Rehabilitation of Musculoskeletal Injuries Using the Rutgers Ankle Haptic Interface: Three Case Reports

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Abstract

The efficacy of virtual reality-based rehabilitation for orthopedic patients needs to be determined. This paper presents three case studies in which the use of the Rutgers Ankle haptic interface for ankle rehabilitation is evaluated. The Rutgers Ankle is a computer-controlled compact robotic platform that measures foot position and orientation and provides resistive forces and torques, It has been integrated with a PC running an airplane piloting VR exercise and a custom electronic control box. The system underwent pilot clinical trials in an outpatient clinic in the State of New Jersey (USA). The goals of the pilot tests were to determine how well the current design of the interface worked in a clinical setting and to provide preliminary evidence of efficacy (whether patients benefited from incorporating the RA into their rehabilitation program). Results on three patients participating in the study showed improvements in range of motion, torque generation capacity and ankle mechanical work over six rehabilitation sessions. Objective measures obtained by the Rutgers Ankle show improvement in task accuracy to 100% for Case 1, a five-fold increase in ankle power output for Case 2, and a three-fold increase for Case 3. Both Case 2 and Case 3 reached 100% task accuracy by the end of the two-week rehabilitation training. Results from these case studies are being used in software enhancements and construction of a dual-platform system.

1. Introduction

Physical rehabilitation may benefit from the recent advances in virtual reality (VR)-based simulations. VR exercises can be used to motivate patients by providing an engaging, multi-modal, interactive rehabilitation environment [2,3]. In order to allow physical rehabilitation, such as the one needed by orthopedic and stroke patients, physical interaction with rehabilitation devices are involved. If the rehabilitation is done in virtual environments, new types of haptic input/output interfaces need to be created. One example is the Computer Assisted Rehabilitation Environment (CAREN) developed in Holland [1]. It uses a computer-controlled six-degree-of-freedom large platform to destabilize the patient standing still on it. Vision tracking is used to measure the patient's response for evaluation purposes.

Another example of a platform-based computer interface used in rehabilitation is the Rutgers Ankle (RA)[5]. The RA is designed for patients that need ankle and knee rehabilitation. It has been applied in the rehabilitation of patients with orthopedic (ankle sprain) [6] and stroke diagnoses [4].

This paper describes first the RA hardware and software system. Subsequently the outcomes of its introduction into a working clinic are presented. We describe three case studies of patients with musculoskeletal ankle injuries of different etiologies. Interpretation of the results and directions for future research conclude this paper.

2. Virtual Reality system

The Rutgers Ankle system consists of a Stewart Platform-based interface, its electro-pneumatic control box, a PC host computer and a mini-compressor, as shown in Figure 1[6].

The platform has dual-acting low-friction piston actuators, installed in parallel with linear potentiometers used as position sensors. A 3-D force sensor placed under a foot attachment measures the real-time forces and torques applied by the mobile platform. The work envelope of the mobile platform accommodates the normal ankle motion for a sitting patient. Its force output depends on the pressure in the pistons, up to a maximum 100 psi.

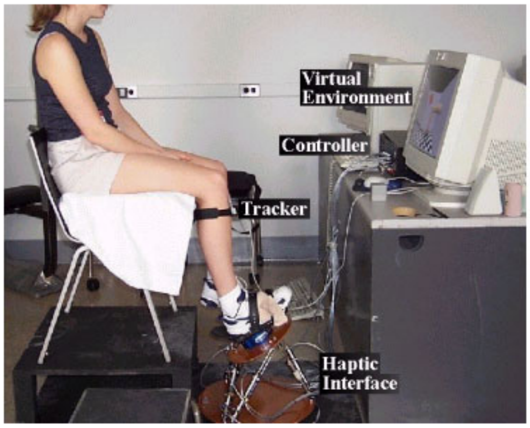

Figure 1. The Rutgers Ankle System [6]. © Rutgers University. Reprinted by permission.

