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THE "RUTGERS ANKLE" ORTHOPEDIC REHABILITATION INTERFACE

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ABSTRACT

This paper presents a novel ankle rehabilitation device currently under development. The haptic interface component has a Stewart platform structure with pneumatic actuators controlled by an electronic interface. It allows movement of the ankle though its full range of motion. The system communicates with a PC through an RS232 port. The PC will run game-like virtual reality exercises that control the movement and output forces of the device. These simulations will make exercising more enjoyable, transparently recording patient progress for evaluation by therapists.

The "Rutgers Ankle" Orthopedic Rehabilitation Interface will facilitate the healing of one of the most often injured joints of the body. Inherently safe and easy-to-operate, it will combine the capabilities of many current rehabilitation devices. This system will enhance rehabilitation routines by providing three types of exercises: strengthening, stretching, and balancing. Eventually, this system will allow patients to exercise in their homes while being monitored remotely by therapists or physicians.

INTRODUCTION

The ankle is one of the most important joints of the body. Medical research therefore devotes much energy toward finding effective methods for treating and preventing ankle injuries. To develop an ankle rehabilitation device, an understanding of rehabilitation concepts is paramount.

Injuries to the ankle's lateral ligaments are the most common in sports and life in general (Tropp and Alaranta, 1993). At the heart of these injuries lies a lack of three important qualities: strength, flexibility, and proprioception. Improving these characteristics will promote healing and help prevent repeat injuries. In fact, patients must develop their flexibility and strength beyond pre-injury levels if they are to safely return to the activities that injured them (Post, 1998).

Physically active rehabilitation has been shown to expedite the healing process (Chandler and Kibler, 1993). Some researchers believe that inactivity following injury may actually damage the body. Detrimental biochemical and biomechanical changes around a joint may occur if it is not moved often enough through its range of motion (ROM) (Donatelli, 1996). In addition to improving strength and flexibility, patients should also work to enhance their proprioception. A lack of sufficient ankle proprioception is often made evident by functional instability, the frequent sprains and/or feeling of weakness in the ankle (Tropp and Alaranta, 1993). Researchers feel that it may be possible to increase proprioception through coordination training, enhancing postural control and pronator muscle strength (Tropp and Alaranta, 1993). Stimulation of joint mechanoreceptors and the muscle spindle may improve position sensing's accuracy and response time (Wilkerson).

Taking this knowledge into account, many companies have produced ankle rehabilitation devices that work to improve patients' strength, flexibility, and proprioception (Girone and Burdea, 1998). Examples of such devices are elastic bands (DMSystems, 1999), foam rollers (Perform Better, 1999), wobble boards (Kinetic Health, 1999), the Biodex Balance System (Biodex, 1999a), and the Multi-Joint System 3 (Biodex, 1999b). 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. Companies typically offer bands of varying elasticities 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 patients' feet. Wobble boards are one of the most common ankle rehabilitation devices. They are circular discs of wood or plastic with a hemispherical pivot in the center of one of the sides. Patients stand on the board with one or both feet with the pivot side to the floor. By shifting their weight, patients make the board tilt. The Balance System by Biodex Medical Systems, Inc. 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, 1999a). 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. System3 is also an exercise machine, granting therapists control of the allowed range of motion as well as the resistive forces (Biodex, 1999b).

By reviewing these devices, several shortcomings with the state of the art of ankle rehabilitation become evident. First, rehabilitation devices are often non-versatile as they rarely perform a variety of exercises using all three of the ankle's degrees of freedom (DOFs). Also, many advanced systems require expert supervision and can only be used at the clinic. The simpler devices, on the other hand, have no quantitative diagnostic capabilities or computerized on-line data collection. Devices are rarely interactive, making exercising repetitive and boring.

Each of these drawbacks was specifically addressed in the design of the "Rutgers Ankle" (Girone et al., 1999). The "Rutgers Ankle" is based on the Stewart platform (Stewart, 1966) and can move and supply forces and torques in all directions. Nearly any ankle rehabilitation device can be realized through virtual reality haptic rendering techniques. Ease of use has also been considered as the system is designed for patients who are computer novices. Another advantage of this system is portability. Its three main parts are: the haptic interface, the controller, and a small air compressor. Each can be easily carried and hooked up to a PC at the exercise site. The system is also inherently safe, unable to push the ankle beyond its normal ROM.

