Orthopedic Rehabilitation Using the "Rutgers Ankle" Interface

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Abstract

A novel ankle rehabilitation device is being developed for home use, allowing remote monitoring by therapists. The system will allow patients to perform a variety of exercises while interacting with a virtual environment (VE). These game-like VEs created with WorldToolKit run on a host PC that controls the movement and output forces of the device via an RS232 connection. Patients will develop strength, flexibility, coordination, and balance as they interact with the VEs. The device will also perform diagnostic functions, measuring the ankle's range of motion, force exertion capabilities and coordination. The host PC transparently records patient progress for remote evaluation by therapists via our existing telerehabilitation system. The "Rutgers Ankle" Orthopedic Rehabilitation Interface uses double-acting pneumatic cylinders, linear potentiometers, and a 6 degree-of-freedom (DOF) force sensor. The controller contains a Pentium single-board computer and pneumatic control valves. Based on the Stewart platform, the device can move and supply forces and torques in 6 DOFs. A proof-of-concept trial conducted at the University of Medicine and Dentistry of New Jersey (UMDNJ) provided therapist and patient feedback. The system measured the range of motion and maximum force output of a group of four patients (male and female). Future medical trials are required to establish clinical efficacy in rehabilitation.

1. Introduction

Rehabilitation regimens aim to promote healing and prevent repeat injuries. Researchers have found that detrimental biochemical and biomechanical changes may result from the absence of post-injury physical activity [6]. Patients must often enhance their flexibility and strength beyond prior-injury levels in order to prevent repeat injuries [16].

Insufficient strength, flexibility, and proprioception are the main causes of ankle injury. Devices designed to reduce these deficits and promote functional rehabilitation are elastic bands [5], foam rollers [13], wobble boards [11], the Biodex Balance System [2], and the Multi-Joint System 3 [3]. Elastic bands are simple devices, each made of a figure-eight-shaped strip of elastic. Patients place both feet through the holes of the resistive elastic strip. Foam rollers act as unstable surfaces and are used to improve balance and proprioception. Wobble boards are circular discs with a hemispherical pivot in the center of one of the sides.

Patients stand on the board and make the board tilt. The Balance System is an advanced wobble-board-like device. The stability of the platform can be changed via an electronic interface. The Multi Joint System3 is a comprehensive rehabilitation system for many of the body's joints. It allows patient evaluation (muscle groups' output forces) and is also an exercise machine.

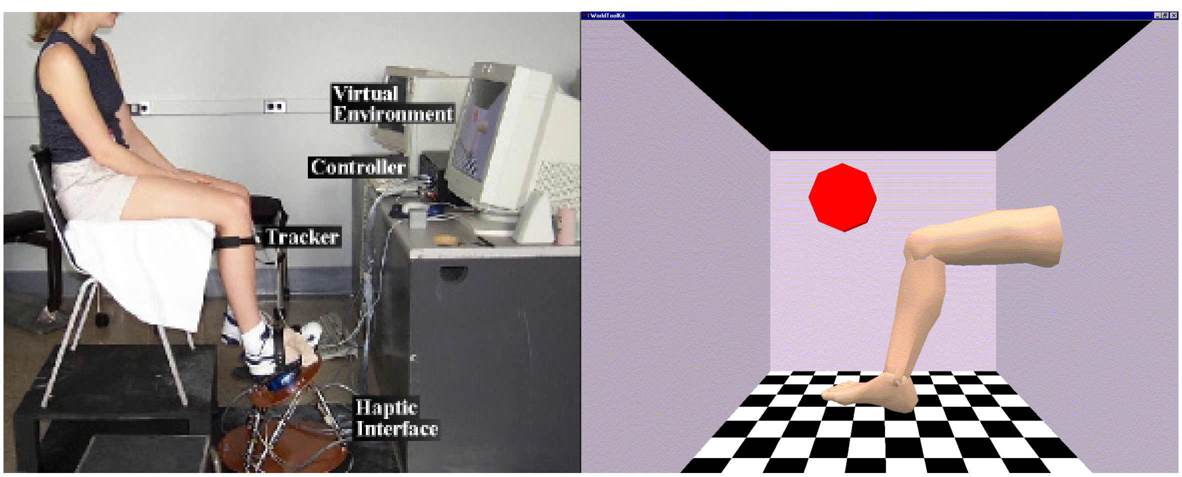
Such rehabilitation devices are typically used in regimens that include exercises both in the clinic and at home. Exercising in the clinic is problematic for patients in remote rural and depressed urban areas. Home exercising typically involves simple mechanical devices loaned to patients from clinics. These devices lack quantitative diagnostic and networking capabilities that would allow therapists to remotely monitor patient's progress. These devices are rarely interactive, making exercising repetitive and boring.