The control interface uses peizo-electric valves that regulate the pressure in the actuator chambers at a bandwidth of 500 Hz. Low-level servo control is performed by an embedded Pentium board (266 MHz), based on pressure sensor information from the valve outputs. The servo control is a user-selectable position or force control loop, which runs much faster than would be possible on the PC host computer. Communication with the PC host is done over an RS232 serial line. The host PC is a single-processor Pentium 300 MHz computer running Windows NT. It displays the VR graphics, user graphical user interface (GUI), and stores data in an Oracle database

3. Exercise software

The exercise software was developed using the WorldToolKit software library for real-time graphics and the Oracle database for transparent patient data collection and analysis. The virtual reality exercise consists of a 3-D piloting of an airplane through multiple hoops, as shown in Figure 2 [4].

The movements allowed by the platform, pitch, roll and yaw, resemble the motions of the talo-crural and subtalar joints, plantar and dorsiflexion, inversion and eversion and pronation and supination [7]. The number and placement of the hoops, as well as airplane speed, viewpoint to the simulation and platform maximum force levels can be modified by the therapist. This gives the therapist the ability to adjust the level of difficulty for each exercise, on a patient-specific basis. Adjustments are based on baseline performance on the RA and exercise performance during a training session. While the patient is exercising, force and displacement data are displayed in real time on the screen and compared with baseline information. The data are transparently and simultaneously stored in a database, which then calculates total exercise mechanical effort, peak and average forces/torques, number of hoops correctly passed, and other variables. Thus the healing process can be quantified based on objective measures, either at the physical level (range, torque, mechanical effort), or functional level (hoops entered/missed, number of hoops, exercise time/level of difficulty).

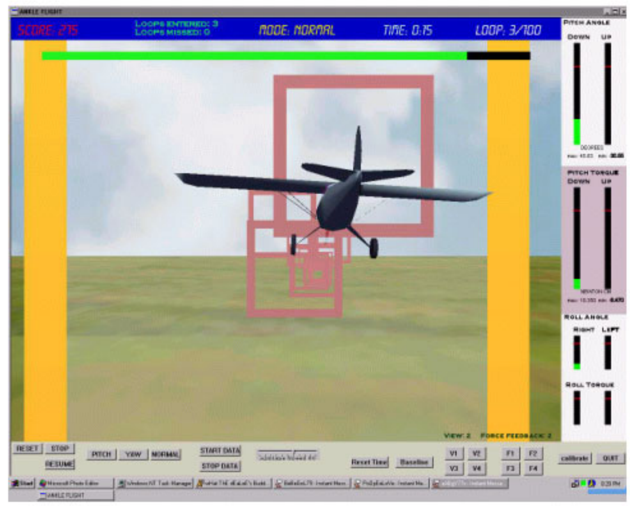

Figure 2. Ankle rehabilitation exercise in VR [4] © Rutgers University. Reprinted by permission

4. Clinical tests

In Summer 2000 the Rutgers Ankle system was installed in an outpatient rehabilitation clinic in the State of New Jersey, for a two-week trial period. The goals of the pilot tests were to determine how well the current design of the interface worked in a clinical setting and to provide preliminary evidence of efficacy (whether patients benefited from incorporating the RA into their rehabilitation program).

4.1. Subjects

Patients who participated in the two-week trials used the Rutgers Ankle to complement their regular rehabilitation program. This paper reports on three of the patients who ranged in age from 14-56 and who had varying musculoskeletal ankle injuries, time since injury and familiarity with computer games. One of the subjects participating in the study is shown in Figure 3.

Figure 3. Subject participating in the Rutgers Ankle pilot study. © Rutgers University. Reprinted by permission.

4.2. Method

On the first day of the trial the subjects received a clinical exam, participated in baseline testing on the RA, were instructed and practiced on the RA and completed a subjective questionnaire. The clinical exam included ankle strength, range of motion (ROM), balance and functional ability measures.

