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Telerehabilitation robotics: Bright lights, big future?

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Abstract—The potential for remote diagnosis and treatment over the Internet using robotics is now a reality. The state of the art is exemplified by several Internet applications, and we explore the current trends in developing new systems. We review the technical challenges that lie ahead, along with some potential solutions. Some promising results for a new bilateral system involving two InMotion2 robots are presented. Finally, we discuss the future direction and commercial outlook for rehabilitation robots over the next 15 years.

Key words: bilateral, cooperative therapy, force feedback, functional rehabilitation, haptics, rehabilitation robotics, shared virtual environments, teleoperation, telerehabilitation, time-delay, virtual reality.

INTRODUCTION

The field of neurorehabilitation is poised, not to mention overdue, for substantial improvements in its standards of patient care. Until now, a remarkable stream of innovative medical technologies has targeted nearly every medical specialty except rehabilitation. Although skilled clinical managers and therapists can achieve acceptable results using even rudimentary equipment, the efficiency limit of their existing "toolbox" is rapidly approaching. The expected surge in demand for services due to a graying population will exacerbate stress on all health professionals, particularly on those not accorded efficient new tools and modalities.

According to the World Health Organization, by 2050, the number of persons over 65 years will increase by 73 percent in the industrialized countries and by 207 percent worldwide [1–2]. By 2050, the percentage of the U.S. population over 65 years should almost double from 12.3 to 20.6 percent (from 40 to 80 million). This age group is particularly prone to cerebrovascular accident (CVA), also known as stroke, since the relative incidence of stroke doubles every decade after age 55. In fact, stroke is the leading cause of permanent disability in industrialized nations. Over 700,000 Americans and 920,000 Europeans have a stroke each year; more than half survive. In the United States alone, over five million stroke patients are alive today, with a prevalence of

Abbreviations: 3-D = three-dimensional, ADL = activities of daily living, COTS = commercial off-the-shelf, CPM = continuous passive motion, CVA = cerebrovascular accident, DOF = degrees of freedom, ISIS = Imaging Science and Information Systems, LAN = local area network, LCD = liquid crystal display, MGA = Maryland-Georgetown-Army, MIT = Massachusetts Institute of Technology, NASA = National Aeronautics and Space Administration, pMA = pneumatic muscle actuator, RMII = Rutgers Master II, ROM = range of motion, SVE = shared virtual environment, UDP = user datagram protocol, VOG = virtual-object generator, VR = virtual reality.

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1,400 per 100,000 of the population. Even higher prevalence is observed in developed countries with an older population, such as Japan's incidence of 2,880 per 100,000 [1]. In addition to stroke, the demand for services will likely increase for other age-related diagnoses such as orthopedics and arthritis, which together represent more than 70 percent of physical therapy demand.

As demand soars, rehabilitation facilities must keep pace with both the standards of care and the unrelenting cost-containment pressures of today's healthcare environment in which inpatient poststroke stays have been shortened by two-thirds in the last decade [3]. Service providers have responded to the cost-containment pressures not only by shortening the length of patient hospitalization but also by delivering services in less costly geriatric care centers (e.g., skilled nursing facilities) versus specialized stroke rehabilitation units and by promoting compensatory strategies (e.g., use of one-handed techniques) to accomplish activities of daily living (ADL) rather than working to remediate impaired motor function. Thus a healthcare delivery system that did not know the most effective regimens for inpatient rehabilitation therapy is now promoting inpatient rehabilitation administered in less than half the time, to a sicker population, and increasingly complementing treatment with outpatient care.

As care is moved from the inpatient setting to the home, mining potential technologies that can extend effective treatment outside the acute care hospital is critical. Many in the health industry thus rank telemedicine and robotics high among the technologies well suited to answering the needs of a growing aging population. Specifically, robotic-assisted telerehabilitation offers innovative, interactive, and precisely reproducible therapies that can be performed for an extended duration and be consistently implemented from site to site. In particular, task-specific neurorehabilitation using robotics can significantly affect the field of rehabilitation and yield considerable benefits for patients with upper- and lower-limb impairments.

