Virtual Reality-Integrated Telerehabilitation System: Patient and Technical Performance

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***Abstract*— Telerehabilitation is the provision of rehabilitation services at a distance, by a therapist at a remote location. Telerehabilitation, integrated with virtual reality, is a relatively new addition to this field. This paper describes the technical and patient performance of a virtual reality based telerehabilitation system for ankle training. Telerehabilitation was introduced in the fourth week of a lower extremity virtual reality-based training program for individuals post-stroke. Technical performance of the system was assessed based on bandwidth and time lag of message transmission, which were found to be suitable for clinic-to-clinic communication. Patient performance in the transition from the third to the fourth week of training remained the same (for accuracy of ankle movement, exercise duration and training efficiency) or increased (mechanical power of the ankle and number of repetitions). These findings strengthen the case for virtual reality based telerehabilitation.**

I. Background and Purpose

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 Rosen [1] for a review). In a clinic-based telerehabilitation environment, a therapist assistant at a remote (or rural) clinic is being coached by a therapist expert at a tertiary care (or university) setting. For home-based telerehabilitation, the patient trains at home while being monitored by a remote therapist from the clinic. Traditionally, telerehabilitation has been administered through video conferencing and video phones, without the use of virtual reality [2,3]. More recently, virtual reality has been investigated as a medium of telerehabilitation, whether at a clinic [4] or at home [5, 6].

Telehealth is recognized by the American Physical Therapy Association 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 [7]. 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 [8].

The Remote Console (ReCon) [9] is a telerehabilitation system designed to provide therapists, at a remote location, the tools necessary to oversee the patient's rehabilitation exercise session in real-time. This system provides to the therapist: three-dimensional representations of patients' movements, virtual reality-based exercise progress, and performance updates in real time, while the patient is exercising (Figure 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.

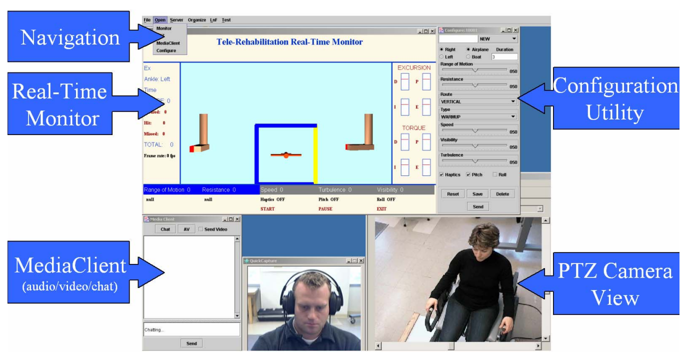

Fig. 1. ReCon Desktop for a Lower Extremity Exercise [9] ©UMDNJ, Rutgers University 2005.

In an effort to make the ReCon a useful tool for telerehabilitation, this system has evolved [10,11] through a series of usability studies and clinical trials, testing its effectiveness, ease of use and acceptance by both patients and therapists [7,12,13]. The telerehabilitation application described here is an implementation of the ReCon for use with the Rutgers Ankle Rehabilitation System (RARS) [14]. The purpose of this paper is to describe the quality of telerehabilitation by examining the technical performance of the ReCon, as well as patient performance during a pilot clinical study conducted by our group.

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II. METHOD

A. Study Overview and Subjects

The main objective of the pilot study, which incorporated one week of telerehabilitation, after three weeks of local rehabilitation, was to test the transfer of training from lower extremity (LE) exercising in virtual environments (VE) to over-ground walking. The detailed methods of this study are described elsewhere [15,16]. Six individuals (1 female and 5 male) between 8 months and 4 years post-stroke participated in this study. They were able to walk fifty feet without physical assistance and exhibited minimal active anti-gravity dorsiflexion. Subjects trained 3 times a week, 1 hour/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*

The performance of individuals post-stroke 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. Individuals continued to perform 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.

B. Telerehabilitation Setup

For the purposes of this study the sessions performed under telerehabilitation were set up from a remote location in the same building with the room where the subjects trained. However, technical tests were performed (as described in section *2C*) to gauge the system performance over geographically longer distances.The therapist logged into the ReCon using Java WebStart, which automatically updated the software with the latest version. 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 instrumented in the RARS by the local therapist and prepared to exercise using airplane and boat piloting simulations. While the patient was exercising, the remote therapist was able to view the subject via video and watch their performance in the monitoring application (Figure 2). This "real-time monitor" is an essential component of the ReCon application depicted in Figure 1.