Baseline testing on the Rutgers Ankle was done to measure displacement and torque for all ankle motions. Subjective evaluations consisted of questions in which participants were asked to rate their experience learning and using the interface. The participants exercised on the virtual reality system for five sessions, which lasted approximately 30 minutes each and were scheduled every other weekday. The progression of training was customized for each patient and was based on their performance with adjustments made for intensity, duration and complexity of ankle movements. Baseline performance was obtained for each session in order to update the settings of the Rutgers Ankle.

Training was supervised by a physical therapist and was a complement to the rehabilitation program for two of the three patients. To ensure consistency between sessions, subjects were positioned in the same way, their knee flexion held within five degrees of flexion, which was measured with a goniometer. The platform was held in the zero position prior to beginning the exercise. On the sixth session patients underwent a clinical exam, re-testing on the Rutgers Ankle and once again completed a subjective questionnaire. The three subjects completed the six exercise sessions.

4.3. CASE 1

The patient was a 14-year old male who was diagnosed with a Grade I inversion sprain that occurred during wrestling. He had injured his ankle two-weeks prior to beginning the trials. His goal was to return to wrestling. He had extensive exposure to computer games, which he used for recreation. The subject quickly mastered the basic virtual reality simulation, which allowed the investigators to test the upper limits of the system. Training sessions ranged between 12 and 20 minutes. Simulations were executed on average for two minutes. His longest continuous session was performed for the combination movement at a speed of 0.72 hoops/sec and difficulty setting of "medium" for ten minutes. He quickly progressed to training at the "difficult" setting and the highest level of resistance. During the final session he was able to increase from his average speed of 0.72 to 1.2 hoops/second. The subject reported enjoying the simulation, but we anticipated that he would lose interest once he mastered it. He did not appear concerned about making errors and learned to anticipate the presentation of the targets. Accuracy for the simulation improved from the first to the final session from, 36-42% for pitch, 37% for roll and 38% for the combination movements to 100% for all movements at a comparable speed, level of difficulty and resistance. Figure 4 shows the increase in task accuracy (% of hoops entered) over all simulations modalities.

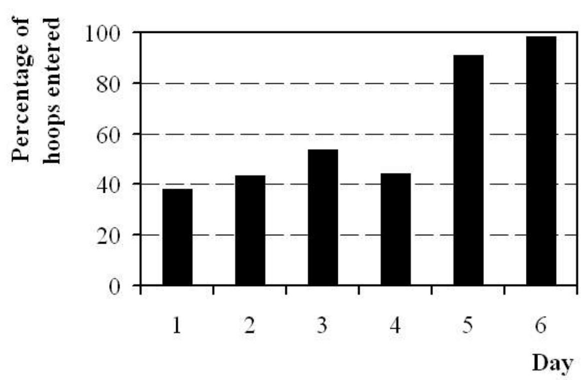

Figure 4. Subject 1 task accuracy (% loops entered) averaged over all modalities (ankle pitch, roll and combination) over the duration of therapy.

Clinically this patient presented with minor deficits in strength and balance and had some complaints of pain while walking down the stairs. After training he improved on the time he could maintain his balance on his right leg with his eyes closed from 12 to 24 seconds. He also decreased the amount of time it took him to ascend and descend 12 steps from 23 to 18 seconds. After training he did not have any pain while climbing the stairs. At the completion of the trail he was discharged from physical therapy and returned to wrestling.

4.4. CASE 2

The patient was a 15-year old female who was diagnosed with a Grade II inversion sprain that occurred while playing softball. She incurred the sprain five months before the beginning of the trial. She used the computer for school but did not play any video games. The subject progressed from the second level of resistance to the third level. She also progressed from the "easy" level to the "medium" level, with only a couple of attempts at the most difficult level. Training sessions varied between nine minutes to as much as 24 minutes. A typical exercise span was two minutes long with her longest continuous bout at eight minutes. Figure 5 shows her affected ankle plantarflexion angles at the start and end of therapy.

