Technical and Patient Performance Using a Virtual Reality-Integrated Telerehabilitation System: Preliminary Finding

Judith E. Deutsch, Jeffrey A. Lewis, *Member, IEEE*, and Grigore Burdea, *Senior Member, IEEE*

***Abstract*—Telerehabilitation is the provision of rehabilitation services at a distance by a therapist at a remote location. Integration with virtual reality (VR) is a relatively new addition to this field. This paper describes the technical and patient performance of a telerehabilitation application the remote console (ReCon) that is integrated with a VR system. The VR system consists of the Rutgers Ankle prototype robot, a local PC which is connected with a remote PC connected over the Internet. Six individuals in the chronic phase poststroke participated in a four week training program. They used the robot to interact with two VR simulations, while the therapist was in the same room during the first three weeks or in another room during the fourth week. Technical and patient performance was assessed in the transition from the third to the fourth week of training. Technical performance of the system was assessed based on bandwidth and lag of message transmission, which were found to be suitable for clinic-to-clinic communication. Patient performance (in terms of accuracy of ankle movement, exercise duration and training efficiency, mechanical power of the ankle, and number of repetitions) did not decrease during telerehabilitation in the fourth week. These preliminary findings over a short telerehabilitation intervention support the feasibility of remote monitoring of VR-based telerehabilitation without adverse effects on patient performance.**

***Index Terms*—ReCon, Rutgers Ankle, telerehabilitation, virtual reality (VR).**

I. Introduction

TELEREHABILITATION is the provision of rehabilitation services (evaluations and interventions) at a distance by therapists at a remote location. Telerehabilitation can be clinic-based or home-based (see [1] for a review). In a clinic-based environment, a therapist assistant at a remote clinic is being coached by a therapist expert at a tertiary care setting. For home-based telerehabilitation, the patient trains at home while being monitored by a therapist from the clinic.

Manuscript received September 15, 2006; revised December 8, 2006; accepted December 18, 2006. This work was supported in part by the National Science Foundation under Grant BES-9708020 and Grant BES-0201687. This paper was presented in part at the 5th International Workshop on Virtual Rehabilitation, New York, August, 2006.

J. E. Deutsch and J. A. Lewis are with the RiVERS Laboratory (Research in Virtual Environments and Rehabilitation Sciences Laboratory) in the School of Health Related Professions at the University of Medicine and Dentistry of New Jersey, Newark, NJ 07101 USA (e-mail: deutsch@umdnj.edu).

G. Burdea is with the Electrical and Computer Engineering Department, Rutgers University, Piscataway, NJ 08854 USA.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TNSRE.2007.891384

Telerehabilitation presents some advantages over on-site training such as access to care for patients living in remote areas or in underserved urban areas where either clinics or therapists are rare [1]. Training at home through telerehabilitation has the potential to save time and expense for both the patient and the provider [2]. Furthermore, the potential exists to have one therapist oversee several patients exercising at the same time, through a multiplexed setting [3].

Traditionally, telerehabilitation has been administered through video conferencing and video phones, without the use of virtual reality (VR) [4], [5]. More recently, VR has been investigated as a medium of telerehabilitation, whether at a clinic [6], or at home [7], [8].

Telehealth is recognized by the American Physical Therapy Association (APTA) and is defined to include physical therapy-related services over a distance. The Board of Directors of the APTA has recently revised their guidelines on telehealth, to reflect the requirement that quality of healthcare be comparable to the physical therapist being physically present with the patient [9]. Meeting these standards with telerehabilitation will play a role in improving therapist acceptance and patient satisfaction, which are regarded as challenges to the success of telemedicine as a whole.[1]

The remote console (ReCon) [10] is a telerehabilitation system designed to provide therapists, at a remote location, the tools necessary to oversee the patient's rehabilitation session in real-time. This system provides the therapist: three-dimensional representations of patients' movements, VR-based exercise progress, and performance updates, while the patient is exercising (Fig. 1). During the session, the therapist evaluates the patient's performance and either modifies the current exercise, or sets up the next one. The remote therapist is also provided with tools for audio and video communication with the local site and chat communication with the local therapist.

