Autonomous Robots 10, 203–212, 2001

A Stewart Platform-Based System for Ankle Telerehabilitation*

M. GIRONE, G. BURDEA, M. BOUZIT AND V. POPESCU
CAIP Center, Rutgers University, Piscataway, NJ, USA
burdea@vr.rutgers.edu

J.E. DEUTSCH
Program in Physical Therapy, UMDNJ-SHRP, Newark, NJ, USA

Abstract. The "Rutgers Ankle" is a Stewart platform-type haptic interface designed for use in rehabilitation. The system supplies six-DOF resistive forces in response to virtual reality-based exercises running on a host PC. The Stewart platform uses double-acting pneumatic cylinders, linear potentiometers as position sensors, and a six-DOF force sensor. The Rutgers Ankle controller contains an embedded Pentium board, pneumatic solenoid valves, valve controllers, and associated signal conditioning electronics. Communication with the host PC is over a standard RS232 line. The platform movement and output forces are transparently recorded by the host PC in a database. This database can be accessed remotely over the Internet. Thus, the Rutgers Ankle Orthopedic Rehabilitation Interface will allow patients to exercise at home while being monitored remotely by therapists. A prototype was constructed, and proof-of-concept trials were conducted at the University of Medicine and Dentistry of New Jersey. The results indicate that the system works well as a diagnostic tool. The subjective evaluation by patients was very positive. Further medical trials are needed before the system clinical efficacy in rehabilitation can be established.

Keywords: telerehabilitation, force feedback, ankle rehabilitation, virtual reality, Stewart platform, hexapod, pneumatic robotics, parallel robots

1. Introduction

A Stewart platform is a closed loop manipulator whose six-DOF end-effector is connected to a base platform by six actuators using prismatic joints. The known heavy payload lifting capabilities of Stewart platforms led to their use in manufacturing and motion platform applications (Burdea, 1996; NASA, 1999). A novel area of application of such parallel-kinematics robots is in medical robotics, specifically in the rehabilitation of the ankle (Girone et al., 1999).

*Based in part on Girone, M. J., G. C. Burdea, M. Bouzit, 1999, The Rutgers Ankle Orthopedic Rehabilitation Interface. In *Proc. of the ASME, Dynamic Systems and Control Division Vol.* 67, pp. 305–312, International Mechanical Engineering Congress and Exposition, Nashville TN, November.
http://www.caip.rutgers.edu/vrlab/ankle.html.

Post-traumatic healing and prevention of repeat injuries are realized through rehabilitation. The aim of such treatment is to develop strength, flexibility, and proprioception in the affected body segment (Tropp and Alaranta, 1993). There are a number of devices available for ankle rehabilitation, ranging from simple mechanical ones (for at-home use), to complex computerized stations (used at the clinic). At-home patients can use elastic bands (DMSystems, 1999), foam rollers (Perform Better, 1999), or wobble boards (Kinetic Health, 1998). Companies typically offer bands of varying elasticity so that the resistance can be controlled. Foam rollers are used to improve balance and proprioception. These cylinders or half-cylinders of foam act as an unstable surface beneath patient's feet. Wobble boards are circular discs with a hemispherical pivot in the center of one of their sides. Patients stand on the board with one or both feet with the pivot side to the floor. By shifting their weight and adjusting their ankle position, patients make the board tilt. At the clinic, such devices are complemented by the Biodex Balance System (Biodex, 1999a), and the Multi-Joint System 3 (Biodex, 1999b). The Balance System by Biodex Medical Systems, Inc., (Shirley, NY) is an advanced wobble-board-like device. Patients stand on a platform that allows them to shift their weight. The stability of the platform can be changed via an electronic interface. Biodex's Multi Joint System3 is a comprehensive rehabilitation system for many of the body's joints. It allows therapists to quantify muscle groups' output forces to facilitate patient evaluation. The System3 is also an exercise machine, giving therapists control over the allowed range of motion and over the level of resistive forces.

Current ankle rehabilitation devices have certain drawbacks. The simple mechanical systems for at-home use are not sensorized or networked. Therefore, there is no remote monitoring or re-evaluation of patient progress. Patients thus need to travel repeatedly to clinics in order to be reevaluated, and such travel is difficult for patients with ankle injuries. Furthermore, those clinic and home exercises that are not interactive can be very repetitive and boring. The patient, therefore, may not be as motivated to do the exercises prescribed, and the lack of timely therapy aggravates the patient's medical condition. More advanced systems cannot be used at home because they require therapists' supervision.

This paper describes a rehabilitation system designed to address the above shortcomings in current ankle rehabilitation technology. The "Rutgers Ankle" is a force feedback device based on a Stewart platform design (Stewart, 1966). The robot can move and supply forces and torques in all directions within the ankle work envelope. Section 2 presents an overview of the system hardware, while section 3 describes the interface control algorithms and virtual reality software. Section 4 presents initial experimental data during patient trials. Section 5 concludes the paper.