Telemedicine has been defined as the use of telecommunications to exchange medical information and services. Consider the case of the *U.S.S. Abraham Lincoln* Battle Group somewhere in the Indian Ocean during a 6-month seaborne mission with 7,000 crew members. A female crew member had an emergency that required immediate surgery. The surgery was successfully performed, although the Battle Group's head surgeon had never performed a similar operation. An experienced gynecological surgeon at Johns Hopkins Medical School (Baltimore, Maryland) "telementored" the Battle Group surgeon via images transmitted by satellite over a 14,400-baud communication line of the carrier (9,600 baud for auxiliary vessels). This act of real-time remote mentoring represented a considerable advancement in telemedicine beyond the standard practice of transmitting medical images for consultation, also known as teleradiology.

The span covered by telemedicine and rehabilitation robotics is very broad. In this article, we focus on the integration of these two technologies—telerehabilitation and robotics—to the upper limbs, which has been the primary area of application thus far. Telerehabilitation is related to, but distinct from, telemedicine and demands unique technologies beyond those of voice and visual communication. Fortunately, advances in robotics have kept pace with advances in communications and information processing. A robot can now be successfully operated from a remote location. Although originally developed for space (e.g., National Aeronautics and Space Administration's [NASA's] Pathfinder Mission to Mars) or underwater applications (e.g., discovery of the *Titanic* shipwreck by the Woods Hole Oceanographic Institution's "Jason"), the application of this technology to medicine is already a commercial realization (e.g., Intuitive Surgical's [Sunnyvale, California] *da Vinci* Surgical System for telerobotic endoscopic surgery [4]).

Note that by "tele," we do not mean "telepresence," the term coined to describe virtual reality (VR) technology used to immerse humans in virtual environments. While VR might be a technology employed in telerehabilitation, it does not define it. Telerehabilitation in this context means remote rehabilitation—that is, the therapist is conducting the therapy from a remote location, as illustrated in **Figure 1** [5]. The enabling technologies are the Internet, which provides the communication link (data and video), and a robot, which allows the user to input motion commands and receive force feedback. Only the patient needs to have a robot to enable telerehabilitation; in this case, the robot's computer receives commands from and sends data back to the therapist's computer. When both the therapist and patient have robots, the therapist can conduct cooperative therapy and remote assessment over the Internet.

