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Invited Paper: Low-Cost Telerehabilitation

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Abstract

The hardware and software costs of telerehabilitation systems are summarized. Several hardware and software examples are given in order to look at what has been done, and what can be done in the future. At present only a single low-cost telerehabilitation system (developed at the University of California at Irvine) has been identified. The author does not claim this to be a comprehensive review, rather an attempt to motivate the reader to look at ways to overcome cost barriers to widespread telerehabilitation use.

Keywords

Telerehabilitation cost, Microsoft Sidewinder, MATLAB, JACK, DirectX, PDA, joystick, Rutgers Ankle, Java Therapy, VRML, WorldToolKit, xBox, PERL, Oracle.

1. Telerehabilitation Cost

At a recent large international conference a well-known company was advertising its product with the following slogan: "*Tracking for the masses"* and further down on their shiny poster: "*$25,000*." This unintended comic poster underscores one of the problems faced by developers of high-technology applications, namely equipment cost. While the cost of computing platforms has seen dramatic reductions, matched by significant performance improvements, the cost of specialized human-computer interfaces has remained high.

Telerehabilitation involves the remote delivery of patient evaluations, diagnostic and therapy over telecommunication networks ranging from the telephone to high-speed Internet and dedicated video-conferencing links. While the beginnings of telerehabilitation are associated with coaching a rural clinic by an urban expert, the future lays in telerehabilitation to the patient's home. In order to extend the supervised therapy in the home the medical professional needs low-cost (tele)rehabilitation tools [Winters et al., 2003]. In an article published by the Journal of Rehabilitation Research and Development the authors state "One of the most significant barriers to telemedicine implementation is cost. The start-up costs for telemedicine infrastructure are high. Despite a dramatic reduction in per-unit costs over the last 5 years, start-up investment and maintenance costs of a telemedicine network are still high relative to per-episode reimbursement" [Hatzakis et al., 2003].

Telerehabilitation is a (newer) component of telemedicine, and its costs need to be analyzed if telerehabilitation is to fulfill its true potential. Such costs include the obvious hardware and software costs associated with the local and remote stations and the networking/communication costs. The less obvious costs are hose for training therapists in the new technology, documentation, regulatory/administrative, maintenance and legal costs. This paper focuses only on the more tractable telerehabilitation costs for hardware and software.

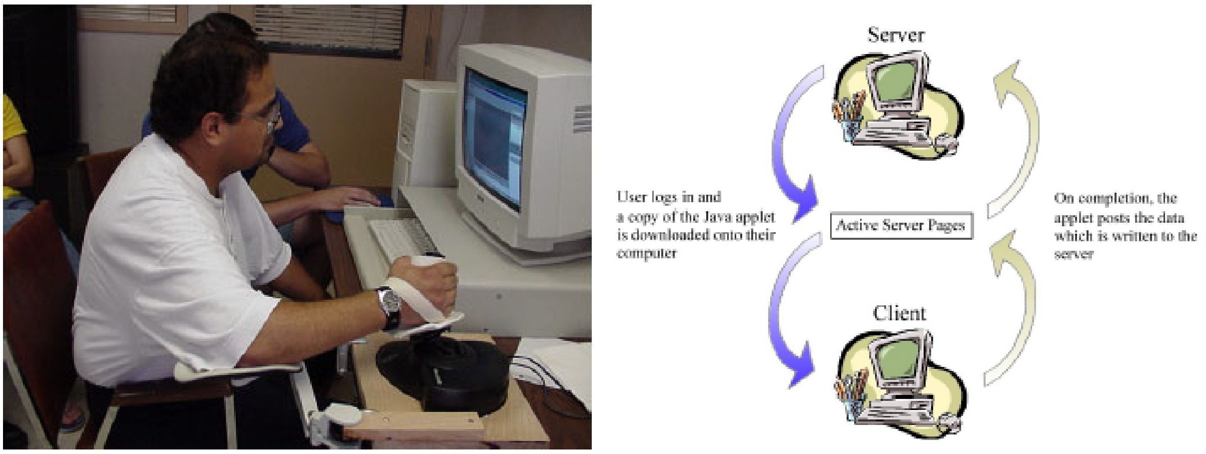
2. Low-cost Telerehabilitation Hardware

Telerehabilitation hardware consists of computing platforms on which the therapy sessions take place, or which serve as remote console for the therapist, the interfaces used by the patient to interact with the computers as well as video/web cameras and microphones. Selecting a low-cost approach means that consumer-grade hardware and game consoles should be used.

