Judith E. Deutsch
Program in Physical Therapy
UMDNJ-SHRP
Newark, New Jersey

Jason Latonio
Grigore C. Burdea
burdea@vr.rutgers.edu

Rares Boian
CAIP Center
Rutgers University
Piscataway, New Jersey 08854
http://www.caip.rutgers.edu/vrlab/ankle.html

Post-Stroke Rehabilitation with the Rutgers Ankle System: A Case Study

Abstract

The "Rutgers Ankle" is a Stewart platform-type haptic interface designed for use in rehabilitation. The system supplies six-degree-of-freedom (DOF) resistive forces on the patient's foot, in response to virtual reality-based exercises. The Rutgers Ankle controller contains an embedded Pentium board, pneumatic solenoid valves, valve controllers, and associated signal conditioning electronics. The rehabilitation exercise used in our case study consists of piloting a virtual airplane through loops. The exercise difficulty can be selected based on the number and placement of loops, the airplane speed in the virtual environment, and the degree of resistance provided by the haptic interface. Exercise data is stored transparently, in real time, in an Oracle database. These data consist of ankle position, forces, and mechanical work during an exercise, and over subsequent rehabilitation sessions. The number of loops completed and the time it took to do that are also stored online. A case study is presented of a patient nine months post-stroke using this system. Results showed that, over six rehabilitation sessions, the patient improved on clinical measures of strength and endurance, which corresponded well with torque and power output increases measured by the Rutgers Ankle. There were also substantial improvements in task accuracy and coordination during the simulation and the patient's walking and stair-climbing ability.

1 Introduction

Impairments of strength, flexibility, sensory processing, coordination, and balance are consequences of stroke and will affect walking ability. Rehabilitation of stroke patients includes the reduction of impairments and the retraining of function (Schenkman, Bliss, Day, Kemppainen, & Pratt, 1999). In the case of patients who have locomotion problems following stroke, the aim is to reduce the impairments of the affected leg and to restore functional mobility. Such treatment has an intensive stage at the hospital, followed by outpatient clinic regimens, and/or home-based therapeutic intervention.

Impaired walking function is a prevalent deficit post-stroke. Immediately post-stroke, only 37% of stroke survivors are able to walk (Jorgensen, Nakayama, Raaschou, & Olsen, 1995). Of those patients with initial paralysis post-stroke, only 10% regain functional independence (Wandel, Jorgensen, Nakayama, Raaschou, & Olsen, 2000). Of stroke survivors who are not initially paralyzed, 75% do regain their ability to use their affected leg and walk

Presence, *Vol. 10, No. 4, August 2001*, 416–430

independently (Jorgensen et al., 1995). These walking outcomes post-stroke, however, may overestimate recovery because they do not relate walking ability to functional indicators of recovery (Sullivan & Duncan, 2000). For example, a patient who may be independent on the Barthel Index measure used in walking outcome studies (Mahoney & Barthel, 1965) may not be able to cross a street in time for the light to change, or clear a curb when there are distractions in the environment.

There is evidence to support intensive training to decrease walking disability for stroke survivors even a year post-stroke (Wade, Collen, Robb, & Warlow, 1992). Researchers of rehabilitation of the upper extremity post-stroke have shown that the efficacy training appears to require a high intensity (Werner & Kessler, 1996, Kwakkel, Wagenaar, Twisk, Lankhorst, & Koeser, 1999) and repetition (Butefisch, Hummelsheim, Denzler, & Mauritz, 1995). Animal and human models of training post-stroke have been used to demonstrate that recovery at the neural (Nudo, Wise, Sifuentes, & Milliken, 1996; Nudo, 1998), as well as the behavioral level (Dean & Shepherd, 1997) is possible. There is also evidence that training at the level of the impairment may effect function (Duncan et al., 1998). Finally, animal work has shown that brain plasticity in the form of synaptogenesis is greater when the training of a task requires some problem solving (Kleim, Lussnig, Schwarz, Comery, & Greenough, 1996). Therefore, post-stroke training has to be intense, repetitive, and requiring problem solving to produce recovery.

Virtual environments appear to be well suited for rehabilitation of impairments as well as function (Burdea, 1996). By engaging patients, they permit the repetition required for their neural and behavioral recovery. Use of virtual environments that simulate upper-extremity tasks have provided preliminary evidence of task improvements and transfer to real-life environments (Holden, Todorow, Callahan, & Bizzi, 1999, Holden, Dyar, Callahan, Schwamm & Bizzi, 2000). The novelty, interactiveness, and real-time characteristics of virtual environments make them an ideal patient motivational tool. Therapists are also interested in the ability to build and customize VR exercises, and to transparently gather real-time, online, objective clinical data. Therefore, it is not surprising that many researchers have been working on VR-based rehabilitation, for patients with orthopedic (Burdea, Popescu, Hentz, & Colbert, 2000), cognitive, and behavior deficits (Rizzo et al., 2000). Pilot studies done recently for post-stroke patients seem to indicate that hand function improved following VR-enhanced rehabilitation of patients who had had no therapy for years (Jack et al., 2001; Merians et al., 2001).

This paper describes a rehabilitation system designed to provide lower-extremity training using VR for patients with lower-extremity dysfunction. Section 2 presents an overview of the experimental system hardware and software. Section 3 is a case study about the use of the system for rehabilitation of a post-stroke patient. Section 4 concludes the paper.

2 Experimental System

2.1 Hardware

Figure 1 illustrates the components of the "Rutgers Ankle" rehabilitation system used in the present study (Girone & Burdea, 1998; Girone, Burdea, & Bouzit, 1999; Girone, Burdea, Bouzit, Popescu, & Deutsch, 2000). The system's main component is a Stewart platform haptic interface that reads foot position and orientation and applies resistive forces (Stewart, 1966). The Stewart platform design allows the control of forces and torques in six DOF and movement throughout the ankle's full range of motion (ROM). The interface actuators are six commercial glass/graphite, double-acting, pneumatic cylinders produced by Airpot Corporation. The low friction of these 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 (133 N at 690 kPa air pressure). Linear potentiometers are attached in parallel with each cylinder and serve as position sensors. A six-DOF force sensor sandwiched between the mobile platform and foot restraint measures the forces and torques at the patient's foot. The assembly's overall dimensions are a cylinder of approximately 22 cm radius and 34 cm height.

