

Haptic Effects for Virtual Reality-based Post-Stroke Rehabilitation

Rares F. Boian
CAIP Center,
Rutgers
University
Piscataway NJ,
USA

Judith E.
Deutsch
Program in
Physical Therapy,
UMDNJ-SHRP,
Newark NJ,
USA

Chan Su Lee
CAIP Center,
Rutgers
University
Piscataway NJ,
USA

Grigore C.
Burdea
CAIP Center,
Rutgers
University
Piscataway NJ,
USA

Jeffrey
Lewis
CAIP Center,
Rutgers
University
Piscataway NJ,
USA

Abstract

The majority of today's haptic interfaces are designed for hand-based interaction with virtual environments. However, there are several real-life tasks that require a person to interact with the environment using one's foot. Researchers have developed systems for simulating walking in a virtual environment. This paper describes a different approach to foot based interactions, intended for users in sitting position. A VR-based rehabilitation system using a prototype Rutgers Ankle device is presented, along with the methods of enhancing interaction realism through haptic feedback. Two application examples used for post-stroke patient rehabilitation are presented. Initial results from pilot clinical testing are briefly described.

1. Introduction

Physical interactions with one's surroundings are commonly mediated by our hands. Consequently, most virtual reality simulations provide hand-based user interaction. This led to a wide variety of interfaces (such as mice, trackballs, joysticks, wands, wheels, and sensing gloves) that facilitate the use of hands in VR simulations.

Feet are another common way of interacting with the (real) environment. Although less dexterous than the hands, the feet are used to

manipulate the environment in several situations, such as driving cars, riding bicycles, playing football, or playing soccer. The interfaces proposed by researchers for foot-based interaction with virtual environments range from position trackers attached to the user's feet, to treadmills, to force feedback robotic devices. Examples of such interfaces are the "Sarcos Biport" and the "Sarcos Treadport" designed by Christensen and Hollerbach [9], Iwata's "Torus Treadmill" and "Gaitmaster" [10,11], the "ATR-GSS" invented by Miyasato [14] and the "Rutgers Ankle" developed by Girone and his colleagues [6].

Classical ankle rehabilitation devices used in clinics and at home are foam rollers [15], wobble boards [13], and the Biodex Balance System [1]. The foam rollers are long foam cylinders used as unstable surfaces for training a patient's balance and proprioception. The wobble boards are circular disks with a hemispherical pivot on one of the sides. A patient stands on the wobble board keeping balance while tilting it. The Balance System is an advanced wobble-board-like computerized device. The stability of the platform can be changed via an electronic interface.

The "Rutgers Ankle" haptic interface [7] is an air-actuated 6-DOF Stewart platform small robot attached to the user's foot (Figure 1). Girone and colleagues [6] used the Rutgers Ankle as an instrument to diagnose ankle

sprains. Later Deutsch and colleagues applied the same system for ankle rehabilitation of patients with musculo-skeletal injuries and a patient post-stroke [3,4]. The Rutgers Ankle was connected to a virtual reality exercise and served the user as foot “joystick” with force feedback.



Figure 1. The Rutgers Ankle Haptic Interface.
© Rutgers University 2002

This paper presents the next-generation design, focusing on the haptic feedback enhancements brought to the system. Section 2 describes the hardware and software setup. Section 3 details the low-level haptic effects integrated in the rehabilitation exercises. Virtual reality exercises performed by patients are presented in Section 4.. Section 5 (briefly presents some experimental data generated during patient trials. Conclusions and future research directions are given in section 6.

2. System Description

The rehabilitation system used in the current round of patient trials consists of two Rutgers Ankle platforms (Figure 2) connected to a single control interface [4]. Depending on the ankle side being trained (left, or right foot), one of the

platforms is powered up before the therapy begins.

The patient sits on an elevated (medical) chair with one foot strapped to the corresponding platform and the upper leg immobilized with Velcro straps. Facing the patient is a PC host running the virtual reality exercises. The electro-mechanical control interface (not shown) is connected to a host PC through a serial port. The VR simulations receive data (positions, orientations, forces and torques) from the interface and can send commands regarding the desired position, orientation and stiffness of the platform.



Figure 2. System setup. © Rutgers University 2002

A second monitor facing the patient is intended as a tele-monitoring portal. This gives the patient a view of a remote rehabilitation specialist that may assist a less-qualified local assistant (or family member). More details regarding the tele-rehabilitation system can be found in [12].