The at-home-exercising capability is perhaps the "Rutgers Ankle's" most interesting feature. Patients will be able to use the device in the comfort of their own homes. This will greatly benefit patients for whom in-clinic treatment is impossible or undesirable. The device's data collection and remote access capabilities will allow therapists to monitor patients' at-home rehabilitation from the clinic.

Injuries often bring with them a sense of loss and frustration. It is important to make rehabilitation as enjoyable as possible in order to foster patients' spirits and promote healing. Virtual reality exercise simulations will provide a motivating, game-like environment for exercising that is not possible with passive devices.

The following sections elaborate on the development of the "Rutgers Ankle." The System Overview section presents a global view of the system. Details are given in sections describing the haptic interface, the controller, the low-level control software, and the driver software. The Conclusions and Future Work section summarizes the paper and and gives future directions.

SYSTEM OVERVIEW

The "Rutgers Ankle" is a component of the *Telerehabilitation with Virtual Force Feedback* project (Popescu et al., 1999). Through this system, patients are able to exercise at home while being monitored remotely by a therapist. Several virtual reality hand exercises have been developed for patients to perform using our RM-II force feedback glove. The "Rutgers Ankle" is being developed to add a new rehabilitation device to the existing telerehabilitation system.

The "Rutgers Ankle" hardware consists of the haptic interface, the controller, and the host PC (see Fig. 1). The system software consists of the low-level control software, the software driver, the rehabilitation library, and a patient database (see Fig. 2).

Figure 1. The "Rutgers Ankle" Orthopedic Rehabilitation System

The haptic interface (platform) uses pneumatic cylinders. This is the part of the system that directly interacts with the patient. It applies forces to the foot during exercising and

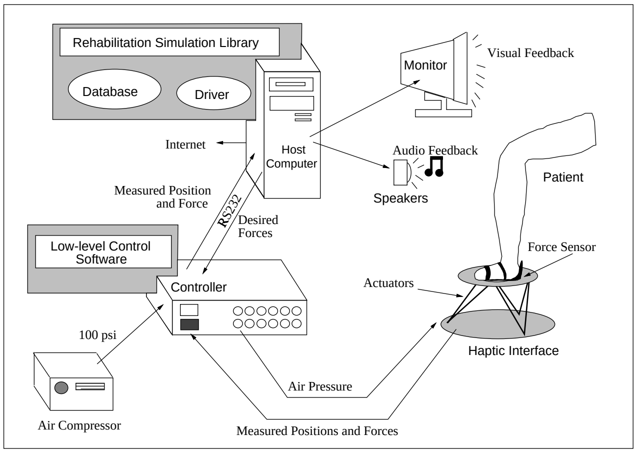

Figure 2. The “Rutgers Ankle” Orthopedic Rehabilitation System Block Diagram

measures the foot’s 3-D position and the forces applied to the foot.

The controller contains the pressure valves, pressure sensors, a power supply, and an embedded PC. The haptic interface connects to the controller through pneumatic tubing (by which the cylinders are controlled) and wires (by which the platform’s sensors are read by the controller). The controller in turn communicates with the host computer via an RS232 line.

The low-level control software runs on the controller’s embedded PC (Pentium 233 MHz). It has several functions namely controlling the pressure regulators, converting raw position sensor data into high-level values to be sent to the host computer, reading the pressure sensors’ data, receiving desired force or position values from the host computer, and performing the kinematic calculations to find the necessary cylinder pressures.

The high-level driver software runs on the host PC. It accepts the position information from the controller and forwards the information to the rehabilitation simulation program. It also accepts desired forces and/or positions from the simulation program and outputs this information to the controller’s embedded PC.

The rehabilitation library is composed of rehabilitation simulation programs that run on the host PC. The library will consist of a variety of different exercise simulations programmed using WorldToolKit $^{(R)}$ (EAI, 1999). Each exercise either mimics a common, real-world ankle rehabilitation exercise or uses the system’s uniqueness as a virtual reality device to simulate a new exercise. The large variety of exercises in the library will allow patients immediate access to many different forms of rehabilitation through a single system. The simulation programs will also forward data to a patient database. The patient Oracle-based database system will provide therapists a method for the quantitative evaluation of the patients’ present status or rehabilitation progress.