In an effort to make the ReCon a useful tool for telerehabilitation, this system has evolved [11], [12] through a series of usability studies and pilot clinical trials, testing its effectiveness, ease of use and acceptance by both patients and therapists [9], [13], [14]. The telerehabilitation application described here is an implementation of the ReCon for use with the Rutgers ankle rehabilitation system (RARS) [15]. This system uses a prototype robot to support and resist the movement of a patient's ankle, while in sitting, as they navigate through two virtual environments.

[1]http://www.apta.org/AM/TemplateRedirect.cfm?template=/CM/ContentDisplay.cfm&ContentID=26233

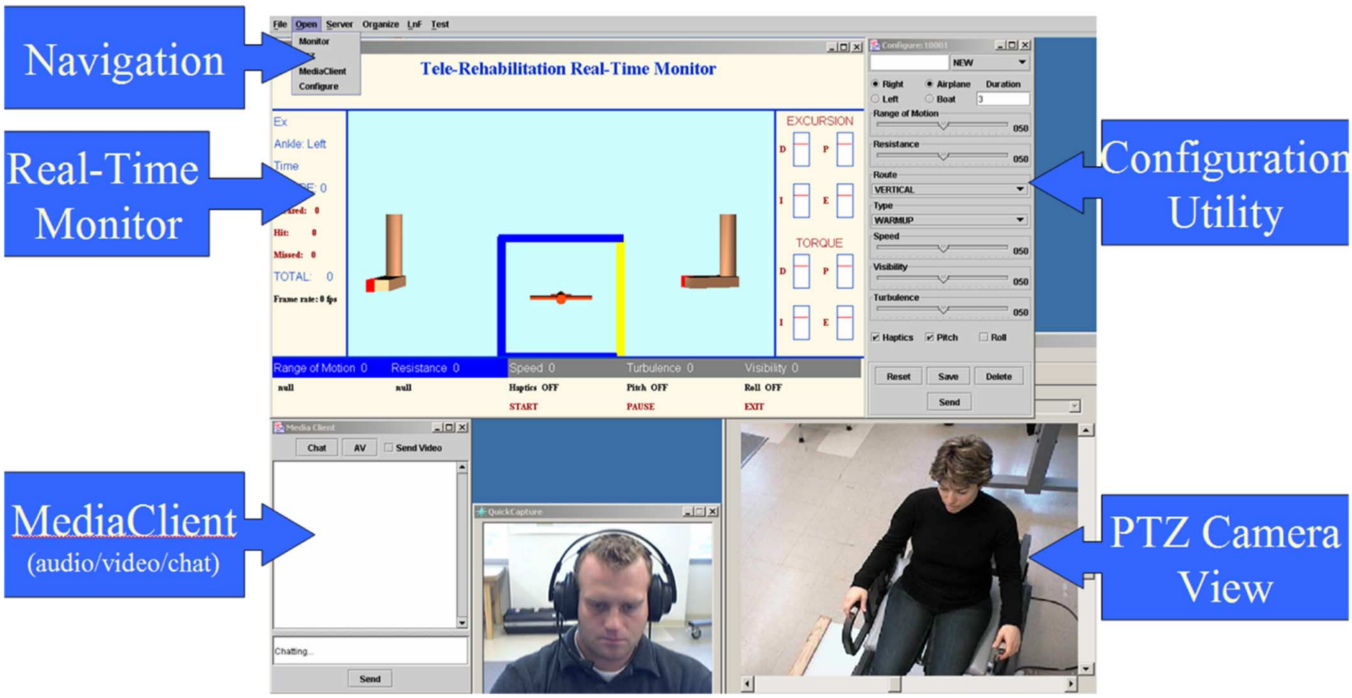

Fig. 1. ReCon desktop for a lower extremity exercise [9].