Similar to an earlier approach using an airplane piloting exercise [3], the patient uses the Rutgers Ankle as a foot joystick, interacting with the virtual world by changing the orientation of the ankle. The Stewart platform maintains a horizontal position opposing the foot motions with variable levels of stiffness. Depending on the patient’s actions, the VR simulation generates haptic effects by sending

real-time position commands to the control interface.

While the patient exercises, the system records the data read from the platform position and force sensors and stores it online. After the therapy session ends, this data is evaluated and written into a central Oracle database. The patient data is subsequently accessible to the remote physician or therapist through a web portal implemented in Java.

3. Low-Level Haptic Effects

The haptic effects implemented by the VR simulations can be grouped in two categories: “low-level” and “task-level”. The low-level effects are general and can be used for a variety of simulations. The task-level effects are directly related to the exercise the user has to accomplish in the virtual world.

The system described here implements three low-level haptic effects: impedance variation [16], stiffness change, and vibrations.

3.1 Impedance Variation

As described by Yoon et al. [16], an effective way of applying force to the user's foot is by using position-based impedance control. The servo controller can read the forces and torques applied by the user's foot through the six-DOF force sensor mounted on the top platform (the blue disk seen in Figure 1 under the user's foot). The impedance control logic computes the platform's desired position from the given position and the sensed disturbance forces and torques. The new target position is computed so that the platform opposes, or augments, the user's motion, depending on the sign of the impedance gains.

This approach provides a flexible way of rendering various surfaces through the Rutgers Ankle. The platform's motion (displacement or orientation) can be restricted for a set of axes by setting large impedance gains for those axes. The platform motion can be made sluggish by

changing the impedance gain of one axis proportionally to the speed of motion on that axis.

Table 1. Platform torque loads at different impedance gain levels (100 PSI input pressure to the electro-mechanical interface)

	Zero gain	50% of max gain	Maximum gain
Torque necessary to displace	1.6 Nm	4 Nm	10 Nm
Maximum torque	6 Nm	10 Nm	12 Nm

The impedance variation uses as input the torques applied by the user. This was a problem with some stroke patients that could apply only small torques with their ankle, making the method impractical. To solve this problem the stiffness change method was applied instead.

3.2 Stiffness Change.

The stiffness of the Rutgers Ankle is easily changed by increasing, or decreasing, the proportional position gains (K_p) of its pneumatic actuators (Equation 1).

$$\Delta P = K_p \Delta L \quad (1)$$

ΔL = measured change in actuator position

ΔP = desired change in air pressure

A lower gain makes the platform more compliant while a higher gain makes it stiffer and more difficult to displace. Beside these effects, the gain change also affects the platform accuracy, its response time, and its stability. A lower gain yields a longer response time and improved stability. A higher gain will do the opposite by decreasing the response time and platform stability.

To avoid slow platform motion or instabilities, lower and upper bounds for the proportional position gains are set. A VR

simulation connected to the system would change the stiffness by specifying the fraction of the gain- interval.

Changing the stiffness does not take in account the torques applied by the user, instead it changes the general platform proportional gains. Comparing the values in Tables 1 and 2 it is obvious that the stiffness change yields less torque capabilities than the impedance variation. However, the range of the stiffness changes was large enough to control the exercise difficulty level.

Table 2. Platform torque load at different stiffness levels (for 100 PSI input pressure to the electro-mechanical interface)

	0% stiffness	50% stiffness	100% stiffness
Torque necessary to displace	1 Nm	1.6 Nm	2 Nm
Maximum torque	4 Nm	6 Nm	10 Nm

3.3 Vibrations

Vibrations are haptic effects that can be used to simulate a wide range of situations by simply changing their frequency and amplitude.

The mechanical bandwidth of the Rutgers Ankle platform is on the order of seven Hz. So the theoretical maximum controllable vibration has a frequency of seven Hz. Higher frequencies can be obtained by increasing the amplitude beyond the platform's physical range. This approach is not acceptable because of an increased risk of instabilities.

The previous section mentioned that the platform stiffness could be changed by increasing, or decreasing, the position proportionality gains. The manipulation of these gains causes the platform to overshoot, or undershoot, making the vibrations either unperceivable, or too large. Figure 3 shows the effect of stiffness change on a 3 Hz frequency vibration of 3 cm amplitude.