This paper describes the "Rutgers Ankle" rehabilitation system designed to address these issues. It is being developed to add new capabilities to the ongoing *Telerehabilitation with Virtual Force Feedback* project [15] at Rutgers University. The interface is based on the Stewart platform [17], and can move and supply forces and torques in all directions. Nearly any ankle rehabilitation routine can be realized through virtual reality (VR) techniques. The device's data collection and remote access capabilities will allow therapists to monitor patients' at-home rehabilitation from the clinic which is not possible with current technology. In addition, VR exercise simulations will provide an enjoyable, game-like environment for exercising. Section 2 is an overview of the system hardware, VR library, and clinical database structure. Proof-of-concept trial results are detailed in Section 3. Section 4 concludes this paper.

2. System Hardware and Software

The "Rutgers Ankle" prototype is shown in Figure 1a [9]. The system hardware consists of the haptic interface, its controller, the host computer, and a small air compressor. The system software consists of low-level control software, a rehabilitation simulation library, a software driver, and a patient database.

The haptic interface, or platform, supplies forces to the patient's foot during exercising. The Stewart-platform design allows the application of forces and torques in all directions and movement throughout the ankle's full ROM. The mobile and fixed platforms



a) b)

Figure 1. a) the "Rutgers Ankle" prototype (adapted from [9] © Kluwer);
b) the VR exercise.

are made of lightweight carbon fiber and are actuated by six double-acting, low-friction, pneumatic cylinders [1]. The position sensors are linear potentiometers [4] attached in parallel to each cylinder. A six-DOF force sensor [10], mounted between the foot attachment and the mobile platform, measures forces and torques at the patient's foot. The position and orientation of the shin can be measured using an InsideTrack 3D tracker [14] in order to calculate the ankle's orientation.

The platform controller regulates the air pressures in the cylinders and communicates with the host PC via an RS232 line. It has an embedded Pentium computer which runs Windows 95 and performs low-level actuator control in software. The low-level control software reads the system's sensors and controls the platform by opening and closing the actuator intake and exhaust valves. It also receives desired force or position data from the host PC, returns measured position and force data to the host PC, and performs kinematics calculations.

The VR rehabilitation library is a collection of virtual environments (VEs), each with its own rehabilitative focus. The variety of VEs and rehabilitation exercises will help to maintain patients' interest, providing many types of rehabilitation through a single system. These game-like VEs are written using the WorldToolKit ® (WTK) [7] C function library and run on the host PC. Each simulation maps rehabilitative exercises to virtual interactions. Foot position, orientation, and output forces become inputs and outputs to/from the VE. As patients move, they animate a virtual leg, for example (see Figure 1b). The resistive force increases as a virtual leg pushes against a spring. The VEs motivate patients by setting virtual goals. These goals can only be achieved by correctly performing the prescribed rehabilitative motions. The desire to achieve the virtual goals therefore becomes a motivator for patients to perform their exercises correctly and with proper frequency. A patient requiring dorsiflexion exercises, for example, would be required to employ the appropriate muscles (anterior tibialis, extensor hallicus longus, extensor digitorum longus) in order to steer a virtual helicopter around obstacles. While patients exercise, the host PC records exercise frequency, position, orientation, and force information.

The virtual environment simulations will be designed to focus on rehabilitation, in order to minimize impairments and improve function. Minimizing impairments includes reducing deficits in strength, flexibility, coordination, and balance. Strength exercises involve the application of resistive forces that simulate a weight opposing ankle motion. Flexibility can be improved through low-force, repetitive movements near the ankle's limits of motion. Balance and coordination deficits can be reduced through proprioception exercises, improving the body's sense of ankle orientation. A lack of sufficient ankle proprioception is often made evident by functional instability, the frequent sprains and/or feeling of weakness in the ankle. It may be possible to increase proprioception by enhancing postural control and pronator muscle strength [18]. Stimulation of joint mechanoreceptors and the muscle spindle may improve position sensing's accuracy and response time [19].

An Oracle [12] patient database stores exercise data transparently. These data consist of the three ankle joint angles and the six forces and torques at the patient's foot with respect to time. A patient database form provides easy access to patient data, allowing the entering, querying, updating, and browsing of patient information. Therapists can view reports that show graphs of the angles, forces, and torques with respect to time along with the standard deviation and average for each data set. The database reports allow therapists to assess the patient's capabilities. By observing the extreme values of the angle and torque graphs, therapists are able to appraise patient's ROM and maximum torque output around each axis. By comparing the angle graphs and prescribed ankle motions, therapists can also evaluate patients' coordination. Deficits and progress in ROM, maximum torque, and coordination can be measured by comparing data from a patient's injured ankle with that of his or her uninjured ankle. To facilitate patient progress assessment, future reports will compare patients' data sets over time. For example, extreme ROM and maximum force output values for each exercise will be plotted with respect to time. As patients' improve, the therapist will be able to modify exercise parameters including required duration, maximum-opposing forces, allowed ROM, and VE complexity.