2.1. Patient Interfaces

The type of interfaces used in telerehabilitation depends on the particular patient populations being trained. In non-immersive cognitive rehabilitation a simple computer screen suffices, and thus there are no interfaces. In other cases, such as patients that had survived a stroke, or had damage to their spine, very expensive interfaces (such as the Haptic Master – FCS Robotics, Holland, or the Lokomat made in Germany) may be used. Even for such demanding populations some newer approaches using gaming hardware are emerging.

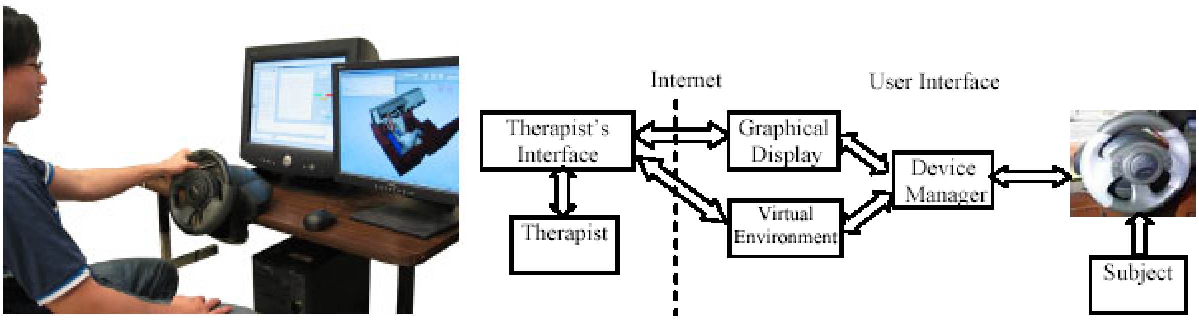
Figure 1*a* shows a Microsoft Sidewinder joystick (costing less than $80) that has been integrated in an upper-extremity telerehabilitation system developed at the University of California – Irvine [Painter 2000]. The patient is asked to perform a series of 2-D games involving reaching targets with or without assistive forces. The joystick samples the patient's position in the horizontal plane (x-y) and transmits the data to a PC running the simulation. The joystick is enhanced by an add-on handle to help the patient grasp, and an elbow/arm support to counteract the effects of gravity. Thus the patient does not have to worry about supporting the weight of his arm and only has to exert horizontal forces. Reinkensmeyer and colleagues [2002] report on a 54 year-old subject that was a chronic post-stroke patient and exercised on the system from his home. Post therapy his mean movement speed increased by 40% and he exhibited much better body/arm coordination.



a) b)

Figure 1: Force feedback joystick used in post-stroke telerehabilitation: a) the patient wears special Velcro strips to secure his arm to the joystick handle and his elbow is supported by an armrest system; b) system architecture [Painter, 2000].

Figure 2*a* shows a Microsoft Sidewinder force feedback driving wheel (costing less than $100) that is being integrated in a home-based diagnostic and rehabilitation tool for patients with UE dysfunctions. The wheel and associated pedals are sampled to change the viewpoint in a 3-D driving exercise being developed at the State University of New York at Buffalo. The exercise protocols are structured as driving simulations along roads of varying complexity. At present the system is under development and no clinical data exist. Tests done on healthy volunteers showed that the system is capable of enough sensitivity to distinguish their driving skills.



a) b)

Figure 2: Force feedback driving wheel used in a virtual driving environment. The patient has to drive roads of varying complexities while being monitored by a therapist [Jadhav and Krovi, 2004];
b) system architecture [Nair et al., 2003].

Figure 3 [Lewis et al., 2003] presents the telerehabilitation system being co-developed by Rutgers University and the University of Medicine and Dentistry of New Jersey (UMDNJ). It differs from the above examples in the use of custom robots for upper and lower extremity rehabilitation, which renders the system more expensive. What makes this system interesting within the topic of this paper is its remote monitoring station, which uses a laptop and low-cost web camera, as well as software components that will be discussed later. The lower extremity part of the system has trained six chronic post-stroke patients, of which 50% showed improvements in their gait.