During the exercise the remote therapist watched the position of the patient's foot from two viewing angles, watched a mock-up of the airplane or boat simulations, 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 modify the duration of the exercise.

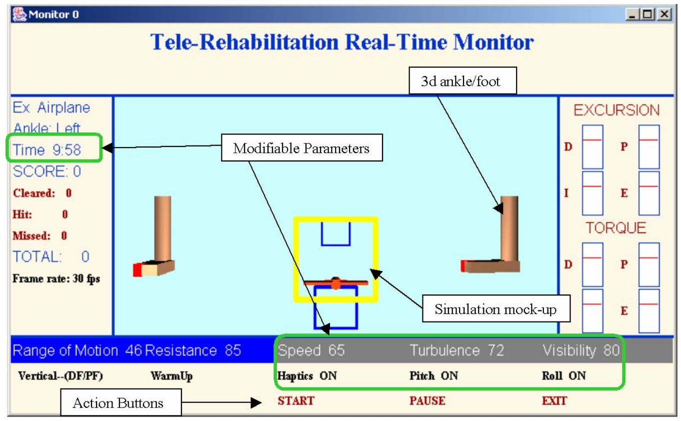


Fig. 2. Real-time monitoring and exercise modification detail [17] ©UMDNJ, Rutgers University 2005.

C. ReCon network performance

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 and UMDNJ (about 50 kilometers 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. Figure 3 (timeline) shows the various remote monitoring tasks, which were deliberately run during testing. Figure 3 (graph) shows the running average of round trip ping times between the ReCon located at UMDNJ and a) the hub node and b) the simulation node at the Human-Machine Interface Lab at Rutgers University and c) a local node on the same machine as the ReCon. The above timeline graph details the various tasks performed during testing (Initialization, Monitoring, Receiving Audio, Receiving and Transmitting Audio and Video).

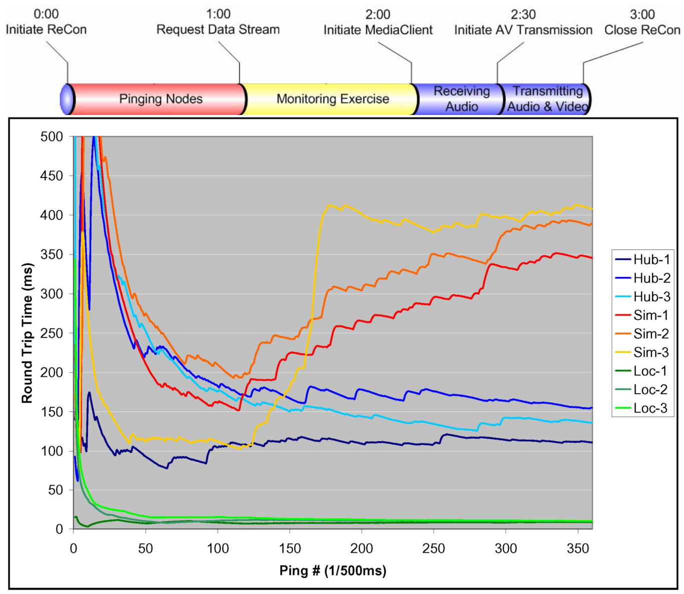


Fig. 3. Running Average of Ping times (UMDNJ-CAIP): The group of lines which end in higher range are simulation nodes; middle range are hub nodes; lower range are local nodes [18].

The messages sent with regularity are meant to remain small (Table 1). 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 [14], 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 2 depicts various network conditions, the delay between messages, and the resultant bandwidth use for that connection.

TABLE I
BANDWIDTH USAGE BY MESSAGE TYPE [18]

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

TABLE II
AVERAGE BANDWIDTH USAGE BY CONNECTION TYPE FOR DATA [18]

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

III. RESULTS OF 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 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 .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 Figure 4:

Accuracy increased from 70 % in the first week to 83% in the telerehabilitation (last) week ($F_{1.8}$= 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) (Figure 4a)

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 ($F_{2.4}$ = 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 (Figure 4b).

