor readings (positions, orientations, forces and torques). The sensors sampling rate is as high as possible to allow for complex (subsequent) analysis.

A set of special situations (events) that could occur during an exercise are also collected and saved on the hard disk. The events include markers of the vehicle passing a target and run-time parameter adjustments made by the therapist *during* the exercise execution. This provides a way to accurately describe of the exercise settings. The target passing events are saved along with the position of the target and weather the target was "cleared," "hit," or "missed." A target is cleared if the vehicle passes inside it without hitting the target surface. A target is missed if the vehicle passes completely outside it. A target is hit if the airplane wings pass through the rectangular frame, or if the boat hits the buoy (either on the inside or on the outside).

The performance data stored during the exercises consists of target accuracy scores, maximum ankle ranges and torques achieved by the patient, and total time exercising. Offline, further performance parameters are extracted from data, such as mean and standard deviation of the ankle range, mechanical work and power output.

At the end of each session the data (stored in files on the host PC) is transferred to a remote database server. A web-base interface is implemented to extract the data from the database and display it in a browser with a restricted (password) access. This data can be viewed as a tabular history of the patient's exercises, the configuration parameters and the target accuracy data. For more detailed data access the web portal can show the data as charts. A Java applet allows easy chart parameter selection by the clinician (see Figure 5).

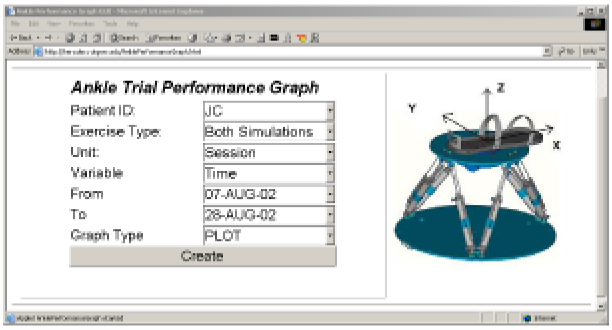



**Figure 5. Web applet for patient database graphing parameter selection. © Rutgers University 2002**

## Preliminary Clinical Testing

Three patients post-stroke (mean age 52 years), who were between 1 and 8 years post-stroke, participated in a pilot study using the above system. They trained three times a week for four weeks. Each exercise session lasted approximately one hour.

All patients were able to use the system and learn both the plane and boat simulations. The flexibility of the system was implemented as demonstrated by the therapists' ability to customize the exercise program for each of these patients. For example, one of the patients had great difficulty with coordinating movements so most of the exercises she performed were executed by limiting the degrees of freedom that she had to control with the affected ankle. For a second patient, the addition of the turbulence and manipulation of the visibility was used to maintain his interest and to challenge him.

All patients increased the time they worked on the system from an average of 20 minutes on the first session to an average of 50 minutes by the fourth week of training. Two of the three patients were able to execute their exercises without requiring that their degrees of freedom be limited. Two of the patients preferred exercising on the plane simulation and the third preferred the boat simulation.

Preliminary review of the data indicates that selected clinical outcomes were correlated with VR data. For instance, all patients demonstrated an increase in power generation for all motions, which correlated with increases in walking speed measured clinically. Mechanical power increases in the VR simulations were correlated with endurance improvement during walking for one of the three patients. This finding is illustrated in Figures 6 and 7 that display increases in power generated during the VR plane simulation for both the vertical and horizontal movements for a patient that increased his endurance as measured by a six-minute walk test from a distance of 995 feet to a distance of 1085 feet.

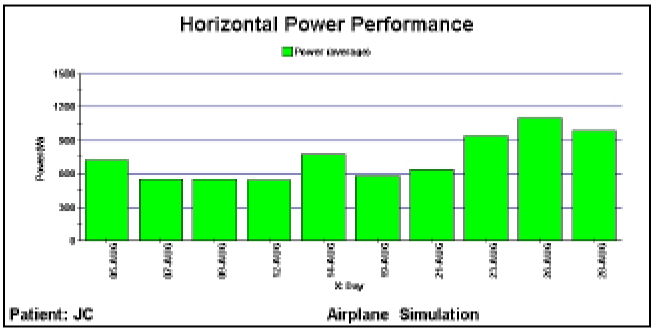



**Figure 6. Daily average roll ankle power output. © Rutgers University 2002**

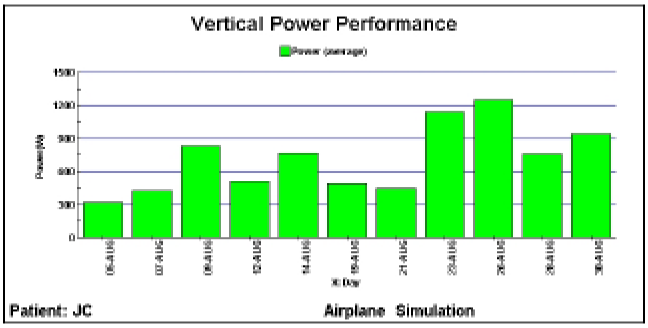



**Figure 7. Daily average pitch power output. © Rutgers University 2002**

## Conclusions and Future Work

The Rutgers Ankle rehabilitation system, described in this paper, was tested in a two-month study in which three chronic post-stroke individuals underwent lower extremity rehabilitation. Improvements in selected VR measures, specifically power, were correlated with increases in gait speed for all three patients and in walking endurance for one patient. These results were achieved with the use of VR training in sitting, therapist feedback and instruction. These findings extend our previous report on the result of a two-week training program for an individual post-stroke [3]. A more in-depth analysis of database functionality, as well as its data content will follow. A redesign of the Rutgers Ankle to sustain standing patients is underway.

## Acknowledgements

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