The electropneumatic controller shown in figure 1 regulates the air pressure in the platform actuators using

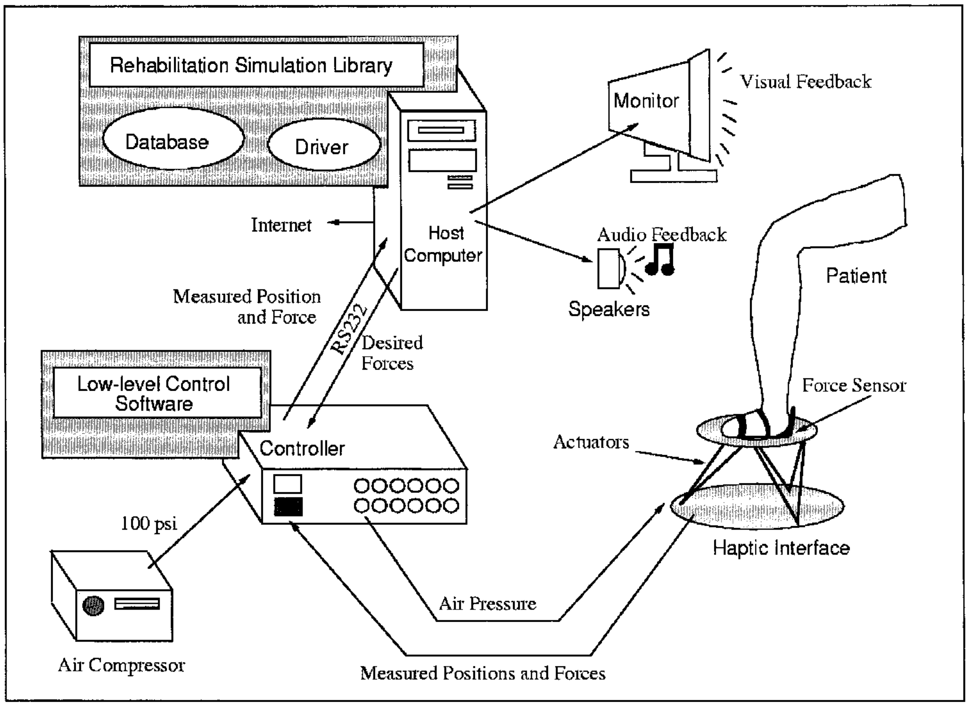

Figure 1. *The Rutgers Ankle rehabilitation system (Girone, Burdea, & Bouzit, 1999). Copyright ASME. Reprinted by permission.*

pairs of exhaust/intake solenoid valves. The valves were chosen for their low response time of 2 ms (500Hz) and high airflow of 200 Nl/min (Patounakis, Bouzit, & Burdea, 1998). In addition to the solenoid valves and their electronic control boards, the controller box contains amplifier boards, A/D/A boards, and an embedded 233MHz Pentium board running Windows 95. The embedded computer handles the actuator servo control, offloading the corresponding computations from a host computer, which is also part of the system.

2.2 Exercise Software

The system software includes the low-level servo control of the platform and the high-level software used for rehabilitation. Other software components are the database necessary to store patient files and the graphical user interface (GUI) that allows the therapist to set exercise parameters. The overall software block diagram is illustrated in figure 2 (Girone, Burdea, & Bouzit, 1999).

2.2.1 Low-level Control Software

The servocontrol software performs the position and force control of the platform. Both types of 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 input is a desired position/orientation of the mobile platform with respect to the fixed (global) coordinate system. Its outputs are 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 cylinder lengths, and its output are the position and orientation of the mobile platform (Dieudonne, Parrish, & Bardusch, 1972; Nguyen & Pooran, 1989).

The low-level control software consists of two functions: an untimed loop and a timed function. 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

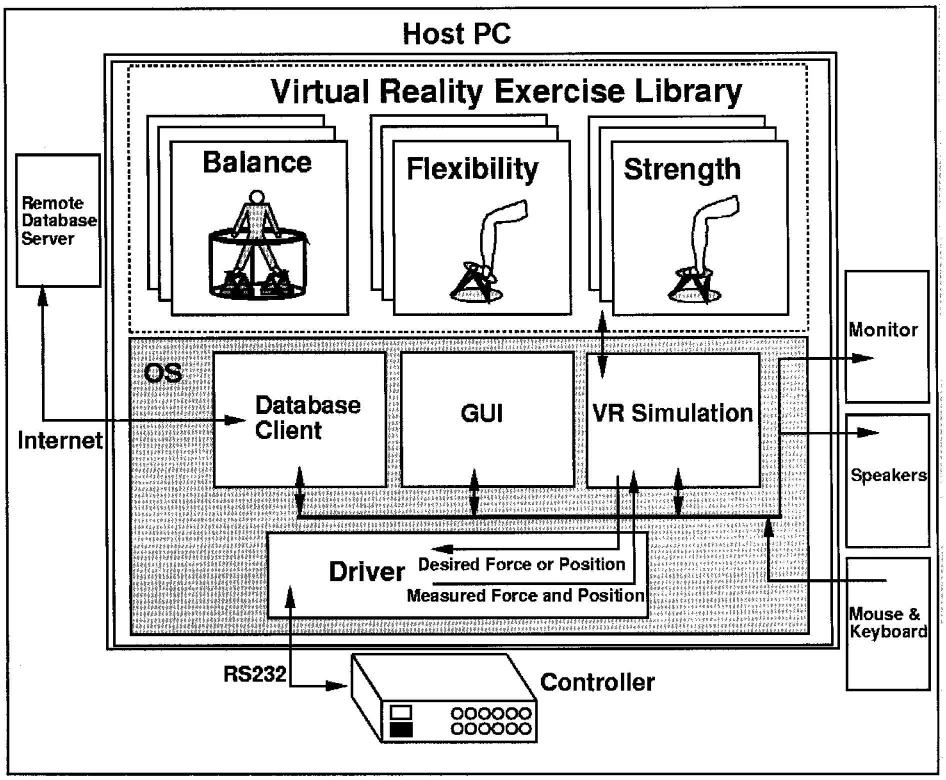

Figure 2. *Software components (Girone, Burdea, & Bouzit, 1999). Copyright ASME. Reprinted by permission.*

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 115Hz. The roundtrip 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 approximately 50 ms.

The position/orientation measurement in Cartesian space has an error margin of 3.5% for translation and 6.7% for rotation due to approximations made in the kinematics model. This position-sensing resolution limits the ankle motion that can be accurately measured by the device. Certain patients may have excursions that are on the order of magnitude of the Rutgers Ankle position resolution. For them, accurate measurement using our system is difficult.