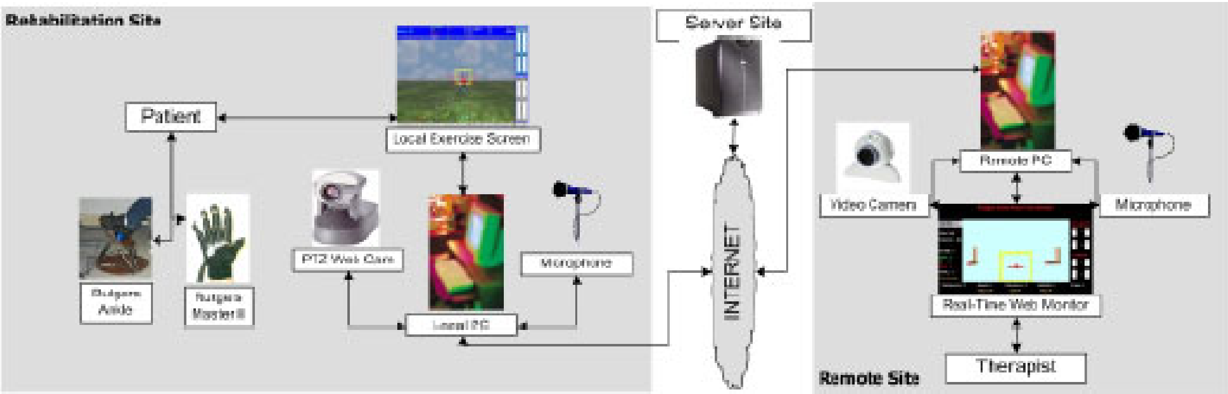


Figure 3: Telerehabilitation monitor hardware block diagram demonstrating the rehabilitation site (left) and the remote site (right). [Lewis et al., 2003]. © Rutgers University 2002. Reprinted by permission.

2.2. Computing platforms

All the telerehabilitation systems described above use PCs (or laptops) for patient's or therapist's stations. While PC prices now average about $800, there are still less expensive alternatives. One is the PDA which cost $200-$400 depending on model and capabilities. Its small price is complemented by its small weight and versatility, which contribute to more freedom of motion. Instead of having to sit in front of a PC, a therapist can walk around, demonstrate exercise through a built-in camera and monitor the patient.

Figure 4 shows a system being developed by researchers at EPFL (Switzerland). The therapist views a simplified version of the exercises being performed by the patient in real time. He can change the exercises difficulty using the PDA stylus and can talk to the patient through its microphone. The patient wears a head-mounted display (HMD) and interacts with an expensive force feedback system. It sees the therapist in the virtual environment over-imposed to the exercise.

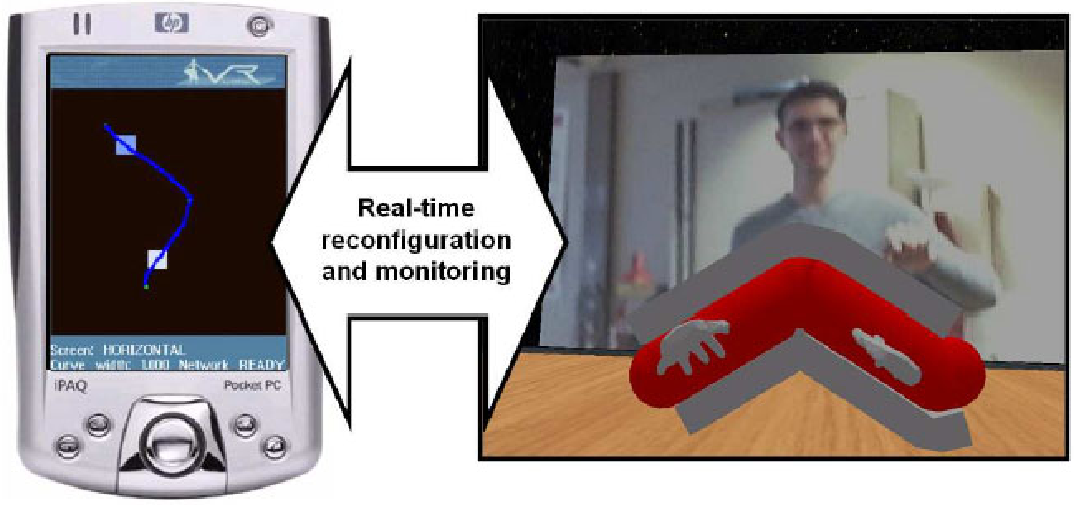


Figure 4: Telerehabilitation monitoring using a PDA. [Thalmann, 2004].