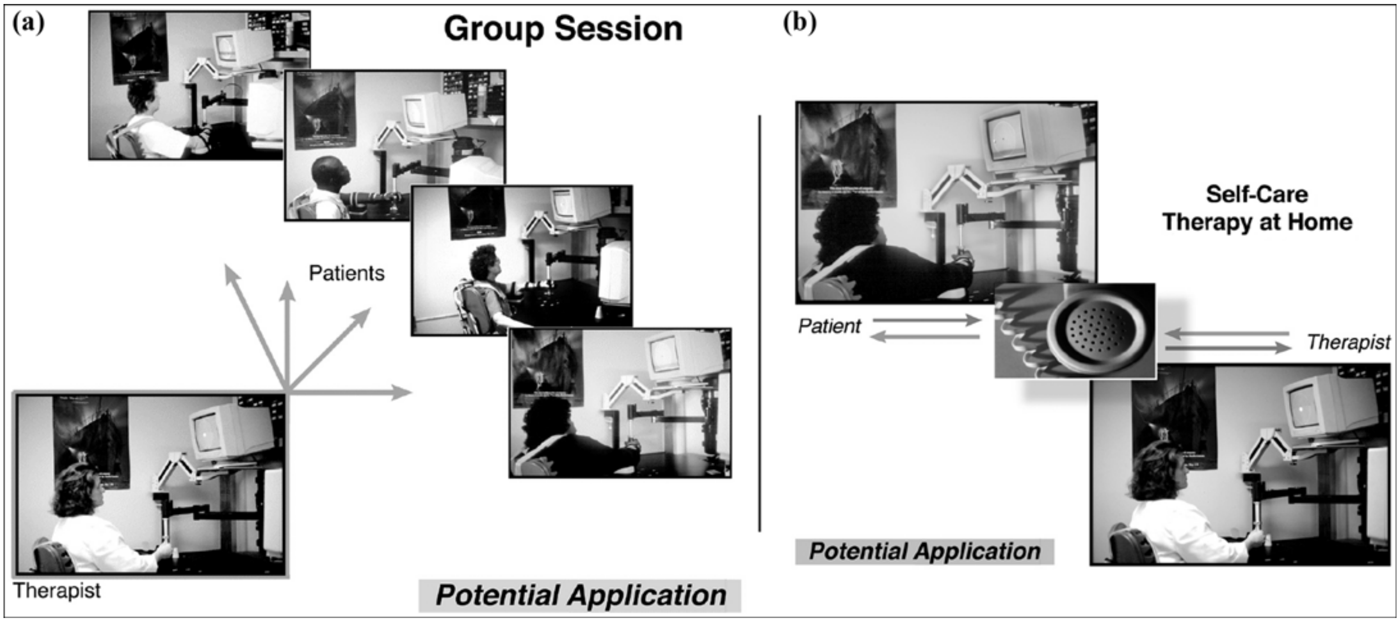

Figure 1.
Potential telerehabilitation applications: **(a)** classroom multiuser or multiplayer scenario and **(b)** possible evaluation session. Reprinted by permission from United Nations Department of Economic and Social Affairs, Population Division [home page on the Internet]. New York (NY): United Nations; c2006 [updated 2006; cited 2006 Jan]. World Population Prospects: The 2004 Revision Population Database [about 1 screen]. Available from: http://esa.un.org/unpp/

CURRENT TELEREHABILITATION SYSTEMS

Telerehabilitation robotic systems fall into two broad classes: unilateral and bilateral.* In the unilateral configuration, only the patient interfaces with a robot. In the bilateral configuration, both patient and therapist use robots. Examples of both configurations are detailed next.

Unilateral Systems

Most current systems use the unilateral configuration shown in **Figure 2** [6]. In this setup, the patient manipulates and receives force feedback from a robot while viewing a graphic of the task on a computer display. The robot's control computer receives protocols either downloaded from the therapist's computer or stored programs that are selected by the therapist's computer. The data from the patient's robot are uploaded in real time to the therapist or are recorded and subsequently uploaded after the session is completed.

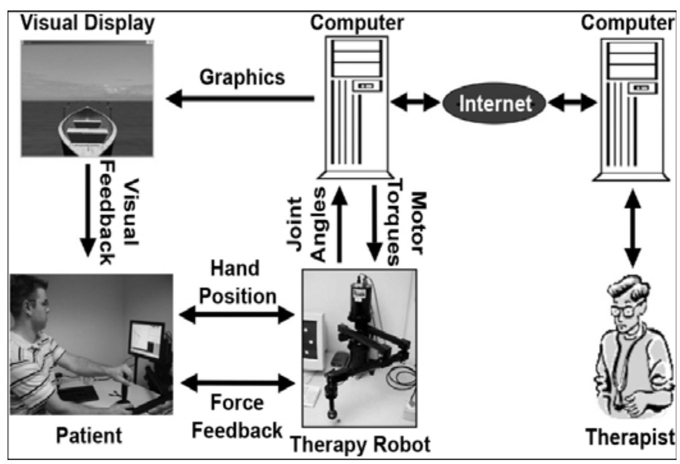

Figure 2.
Unilateral telerehabilitation system.

Perhaps the first widespread application of telerehabilitation robotics is the JavaTherapy system developed by Reinkensmeyer et al. at The University of California, Irvine (Irvine, California) [7]. JavaTherapy is a unilateral

*While therapists use the term "bilateral" to indicate involvement of both left and right limbs, engineers use the term "bilateral" to describe two robots commanding each other. To introduce a distinct neologism to aptly describe what we do in robotic telerehabilitation would only confuse the issue further, particularly considering that "bilateral" is standard terminology in robotic teleoperation. We opt to caution the reader of the potentially different meanings.

architecture realized with a commercial force-feedback joystick connected to an orthopedic splint attached to the patient's wrist. Patients log onto the Web site www.javatherapy.com and an online occupational therapist guides them through a repetitive movement regimen intended to improve their sensorimotor skills. In a speed test requiring 16 target movements, one subject improved his/her speed by 40 percent over a period of 12 weeks. Such therapy has been demonstrated to be useful even several years following hemiplegic stroke [8].