The following sections present the design of the haptic interface, the controller, the low-level control software, the driver software, and the rehabilitation library.

THE HAPTIC INTERFACE

The “Rutgers Ankle” is based on a Stewart platform design. This allows the interface to supply forces and move in any direction (x, y, z, roll, pitch, and yaw) within the ROM of the ankle joint (see Table 1). See Fig. 3 for a photograph of the prototype.

Table 1. Approximate Maximum Angles of the Ankle (Donatelli, 1996)

DOF	Approximate Maximum Angle
pitch down (plantar flexion)	35^0
pitch up (dorsiflexion)	$30\text{-}42^0$
roll	25^0
yaw	$25\text{-}30^0$

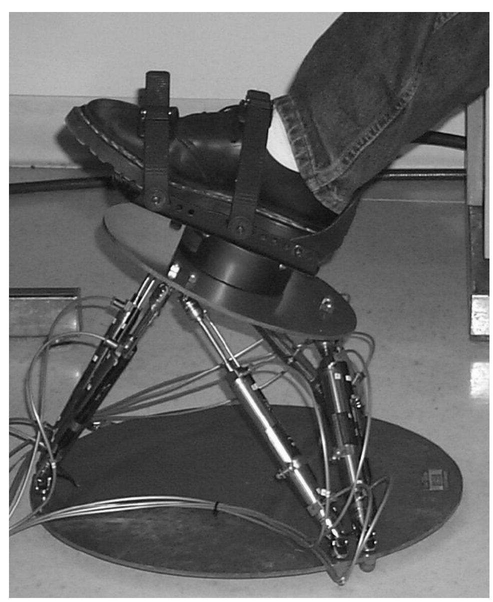

Figure 3. The “Rutgers Ankle” Haptic Interface

Table 2. The "Rutgers Ankle" Workspace and Output Forces/Torques (Girone et al., 1998)

DOF	Maximum Displacement	Maximum Output
x	12 cm	371 N
y	9 cm	316 N
z	12 cm	752 N
pitch	45^0	35 N·m
roll	40^0	22 N·m
yaw	80^0	41 N·m

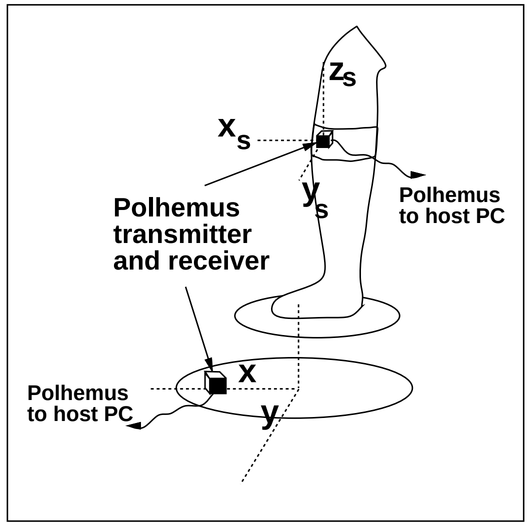

Figure 4. Measuring Joint Angle using a Polhemus 3D tracker

The upper and lower circular platforms are made up of a light-weight carbon-fiber material. This material was chosen because it contributes very little to the device's structural weight. The haptic interface's outside dimensions are a cylinder of radius 22 cm and height 34 cm. The actuators are double-acting Airpel Anti-Stiction Cylinders from Airpot Corporation (Airpot, 1999). They are specially designed to have very low friction, have a stroke length of 10 cm and a maximum pressure rating of 690 kPa. The low static friction of the cylinders coupled with high output forces results in a high dynamic range. The maximum force output of 137 N and friction of about 1% of the load yields a dynamic range of over 100.

Linear potentiometers were attached mechanically in parallel with each cylinder and serve as the interface position sensors. Their resolution and precision are derived from that of the A/D converter. The potentiometers' resistances are measured and converted into linear displacements by the controller.

A six-DOF force sensor (JR3, 1999) is used to measure forces at the user's foot in real time. It's maximum load range is $F_{x,y}$ = 1112 N, F_z = 2224 N, and $M_{x,y,z}$ =127 N·m. The sensor can therefore safely withstand the weight of a heavier-than-average person. The sensor is placed directly between the shoe harness and the top platform and is electrically connected to the controller.