A less intuitive way PDAs could be used in telerehabilitation is to run simulations for the patient. Normally a PDA input is through handwriting with a stylus. However, if a PDA is connected with other peripherals, it could sample patient data and then transmit them to the remote therapist station. An interesting technology being developed by Canesta Inc. (San Jose, CA) is to add a projected full-size keyboard using the system depicted in Figure 5 [Tomasi et al., 2003]. The approach uses a projector, a sensor light source and a sensor, which together draw less power than a cell phone. Researchers report typing error rates and words-per-minute speeds comparable with those of mechanical keyboards. One way the projection keyboard could be used in rehabilitation is to exercise finger fractionation, or the patient's ability to move a finger independently of its neighbors. This function degrades in patients with stroke, and rehabilitation exercises could involve changing the graphics projected by the PDA to show a piano keyboard. A virtual piano keyboard was used effectively to train chronic post-stroke patients at Rutgers University, but with more expensive hardware [Jack et al., 2001].

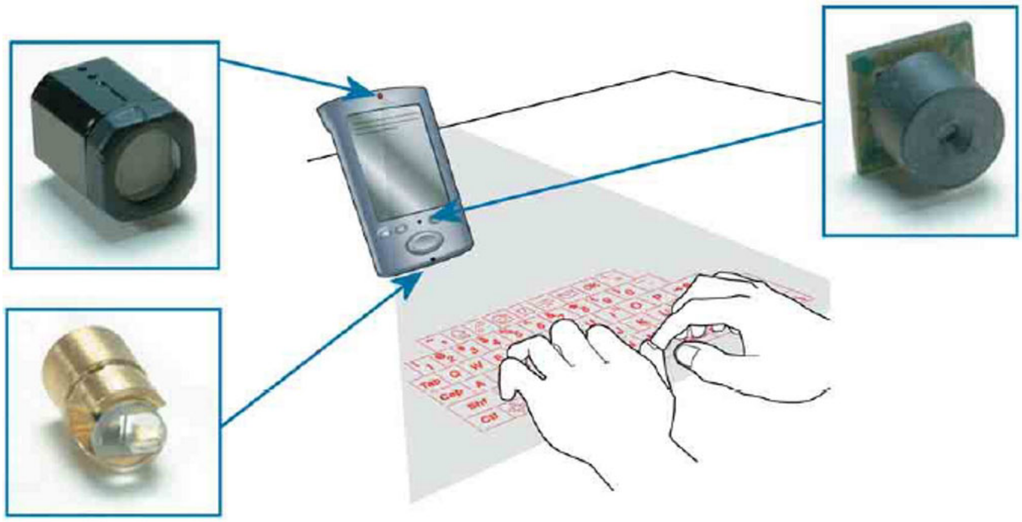


Figure 5: Block diagram demonstrating the projection keyboard being developed for mobile computing [Tomasi et al., 2003].

Another type of low-cost computing platform available in many homes, which could be used in telerehabilitation is game consoles. Microsoft has recently introduced its xBox 2 (or "Xenon"), which is much more powerful that the original xBox sold in stores for less than $200. The second-generation game console uses 64-bit architecture and a CPU speed of more than 3.5 GHz. It has a built-in Graphics Processing Unit, Ethernet connection, DVD, hard disk, video/audio output, and all the other facilities normally found on a much more expensive PC. The ability to run Linux and Java3D makes this powerful gaming console a potential patient rehabilitation station. Since many researchers share the view that rehabilitation exercises should be in the form of games (to allow repetitive and motivating therapy) the use of an xBox, Playstation or other gaming consoles seems a natural way to reduce the cost of telerehabilitation.