3. Proof-of-Concept Trial

A proof-of-concept patient trial study was conducted at the University of Medicine and Dentistry of New Jersey (UMDNJ). The device's feasibility was tested for use by patients with lower extremity pathology affecting ankle mobility and function. The three females and one male participating in the study were heterogeneous in age (26-81 years), computer experience (0-13 years), and clinical presentation. Two patients (Patients 1 and 2) exhibited hypermobility secondary to chronic ankle instability and the other two presented with hypomobility as the sequelae of fractures.

3.1 Clinical Exam

A physical therapist examined impairments of ROM, strength, and balance as well as sensation, pain, and skin condition. Patients presented varying degrees of ROM loss, weakness, and standing balance deficits as well as edema. Their functional status was determined by interview. Two of the patients were independent community ambulators, who could walk distances longer than 153 m and could negotiate curbs, ramps and stairs. These patients had limitations with recreational and sports activities. The other patients required assistive devices for gait and had limitations with distances. One was a household ambulator with mobility limited to level surfaces and a distance of less than 30 m. Table 1 summarizes the results of the clinical exam.

3.2 Procedure

Patients signed an informed consent and were given an explanation of the study's purpose. They were assisted to the chair placed in front of the host PC, and their foot was positioned in the "Rutgers Ankle" foot restraint. Patients were instructed to move their ankle into either dorsiflexion and plantarflexion, or inversion and eversion. While moving, they observed a virtual leg and foot on a monitor. The movement ratio between the real and virtual leg was adjusted to provide clear visual feedback. Patients had an opportunity to practice a few repetitions prior to data collection. Data were collected in 30-60 second intervals while subjects performed movements at either their self-selected or fastest speeds. Patients performed ten trials, each alternating between dorsiflexion/plantarflexion and inversion/eversion motions. There were one to two minutes of rest between each trial. Over the course of the ten trials, the device's opposing force and upward support were decreased incrementally. High opposing forces and upward support challenged patients' strength while low values targeted their endurance and coordination. At the end of each trial, subjects were asked to report any symptoms such as pain or fatigue. Following the study, subjects were asked to complete a questionnaire about their ease in learning to use the interface and its perceived utility.

Table 1. Clinical exam results (adapted from [9] © Kluwer)

Patient	Side	Skin	ROM	Strength	Balance	Kin.	Pain	Gait
1	Left	Warm Min Edema	WNL	4 to 4+	WNL EO impaired EC	WNL	Upon palpation	CA
1	Right	WNL	WNL	5	WNL EO impaired EC	WNL	None	
2	Left	Min Edema	Min decreased to WNL	4 to 5	WNL EO impaired EC	WNL	None	CA
3	Right	Mod Edema Warm	min to moderately decreased	3+ to 4-	Impaired EO and EC	WNL	Upon palpation	HA with cane
3	Left	Min Edema	Min decreased to WNL	4- to 5	Impaired EO and EC	WNL	Upon palpation	
4	Left	Warm Mod Edema	Min to moderately decreased	NT	NT	WNL	None	Limited CA with crutches

- Kin: Kinesthesia, WNL: within normal limits, Min: minimal, Mod: moderate, NT: not tested
- Strength is measured on a scale of five, highest strength is 5/5
- Balance is tested with EO (eyes open) and EC (eyes closed)
- Pain is tested using a 0- 10 scale (O= no pain; 10 is the worst pain)
- Gait: CA (community ambulator) HA (household ambulator)

3.3 Patient Reaction

All the patients learned to use the "Rutgers Ankle" interface rapidly. There were some reports of fatigue for those patients working at their fast velocity. There were no reports of pain. All subjects responded favorably to the use of the device and stated that they would enjoy having this device complement their current rehabilitation programs. Table 2 summarizes the patients' answers to the subjective evaluation questionnaire. The most notable limitation was the delay between ankle movement and the corresponding visual feedback. This was particularly troublesome for the patients who were asked to exercise at their highest speeds. The lack of support for holding the limb in place while the interface was set at the lower levels of upward support was also reported as a concern.