The device is inherently safe as it is physically unable to push the ankle beyond its ROM due to the fact that the shin is free to move. The position and orientation of the shin can be measured using a Polhemus 3D magnetic tracker in order to calculate the ankle's orientation (see Fig. 4).

THE CONTROLLER

Figure 5 presents a block diagram of the electronic controller. It outputs 12 air pressures that drive the six double-acting cylinders. Each of these pressures is controlled by two solenoid pneumatic valves: one for intake and the other for exhaust. Seeking to maximize haptic bandwidth, the interface's valves were specially chosen for their low response time and high air flow which are less than 2 ms (500 Hz) and 200 Nl/min, respectively.

The pressures in each of the 12 cylinder air compartments are read by pressure sensors. These differential signals are amplified and are sent to the embedded PC via the A/D card. These pressure values serve as inputs to the low-level pressure regulation loop.

The embedded PC (via the low-level control software) outputs a control signal for each of the 24 pressure valves. These control signals specify whether the valves need to be open or closed. These signals are output as digital signals by the A/D card.

The six position signals from the haptic interface's potentiometers are first filtered and amplified by custom-made boards. They, along with the six force and torque signals from the force sensor, are then sampled and converted to digital by an A/D card and sent to the embedded PC where they serve as inputs to the position and force control loops.

The host PC continually transmits the desired force vector it wants applied to the patient's ankle or the desired position/orientation of the platform. This information comes in across the RS232 line. It is used as an input to the kinematics calculations (performed by the low-level control software) that finds the necessary pressures in the cylinders. The embedded PC's operating system is Windows 95. It runs off of

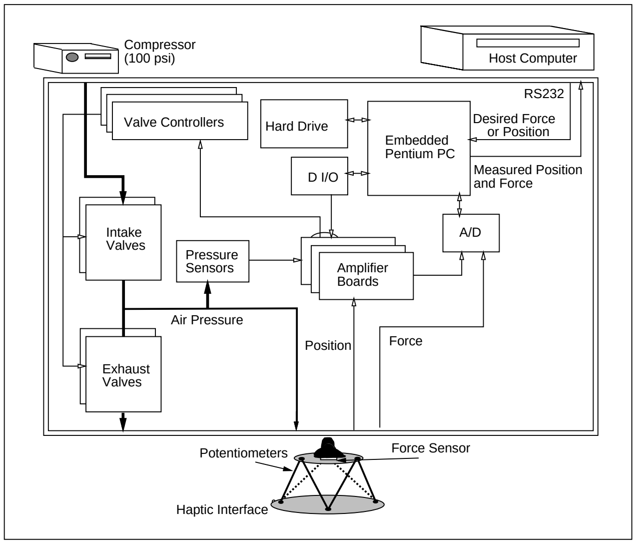

Figure 5. The Controller: Electrical and Pneumatic Block Diagram

a 400 MB hard drive inside the controller.

In the future, the controller will have a compact design and will be attached to the haptic interface (see Fig. 6). This will increase the system's portability and compactness.

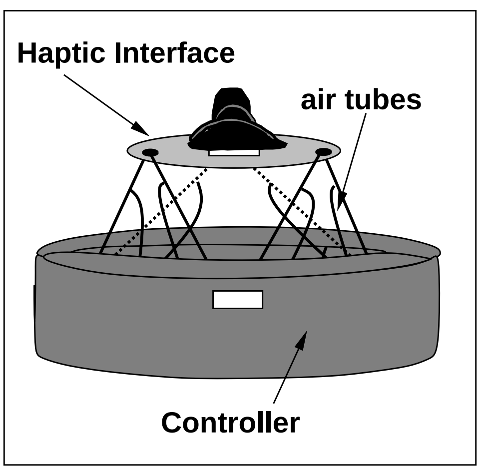

Figure 6. The Compact Design

THE LOW-LEVEL CONTROL SOFTWARE

The low-level control program running on the embedded PC reads the pressures in the actuator cylinders, the actuator translation values, and the force sensor output. The host PC contributes the desired output force or desired position/orientation for the mobile platform.

This program outputs 24 open/close signals to the pressure valve modules during each control loop cycle. The low-level control software sends to the host PC the six force/torque values read by the force sensor and the 3-D position of the mobile platform computed from the six cylinder lengths.