The Rutgers Master II (RMII), developed by Popescu et al., is used to increase hand strength in stroke patients using teletherapy [9]. The RMII is worn as an exoskeleton on the inside of the patient's hand, which provides resistive forces to the thumb and three of the fingers through the action of pneumatic pistons. When the patient picks up a virtual object on a computer screen (**Figure 3**), the computer actuates the piezoelectric servo valves on the exoskeleton to provide resistance to the fingers as the hand clenches the object. A therapist can remotely modify this resistance during the sessions to increase the patient's strength and also design an increasingly complex array of virtual tasks for the patient to perform to hone his/her dexterous motor skills. A VR library allows automatic transparent data collection of the patient joint motion and exertion forces and remote monitoring of patient progress. Pilot clinical trials on post-stroke patients have shown four-fold increases in finger strength over 2 months.

Figure 3.
Rutgers Master II being used for virtual pegboard filling to increase strength and hand-eye coordination. Reprinted by permission by Popescu VG, Burdea GC, Bouzit M, Hentz VR. A virtual-reality-based telerehabilitation system with force feedback. IEEE Trans Inf Technol Biomed. 2000;4(1):45–51. [PMID: 10761773]. (© [2000] IEEE.)

The Virtual Driving Environment, developed by Jadvah and Krovi at the University of Buffalo (Buffalo, New York), consists of an immersive virtual environment with which the patient can interact through various kinesthetic interface devices such as a commercial force-feedback steering wheel used in gaming applications [6]. A cadre of exercise scenarios reflecting real-life driving scenarios (sharp turns, increasing curvature, etc.) can be simulated using software modules deployed on the patient's home computer. Steering inputs are fed into the virtual environment through the force-feedback steering wheel, which generates motions and forces in response to the patient's actions.

The therapist interface consists of a synthesized rigid body model of the patient's motion based on sensors attached to the subject as well as several assessment and diagnostic tools. A diagnostic module uses captured biomechanical data (human motion and force) for development of quantitative performance measures such as range of motion (ROM) and strength. The interface can also be used to postprocess the data in the form of graphs and charts to assist the therapist, who can then download modified therapeutic regimen to the patient's machine.

Bilateral Systems

In bilateral telerehabilitation, both the patient and therapist interact with each other over the Internet through a shared virtual environment (SVE) as illustrated in **Figure 4** [10]. Each user manipulates the handle of his or her robot, which commands the motion of an object being commonly grasped in the virtual environment. A virtual-object generator (VOG) applies the sensed "interaction" forces from the robots to the simulated object, then the computer calculates the resultant motion. The motion of the object at each "contact" point is subsequently transmitted back to each robot where it is tracked by a local controller.

The basic architectures for creating SVEs over the Internet are [11]—

1. Server-Client (Hierarchical). A single virtual environment (simulated task) is running on the server. The clients (patient/therapist robots) pass local information to the server, which then updates the virtual environment and sends graphic and haptic (force command) updates to the clients. This is the architecture used by the system

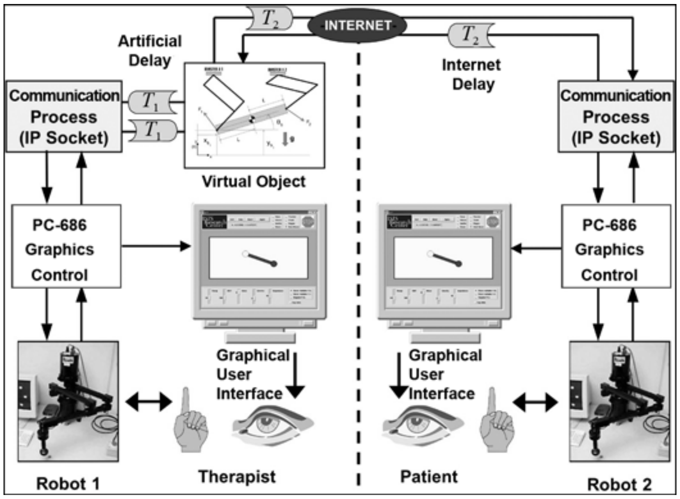

Figure 4.
Bilateral telerehabilitation test bed at Georgetown University Imaging Science and Information Systems Center. System uses client-server architecture in which graphics and control run on local robot host computers (PC-686) while exchanging information over Internet through Internet protocol (IP) socket. T_1 and T_2 represent artificial and Internet time delays, respectively.

in **Figure 4** and is described in more detail in the "Cooperative Telerehabilitation" section.