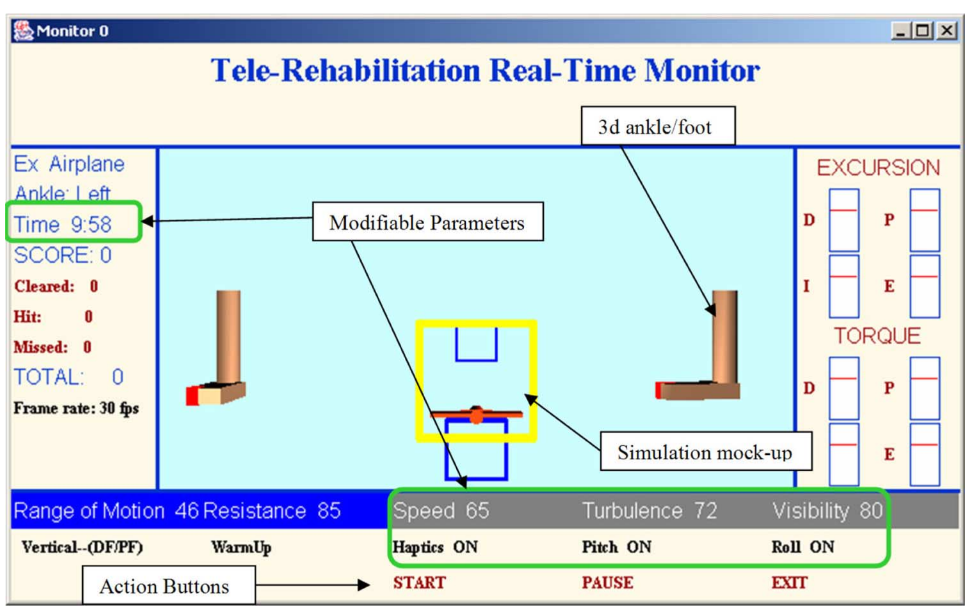

Fig. 2. Real-time monitoring and exercise modification detail [16]. Used with permission, UMDNJ, Rutgers University 2005.

The purpose of this paper is to evaluate the integrated telerehabilitation system by examining the technical performance of the ReCon, as well as patient performance during a pilot clinical study using the RARS conducted by our group. We sought to determine if patients' performance would be adversely affected once the therapist directed the training remotely.

II. Methods

A. *Telerehabilitation Setup*

For rehabilitation sessions, conducted from a remote location, the therapist would log into the ReCon using Java WebStart. When the ReCon was initialized it connected to the hub node located on a specific server to identify additional server nodes and rehabilitation sessions. The therapist then selected the rehabilitation location from a list to connect via the MediaClient, the component that handles audio and video communication as well as chat. At the rehabilitation location, the subject was positioned in the RARS by the local therapist and prepared to exercise. While the patient was exercising, the remote therapist was able to view the subject via video and watch their performance in the monitoring application (Fig. 2). This "real-time monitor" is an essential component of the ReCon application depicted in Fig. 1 because it displays the subject's current status and progress while allowing the therapist to modify the exercise remotely.

During the exercise, the remote therapist monitored the patient by observing the position of the patient's foot from two viewing angles, followed a mock-up of the airplane or boat simulation trajectories, and viewed gauges of their ankle excursion and torque current values in dorsiflexion, plantarflexion, inversion, and eversion. The remote therapist chose various parameters and interacted directly with the simulation in real time. As an example, the therapist could increase the speed of the airplane (or boat) to make the exercise more difficult, or decrease the duration of the exercise if the patient appeared fatigued and was making errors.

B. Technical Performance: Quality of Service Testing

The server nodes, used in the ReCon networking framework, communicate with each other via flexible and expandable message structures. An application programmer interface (API) was implemented in Java and C in order to pack and unpack messages sent between the rehabilitation and remote sites. The API allows bidirectional communication between the ReCon used by the remote therapist (developed in Java) and VR Simulations (developed based on C, C++, or Java) via the communication protocol (C++). The ReCon node continuously pings each node on the network to determine from which node it should retrieve the simulation data.