The Software Pressure Control Loop

The main process of the controller interface software is the pressure control loop. The control loop runs at fixed timing rate of 2000 Hz generated by hardware interrupts. Each interrupt, one of the six actuators are controlled, yielding an actuator control bandwidth of 333 Hz. The software loop consists of reading the pressure sensor, comparing it with the desired pressure for the cylinder compartment and then sending a signal to open or close the valves. A software low-pass filter reduces pressure sensor noise.

Kinematic Transformations

The inverse kinematics algorithm is a straight-forward process with a single solution. Its input is a desired position and orientation of the mobile platform with respect to the fixed (global) coordinate system. This is expressed by six components: x, y, z, ψ, θ, and ϕ. Its output is the six lengths of the cylinders necessary to reach that position. In the "Rutgers Ankle," this transformation is used in the position and force control algorithms discussed in the next section.

The forward kinematics algorithm is not as straight forward. It has many solutions and thus requires the use of an iterative method. Its inputs are the six measured lengths of the cylinders 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 as described by six variables: x, y, z, ψ, θ, and ϕ. In the "Rutgers Ankle," 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)

Device Control Loops

Another task of the controller software is to process the control loops that determine the position, orientation, and force/torque output of the haptic interface. It achieves this through both position control and force control. The "Rutgers Ankle" will allow the rehabilitation simulation software to specify either a desired position and orientation of the mobile platform or desired output force and torque vectors. Depending on which data is transmitted, the controller software will implement either position control or force control. These two control modes are necessary in order to allow a wide range of exercise simulations.

Figures 7 and 8 depict the two control loops. They use the following notation conventions:

L is the length of each cylinder.
F is a force vector.
X is a the position/orientation of the mobile platform.
A subscript X means the global, world coordinates.
A subscript L means that that object is related to particular cylinders. For example, L_L is the length of each cylinder, F_L is the force exerted by each cylinder, and P_L is the pressure in each cylinder air compartment.
Desired quantities are denoted by a subscript d.
Measured quantities are denoted by a subscript m.
Errors, differences, and changes are denoted by E. For example, $E_{P_{L_d}}$ is the desired change in the pressure in each of the air compartments.

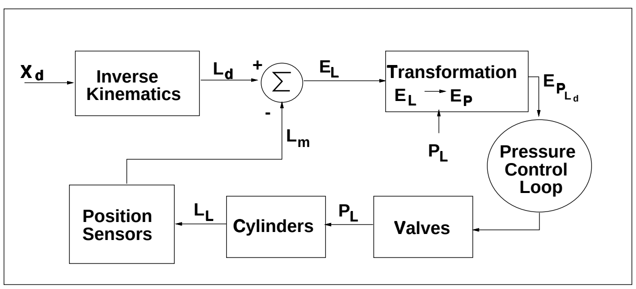

Figure 7. The Position Control Loop

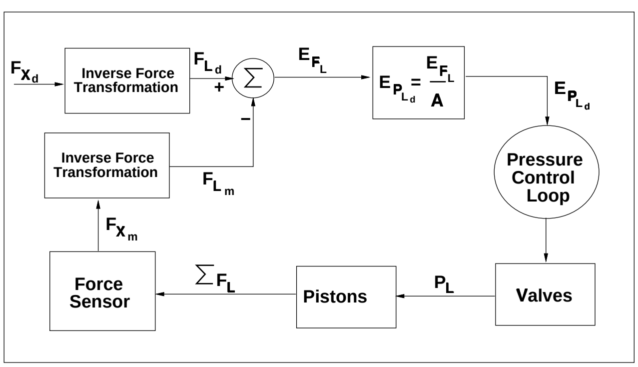

Figure 8. The Force Control Loop

Figure 7 depicts the position control loop. Its input is the desired position of the mobile platform. It uses inverse kinematics to find the desired length of each cylinder. This desired length is compared with the measured length from the position sensors and is converted into a change in length for each cylinder. A transformation is applied to convert the change in length for each cylinder into a change in pressure for its air compartments. This transformation ensures that the change in pressure is directly proportional to the change in length and the measured pressure in each compartment. This change in pressure is fed to the Pressure Control Loop (discussed earlier) which controls the valves to realize the desired pressure at the cylinder's compartments. Position-control exercises include those in which the ROM is limited hapticly. By modeling virtual walls on the foot's sides, for example, the ankle can be limited to planar motion only.