2. System Hardware

Figure 1 illustrates the components of the "Rutgers Ankle." The system hardware consists of the Stewart platform haptic interface, its electro-pneumatic controller, the PC host computer, and a small air compressor. The system software consists of low-level servo-control software, a high-level rehabilitation library, other software drivers, and a patient database.

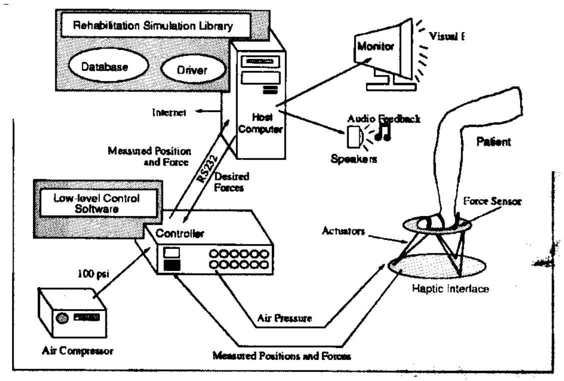


Figure 1. The "Rutgers Ankle" system architecture (Girone et al. 1999). © ASME; reprinted with permission.

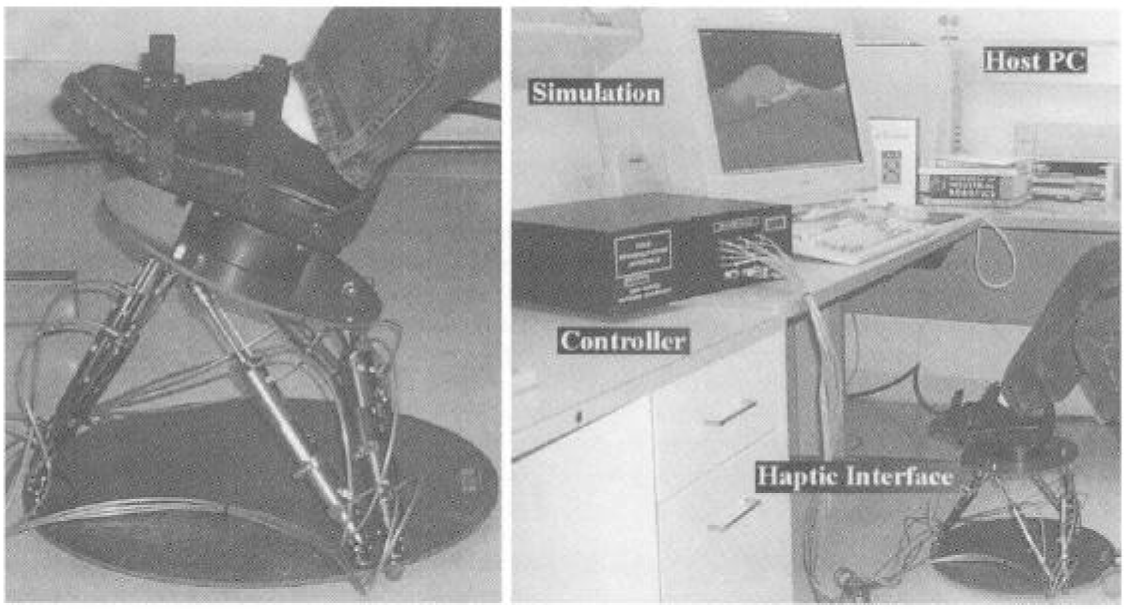
2.1. *The Haptic Interface*

The haptic interface is shown in Fig. 2a. It is a Stewart platform robot that supplies forces to the patient's foot during the rehabilitation exercises. The Stewart platform design allows the control of forces and torques in six DOFs and movement throughout the ankle's full range of motion (ROM). Its work envelope and maximum force output are detailed in Table 1 (Girone et al., 1998).

The interface's actuators are six commercial glass/graphite, double-acting, pneumatic cylinders produced by Airpot Corporation (Norwalk, CT) (Airpot, 1999). The cylinder stroke is 10 cm and its maximum force is 133 N (at 690 kPa air pressure). The low friction of the actuators (1% of the load) allows control of the very small forces required for low-impact exercises. Their high output force permits high-force exercises as well. Linear potentiometers (Data Instruments, 1999) are attached in parallel with each cylinder and serve as position sensors. The cylinder/potentiometer assemblies are attached at one end to a fixed platform and at the other to a mobile platform using universal joints. Both platforms are made of a lightweight carbon fiber, contributing very little to the device's weight. The "Rutgers Ankle" is designed to be inherently safe, as the patient's shin is free to move. This ensures that the device cannot push the ankle beyond its normal ROM. A six-DOF force sensor (JR3, 1999) is sandwiched between the mobile platform and a foot restraint.

Table 1. The "Rutgers Ankle" workspace and output forces/torques. Adapted from (Girone et al., 1999). © ASME; reprinted with permission.