The technical performance of the system described above was assessed during testing over the Internet between Rutgers University, Piscataway, NJ, and the University of Medicine and Dentistry of New Jersey (UMDNJ), Piscataway, NJ (about 50 km apart). The communication parameters of the ReCon were tested under various conditions. Round trip delay times were calculated between the ReCon at one site, server nodes located on and off site, as well as a simulation node, which is transmitting from a rehabilitation location. To determine round trip time, the ReCon server node sent a ping message to every node on the network and documented the time it took to receive the message back. This was done during various remote monitoring tasks, which were deliberately run during testing (initialization and pinging, monitoring, receiving and transmitting audio and video). Round trip delay was recorded between the ReCon located at UMDNJ and 1) the **hub** node; 2) the **simulation** node at the Human–Machine Interface Laboratory at Rutgers University; 3) a **local** node on the same machine as the ReCon. The hub node maintains the network of nodes and node information, the simulation node communicates directly with the VR exercise application and sends the data to the network of nodes, and the local node is the node closest to the ReCon on the network.

C. Patient Performance: Study Overview and Subjects

The main objective of the pilot study, which included one week of telerehabiliation was to test the transfer of training from lower extremity (LE) exercising in virtual environments (VE) to over-ground walking. Detailed methods are described elsewhere [17], [18]. Six individuals (one female and five male) between eight months and four years poststroke participated in this study. They were able to walk 50 ft without physical assistance and exhibited minimal active antigravity dorsiflexion. Subjects trained three times a week, for 1 h per session, over four weeks using the following schedule:

Week 1: plane piloting exercise;
Week 2: plane piloting with haptic effects;
Week 3: boat sailing and plane piloting with haptic effects;
Week 4: boat sailing and plane piloting with haptic effects *performed under telerehabilitation.*

Individuals poststroke performed LE training in the VE using two simulations (plane piloting and boat sailing through targets) embedded in a series of exercises that combined warm up, endurance, strengthening, coordination, and speed of their affected ankle. Their performance was evaluated as they transitioned from having a therapist on-site to working with the therapist remotely. This transition occurred between the third and fourth week of training. The sessions performed under telerehabilitation were monitored in a remote location in the same building as the room where the subjects trained.

TABLE I
BANDWIDTH USAGE BY MESSAGE TYPE [19]

Message Type	Msg/s	Size(Bytes)	bps
Ping	1.0	24	192
Ankle Baseline Data	33.3	100	26667
Ankle Configuration Data	33.3	64	17067
Airplane Data	33.3	173	46133
Boat Data	33.3	185	49333

III. RESULTS

A. Technical Performance

Technical tests were conducted to gauge the system performance over geographically longer distances than on-site monitoring. The messages sent with regularity are meant to remain small (Table I). For instance, to send a complete record of an airplane simulation, including the position and orientation of the plane, the subject's foot position, force measurements on the Rutgers Ankle platform [15], target placements, and all simulation parameters, 173 bytes are passed. Since, typically, audio and video are transmitted from the same machine, a mechanism was put in place to reduce the frequency of messages sent based on the available bandwidth. Table II depicts various network conditions, the delay between messages, and the resultant bandwidth use for that connection. Finally, Table III details the lag time when sending messages between the ReCon and nodes on the network under various conditions of telerehabilitation. This measure would indicate the time that will pass between the occurrence of an action and the time it is displayed or implemented on the opposite end.

B. Patient Performance

The patients' performance was assessed by extracting the following variables from the RARS database: accuracy (the number of targets successfully negotiated by the plane or boat, out of all targets presented); power (mechanical work achieved

TABLE II
AVERAGE BANDWIDTH USAGE BY CONNECTION TYPE FOR DATA [19]

Connection Type	Delay(ms)	Msg/s	bps
T1 / LAN	30	33.3	44725
DSL / Cable	60	16.7	22459
Dial-Up	120	8.3	11325

TABLE III
AVERAGE LAG BETWEEN REHAB SITE AND VARIOUS NODES (MILLISECONDS)

Condition / **Node**	**Hub**	**Simulation**	**Local**
Pinging	56.8	55.3	4.7
Monitoring	61.5	278.4	4.4
AV	60.5	257.9	4.8

during exercise as a function of the time spent exercising); repetitions (the number of targets presented, where each target represents a required movement); duration (sum of actual exercise time across all trials in a session); and efficiency (the ratio of actual exercise time versus the total time spent with each subject in one day).