2.2.2 High-level Software The host PC high-level software components are the VR exercise library, the patient database, and the GUI. The PC runs a VR rehabilitation simulation written in WorldToolKit (WTK). The VR exercise consists of three main components: the baseline procedure, the Difficulty Level Selection GUI, and the main ankle exercise.

Figure 3a illustrates a baseline screen used to record the patient's performance before and after an actual routine. The parameters displayed are ankle range of motion (plantarflexion, dorsiflexion, inversion, and eversion), as well as maximum force/torque exertion. The therapist guides the patient through the baseline procedure while the system stores data transparently in a database. The therapist can set the resistance level for the ankle baseline motion at four levels ((1) smallest to largest (4)). The baseline values are then stored and replicated in the difficulty level screen, shown in figure 3b. There are three options for placement of the hoops through which the airplane has to pass: vertical, hori-

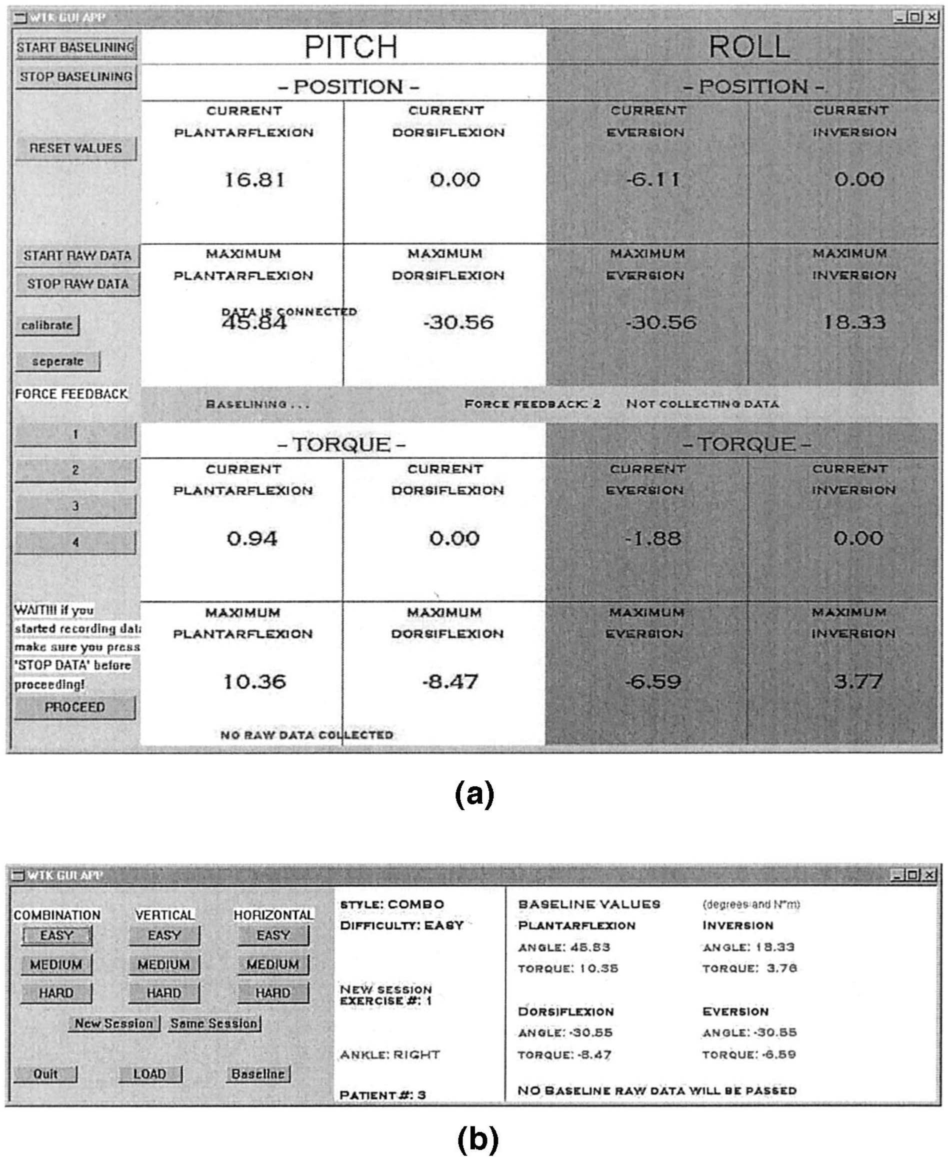

Figure 3. *The GUI screen used in ankle rehab: (a) baseline; (b) level of difficulty. Copyright Rutgers University. Reprinted by permission.*

zontal, and combination. For each hoop placement setting, there are three levels of difficulty: easy, medium, and hard. The levels of difficulty adjust the excursion of the motion. The easy setting requires that patients move the ankle through only part of their available range of motion, the medium setting is at their maximum range, and the hard setting is greater than the maximum range. The level of difficulty and the type of motions are selected by the therapist, based on a patient's individual needs and characteristics, and from the therapy progression.

Figure 4 shows a typical exercise screen with the VR simulation routine, requiring the patient to steer the airplane through loops. The target loop is colored yellow, but once successfully passed it turns green. If the patient clips the loop frame, that portion of the target changes color to red, and a specific auditory cue is provided (see also the back cover of this issue).

Figure 4. *Exercise screen showing the airplane piloted by the patient's ankle. Copyright Rutgers University. Reprinted by permission.*

A score, the number of loops missed, number of loops entered, mode, time, and current loop number are displayed throughout the exercise. The bars on the right side of the exercise screen display the patient's current ankle angles and forces with respect to the patient's baseline values. When the baseline value, represented as a horizontal line, is exceeded, the graph bar turns yellow, indicating that the patient has surpassed the ROM recorded in the baseline procedure.

The therapist can set a multitude of options in the user interface. As in the baseline procedure, the therapist can record data transparently during the exercise, as well as adjust the amount of force applied to the ankle. To adjust the difficulty of the simulation, a variety of parameters can be changed. The airplane movement can be limited to strictly plantarflexion and dorsiflexion, or eversion and inversion, by pressing the respective buttons in the user interface ("normal," "pitch," or "yaw"). This would help a patient that has difficulty controlling one range of movement. The speed of the airplane, as well as the view of the simulation, can also be adjusted. If the therapist sees the patient having difficulty maneuvering the airplane, the therapist can slow down the speed to give the patient more time to get to each loop. Conversely, the therapist can increase the speed to make the patient exercise at a higher level of difficulty. If the patient has difficulty seeing target loops, the therapist can adjust the view of the virtual scene accordingly.