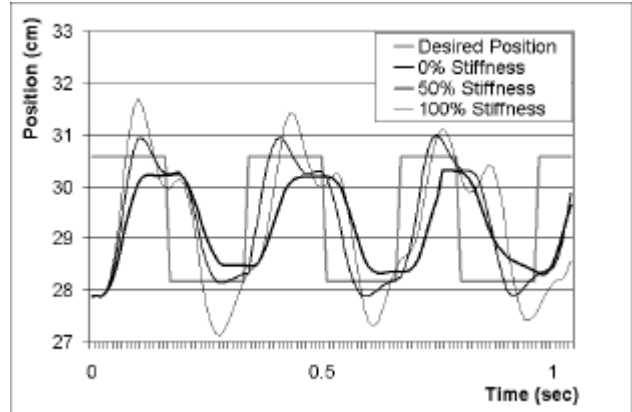


Figure 3. Platform vibrations at different stiffness levels © Rutgers University 2002

4. Task-Level Haptic Effects

4.1 VR Exercises

Two exercises were developed and tested on patients during Summer 2002. Both exercises were designed to provide similar types of therapy, but the virtual worlds were different to avoid monotony.

The first exercise is a revision of the airplane simulation previously reported [3]. The patient uses the Rutgers Ankle platform to fly an airplane through 3-D hoops. The hoops are placed equidistantly and vertically, in one of the nine possible directions (N, NE, E, SE, S, SW, W, NW). The therapist chooses the position of the hoops, so that the patient exercises the desired type of ankle motion.

The orientation of the airplane is mapped to the orientation of the Stewart platform. The direction of the airplane is computed by scaling the platform orientation angle to the angle between the hoops using the patient's maximum available ankle range. This insures that no matter how small this capability is, the exercise can still be executed. The weather conditions and visibility can be changed, from clear to stormy weather as well as adding fog. During stormy weather visual and sound effects (lightning and thunder) are added for increased realism (as seen in Figure 4).

The second exercise involves a boat that has to be navigated between pairs of buoys sitting on the crest of waves. The boat is driven in the same manner as the airplane, with the difference that the patient has to keep the boat above water at all times. This requires more accuracy than the airplane exercise, as the airplane could take any route from one target hoop to the next. The weather conditions and visibility can also be changed.

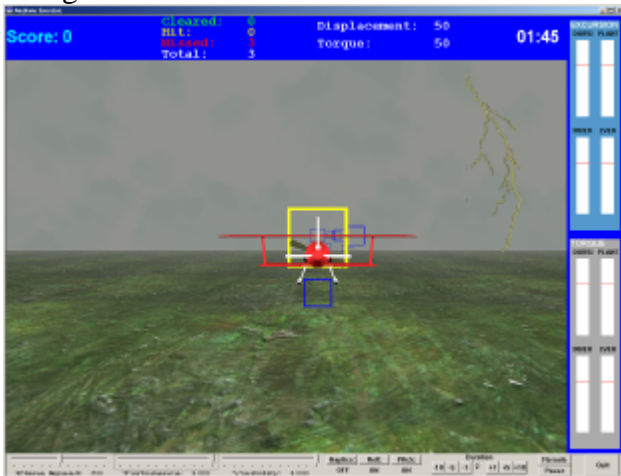


Figure 4. Airplane exercise. © Rutgers University 2002

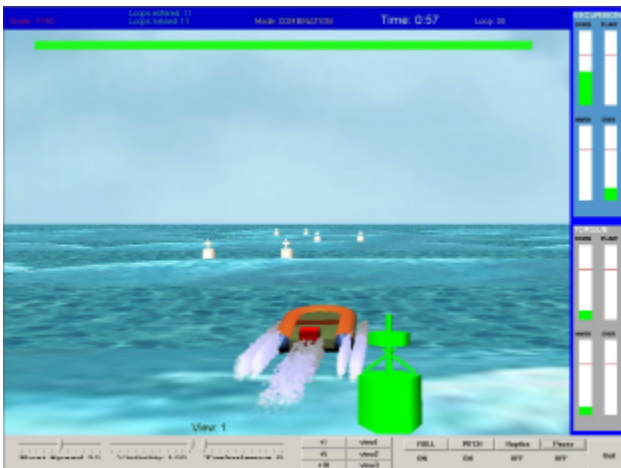


Figure 5. Boat exercise. © Rutgers University 2002

To make the exercises more challenging and ecologically valid, two types of task-level haptic effects are implemented: “jolts” and “turbulence.” The jolts are applied when the

airplane (or the boat) hits the hoop frame (or buoy). The turbulence simulates the effects of stormy weather and its intensity can be set from zero (clear day) to a maximum value (within safety and conform limits). The haptic effects modify only the position of the platforms, acting as a disturbance, leaving the orientation to be controlled by the patient.