Each of these variables was analyzed using repeated measures ANOVA with training week as the repeated measure. Statistical significance was established with an alpha level of 0.05. Post hoc comparisons were made using paired t-tests with the alpha level adjusted for multiple comparisons $.05/3 = .02$.

The following results for the group performance measures are also illustrated in Fig. 3.

Accuracy increased from 70% in the first week to 83% in the telerehabilitation (last) week ($F1.8 = 6.8$, $p = .018$). The only significant difference was between weeks 1 and 2. Accuracy did not decrease in the transition between the local training (third week) and telerehabilitation training (fourth week) [Fig. 3(a)].

Mechanical Power for the affected ankle increased from a mean of .42 Nm/s (.22 sd) in the first week to 0.71 Nm/s (.30 sd) in the last week ($F2.4 = 8.83$, $p = .004$). The only significant difference was between weeks one and two. Power increased by 6.4% from week 3 to week 4 [Fig. 3(b)].

Repetitions of ankle movements increased from an average of 173 (44 sd) repetitions the first week to 473 (77 sd) repetitions by the telerehabilitation (fourth) week ($F1.5 = 44$; $p < .000$). Increases between weeks 1, 2, and 3 from 173 to 324 to 401 repetitions, respectively, were significant. The increase from week 3 to 4 from 401 to 453 repetitions was not significant ($p = .07$) [Fig. 3(c)].

Duration of training (sum of all time spent exercising during a session) increased from an average of 32 min the first week to 50 min the last week ($\mathrm{F3} = 12.38$, $\mathrm{p} < .000$). The total exercise duration increments from week 1 (32 min) to week 2 (40 min), and week 2 to week 3 (50 min), were significant. Duration was the same for week 3 and four (50 min) [Fig. 3(d)].

Efficiency of training time improved from 56% at week 1 to 72% at week 4 ($F1.6 = 9.1$, $p = .01$). The increase in efficiency from 54% at week 1 to 70% at week 2 was the only significant weekly change. Efficiency between week 3 and 4 remained the same at 72% [Fig. 3(e)].

IV. DISCUSSION

A. *Technical Performance*

The results of the technical tests suggest that as message sizes were relatively small, messages were transmitted frequently enough, without significant lag and consuming excessive bandwidth. These parameters were considered acceptable for a clinic-to-clinic monitoring system where network conditions might be optimized. To account for various network conditions, the latest version of the ReCon allows for several settings for different connections to the internet (dialup, cable/DSL, T1). Under lower bandwidth conditions, frequency of real-time data transmission, and, therefore, bandwidth requirements, are reduced. This is done partially to preserve the integrity of audio streaming. Additionally, video quality is reduced to free additional bandwidth. While the video and the real-time monitor are still effective at lower rates and quality settings, audio degradation renders sound feedback unusable if the bandwidth is not sufficient. A separate speakerphone connection may be used to alleviate the problem.

B. *Patient Performance*

Initial findings on this small patient sample indicate that patient performance was not adversely affected by the transition of the therapist from the same room as the patient to a "remote" site. The average weekly data indicate that patients were able to either sustain their performance (accuracy of ankle movement, exercise duration, and training efficiency) or increase it (mechanical power of the ankle and repetitions) under telerehabilitation settings. However, the increases for the subjects group were not statistically significant in the telerehabilitation setting. The sessions that mark the transition between the third and fourth week of training (sessions 9 and 10) indicate there was some decrease in performance on the first day (see, for example, power, repetition and exercise duration) of telerehabilitation. This finding, however, is comparable to the transition between week two and three (sessions 6 and 7) when a new simulation exercise is introduced. Thus, it is possible that the temporary reduction in group performance in the first telerehabilitation session was due to exposure to a new way of communicating with the therapist, which the poststroke participants had to learn. Previously we reported patient acceptance of the ReCon system and with one notable exception the participants were comfortable with the remote monitoring [12].