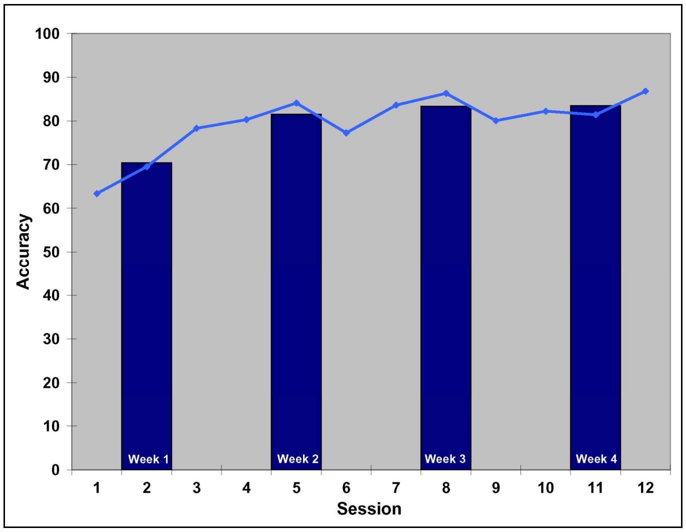
Repetitions of ankle movements increased from an average of 173 (44sd) repetitions the first week to 473 (77 sd) repetitions by the telerehabilitation (fourth) week ($F_{1.5}$ = 44; p < .000). Increases between weeks 1, 2 and 3 from 173 to 324 to 401 repetitions, respectively, were significant. The increase from week 3 to 4 from 401 to 453 repetitions was not significant (p = .07) (Figure 4c).

Duration of training (sum of all exercise time in a session) increased from an average of 32 minutes the first week to 50 minutes the last week (F_3 = 12.38, p < .000). The total exercise duration increments from week 1 (32 min.) to week 2 (40 min.), and week 2 to week 3 (50 minutes), were significant. Duration was the same for week 3 and four (50 minutes) (Figure 4d).

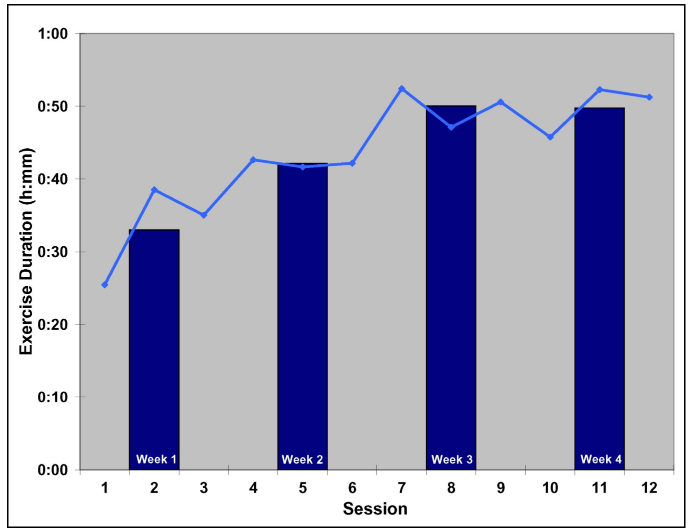
Efficiency of training time improved from 56% at week 1 to 72% at week 4 ($F_{1.6}$ = 9.1, p = .01). The increase in efficiency from 54% at week 1 to 70% at week 2 was the only significant weekly change. Efficiency between week 3 and 4 remained the same at 72% (Figure 4e).

IV. DISCUSSION AND CONCLUSION

The technical performance of the ReCon and patient performance during the telerehabilitation were evaluated. The results of the pinging test suggest that as message sizes were relatively small, messages were transmitted frequently enough, without significant lag and consuming too much 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



(a)