4.2 Jolts

The jolts were implemented as sudden jerks of the platform in the opposite direction of the collision location, followed by a return of the platform to a neutral position.

Tests showed that moving the platform on the vertical axis was uncomfortable due to the straps holding the upper leg in place. Therefore the jolts are constrained to the horizontal plane of the platform.

Lateral motion of the jolts also had to be removed to avoid straining the knee joint along that axis. Although the implementation of the air turbulence (described below) involved lateral swaying of the platform, the movements were smooth, whereas a sudden lateral jolt was likely to cause discomfort.

The optimal platform displacement for a jolt to be noticeable and comfortable was empirically found to be 2 cm.

4.3 Turbulence

Turbulence was implemented as low-frequency side-to-side vibrations of the platform. To implement different levels of turbulence, a choice had to be made between keeping the frequency constant and increasing the amplitude, or keeping the vibration amplitude constant and increasing the frequency.

Changing the amplitude of the vibration was not a safe option due to the overshoot that appeared at high stiffness levels. As mentioned previously, lateral motions of the knee had to be avoided. Tests were used to identify the safe

maximum amplitude to be 3 cm. Increasing the frequency of the vibrations was used to simulate larger turbulence levels. The maximum level of turbulence was mapped to a vibration frequency of 1.5 Hz.

5. Preliminary Outcomes of Clinical Testing

Three patients participated in a four-week VR based training protocol in which the new system was tested in Summer 2002. The patients' lower extremity Fugl-Meyer (FM) Scores [5] ranged from 27 to 34 (out of total of 46 points). Two of the subjects had normal sensation and the third had a decrease with 8/12 on the FM lower extremity sensory score.

Task-level haptic effects were introduced during the airplane simulation in the second week and during the boat simulation in the fourth week of therapy.

Jolts were introduced first. As the torque level at which the patient worked was increased so was the effect of the jolt. Observed exercise accuracy (the percentage of targets entered) was used as a gauge to increase the frequency with which jolts were introduced.

Turbulence was added at first to simulations in which the subject had to control the airplane, or the boat, in only one plane (vertical or horizontal). After subjects appeared comfortable with the turbulence effects, both vertical and horizontal planes were activated in the exercises. Haptic effects were used with all three subjects in different ways based on their rehabilitation needs.

It was anticipated that during a four-week period using the exercises that involved repetition and overload, there would be strength gains for selected muscles. These gains were measured clinically using a hand held dynamometer [2]. Dynamometer measurements were taken prior to, and after, the four-week therapy. Three peak measurements were collected for each motion of the ankle pitch and yaw (dorsiflexion, plantarflexion, inversion and

eversion) using standard manual muscles test positions [8]. The average of the three measures is reported here. Subject 1 increased strength in all four muscle groups, subject 2 in two muscle groups and subject 3 in three muscle groups. The results of the strength gains for the lower extremity muscles tested are summarized in Table 3, where strength is reported in N.

Table 3. Strength Changes After Training for the Affected Ankle (in N) Rares please take the lower values

Subject	Dorsiflexion		Plantarflexion	
	Pre	Post	Pre	Post
1	12	18	18	31
2	21	26	21	18
3	26.5	27	42	32

Subject	Inversion		Eversion	
	Pre	Post	Pre	Post
1	8	16	3	9
2	17	12	13	15
3	15	27	14	26

Prior to the trials, the investigators were unsure if the introduction of haptic effects would interfere, or assist, with performance on the Rutgers Ankle. In order to answer that question, accuracy scores for similar exercises in which haptic effects were either present or not were compared for subject 1 using the airplane simulation. There were no detrimental effects when turbulence was introduced in the horizontal movement. In the third session accuracy during the performance of a three-minute exercise with the hoops placed horizontally, with the torque set at 75%, the displacement at 75% of his baseline range and the speed at 40, was 89% cleared targets (11% of targets hit inside). On the fifth session with the same displacement and speed parameters (resistive torque was increased to 85%) and turbulence set at 25%, accuracy on the simulations was 95% cleared (5% of targets hit inside). By the seventh session accuracy for the same simulation improved to 100% (all hoops

entered without any contact with the airplane wings). While one cannot attribute the improvements to the addition of turbulence alone, one can interpret these results as indicating that turbulence did not interfere with the ability to perform the exercise accurately.

Functional carry over was measured using gait speed, gait endurance and stair climbing speed. Preliminary review of increases in gait speed after training are positive. Further patient pilot clinical trials are scheduled in the near future.