At the end of an exercise, the time history of the ankle motion and forces, as well as mechanical work, is sent to the Oracle database and recorded for future reference. A second layer of data logs the variation of the stored variables between sessions, providing the therapist with objective measures of patient performance. Reports are generated to provide high-level information to the therapist based on the measured raw data. 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 performance improvement by looking at graphs depicting, for example, the number of loops missed for a given difficulty level, or whether the patient is exercising close to his maximum capability.

3 Case Study

3.1 Patient

The patient was a 69-year-old male who sustained a left cerebral vascular accident (CVA) nine months before enrolling in this study. At the time of the stroke, he presented with slurred speech and left-sided paresis. After his stroke, he received three months of inpatient therapy followed by five weeks of physical therapy in his home. At the conclusion of home physical therapy, he was walking short distances with a walker, and on occasion he used a cane.

At the time the patient participated in the virtual reality training, he was attending outpatient physical therapy two times a week. His therapy had focused on improving the use of his right hand, the strength and coordination of his right leg, and his balance and coordination in standing. The patient described that he was walking short distances, approximately a block, using a small base-quad cane, and he was able to negotiate four steps in his house. He occasionally caught or tripped over his left foot during walking. The toe area of his shoe was scuffed.

The purpose of the case study was to determine if VR training (i) produced changes in the patient's ankle and foot mobility, force generation, and coordination, and (ii) whether the VR training transferred to his ability to walk and climb stairs.

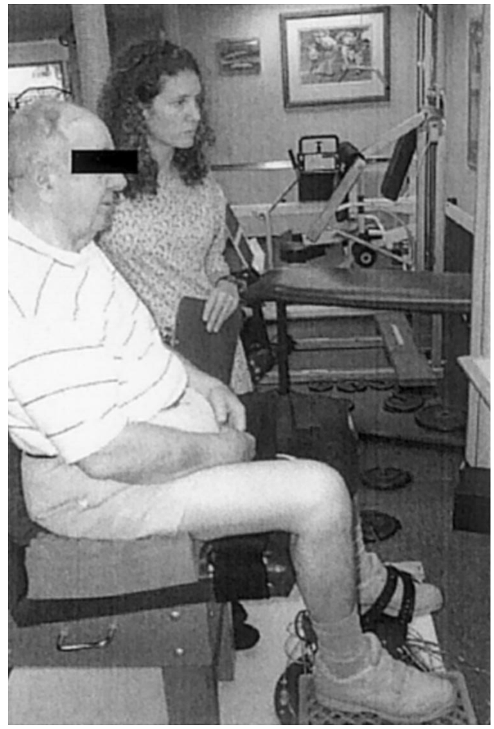

Figure 5. *Stroke patient exercising on the Rutgers Ankle system. Copyright Rutgers University. Reprinted by permission.*

3.2 Protocol

The patient agreed to participate in a two-week pilot study using virtual reality to complement his current therapy and signed a consent form. A baseline clinical exam testing impairments and abilities was performed prior to initiating the VR training. The patient presented with active isolated movement in both lower extremities. There was no resistance to speed-dependent movements of the affected lower extremity. His left upper-extremity motor control was impaired, and he was able to isolate movement against gravity, but had difficulty with fine motor coordination. The patient exhibited speed-dependent resistance to movement in the elbow, wrist, and finger flexors. During gait, he presented with some associated reactions of the right upper extremity. The same clinical tests were administered at the end of the two-week training program.

The Stroke Impact Scale (SIS) (Duncan et al., 1999) was administered at the beginning of the study. His self-report on the SIS section related to mobility and home community indicated that he could not walk one block, walk fast, climb one flight of stairs or several flights of stairs. He reported that it was very difficult to get out of a chair without the use of his hands. Standing and walking without losing his balance and moving from bed to chair were only a little difficult. Sitting and getting in and out of the car were not difficult at all. With the exception of cutting his food and going shopping, he reported that activities that were executed in a typical day were not difficult at all. On a scale of 0–100, he reported that he was 55% recovered from his stroke.

Baseline measures were collected for both the affected and the unaffected lower extremities, using the Rutgers Ankle. Motions were executed first with the unaffected side and then with the affected side. The baseline consisted of having the patient move as far as possible into plantarflexion/dorsiflexion (corresponding to pitch) and inversion/eversion (a combination of roll and yaw) for five repetitions. These movements were performed at four different resistance levels of the Rutgers Ankle platform. A second baseline, which was used to gauge the appropriate level of difficulty of the VR routine, was established by working at the second level of resistance and asking the patient to move as far and as fast as possible. A subjective evaluation was administered on the first, second, and sixth sessions of training, in which the patient was asked to rate aspects of the device and training.

After the baseline testing on the first day, the patient was instructed in the use of the virtual exercise. The plane simulation and its relationship to foot movements were explained briefly to the patient who then practiced piloting the plane. On the second through sixth days of the study, the patient practiced on the device, as illustrated in figure 5.

To ensure reliability of the patient's position with respect to the Rutgers Ankle and the angle at which his lower extremity worked on the device, several measures were taken. First, the distance of the chair to the device was standardized for each session. Second, the knee angle was measured with a goniometer to ensure that the patient worked within ± 5 deg. between sessions. Finally, each time the patient used the Rutgers Ankle, the device was manually set so that the interface read the movement starting from the zero position in the x, y, and z planes.

On the third day of training, changes were made to the inversion/eversion (roll and yaw) motion to make the movements better match the foot. Throughout the training, the degree of difficulty was adjusted by increasing the speed of the plane or the excursion of the foot. As the number of errors (missed loops) decreased, the simulation was made more challenging. The time that the patient practiced was increased, as he was able to tolerate longer durations of exercise. Table 1 summarizes the patient's training schedule. At the sixth session, post-testing was performed.

3.3 Experimental Results

The results from the patient's clinical exam are presented in table 2. The results of the patient's subjective questionnaire are presented in table 3. Post-test results comparing the torque and excursions of the affected and unaffected ankles during performance baselines are presented in table 4. Results comparing the performance accuracy of the affected and unaffected side during the VR simulations are presented in table 5. Results for plantar flexion range of motion changes are shown in figure 6. Results for changes in torque for dorsiflexion and eversion, measured with the Rutgers Ankle, are plotted in figures 7 and 8. Changes in power output of the affected and unaffected ankles are presented in figure 9. The variation in the number of loops entered/minute is shown in figure 10.