3. Software for Telerehabilitation

The discussion so-far has focused on the hardware aspects of telerehabilitation. It is now time to look at the software that is used to evaluate or train patients at a distance. The three main modules are: a) the exercise software running on the patient's station; b) the remote monitoring/exercise adjustment software running at the therapist site; and c) the database and remote graphics capability used for patient's medical data. The options available to the designer are expensive (but well documented) toolkits or public-domain software that is less documented (but free). Ideally, to maintain costs low, researchers should couple the inexpensive hardware described above with free software packages. As we will see shortly, this is not always the case, because software stability for medical needs is as important as its cost.

3.1 Exercise software

The telerehabilitation software running on the patient's station allows the therapist to "baseline" the patient (in order to adjust the simulations to his/her abilities) and to configure the exercise session (the sequence of exercises being done). The system developed at the University of California at Irvine uses an active web page to allow the remote patient to download exercises. These exercises are written using Java applets and Active X. The ActiveX controller (developed by Immersion Co.) implements the joystick forces and takes commands over the Internet from the server using JavaScript. The exercises consist of a variant of the classic arcade game "Breakout!" in which the patient controls a paddle in order to rebound a moving ball into a bank of targets. The score is the number of targets destroyed in three attempts.

The driving simulator being developed by the group at SUNY Buffalo uses CAD and VRML to create the 3-D road scene (depicted in Figure 6*a*). While VRML is free, CAD packages tend to be costly. The steering wheel and pedals are sampled using the MATLAB data acquisition toolbox. MATLAB is also used for its 2-D GUI capabilities, to generate a set of parametric paths (Figure 6*b*). These paths are used to calculate the error between the desired and the patient-generated paths at each time instant. MATHLAB is called to plot this variable at the end of trials, as a way to diagnose the patient. In a rehabilitation scenario the steering wheel can create assistive or resistive torques, which are called as DirectX software from within MATLAB.

a) b)

Figure 5: Examples of 3-D driving interfaces for the driving simulator developed at SUNY Buffalo: a) realistic road; b) simple parametric path [Nair et al., 2003].

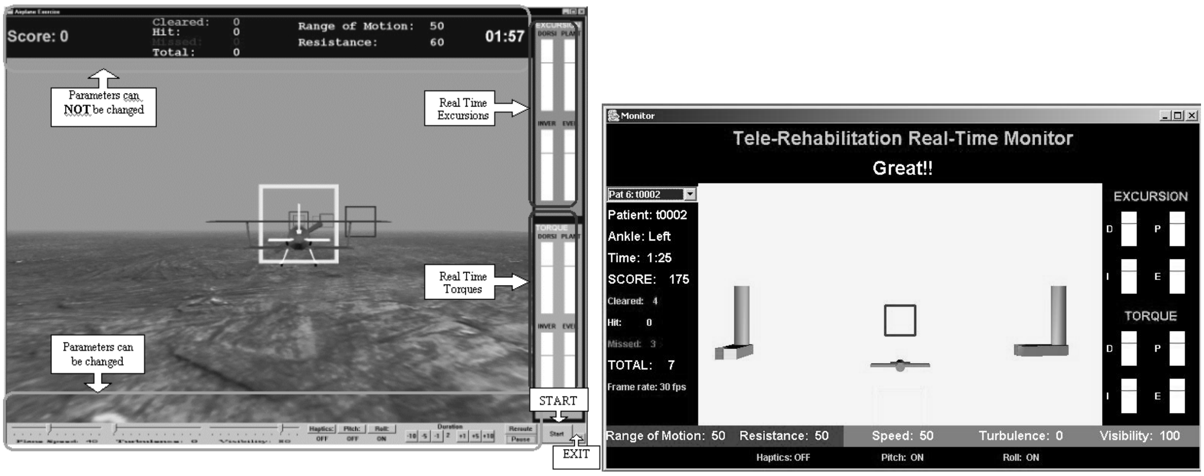
The lower-extremity exercises developed at Rutgers University ask patients to use their foot as a joystick in order to navigate through 3-D hoops (see also Figure 6*a*). A patient baseline module and the real-time simulation are written in WorldToolKit, which is a well-known, but expensive 3-D programming library. The haptic effects associated with turbulence during simulated storms, or the programmed resistance applied on the patient's ankle, are written in C/C++. The right side of the screen is used to display real-time feedback on the level of ankle excursion (angles) and torques applied during the exercise. The same variables, as well as patient hit/miss scores, levels of resistance produced by the Rutgers Ankle platform on which the patient places his foot, length of exercise, etc. are transparently stored in an Oracle database. This is a well-known, but also expensive database software.