It is important to note that, during the fourth week, patients were not exercising independently. While the primary therapist that had overseen the treatment in the previous three weeks was in another room, a second therapist remained in the same room with the patients. While the local therapist did not direct the session, he was nonetheless a presence in the room. In addition,

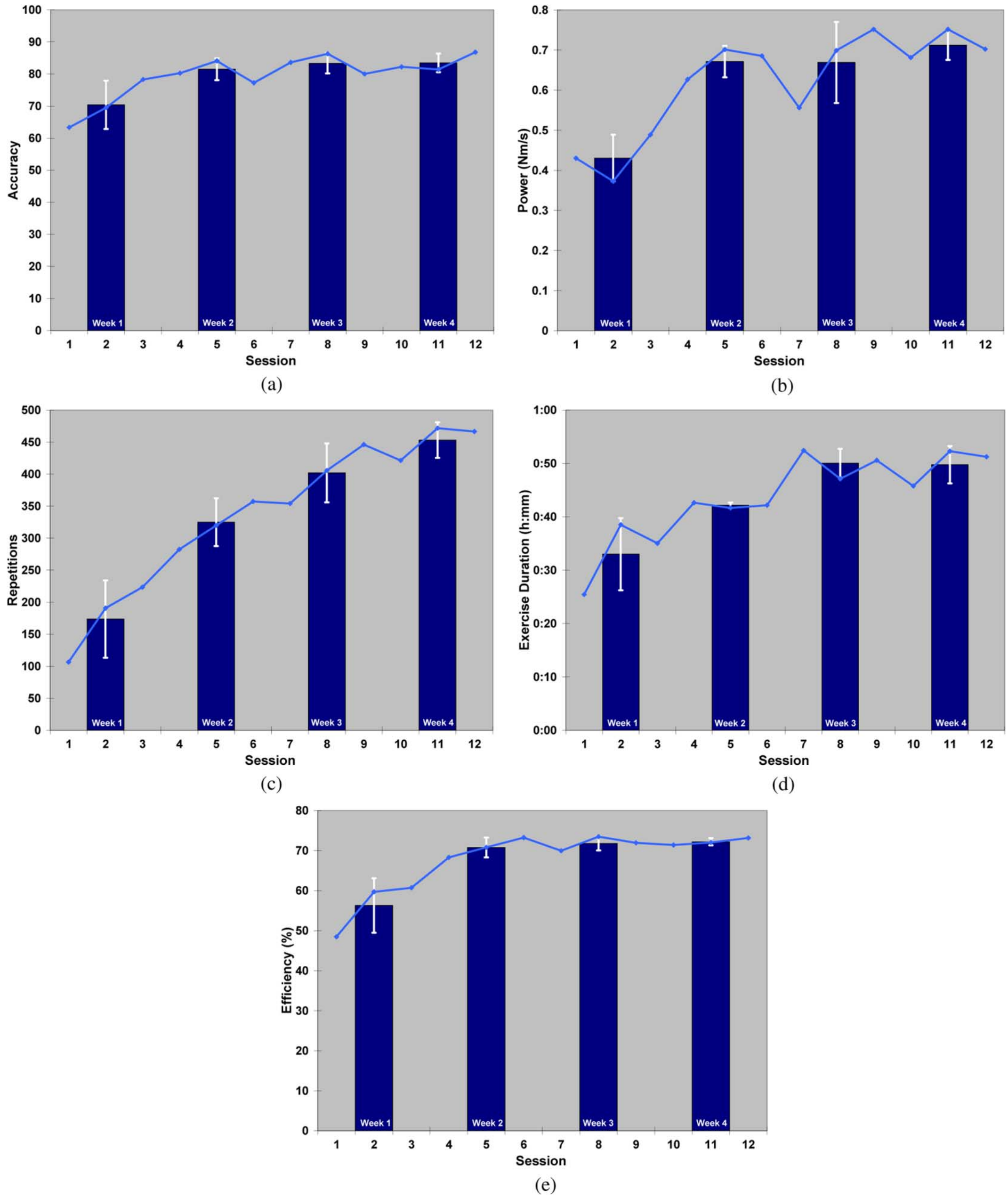

Fig. 3. Patient performance as a group during VR training of their affected ankle. Bars represent weekly averages. Lines represent session averages across all subjects. Used with permission UMDNJ and Rutgers University, 2006. (a) **Accuracy** (%): percentage targets hit out of targets presented. (b) **Power** (Nm/s): mechanical works as a function of exercise duration. (c) **Intensity** (repetitions): number of movement repetitions per session. (d) **Durantion**: (h: min): time spent exercising during a rehabilitation session. (e) **Efficiency** (%): time spent actually exercising out of total session lenght.