3.4 Discussion

Upon the completion of a six-session, VR training program of the ankle, improvements were noted in the force generation, endurance, and coordination of the affected ankle, as well as in the functional mobility of the patient. Improvements in the clinical measures correlated well with the variables collected by the Rutgers Ankle interface.

Clinical measures of force generation (using manual muscle test scores, see table 2) corresponded with changes in torque measured with the Rutgers Ankle during the uniplanar movements for dorsiflexion torque (see figure 7) and everter torque (see figure 8) as well as the performance baseline peak torque values (see table 4). The changes in the clinical muscle test scores may be attributed to neural, rather than skeletal, changes in the muscle. Use of a dynamometer would aid in increasing the sensitivity of the muscle test scores.

Clinically endurance was quantified by the length of time the patient was able to execute individual simulations and the total training time for each session. (See table 1.) These values increased steadily and corresponded well with the measures of power output, collected using the Rutgers Ankle system. The power output of the affected ankle, namely the sum of ankle

Table 1. *Exercise Progression*

	Day Two		Day Three		Day Four		Day Five		Day Six	
Exercise	Speed	Time	Speed	Time	Speed	Time	Speed	Time	Speed	Time
Pitch	40*	3:50	40*	5:00	40	5:00	35**	2:30	40*	2:00
			---	---					50*	1:30
			50*	2:00					30−	2:00
			40*	5:15					40**	
Roll	30*	5:00	30*	3:00	20*	5:00	20−	1:15	30*	2:00
			---	---	15−	3:00	30**	2:15	20**	2:00
			20*	5:00	20**		20**	2:00	20**	2:00
							40*			
Combined	10−	5:00	20*	3:00	15*	5:00	40*	3:00	20*	2:00
	20*		---	---	15**	5:00	25**	2:20	35*	2:00
			10*	4:00			40*	1:00	25**	2:00
	Total Time									
All Exercises	13:50		11:00 --- 17:00		23:00		14:20		17:30	

Speed is in frames
Time is in minutes
Difficulty setting in degree of excursion, related to the performance baseline: it was rated as * easy (part of the excursion) ** medium (the complete excursion)
---line on day three indicates work before the modification in the simulation (above the line) and after the modification of the simulation (below the line)

Table 2. *Clinical Exam*

	Before Virtual Reality Training		After Virtual Reality Training	
	Affected Side	Unaffected Side	Affected Side	Unaffected Side
Strength (MMT)*				
Dorsiflexion	5	5	5	5
Inversion	4	4	5	5
Eversion	5	4	5	5
Pain/discomfort	To palpation along the posterior malleolus and with eversion		Soreness along the posterior tibialis	Soreness along the everter surface
Stairs	Negotiated four steps rail on left in 1:30 sec. (descended with a step-to-step pattern)		Negotiated four steps rail on left 20 sec. (descended with a reciprocal pattern) Negotiated eleven steps which he declined to do pre-training	

MMT manual muscle test: strength measured on a scale of 0-5, with 5 being the strongest.

Table 3. *Subjective questionnaire.*

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
I found the ankle interface easy to use:		Day 1, Day 2 Day 6			
It was difficult for me to use the ankle interface				Day 1	Day 2 Day 6
It was difficult for me to learn how to move my foot while attached to the ankle interface				Day 1 Day 6	Day 2
I had no trouble understanding what to do in the study	Day 2 Day 6		Day 1		
The screen 3-D graphics displays sometimes confused me		Day 6*			Day 1 Day 2
The experiment took too long				Day 1 Day 2	Day 6
My ankle became extremely tired in the experiment		Day 2			Day 1 Day 6
My leg became extremely tired in the experiment		Day 2	Day 1		Day 6
I made many errors		Day 1 Day 2	Day 6		
It was very easy for me to move and hold the virtual foot		Day 1 Day 2 Day 6			
I found it difficult to pay attention to the plane moving through the targets				Day 2 Day 6	Day 1
I did not have any difficulty pressing the interface with the correct force	Day 1 Day 2	Day 6			
There was an improvement in my ability to use the plane simulation	Day 6				
There was an improvement in my ankle during these two weeks	Day 6				
I enjoyed the VR as a complement to my therapy	Day 6				

*for slow speeds

mechanical effort over time (see figure 9), had robust increases over the six sessions.

Coordination, which was measured as an accuracy score reflecting the number of loops the airplane successfully passed, also improved. This was especially true for the Rutgers Ankle configurations that required moving the ankle into all its available motions, switching from agonist to antagonist. (See table 5.) Accuracy scores improved for the affected ankle, and, at the completion of training, they even surpassed the scores of the

Table 4. *Post-Test Results Comparing the Affected and Unaffected Sides During Performance Baselines*

	Day Two		Day Six	
	Affected Side	Unaffected Side	Affected Side	Unaffected Side
Excursion*				
Dorsiflexion	42	50	35	40
Plantarflexion	12	18	26	35
Inversion	37	42	42	38
Eversion	2	18	12 (20 on day 5)	20
Torque**				
Plantarflexion (y)	6	5	8	9
Dorsiflexion (y)	6	4	8	4
Inversion (x)	5	8	8	8
Eversion (x)	2	5	4	5

*Excursion: Range during performance baseline comparison is between day 2 and day 6
**Torque during performance baseline (on day 2 and day 6).

Table 5. *Accuracy during VR simulations*

	Day Three		Day 6	
	Affected	Unaffected	Affected	Unaffected
Accuracy*				
PF/DF vertical	32% (50)	NT	95% (50)	60% (50)
Inv/Ev horizontal	84% (20)	NT	86% (30)	90% (30)
Combination	58%	NT	88% (30)	62% (30)

*Accuracy Targets Hit/Targets Entered * 100 during comparable simulations, speed of plane in parenthesis

unaffected ankle. Furthermore, the rate at which loops were entered improved by 45% over the six rehabilitation sessions, as illustrated in figure 10. This is further indication of increased coordination on the affected ankle.