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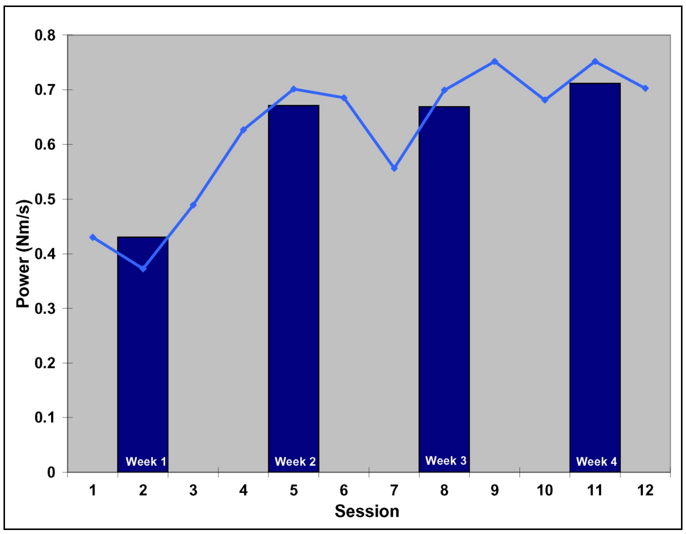
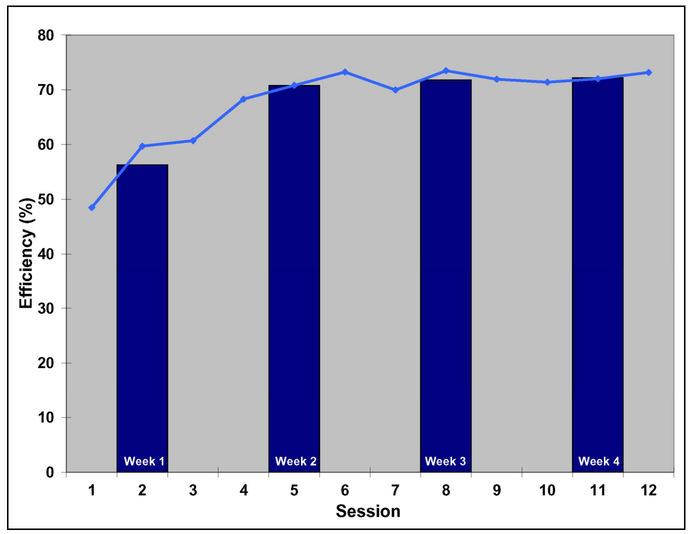
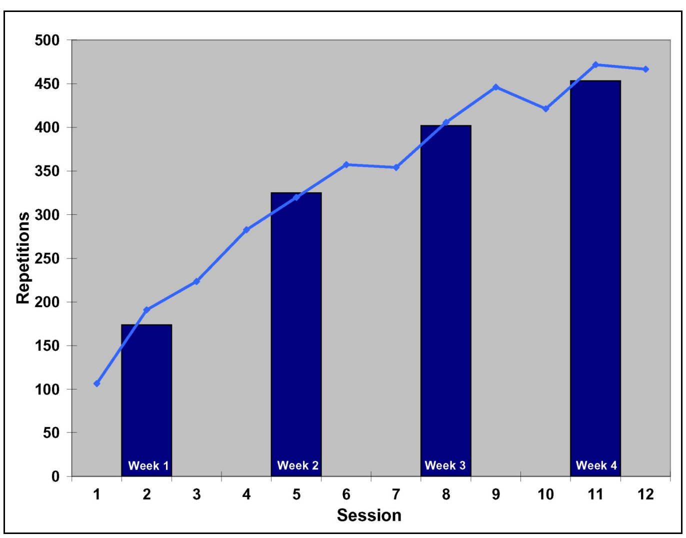


(b)



(e)



(c)

Fig. 4. Patient Performance as a group during VR Training of their affected ankle. Bars represent weekly averages, line represents session averages across all subjects:
a) **Accuracy** (%): percentage of targets hit out of targets presented
b) **Power** (Nm/s): mechanical work as a function of exercise duration
c) **Intensity** (repetitions): number of movement repetitions per session
d) **Duration** (h:min): Time spent exercising during a rehabilitation session
e) **Efficiency** (%): Time spent actually exercising out of total session length

latest version of the ReCon allows for several settings for different connections to the Internet (Dial-Up, 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.

Patient performance was not adversely affected by the transition of the therapist from the local 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 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 post-stroke 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 at the remote site, a second therapist remained on site. While the local therapist did not direct the session, he was nonetheless a presence in the room. In addition the remote monitoring was done within the same building eliminating many of the technical challenges that would be encountered at a greater distance.

These preliminary findings indicate that technical requirements for a clinic-based telerehabilitation environment were successfully addressed. However, more work remains to be done for ReCon to be used under degraded network conditions, and when patients exercise independently. The main finding here with regard to telerehabilitation is that the group performance was either maintained or improved during the transition from onsite to remote rehabilitation.

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