DOF	X	Y	Z	Pitch	Roll	Yow
Maximum diplacement	12 cm	9 cm	12 cm	45°	40°	80°
Maximum output	371 N	316 N	752 N	35 N · m	22 N · m	41 N · m



(a) (b)

Figure 2. The "Rutgers Ankle": a) the haptic interface; b) the system view (Girone et al., 1999). © ASME; reprinted with permission.

It measures the actual forces and torques at the patient's foot. The assembly overall dimensions are a cylinder of 22 cm radius and 34 cm in height. Finally, the position and orientation of the patient's shin can be measured using a separate InsideTrack magnetic 3D tracker produced by Polhemus Co. (Colchester, VT) (Polhemus, 1993).

2.2. *The Platform Controller*

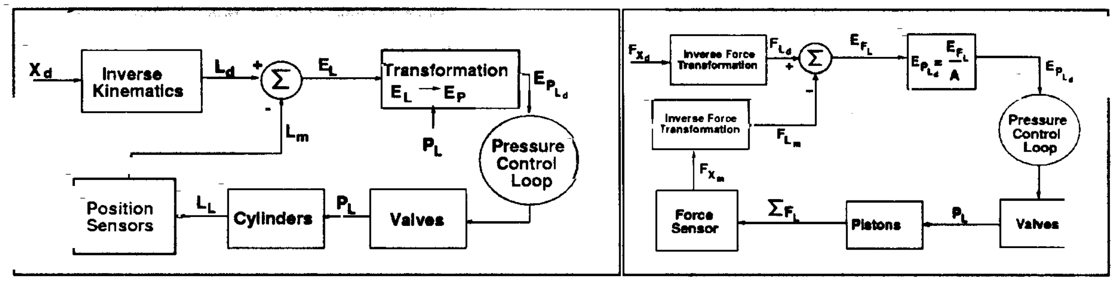
The electro-pneumatic controller is shown in Fig. 2b. It regulates the air pressures in the platform actuators and communicates with the host PC via an RS232 line. The pressure in each of the actuators' air chambers is controlled by an exhaust/intake pair of solenoid valves and measured by a pressure sensor. The valves were chosen for their low response time of 2 ms (500 Hz) and high airflow of 200 Nl/min (Patounakis et al., 1998). In addition to the solenoid valves and their electronic control boards, the platform controller box contains amplifier boards, A/D/A boards, and an embedded computer. This is a 233 MHz single-board Pentium running Windows 95, which handles the actuator servo control.

3. System Software

The system software includes the low-level servo-control of the platform and the high-level software necessary for the rehabilitation library. Other software components are the database necessary to store patient files and the graphical user interface (GUI).

3.1. *The Low-Level Control Algorithms*

The system design allows for both position and force control of the platform. Position control is used for



(a) (b)

Figure 3. The Rutgers Ankle servo loop: a) position control b) force control (Girone et al., 1999). © ASME; reprinted with permissi

flexibility and coordination exercises, where the host PC transmits the desired position-orientation information. This control method, for example, allows therapists to limit exercises' ROMs, focusing on specific foot motions. Force control maintains forces and torques at the patient's foot as directed by the host PC. When implemented, this control method will be used for weight-training exercises and zero-force ROM exercises.

Figure 3 depicts the position and force control loops realized by the low-level software. The following notation is used:

- L is the length of each cylinder;
- F is a force vector;
- X is a position-orientation of the mobile platform in Cartesian space;
- A subscript X means that the value is in Cartesian space;
- A subscript L means that the value is in joint space, related to the particular cylinders. For example, L_L is the length of each cylinder;
- Desired quantities are denoted by a subscript d;
- Measured quantities are denoted by a subscript m;
- Differences and changes are denoted by E. For example, E_{PLd} is the desired change in the pressure in each of the air compartments;

Both position and force control use inverse and forward kinematics algorithms to map the lengths of the cylinders to the position-orientation of the mobile platform. The inverse kinematics algorithm yields a single solution. Its input is a desired position-orientation of the mobile platform with respect to the fixed (global) coordinate system. Its output is the six cylinder lengths necessary to reach that position.

The forward kinematics algorithm has many solutions and thus requires the use of an iterative approach. Its inputs are the six measured cylinder lengths and the guessed position and orientation of the mobile platform (as found by the previous cycle through the algorithm). Its output is the position and orientation of the mobile platform. This transformation is used continuously to report to the host PC the current position and orientation of the mobile platform (Dieudonne et al., 1972; Nguyen and Pooran, 1989).

The low-level control software consists of two functions: an un-timed loop and a timed function. The un-timed loop receives from the host PC the desired position-orientation or force of the mobile platform. It returns to the host PC the measured platform position and force sensor data. If the servo loop receives a position-orientation from the host PC, it transforms this data into six desired cylinder lengths using the inverse kinematics algorithm. If the software receives force and torque targets from the host PC, it transforms these values into desired forces for each cylinder. It also transforms the measured forces and torques from the force sensor into forces for each cylinder. Regardless of the command received, the control software uses forward kinematics to transform the measured cylinder lengths into platform position-orientation for transmission to the host PC. This loop typically operates at 115 Hz.