Several outcomes of the VR training were measured (strength, range, coordination, and flexibility), but several variables that may have been affected by the VR training were not specifically measured. For example, the contribution of the sensory input from the Rutgers Ankle provided by the force feedback may have stimulated the patient's proprioceptive and kinesthetic processing. The visual perceptual effects of looking at the 3-D simulation and coordinating it with the foot movements were also not quantified in this case study. Explanations for the positive outcome of the training will be enhanced with the measurement of these factors.

The patient was able to learn the VR simulation and concentrate on the therapy in an active rehabilitation clinic, with activity and distractions. His subjective evaluation of the experience (detailed in table 3) suggests the patient was engaged in the simulation and found it to be a useful complement to his rehabilitation. His reports of most challenging motions for him—horizontal movements at first (especially eversion) and then the combination movements—are consistent with his performance (using accuracy scores) during the trial.

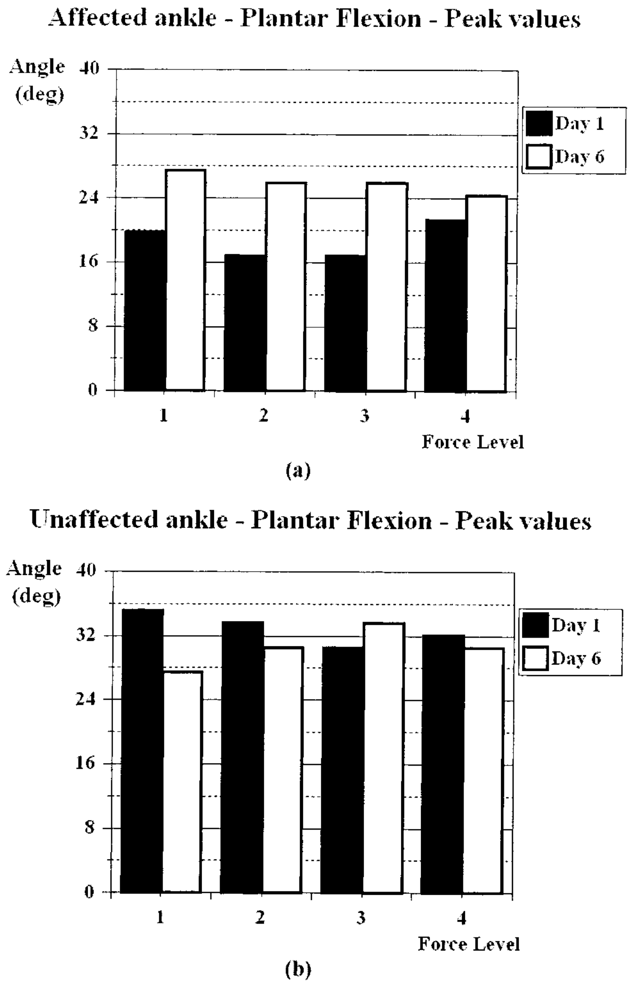

Figure 6. *Plantarflexion range: (a) affected ankle; (b) unaffected ankle.*

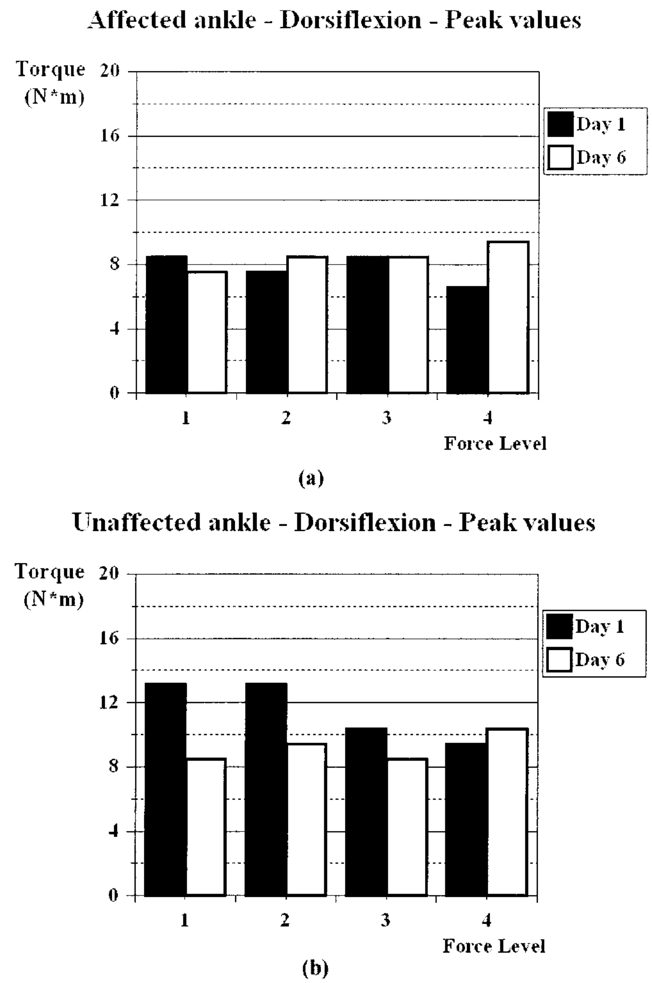

Figure 7. *Dorsiflexion peak torque: (a) affected ankle; (b) unaffected ankle.*

The intensity and duration of training during this trial was lower than that reported by other studies training the upper extremity of patients with chronic stroke (Taub et al., 1993), (Wolf, LeCraw, Barton, & Jann, 1989). The positive results then may be partially explained by the high degree of repetition that is afforded by training in the VR environment and is consistent with work on hand strength (Butefisch et al., 1995). It is important to note that intensity and duration required to train lower-extremity activities for transfer to function are not well described in the literature.