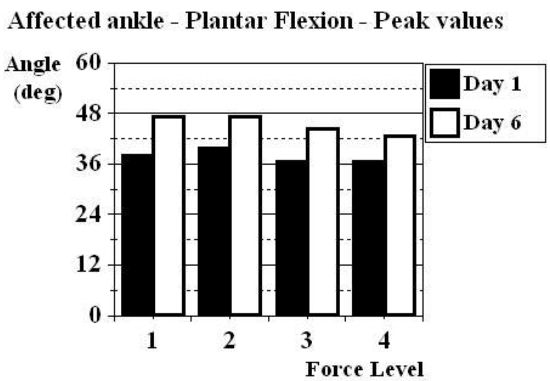

Figure 5. Peak values for plantar flexion angle of Subject 2 affected ankle, over the duration of the rehabilitation intervention. Force levels 1,2,3,4, indicate increasing platform resistance settings.

The training aggravated her symptoms and her ability to work on the system was influenced by her pain complaints. Therefore the power output fluctuated from a low of 390 watts to a high of 2020 watts. Often after the VR simulation ice packs were applied to the ankle. She reported enjoying the simulation initially, but after many repetitions she revealed that she found it somewhat boring. At the end of training her clinical exam revealed improvements in strength and balance. Strength increased by 1 manual muscle test grade from a 4 to a 5 for ankle dorsiflexion, inversion and eversion. She was able to stand on her involved leg for 60 seconds compared to 45 before training and was able to stand on her involved leg with her eyes closed for 28 seconds compared to 7 seconds before training. Recordings from the Rutgers Ankle showed that she improved in her ankle dorsiflexion plantarflexion (see Figure 5), dorsiflexor and everter peak ROM, as well as her dorsiflexor and everter and plantarflexor torques (see Figure 6). Her accuracy with the VR simulation from the second day to the final day of training improved from 56% for pitch, from 67% for roll and from 65% for the combination movement to 100% for all the movements. Currently she is playing softball.

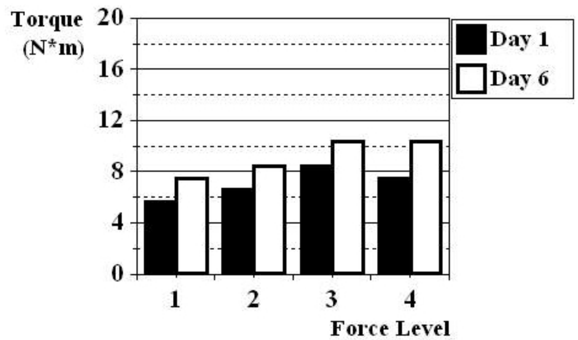

Figure 6. Peak values for dorsiflexion torque for the affected ankle of Subject 2, over the duration of the rehabilitation intervention. Force levels 1,2,3,4, indicate increasing platform resistance settings.

4.5. CASE 3

The third patient was a 56-year old female who had a bi-malleolar fracture. The fracture had been reduced with an external fixator two months earlier. Her goal was to resume recreational hiking. She used the computer in her job as a school administrator but had no experience with VR games. This patient required that some of her motions be held constant. For example, when she worked on the pitch motion, the therapist had to control the ankle yaw to avoid having the foot deviate out of position.

Early in the training the therapist had to manually guide the platform and provide verbal cues to assist the patient with the simulation. She performed at the very low speeds of 0.04 and 0.07 hoops per second on the first day on the easy ROM setting. After the simulation was modified to better represent the inversion/eversion movements she immediately increased her speed to 0.18 hoops/second. By the end of the training she was able to exercise at 0.6 hoops /second for all motions at the medium ROM setting. Her training sessions were between 15 and 22 minutes with her longest bout for a single exercise was six minutes. She reported enjoying the simulation and felt it was a good addition to her program.