the remote monitoring was done within the same building eliminating many of the technical challenges that would be encountered at a greater distance. Finally, the telerehabilitation component of this study was only 25% of total training. Familiarization with the system and the exercises was provided by the on-site therapist. Telerehabilitation of the entire training program compared to on-site training will allow more definitive statements about the effectiveness of remote rehabilitation.

V. Conclusion

These preliminary findings indicate that technical requirements for a clinic-based telerehabilitation environment were successfully addressed. However, additional testing of the VR integrated rehabilitation system should be performed under degraded network conditions, as well as when patients exercise independently, without any therapist present in the room. The main finding here with regard to telerehabilitation is an indication that the group performance was maintained during the transition from onsite to remote rehabilitation.

Acknowledgment

The authors would like to thank C. Vecchione DPT, C. Paserchia DPT, A. Mirelman MS, PT, for assistance with data collection.

REFERENCES

[1] M. Rosen, "Telerehabilitation," *Neuro. Rehabil.*, vol. l, no. 12, pp. 11–26, 1999.

[2] S. Dhurjaty, "The economics of telerehabilitation," *Telemedicine J. E-Health*, vol. 10, no. 2, pp. 196–199, 2004.

[3] G. C. Burdea, "Low-cost telerehabilitation," presented at the Proc. 3rd Int. Workshop Virtual Rehabil., Lausanne, Switzerland, Sep. 1–7, 2004.

[4] P. Clark (Forducey), S. J. Dawson, C. Scheideman-Miller, and M. Post, "TeleRehab: Stroke teletherapy and management using two-way interactive video," *Neurol. Rep.*, vol. 26, no. 2, pp. 87–93, 2002.

[5] Telerehabilitation Alina hospitals and clinics, 2006 [Online]. Available: http://www.allina.com/ahs/ski.nsf/page/ar_tele

[6] G. Burdea, V. Popescu, V. Hentz, and K. Colbert, "Virtual reality-based orthopedic tele-rehabilitation," *IEEE Trans. Rehabil. Eng.*, vol. 8, no. 3, pp. 429–432, Sep. 2000.

[7] D. J. Reinkensmeyer, C. T. Pang, C. A. Nessler, and C. C. Painter, "Web-based telerehabilitation for the upper-extremity after stroke," *IEEE Trans. Neural Sci. Rehabil. Eng.*, vol. 10, no. 2, pp. 102–108, Jun. 2002.

[8] M. K. Holden, T. Dyar, and L. Dayan-Cimadoro *et al.*, "Virtual environment training in the home via telerehabilitation," *Arch. Phys. Med. Rehabil.*, vol. 85, no. 8, p. E12, 2004.

[9] J. A. Lewis, R. Boian, G. Burdea, and J. E. Deutsch, "Remote console for virtual telerehabilitation," in *Proc. MMVR 2005*, Long Beach, CA, Jan. 2005, pp. 294–300.

[10] K. Collins, P. Nicolson, and I. Bowns, "Patient satisfaction in telemedicine," *Health Informatics J.*, pp. 81–85, Feb. 2000.

[11] V. G. Popescu, G. Burdea, and R. Boian, "Shared virtual environments for telerehabilitation," in *Proc. Med. Meets Virtual Reality 2002*, Newport Beach, CA, Jan. 23–26, 2002, pp. 362–368.

[12] J. A. Lewis, R. F. Boian, G. C. Burdea, and J. E. Deutsch, "Real-time web-based telerehabilitation monitoring," in *Proc. Med. Meets Virtual Reality 11*, Newport Beach, CA, Jan. 2003, pp. 190–192.