The patient's improvement in stair climbing in the absence of stair-climbing training is remarkable. It appears that training to ameliorate critical impairments may have transferred to function (Schenkman et al., 1999). In this case, the patient's torque increases as well as the endurance of the ankle may be associated with the improved stair-climbing performance. Associations between strength and function have been shown for walking (Bohannon, 1986) and stairs (Bohannon, 1991). Strength gains of the ankle dorsiflexors and everters may partially account for the improvements in stair climbing, and the contributions of coordination as well as sensorimotor integration should also be considered. It would be of interest to parcel the effects of the combination of task-specific

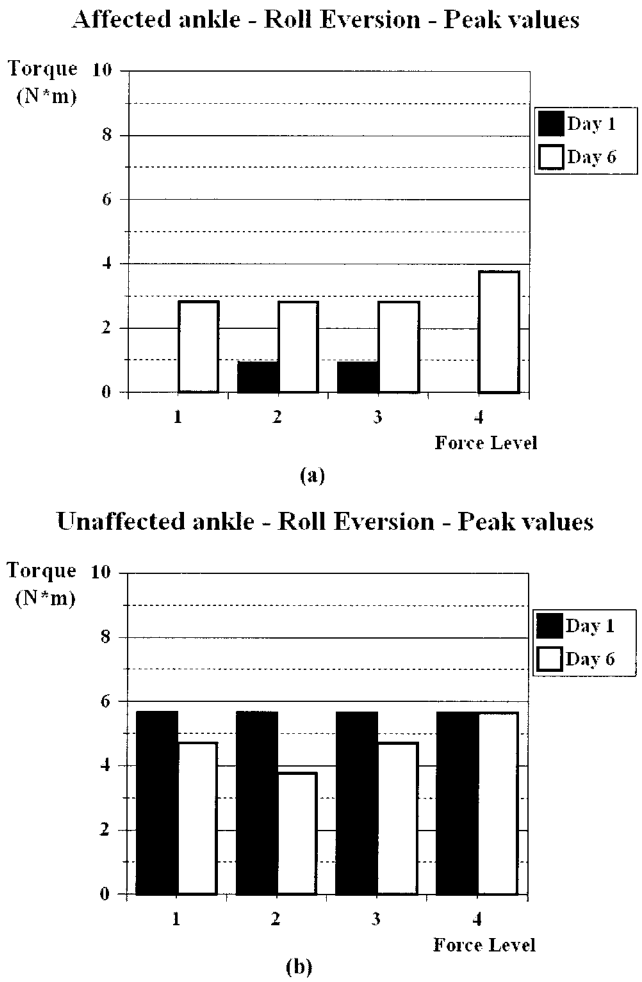

Figure 8. *Eversion peak torque: (a) affected ankle; (b) unaffected ankle.*

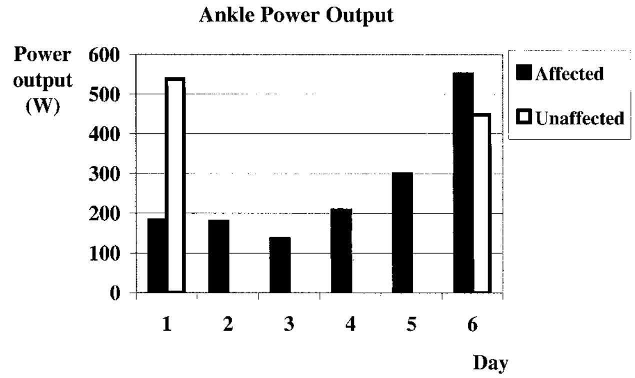

Figure 9. *Power output of the affected versus unaffected ankle.*

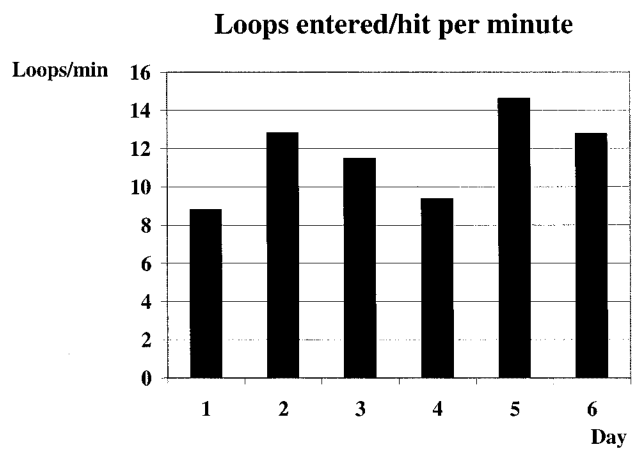

Figure 10. *Loops per minute entered using the Rutgers Ankle on the affected ankle.*

training complemented with this VE simulation as well as the use of VR simulations that include task-specific training.

4 Conclusions and Future Work

To our knowledge, this is the first time that a virtual environment with force feedback has been reported for the use of lower-extremity rehabilitation for a patient post-stroke. The Rutgers Ankle is a novel approach to ankle rehabilitation for stroke patients. Patients interact with a Stewart platform robot, exercising their ankles' three degrees of freedom. The high-level control of positions and forces is handled by a host PC running an interactive virtual environment (VE) simulation. The system with its use of VEs is intended to make rehabilitation more accessible, effective, fun, and motivating.

This case study provides preliminary and promising results about the efficacy of using the Rutgers Ankle for lower-extremity rehabilitation of an individual post-stroke. Further study using controlled research designs is required to define the intensity and duration of the training, as well as how it should complement functional training. The sensitivity of the strength measures could be increased by using a dynamometer instead of the ordinal manual muscle testing scores. The mechanism by which the VE promotes rehabilitation will also have to be elucidated.

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 strap.

Further improvements will be done on the technology side as well. In the future, the electronic controller may be integrated into the base of the Stewart platform to increase the compactness and portability of the system. Furthermore, a calibration routine will be added, such that forces due to the foot's passive weight will be "zeroed out" at the start of the exercise routine. Similarly, position measurements will be zeroed out when the platform supporting the patient's foot is in its initial position parallel to the floor. This calibration will allow a more accurate and reliable measure of foot excursion and mechanical exertion during the VR rehabilitation exercise.

The system will be extended using the Internet as a communication link with the patient's home. Data will then be uploaded from the host PC by a therapist at a remote site for evaluation. As the patient improves, the therapist should be able to remotely modify exercise parameters such as required duration, maximum-opposing forces, allowed ROM, and VE complexity. Finally, the simulations will include standing and walking activities. This will allow the patient to train the limb in the loaded position, which is consistent with many of the functions of the lower extremity.

Acknowledgments

The research reported here was supported by grants from the National Science Foundation (BES-9708020 and REU) and from Rutgers University (SROA and CAIP grants). We wish to acknowledge the Suburban Physical Therapy Center for the use of their facility to conduct the clinical trial. We also thank Jeff Fitzgerald, M.S. P.T., for invaluable assistance with patient recruitment.

References

Bohannon, R. W. (1986). Strength of lower limb muscle related to gait velocity and cadence in stroke patients. *Physiotherapy Canada, 38*(4), 204–206.

———. (1991). Association of paretic lower extremity strength and balance with stair climbing ability in patients with stroke. *Journal of Stroke and Cerebrovascular Disease, 1*, 65–69.