The timed function operates at over 2800 Hz by hardware interrupts. It alternates between two actions, sensor reading and pressure control. At every interrupt, the system closes all the valves that have been open for their desired duration of time (i.e., number of interrupts). Then, it either reads the sensors' raw data or runs the pressure control algorithm. The first step of the pressure control algorithm is to convert raw sensor data into real-world values (i.e., the binary output of the A/D must be converted into cm, N, N · cm, psi, and radians). Then, the cylinder length, pressure, and force sensor data are passed through six-tap lowpass filters.

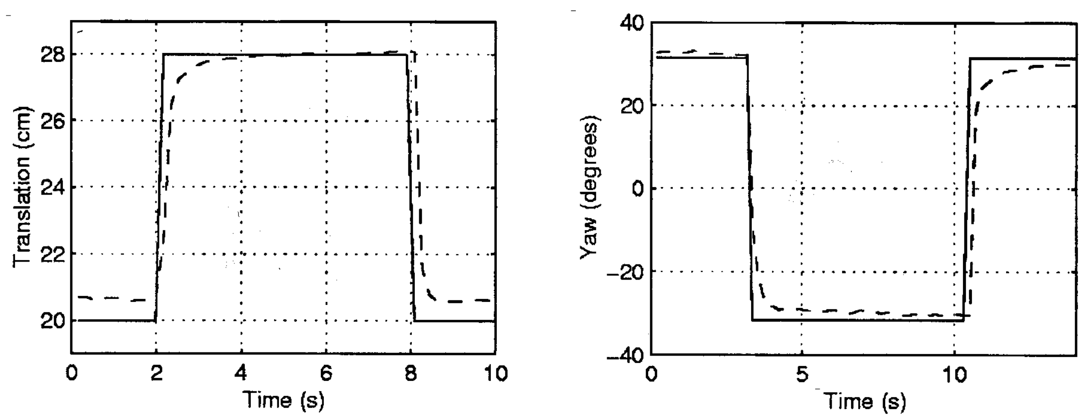


Figure 4. Measured (dashed line) and desired (solid line) translation and yaw of the mobile platform versus time.

If a desired position-orientation was sent from the host PC, each cylinder's desired length (calculated by the un-timed loop) is compared with its measured length. The difference is converted into a desired change in pressure by a linear transformation. If a desired force was received from the host PC, each cylinder's desired force (calculated by the un-timed loop) is converted into a desired pressure by a linear transformation. The measured and desired pressures for each cylinder's two air compartments are then compared. For each air compartment i, an integer n_i is calculated on [0, 11] proportional to the desired pressure change. If n_i is negative, the exhaust valve of air compartment i is kept open for $|n_i|$ interrupts and the intake valve is closed. If n_i is positive, the intake valve is kept open for n_i interrupts and the exhaust value is closed. Each cylinder is controlled in turn, every two interrupts. Therefore, sensors are read and each cylinder is controlled at 1429 Hz and 238 Hz, respectively.

Figure 4 shows two plots comparing the desired and measured translation and yaw values of the mobile platform. The plots were obtained by entering a square-wave signal for desired platform position and orientation. This input spanned the full ROM of the device in order to measure the haptic interface's bandwidth. The worst-case translation and rotation bandwidths are 1.2 Hz and 1.3 Hz, respectively. It should be noted that such worst-case bandwidths are for extreme cases of motion that are not used during rehabilitation exercises. The position-orientation measurement in Cartesian space has an error margin of 3.5% for translation and 6.7% for rotation. This error is due to approximations made in the kinematics model. The model assumes that the actuator joints are co-located while in reality there is a small distance between them.

Data were also collected to measure the entire system's control latency. The position and orientation of the mobile platform was continually returned to the host PC. A signal was sent by the host PC to the controller to initiate a motion. These measurements showed a system latency of 53 ms. This round-trip delay is the time between the host computer sending a desired position-orientation and the interface controller reporting that the motion has begun. It is not the time until the motion has completed, as that varies depending on the desired position change.