6. Conclusions and Future Work

The work presented in this paper is the second version of our VR-based ankle rehabilitation system. Task-level haptic effects have been added to the system to enhance the patient's experience and alleviate boredom. The interaction between the platform stiffness and the vibrations imposed safety limitations on the system. Work will be done to improve the correlation between these to parameters.

The preliminary results show that the haptic effects did not interfere with patients' ability to use the platform. Patients improved their strength capabilities for some of their ankle muscles. This can be attributed to the low-level effects, which generated continuous resistive forces the patients had to overcome. The contribution of the task level effects in terms of sensory feedback and priming for the muscle contraction cannot be determined from this study. In the future patient's subjective responses to the addition of task level effects will have to be correlated with their performance on the platform.

Acknowledgements

Research reported here was supported by grants from the National Science Foundation (BES-0201687), and from the New Jersey Commission on Science and Technology (R&D Excellence Grant).

References

- [1] Biodex Medical Systems, Biodex Balance System, <http://www.biodex.com/dir24/945300.htm>, 1999.
- [2] Chatillon, AMETEK, <http://www.chatillon-scales.com/index.html>, 2003
- [3] Deutsch, JE., J. Latonio, G. Burdea and R. Boian, "Post-Stroke Rehabilitation with the Rutgers Ankle System - A case study," Presence, MIT Press, Vol. 10(4), pp. 416-430, August 2001.
- [4] Judith E. Deutsch, Jason Latonio, Grigore Burdea, and Rares Boian, "Rehabilitation of Musculoskeletal Injuries Using the Rutgers Ankle Haptic Interface: Three Case Reports," Eurohaptics Conference, Birmingham UK, pp. 11-16, July 1-4, 2001
- [5] Fugl-Meyer AR Post-stroke hemiplegia assessment of physical properties. Scan J Rehabil Med 1980;7:85-93
- [6] Girone M., Burdea, G., M. Bouzit, V.G. Popescu, and J. Deutsch, "A Stewart Platform-based System for Ankle Telerehabilitation," invited article, Special Issue on Personal Robotics, Autonomous Robots, Vol. 10, pp. 203-212, Kluwer, March 2001
- [7] M. Girone, G. Burdea, M. Bouzit, V.G. Popescu and J. Deutsch, "Orthopedic Rehabilitation using the 'Rutgers Ankle' Interface," Proceedings of Virtual Reality Meets Medicine 2000, IOS Press, pp. 89-95, January 2000.
- [8] H Hislop, J Montgomery., Daniels and Worthingham's Muscle Testing: Techniques of Manual Examination 6th Ed.. WB Saunders, Philadelphia. 1995.
- [9] J.M. Hollerbach, Y. Xu, R. Christensen, and S.C. Jacobsen. Design specifications for the secondgeneration Sarcos Treadport locomotion interface. In Haptics Symposium, Proc. ASME Dynamic Systems and Control Division, volume 69, pages 1293-1298, November 2000.
- [10] H. Iwata. Walking about virtual environments on infinite floor In Proceedings of IEEE Virtual Reality T. Miyasato. Tele-nursing system with realistic sensations using virtual locomotion interface. In Proceedings of the 6th ERCIM Workshop "User Interfaces for All", Florence, Italy, October 2000.
- [11] H. Iwata, H. Yano, and F. Nakaizumi, Gait master: A versatile locomotion interface for uneven virtual terrain, in Proceedings of the IEEE VR2001 Conference, 2001.
- [12] J. Lewis, R.F. Boian, G.C. Burdea, J.E. Deutsch, "Real-time Web-based Telerehabilitation Monitoring ", Proceeding of Medicine Meets Virtual Reality 11, Newport Beach, CA, January 2003 (to be published).
- [13] Kinetic Health Corporation, Wobble and Rocker Boards, <http://www.kinetichealth.com/edu11.html>, 1999.
- [14] T. Miyasato, Tele-nursing system with realistic sensations using virtual locomotion interface, in Proceedings of the 6th ERCIM Workshop "User Interfaces for All", Florence, Italy, October 2000.
- [15] Perform Better, Biofoam Rollers, <http://www.performbetter.com/page11.html>, 1999.
- [16] Jungwon Yoon, Rares Boian, Jeha Ryu and Grigore Burdea, Control of the Rutgers Dual-Ankle Rehabilitation Interface, submitted to IEEE/ASME Transactions on Mechatronics, Special Section on Advances in Robot Dynamics and Control (ARDC)