3.2 Remote monitoring

The remote monitoring for the system developed at the University of California at Irvine uses a web-based approach, which mirrors the web-based architecture of the patient's station. The therapist's page provides the ability to add new patients, to design/adjust rehabilitation programs and to monitor the rehabilitation progress for a group of patients. The remote monitoring is done by viewing three types of progress charts. The first chart keeps track of system usage, showing desired vs. actual frequency of use by a given patient. The second type of progress chart provides performance feedback (score) immediately after the completion of an exercise, compared to previous performance. The third type of chart is a graphical history of the patient's scores as a function of time compared to corresponding target scores. These charts are implemented through Java applets. The database storing the patient's data is implemented in Microsoft Access and managed through PERL scripts.

The driving simulator developed at SUNY Buffalo transmits selected parameters (steering wheel angle, arm joint angles) over the Internet to the remote therapist. This data is then used to replicate the patient's movement using the JACK toolkit. While expensive, this 3-D avatar of the patient allows the therapist to view from different viewpoints, and play back captured motions.

The remote monitoring for the LE stroke rehabilitation system developed by Rutgers University and UMDNJ is done over the web. One window on the therapist's station displays a simplified version of the exercise performed by the patient, while another window shows the patient's image captured by a Pan-Tilt-Zoom (PTZ) web camera. The 3-D scene is programmed in Java 3D, while the communication uses Java applets. The center of the therapist GUI shows the exercise in real time, while the left and right side bars display numerical data (similar to what the patient sees on his screen). The bottom portion of the therapist's GUI allows her to change exercise parameters remotely and dynamically, while the patient is exercising. For example the therapist can change the visibility from good visibility to low visibility and stormy weather. Low-visibility helps stroke patients focus on the (near) target, while storms induce turbulence and disturbances in the Rutgers Ankle haptics. The therapist can also remotely change the airplane speed, or the duration of flight, fine-tuning the exercises to patient abilities.



a) b)

Figure 6: Telerehabilitation screens for the system developed at Rutgers University and UMDNJ: a) the patient's screen; b) the console for the remote therapist [Deutsch et al., in press].

4. Summary and Conclusions

The hardware and software costs of the telerehabilitation systems described in this paper are summarized in Table 1. It can be seen that the only system which uses low-cost hardware *and* software is that developed at University of California at Irvine. The SUNY Buffalo system has an inexpensive interface device (the Microsoft Sidewinder driving wheel), but expensive software (JACK, MATLAB, CAD). The Rutgers/UMDNJ system uses free monitoring software (Java3D), but relies on expensive hardware (the Rutgers Ankle) and exercise/database software (WTK, Oracle).

Table 1. Summary of systems reviewed in this paper. © G. Burdea 2004

Project Name and Location	**Hardware Interface/cost**	**Exercise Software/cost**	**Remote Monitoring Software/cost**	**Database Software/cost**
Univ. California Irvine (stroke rehab)	Joystick (Low)	Java applet, ActiveX (Low)	Java applet (Low)	Micros. Access PERL (Low)
SUNY Buffalo (diagnosis/rehab)	Force feedback wheel (Low)	CAD, MATLAB, VRML, DirectX (High)	JACK, MATLAB (High)	MATLAB (High)
Rutgers/UMDNJ (stroke rehab)	Rutgers Ankle (High)	WorldToolKit (High)	Java3D (Low)	Oracle (High)

Telerehabilitation technology is under active research and rapid change, and no comprehensive solutions exist. Thus the selection in this review paper was based on what low-cost approaches exist (in various stages of development) or what could be used as part of future low-cost telerehabilitation. The author does not claim this to be a comprehensive review, rather an attempt to motivate the reader to look at ways to overcome cost barriers to widespread telerehabilitation use.

Acknowledgements

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