3.2. The High-Level Virtual Reality Rehabilitation Library

The "Rutgers Ankle" is a component of an ongoing *Telerehabilitation with Virtual Force Feedback* project at Rutgers University (Popescu et al., 2000). Using this system, patients will be able to exercise at home while being monitored remotely by a therapist. Several virtual reality (VR) hand exercises have already been developed for patients needing hand rehabilitation. These use our laboratory's Rutgers Master II (RM-II) force feedback glove and a similar interface controller. Initial tests at Stanford Medical School were encouraging for the potential of this technology in rehabilitation, as the patient did improve his condition using the above system. Furthermore, patient progress was monitored remotely from the East Coast (Rutgers) by

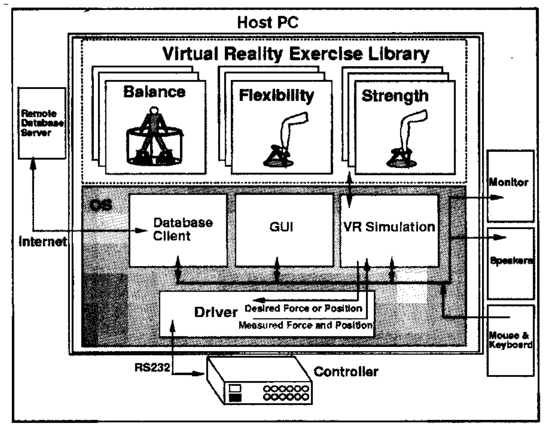


Figure 5. The host PC's software architecture (Girone et al., 1999). © ASME; reprinted with permission.

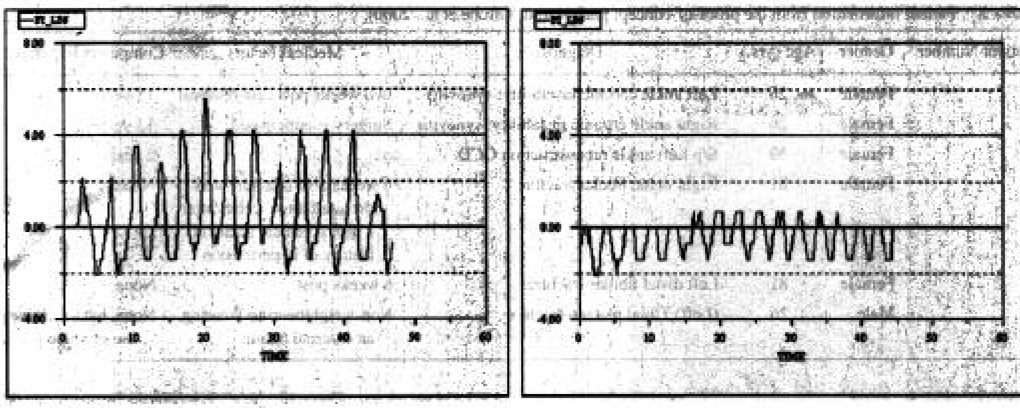
accessing the database. The "Rutgers Ankle" is being currently developed to add a new rehabilitation device, and thus new capabilities, to our existing telerehabilitation system.

The host PC high-level software architecture is illustrated in Fig. 5 (Girone et al., 1999). Its components are the VR exercise library, the patient database, and the graphical user interface (GUI). The PC runs VR rehabilitation simulations written in WorldToolKit® (WTK) (EAI, 1999). This is a commercial library of hundreds of general-purpose C functions designed to help the VR developer. The VR library offers patients a variety of exercises, each with a particular rehabilitative focus and virtual environment (VE). While patients exercise, their foot position, orientation, and output forces become the inputs and outputs to/from the VE. On the screen of the host PC, the patient views a game-like VR simulation. The simulation may be of a virtual leg, a racecar, a plane cockpit, or any other interactive VE. As patients move their feet, they interact with the VE. By rotating their ankles, for example, they move the virtual leg or accelerate the racecar. Through force feedback, the VE affects the patients. The device pushes back, for example, as the virtual leg kicks a soccer ball and the racecar's accelerator is further pressed. Scores are kept to motivate patients to apply more effort and exercise more frequently. Soccer goals and racing times become records to break. In striving to break their records, patients must continually perform rehabilitative motions as means of advancing in the VE. As they exercise, the host PC records exercise frequency, position, orientation, and force information.

The VR exercises focus on improving ROM, strength, coordination, and balance as well improving lower extremity function. Strength exercises are similar to conventional weight-training exercises. Patients move their feet as the "Rutgers Ankle" applies resistive forces. Flexibility exercises improve the patient's ROM by performing repetitive movements near their current ankle limits of motion. During this time there are little or no opposing forces. Balance exercises are not implemented at the present time as they may require the simultaneous use of two platforms (one for each foot). The large variety of exercises in the library will allow patients immediate access to many different forms of rehabilitation through a single system. Physical therapy focuses on functional mobility, aimed at improving "function" (i.e., the ability to use the affected limb/joint similar to its use in everyday tasks). By creating real-life environments, the therapist may better simulate the conditions under which training will transfer to function.

The simulation program transparently stores data in a patient database. This Oracle (1995) database stores the three ankle joint angles and six forces and torques at the patient's foot. A GUI facilitates entering patient information, querying, updating, browsing, and deleting records. Reports are generated to provide high-level information to the therapist based on the measured raw data. Graphs display the angles, forces, and torques with respect to time as well as the standard deviation and average for each data set. Currently, the system reports angle and torque data around three orthogonal axes: x, y, and z. In the future, this data will be aggregated to produce more clinically useful information with respect to the axes of dorsiflexion, plantar flexion, eversion, and inversion, the ankle's natural DOFs (Donatelli, 1996). Figure 6 shows two sample torque graphs from a proof-of-concept-trial patient report (see also Section 4).