[13] J. E. Deutsch, J. A. Lewis, E. Whitworth, R. F. Boian, G. Burdea, and M. Tremaine, "Formative evaluation and preliminary findings of a virtual reality telerehabilitation system for the lower extremity," *Presence*, vol. 14, no. 2, pp. 198–213, 2005.

[14] J. Lewis, J. E. Deutsch, and G. Burdea, "Usability of the remote console (ReCon) for virtual reality telerehabilitation: Formative evaluation," in *Int. Workshop Virtual Rehabil. (IWVR05)*, Catalina Island, CA, Sep. 2005, pp. 83–92.

[15] M. Girone, G. Burdea, M. Bouzit, V. G. Popescu, and J. Deutsch, "A Stewart platform-based system for ankle telerehabilitation," *Autonomous Robots*, vol. 10, pp. 203–212, Mar. 2001.

[16] J. E. Deutsch, C. Paserchia, C. Vecchione, A. Mirelman, J. A. Lewis, R. Boian, and G. Burdea, "Improved gait and elevation speed of individuals post-stroke after lower extremity training in virtual environments," *J. Neurologic Phys. Therapy*, vol. 28, no. 4, pp. 185–186, 2004.

[17] J. E. Deutsch, R. Boian, and G. Burdea*, Transfer of training from lower extremity virtual reality training of the lower extremity to gait and elevations for individuals post-stroke*, submitted for publication.

[18] J. E. Deutsch, J. A. Lewis, and E. Whitworth, Virtual reality and remote monitoring training tutorial RiVERS Lab., Univ. Medicine Dentistry New Jersey (UMDNJ), Newark, Aug. 2004.

[19] J. A. Lewis, "Remote console for telerehabilitation in virtual environments," M.S. thesis, Elec. Comp. Eng. Dept., Rutgers Univ., Piscataway, NJ, May 2005.

Judith E. Deutsch received the B.A. in human biology from Stanford University, Stanford, CA, the M.S. degree in physical therapy from the University of Southern of California, Los Angeles, and the Ph.D. degree in pathokinesiology from New York University, New York. She completed a postdoctoral fellowship in Rehabilitation Research at the University of Medicine and Dentistry New Jersey (UMDNJ), Newark.

She is Professor and Director of the Research in Virtual Environments and Rehabilitation Sciences (RiVERS) in the doctoral programs in physical therapy at UMDNJ. She contributes to the advancement of rehabilitation for individuals poststroke through her scholarship of teaching and research. Her current research includes the development and testing of virtual reality rehabilitation systems to improve functional mobility. She is the Editor in Chief of the *Journal of Neurologic Physical Therapy* and a member of the Editorial Board of the *Journal of Neural Engineering Research*. She is a member of the Master Educator Guild at UMDNJ.

Jeffrey A. Lewis (M'02) received the B.S. in computer engineering from the School of Engineering, Rutgers University, Piscataway, NJ, in 2002 and the M.S. in computer engineering from the Graduate School of New Brunswick, Rutgers University, New Brunswick, NJ, in 2005. His thesis work, *Remote Console for Telerehabilitation in Virtual Environments*, focused on the development of a telerehabilitation system utilizing virtual reality.

He is currently the Research Engineer in the doctoral program in physical therapy, the Research in Virtual Environments and Rehabilitation Sciences (RiVERS) Laboratory, University of Medicine and Dentistry of New Jersey (UMDNJ), Newark. He also serves as a consultant for research and development on virtual reality rehabilitation systems.

Grigore Burdea (M'86–SM'89) received the Ph.D. degree in applied science from New York University, in 1987. He has been with Rutgers University, Piscataway, NJ, since 1988, currently serving at the rank of Full Professor in the Department of Electrical and Computer Engineering.

In 1988, he founded and since served as Director of the Human–Machine Interface Laboratory. His team research produced novel robots to provide force feedback to the fingers or the ankle during virtual reality interactions. Currently, he is pursuing research in virtual rehabilitation, a term Burdea coined. His publications include over 120 refereed scientific publications, as well as several textbooks on virtual reality and haptics.

Dr. Burdea served as General Chair of the IEEE Virtual Reality International Conference (2000) and of the International Workshop on Virtual Rehabilitation (2003 and 2006).