Patients' displacement and torque data were collected and analyzed. This allowed the tester to evaluate the patients' deficits. The performance of the involved and uninvolved ankle was compared. Figure 2 illustrates the greater displacement and torque generated by the uninvolved leg compared to that of the involved leg. The displacement of the uninvolved leg is comparable to normal ROM at the ankle with five degrees of dorsiflexion (the negative deflection on the plot) to 45 degrees of plantarflexion. The angle of the involved limb reflects a loss of ROM of –10 degrees of dorsiflexion and 28 degrees of plantarflexion. The maximum torque generated by the uninvolved limb is much larger (4 ft•lbs. for dorsiflexion and 8 ft•lbs. for plantarflexion) than that generated by the involved limb (0.5 ft•lb. for dorsiflexion and 4 ft•lbs. for plantarflexion).

4. Conclusions and Future Work

The "Rutgers Ankle" is a novel rehabilitation device being developed for at-home use. This computer-controlled haptic interface allows exercising of the ankle's three DOFs while patients interact with a virtual environment. A proof-of-concept patient trial found that the device can be used for ankle rehabilitation in patients with hyper and hypomobile ankles. Future studies will be required, however, to establish the systems' measurements' reliability, the predictive validity of training on the device, and its ability to improve

Table 2. Questionnaire Responses

Question	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
I found the ankle interface easy to use:	**	**			
It was difficult for me to use the ankle interface				***	*
It was difficult for me to learn how to move my foot while attached to the ankle interface				***	*
I had not trouble understanding what to do in the study	***	*			
The screen 3-d graphics displays sometimes confused me	*	*		*	*
The experiment took too long				**	**
My ankle became extremely tired in the experiment		*			***
My leg became extremely tired in the experiment					****
I made many errors			**	*	*
It was very easy for me to move and hold the virtual foot	**			**	
I did not have any difficulty pressing the interface with the correct force	***		*		

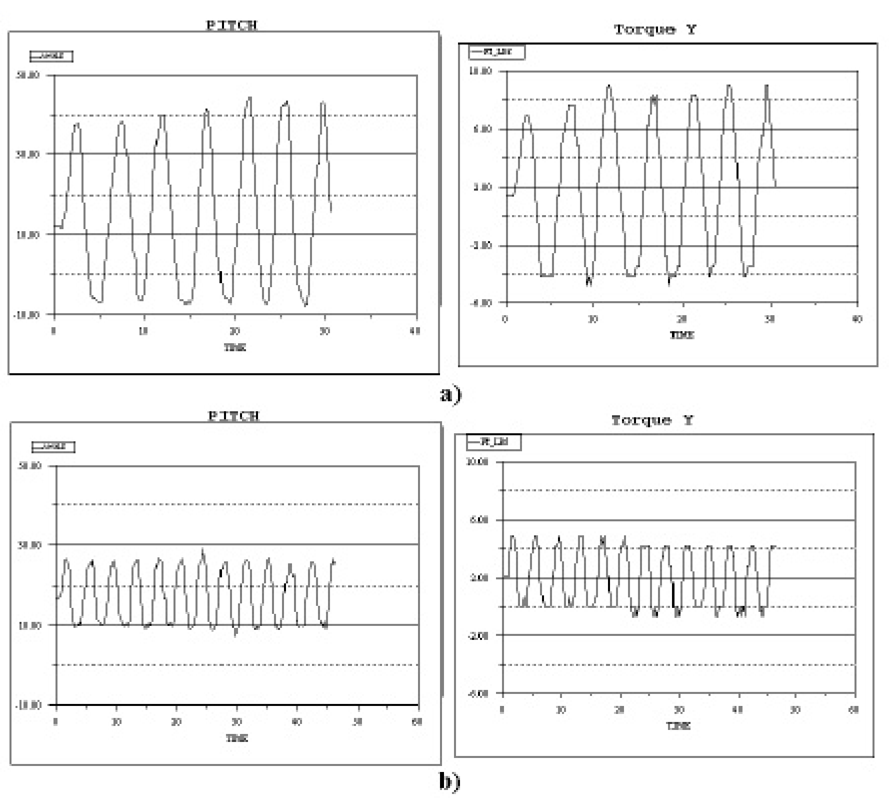


Figure 2. A patient's pitch (in degrees) and torque (in ft•lbs) vs. time (in seconds): a) for the healthy ankle and b) for the injured ankle.

patient's function. Future modifications to improve the comfort of the device include altering the foot-attachment straps, using an adjustable chair, and stabilizing the knee with a cushion. Other modifications will include providing higher-level data in the therapist's patient reports and using a head-mounted display to increase immersion. A library of VEs will be developed incorporating rehabilitative motions and parameters.

Acknowledgements

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