Patient progress can be measured directly in three main respects: ROM, maximum force output, and coordination. To assess a patient's ROM and force output capabilities, therapists can observe the extreme values of the joint angle graphs and torque graphs, respectively. The therapist can observe coordination deficits and progress by comparing the pattern of ROM between the injured and non-injured lower extremity as well as observing the variations within the limb. Future reports will quantify progress by plotting such extreme



(a) (b)

Figure 6. A patient's torque graphs showing torque around the x axis (in ft · lbs) vs. time (in seconds): a) for the healthy ankle; b) for the injured ankle (Girone et al., 2000).

values as a function of time. In the future, these data will be uploaded from the host PC by a therapist at a remote site for evaluation. As the patient improves, the therapist will be able to modify exercise parameters such as required duration, maximum-opposing forces, allowed ROM, and VE complexity.

4. Proof-of-Concept Trial

A proof-of-concept patient trial was conducted at the University of Medicine and Dentistry of New Jersey (see Fig. 7). This initial trial was designed to evaluate the system's capabilities. Ankle rehabilitation patients sat on a fixed chair, and their right or left foot was placed on the Stewart platform. They were briefed about the system and then asked to perform exercises at several degrees of opposing force while interacting with a virtual environment. The position, orientation, and output forces were recorded in a database and evaluated by a physical therapist. ROM and maximum output forces were derived from the data in order to evaluate the system as a diagnostic tool.

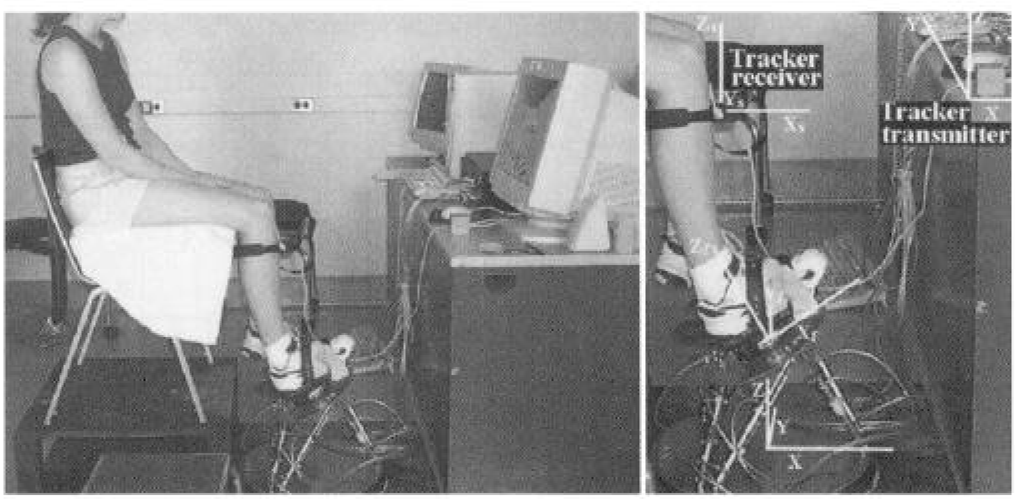


Figure 7. A patient during trials (Girone et al., 2000).

Table 2. Patient information from the proof-of-concept patient trial (Girone et al., 2000).

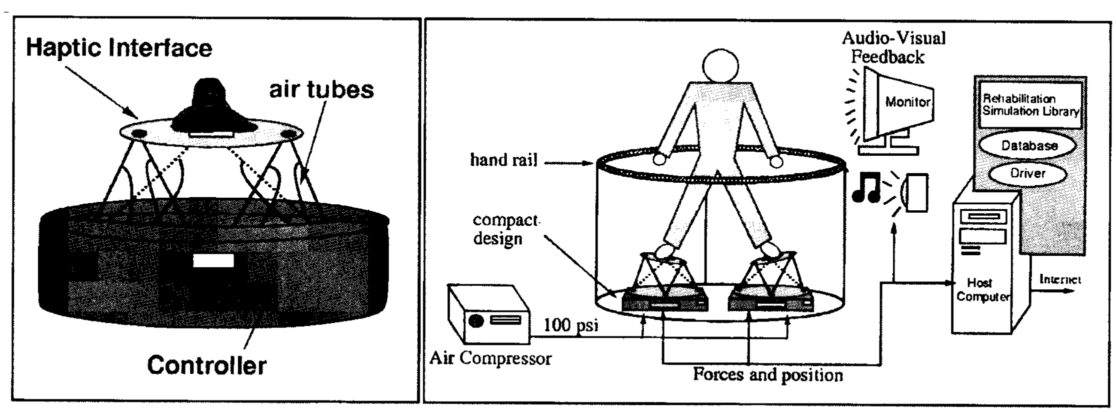
Patient Number	Gender	Age (yrs.)	Diagnosis	Medical factors	Computers Experience
	Female	26	Left ankle chronic instability: synovitis	two weeks post cast-removal	13 years
	Female	26	Right ankle chronic instability: synovitis	Surgery is anticipated	13 years
	Female	39	S/p Left ankle reconstruction OCD		2 years
	Female	81	Right distal fibular fracture	6 weeks post (fracture was detected three weeks after a motor vehicle accident) history of hypertension	None
	Female	81	Left distal fibular fracture	6 weeks post	None
	Male	26	(Left) Tibial plateau fracture	Non-weightbearing Wearing an external fixator	None, but extensive use of video games