Burdea, G. (1996). *Force and touch feedback for virtual reality.* New York: John Wiley & Sons. Inc., New York.

Burdea, G., Popescu, V., Hentz, V., & Colbert, K. (2000). Virtual reality-based orthopedic tele-rehabilitation. *IEEE Transactions on Rehabilitation Engineering*, *8*(3), 429–432.

Butefisch, C., Hummelsheim, H., Denzler, P., & Mauritz, K. H. (1995). Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand. *Journal of the Neurological Sciences*, *130*(1), 59–68.

Dieudonne, J. E., Parrish, R. V., & 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).

Dean, C. M., & Shepherd, R. B. (1997). Task-related training improves performance of seated reaching tasks following stroke: A randomized clinical trial. *Stroke*, 28, 722– 728.

Duncan, P. W., Richards, L, Wallace, D., Stoker-Yates, J., Pohl, P., Luchies, C., Ogle, A., & Studenski, S. (1998). A randomized controlled pilot study of a home-based exercise program for individuals with mild and moderate stroke. *Stroke, 29,* 2055–2060.

Duncan, P. W., Wallace, D., Min Lai, S., Johnson, D., Embretson, S., & Jacobs Laster, L. (1999). The Stroke Impact Scale Version 2.0-Evaluation of reliability, validity and sensitivity to change. *Stroke, 30*, 2131–2140.

Girone, M. J., & 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., & Bouzit, M. (1999). The Rutgers Ankle orthopedic rehabilitation interface. *Proc. of the ASME, Dynamic Systems and Control Division*, 67, 305–312.

Girone, M. J., Burdea, G. C., Bouzit, M., Popescu, V. & Deutsch, J. E. (2000). Orthopedic Rehabilitation Using the "Rutgers Ankle" Interface. *Proc. of Medicine Meets Virtual Reality 2000*, 89–95.

Holden, M., Todorow, E., Callahan, J., & Bizzi, E. (1999). Virtual environment training improves motor performance in two patients with stroke: Case report. *Neurology Report, 23* (2), 57–67.

Holden, M. K., Dyar T., Callahan, J., Schwamm, L., & Bizzi, E. (2000). Motor learning and generalization following virtual environment training in a patient with stroke. *Neurology Report, 24*(5), 170.

Jack, D., Boian, R., Merians, A., Tremaine, M., Burdea, G., Adamovich, S., Recce, M., & Poizner, H. (2001). Virtual reality-enhanced stroke rehabilitation. *IEEE Transactions on Rehabilitation Engineering* (forthcoming).

Jorgensen, H. S., Nakayama, H., Raaschou, H. O., & Olsen, T. S. (1995). Recovery of walking function in stroke patients: The Copenhagen Stroke Study. *Archives of Physical Medicine and Rehabilitation, 76* (1), 27–32.

Kleim, J. A., Lussnig, E., Schwarz, E. R., Comery, T. A, & Greenough, W. T. (1996). Synaptogenesis and Fos Expression in the motor cortex of the adult rat after motor skill learning. *J. Neuroscience, 16*, 4529–4535.

Kwakkel, G., Wagenaar, R. C., Twisk, J. W. R., Lankhorst, G. J., & Koesier, J. C. (1999). Intensity of leg and arm training after primary middle cerebral artery stroke: A randomised trial. *Lancet* 354, 191–196.

Mahoney, F. I., & Barthel, D. W. (1965). Functional evaluation: The Barthel Index. *Maryland State Medical Journal, 14*, 61–65.

Merians, A., Jack, D., Bolan, R., Tremaine, M., Burdea, G., Ademovich, S., Recce, M., & Poizner, H. (2001). Virtual Reality—Augmented Rehabilitation for Patients Post Stroke: Three Case Studies. *Physical Therapy* (submitted).

NASA Langley Research Center. (1999). Simulation Systems Branch. Visual Motion Simulator. Available at: http://bigben.larc.nasa.gov/facility/vms.html.

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

Nudo, R. J., Wise, B. M., Sifuentes, F., & Milliken, G. W. (1996). Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct. *Science, 272*, 1791–1794.

Nudo, R. J. (1998). Role of cortical plasticity in motor recovery after stroke. *Neurology Report, 22* (2), 61–67.

Patounakis, G., Bouzit, M., & Burdea, G. (1998). *Study of the electromechanical bandwidth of the Rutgers Master* (Technical Report CAIP-TR-225) Piscataway, NJ: Rutgers University.

Rizzo, A., Buckwalter, J., van der Zaag, C., Neumann U., Tiebaux, M., Chua, C., van Rooyen, A., Humphrey, L., & Larson, P. (2000). Virtual environment applications in clinical neuropsychology. *Proc. of IEEE Virtual Reality 2000,* 63–70.

Schenkman, M., Bliss, S. T., Day, D. L, Kemppainen, S., & Pratt, J. (1999). Multisystem model for management of neurologically impaired adults: An update and illustrative case. *Neurology Report, 24* (4), 145–157.

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

Sullivan, K. J., & Duncan, P. W. (2000). New perspectives for locomotor training after stroke: Emerging evidence from basic science and clinical research. *Neurology Report, 25*(2), 55–59.

Taub, E., Miller, N. E., Novack, T. A., Cook, E. W., Fleming, W. C., Nepomuceno, C. S., Connell, J. S., & Crago, J. E. (1993). A technique for improving chronic motor deficit after stroke. *Archives of Physical Medicine and Rehabilitation, 74*, 347–354.

Wade, D. T., Collen, F. M., Robb, G. F., & Warlow, C. P. (1992). Physiotherapy intervention late after stroke and mobility. *British Medical Journal, 304*, 609–613.

Wandel, A., Jorgensen, H. S., Nakayama, H., Raaschou, H. O., & Olsen, T. S. (2000). Prediction of walking function in stroke patients with initial lower extremity paralysis: The Copenhagen Stroke. *Archives of Physical Medicine & Rehabilitation, 81*(6), 736–738.

Werner, R. A., & Kessler, S. (1996). Effectiveness of an intensive outpatient rehabilitation program for postacute stroke patients. *Am. J. of Physical Medicine, 75*(2), 114–120.

Wolf, S. L., LeCraw, D. E., Barton, L. A., & Jann, B. B. (1989). Forced used of hemiplegic upper extremities to reverse the effect of learned nonuse among chronic stroke and head injured patients. *Experimental Neurology, 104*, 125–132.