Clinically she demonstrated improvements in ROM (5 degree increase in plantarflexion), balance (increased single limb support from 3 to 8 seconds), strength (1/2 grade increases for inversion and eversion) and speed (50% decrease) at which she climbed the stairs. Results from the Rutgers Ankle showed that she made gains in ROM of the ankle everters and plantarflexors, which corresponded with clinical measurements. Her ROM increased for plantarflexion (50%) and eversion (55%). The amount of torque she could generate increased for ankle everters (60%), and dorsiflexion (25%). At the end of training her power output (calculated from the variables collected by the RA) increased from 175 watts to 475 watts for the affected ankle and surpassed that of the unaffected ankle. This is illustrated in Figure 7. Accuracy of the movements increased from 22% for pitch, 28% for roll and 26% for the combined movements on the first day to 100% for all movements on the sixth day. During the training period she returned to hiking.

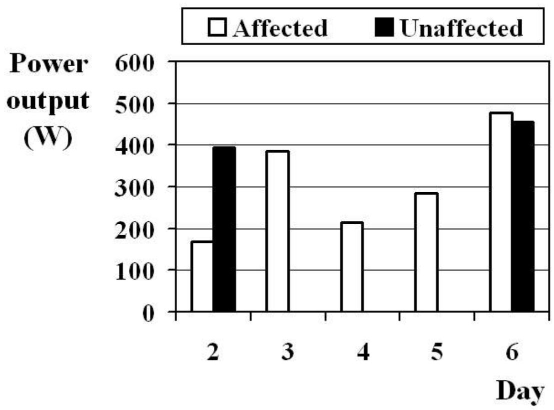

Figure 7. Peak values for ankle mechanical power for the Subject 3, over the duration of the rehabilitation intervention.

5. Interpretation /Discussion

The RA was successfully introduced into a clinical setting. Patients with varying diagnoses and ages were able to learn the simulations and train on the device. The greatest improvements were found for the patient with bi-malleolar fracture who presented with hypomobility and strength deficits. The patients with the sprains were functioning at a higher level and would have benefited from having their rehabilitation done in standing position. Clinical improvements were noted for strength and range of motion as well as for balance ability. Clinical exams and VR-related measures showed that all subjects had some degree of improvement and reported that they were able to use the device and enjoyed it as a complement to their regular rehabilitation program. Only one subject (case 2) was not receiving concurrent physical therapy, so it is difficult to conclusively attribute the clinical and functional gains to the VR training alone.

All three subjects were able to complete their exercises sessions without any prolonged adverse effects. Although the RA was installed in an open area with treatment tables on one side and an exercise area on the other, the three subjects were able to concentrate on the VR simulation. They were immersed in the virtual environment, and were not distracted by other patients exercising in the vicinity. The mapping of the foot motions to the RA was modified based on subjects input and observed difficulties with selected motions. Specifically, the degree of yaw, and roll movement that accurately corresponded with the inversion and eversion motions had to be adjusted. Difficulties with using the system were encountered with maintaining the pressure in the pistons during longer exercise spans. The compressor often became overheated, which resulted in a drastic reduction in its output pressure, requiring that exercise bouts be interrupted. In addition, the seating system was cumbersome when making adjustments for patient positioning, taxing the therapist. Finally, the calibration of the "zero" starting position will need to be refined.

6. Conclusion and Future Work

The case studies described here constitute the first clinical data indicating preliminary evidence of efficacy of the Rutgers Ankle system as a rehabilitation device for orthopedic patients. As a result of these trials several improvements are planned to the RA controller, in order to increase reliability, reduce vibrations and increase force output capabilities. It became clear that pneumatic control needs accurate temperature compensation of the pressure sensors, otherwise unwanted vibrations result. The compressor needs to have sufficiently large storage in order to avoid frequent starts under load, which in turn result in overheating and the subsequent inability to maintain high pressures.

Furthermore, a dual-platform system that would allow the patient to exercise while standing is being designed. This will allow the addition of virtual exercises in standing, followed by more clinical trials. In addition, more simulations are being developed with the goal of providing greater variety as well as increasing the ecological validity of the exercises. By providing several kinds of VR simulations the patient boredom may be alleviated. Studies in which the RA replaces selected aspects of rehabilitation such as strength, balance and proprioceptive training will assist with further evaluating the efficacy of the RA.

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