The patients tested were diverse in terms of their age, diagnosis, familiarity with computers, and rehabilitation goals (see Table 2). Their ages ranged from 26 to 81 years with general conditions varying from an injured athlete to an elderly person regaining the ability to walk. Clinical presentation varied from patients with low ankle mobility and decreased strength to patients with hypermobility and coordination deficits. Comparing the performance of the injured to the non-injured ankle, the therapist was able to characterize a patient's movement dysfunction by identifying the deficits in ROM, strength, and coordination (see Fig. 6). All patients responded favorably to the experience.

5. Conclusions and Future Work

The "Rutgers Ankle" is a novel approach to ankle rehabilitation. Patients interact with a Stewart platform robot, exercising their ankles' three DOFs. The high-level control of positions and forces is handled by a host PC running an interactive virtual environment (VE) simulation. The system is intended to make rehabilitation more accessible, effective, and fun by simulating a large variety of exercises and motivating patients using VEs. It is hoped that its at-home rehabilitation capabilities will allow timely care for patients who otherwise would not have access to necessary therapy.

Through the proof-of-concept patient trial, we were able to receive feedback from patients and physical therapists. Their suggestions for improvement will be taken into account as the system matures. Suggestions to improve the comfort of the device include modifying the foot-attachment straps, using an adjustable chair, and stabilizing the knee with a cushion. Other suggestions include providing higher-level data in the



(a) (b)

Figure 8. A proposed future design: a) compact controller design; b) ttwo-platform system. (Girone et al., 1999). © ASME; reprinted with permission.

therapist's patient reports and using a head-mounted display to increase immersion. In the future, a library of exercise simulations must be created that involve the proper rehabilitative motions and exercise parameters. Force control must also be developed in order to allow certain exercise types. Future studies will establish the reliability of measurements, the predictive validity of training on the device, and its ability to improve patients' function (such as gait).

In the future, the electronic controller will be integrated into the base of the Stewart platform to increase the compactness and portability of the system (see Fig. 8a). Furthermore, two such platforms need to be integrated to allow balance-type exercises (see Fig. 8b).

Acknowledgments

The research reported here was supported by grants from the National Science Foundation (BES-9708020) and from the Center for Advanced Information Processing (CAIP) at Rutgers University (SROA and CAIP grants).

References

Airpot Corporation. 1999. http://www.airpot.com/.

Biodex Medical Systems. 1999a. Biodex Balance System, http://www.biodex.com/dir24/945300.htm.

Biodex Medical Systems. 1999b. Biodex Multi-Joint 3, http://www.biodex.com/dir24/mjs3.htm.

Burdea, G. 1996. *Force and Touch Feedback for Virtual Reality*, John Wiley& Sons, Inc.: New York.

Chandler, T.J. and Kibler, W.B. 1993. Muscle training in injury prevention. In *Sports Injuries: Basic Principles of Prevention and Care*, Oxford, p. 253.

Data Instruments. 1999. http://www.datainstruments.com/.

Dieudonne, J.E., Parrish, R.V., and Bardusch, R.E. 1972. *An Actuators Extension Transformation for a Motion Simulator and an Inverse Transformation Applying Newton-Raphson's Method.* Langley Research Center. NASA. TN D-7067.

DMSystems, Inc. 1999. Ankle Tough. http://dmsystems.com/.

Donatelli, R.A. 1996. *The Biomechanics of the Foot and Ankle*, F.A. Davis: Philadelphia.

Engineering Animation, Inc. 1999. http://www.eai.com/.

Girone, M.J. and Burdea, G.C. 1998. Ankle rehabilitation in virtual reality. Report to the National Science Foundation on grant BES-970802.

Girone, M.J., Burdea, G.C., and Bouzit, M. 1999. The Rutgers ankle orthopedic rehabilitation interface. In *Proc. of the ASME, Dynamic Systems and Control Division Vol. 67*, pp. 305–312, International Mechanical Engineering Congress and Exposition.

Girone, M.J., Burdea, G.C., Bouzit, M., Popescu, V., and Deutsch, J.E. 2000. Othopedic rehabilitation using the "Rutgers ankle" interface. In *The Proc. of Medicine Meets Virtual Reality 2000*, pp. 89–95.