Figure 8 depicts the force control loop that uses the foot force sensor to close the loop. The input to this loop is the desired global force specified by the host computer. The desired global force and the measured global force are each fed into an inverse force transformation. The desired change in each cylinder's output force is then calculated and transformed into a desired change in pressure. The pressure control loop then realizes the new pressure. Some exercises requiring force control will include load lifting exercises and zero-force ROM exercises in which the ankle moves freely while the platform's weight is gravity compensated.

REHABILITATION LIBRARY

The rehabilitation library is composed of a variety of rehabilitation simulation programs that run on the host PC. While patients exercise, their foot position, orientation, and output forces become the inputs and outputs to and from a virtual world. The simulation program forwards data to a patient database which provides a method for the quantitative evaluation of the patient's progress.

Figure 9 shows a block diagram of the host computer software architecture. The device's main exercise types are: strength, flexibility, and balance. Strength exercises are similar to conventional weight-training exercises. Patients move their feet as the device applies resistive forces. Flexibility exercises involve improving patients' ROM by performing repetitive motions near their current limits of motion with little or no opposing forces. Some balance exercises may require the simultaneous use of two mechanical devices, one for each foot (see Fig. 10 for this future design). The large variety of exercises in the library will allow patients immediate access to many different forms of rehabilitation through a single system.

The high-level driver software runs on the host PC. It provides a level of abstraction to help the virtual reality simulation programmer control the platform.

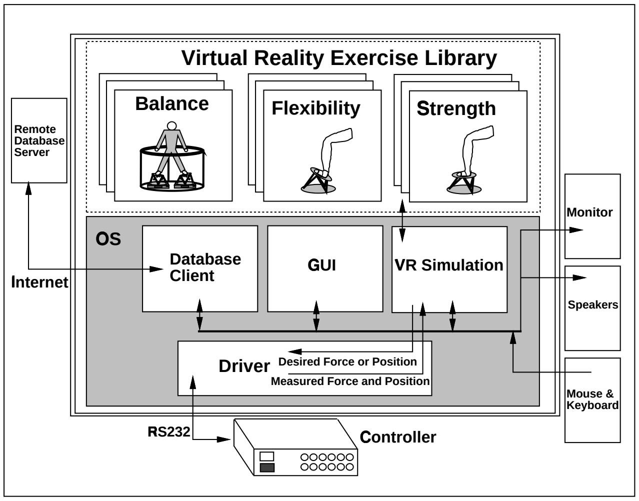

Figure 9. The Host Computer Software Architecture

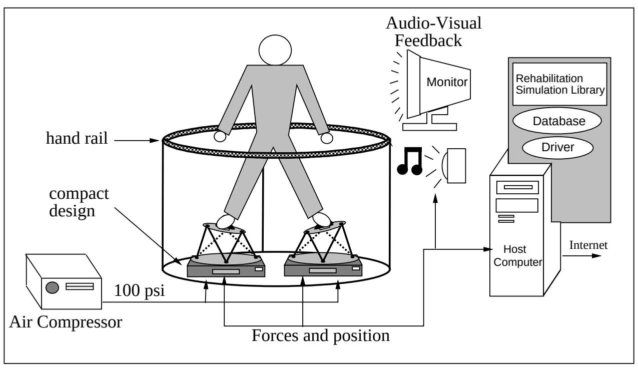

Figure 10. Balance Exercising Using Two Platforms

CONCLUSIONS AND FUTURE WORK

The "Rutgers Ankle" will give patients the ability to perform a variety of different exercises in the comfort of their homes. Because this device interfaces with a computer, a library of virtual reality rehabilitation exercises will be created to make rehabilitation more fun and effective. These simulations will record patient's progress including range of motion and force output. Therapists will be able to monitor the rehabilitation progress of their patients by accessing this patient database.

The "Rutgers Ankle" will provide a novel and hopefully effective way for patients to regain the use and prevent the future injury of the ankle. This device is scheduled to undergo proof-of-concept patient trials during the Summer and Fall 1999. It will subsequently be integrated with our existing orthopedic telerehabilitation system designed for hand, elbow, and knee injuries (Popescu et al., 1999).

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