JR3, Inc. 1999. http://www.jr3.com.

Kinetic Health Corporation. 1998. Wobble and Rocker Boards, http://www.kinetichealth.com/edu11.html.

Koepfer, C. 1997. "Hexapod—It's Working." Modern Machine Shop Online.http://www.mmsonline.com/articles/109702.html.

Laskowski, E.R., Newcomer-Aney, K., and Smith, J. 1997. Refining rehabilitation with proprioception training: Expediting return to play. *The Physician and Sports Medicine*, 25(10) October. http:// www.physsportsmed.com/issues/1997/10oct/laskow.htm.

NASA Langley Research Center. 1999. Simulation systems branch. Visual motion simulator. http://bigben.larc.nasa.gov/facility/vms.html.

Nguyen, C.C. and Pooran, F.J. 1989. Kinematic analysis and workspace determination of a 6 DOF CKCM robot end-effector. *Journal of Mechanical Working Technology*, 20:283–294.

Oracle Co. 1995. *Oracle User's Manual*, Redwood City, CA.

Patounakis, G., Bouzit M., and Burdea, G. 1998. Study of the electromechanical bandwidth of the Rutgers master. Technical Report CAIP-TR-225, Rutgers University, Piscataway, NJ.

Perform Better. 1999. Biofoam Rollers. http://www.performbetter.com/page11.html.

Polhemus Navigation Science Division. 1993. *Insidetrak User's Manual*, Colchester, VT, Mc-Donnell Douglas Electronics Co.

Popescu, V., Burdea, G., Bouzit, M., and Hentz, V. 2000. A Virtual reality-based telerehabilitation system with force feedback. In *IEEE Transactions on Information Technology in Biomedicine*, 4(1):45–51.

Post, W.R. 1998. Patellofemoral pain: Let the physical exam define treatment. In *The Physician and Sportsmedicine*. 26(1), January. http://www.physsportsmed.com/issues/1998/01jan/post.htm.

Stewart, D. 1966. A platform with 6 degrees of freedom. In *Proc. Of the Institution of Mechanical Engineers*, pp. 1965–1966.

Tropp, H. and Alaranta, H. 1993. Proprioception and coordination training in injury prevention. In *Sports Injuries: Basic Principles of Prevention and Care*, Oxford.

Wilkerson, G.B. and Behan. E. *Biodex Integrated Physical Rehabilitation*. Distributed by Biodex Medical Systems.

Michael Girone obtained his B.S. in Electrical Engineering from Rutgers University in 2000. His undergraduate research interests included virtual reality haptic interfaces for telerehabilitation and high-data-rate, wireless connectivity to the Internet. He is presently pursuing an S.M. at the Massachusetts Institute of Technology in the Electrical Engineering and Computer Science Department, focusing in digital communications.

Grigore Burdea obtained his Ph.D. in Robotics from New York University in 1987. He joined Rutgers University in 1988 and presently is Associate Professor of Computer Engineering and Director of the Human-Computer Interface Laboratory. Burdea's research interests are force feedback for virtual reality and its medical applications. Burdea has authored the books *Virtual Reality Technology*, and *Force and Touch Feedback for Virtual Reality*, published by John Wiley & Sons. He is Co-Editor of the book *Computer-Aided Surgery* published by The MIT Press. Burdea is Senior Member of IEEE, member of the Editorial Boards of several journals and served as General Chair of IEEE Virtual Reality 2000 Conference.

Mourad Bouzit obtained his Ph.D. in Robotics and Computer Science from University Paris VI in 1996. He is presently a Post Doctoral fellow at the Center for Advanced Information Processing (CAIP) at Rutgers University. His research topics include teleoperation, dextrous telemanipulation, artificial hand and force feedback systems for Virtual Reality applications. He prototyped the LRP Master, the first French force feedback glove for Virtual Reality.

Viorel G. Popescu obtained his B.S./M.S. from the University "Politehnica" of Bucharest in 1993. He graduated from the Electrical and Computer Engineering Department at Rutgers University with a Ph.D. in January 2001. His research involved haptic display systems and medical application of virtual reality. Presently he is with IBM T.J. Watson Research Laboratory, Hawthorne, NY.

Judith Deutsch obtained her Ph.D. in Pathokinesiology from New York University in 1994, her M.S. in Physical Therapy from the University of Southern California in 1985, and her B.S. in Human Biology in 1982. She was a NIDRR Post Doctoral Fellow at the Advanced Rehabilitation Research Kessler Institute for Rehabilitation in 1996. She is currently Assistant Professor in the Program In Physical Therapy at the University of Medicine and Dentistry of New Jersey—School of Health and Related Professions. Her research looks at the outcomes of Structural Integration in selected rehabilitation populations and the effects of mental practice on motor learning in post-stroke patients, including brain mapping and behavioral studies. She is editor of *Neurology Report*, the official peer-reviewed journal of the Neurology Section of the American Physical Therapy Association (APTA).