2. Peer-to-Peer (Federated). Each robot client is running its own virtual environment (task) simulation. The clients update their own graphics and haptic loads and exchange the local updates with each other. This is the architecture most commonly used in gaming applications over the Internet.

Several investigators have created SVEs using the client-server approach. Researchers at the Massachusetts Institute of Technology (MIT) (Cambridge, Massachusetts) and University College London (London, England) performed a cooperative "ring on a wire" task over a local area network (LAN) using a pair of PHANTOM™ haptic devices (SensAble Technologies Inc, Woburn, Massachusetts) [12]. The endpoints of the haptic devices were "connected" to opposite sides of a virtual ring, which was manipulated along the wire by moving the endpoints of the haptic devices. The distance between the contact points was maintained by a virtual spring with the relaxed distance equal to the diameter of the virtual ring. The video signal coming from the server was split and displayed to each operator so that he or she received concurrent graphics as well as haptic feedback.

Another LAN-based system was developed by Goncharenko et al. at Nagoya University (Nagoya, Japan) to simulate dual-arm haptic interaction with a steering wheel [11]. The operator grasps a PHANTOM™ haptic device with each hand to simulate grasping a steering wheel at the 10 o'clock and 2 o'clock positions. The contact with the virtual object is not interceded by a virtual spring-damper in Goncharenko et al.'s system; however, the time delay in transmission between PHANTOMs™ was negligible because of the collocation of the haptic devices. Large time delays can destabilize a system and may even prevent tasks from being performed cooperatively over the Internet.

Cooperative manipulation of virtual objects over the Internet was realized at the Nagoya Institute of Technology in Nagoya, Japan, using a "synchronization maestro" to buffer the server inputs from a pair of PHANTOM™ haptic devices [13]. Although Ishibashi et al. established concurrent information arrival for the devices in their experiments, a relatively small (~15 ms) time delay was still left uncompensated. In addition, the haptic devices were "connected" to the virtual object through a spring dashpot, detracting from the realism of the contact forces experienced during manipulation.

Alternatively, researchers at the MIT Touch Lab and University College London used peer-to-peer architecture to perform a "transatlantic" touch experiment in which a virtual box was lifted using PHANTOM™ haptic devices [14]. User datagram protocol (UDP) transmission enabled fast exchange of information between clients across the Atlantic. However, as mentioned earlier, the Internet introduces a time delay in the signals between the two devices and, if left uncompensated, can cause the system to become unstable. This destabilizing effect was compensated for by interjecting virtual damping through the controller at various stages throughout the system. Unfortunately, this ad hoc approach provides no guarantee of stability and limits the firmness of hard contact and realism of the interaction.

Only recently, researchers at Georgetown University (Washington, DC) and Interactive Motion Technologies, Inc (Cambridge, Massachusetts), used the client-server architecture with input buffering and time-delay compensation to realize a rehabilitation application [15]. Stability in the presence of time delay was achieved with wave variables to interject passivity in the communications link. This system will be described in more detail in the "Toward Bilateral Telerehabilitation" section.

TECHNICAL CHALLENGES

Even given the isolated successes of the systems just described, many technical challenges remain for attaining true bilateral telerehabilitation: large-scale haptics, haptic/VR blending, interactive control, Internet time delay, and patient safety. Here, we briefly review these topics, highlighting the challenges facing researchers.

Large-Scale Haptics

Most of the haptic devices developed to date are "desktop" haptic interfaces such as the PHANTOM™ [16]. The most widely used model produces continuous translational forces at the tip of approximately 1.5 N in all three directions through the action of motors mounted in their bases. While such devices have found widespread use as force "displays" in a variety of applications such as computer games and surgical simulators, they are not capable of very high force output and have fairly small work spaces, usually well under a cubic foot. Human-scale haptic interaction generally requires a larger ROM and greater force than can be provided by these devices.

Industrial manipulators are capable of producing the larger reach and forces required for human-scale haptics, but their bigger actuators, drive mechanisms, and linkages all lead to more inertia and friction. Uncompensated, these natural dynamics are superposed at the haptic interface, degrading the accuracy of the simulated environment. However, the effect of these dynamics can be significantly reduced through the use of active control, enabling the successful implementation of manipulators in a variety of applications. Some examples of this approach include manipulators used as driving and flight simulators [17–18] and mass simulators for extravehicular training [19].

When robots are being designed for use as haptic interfaces, the classic trade-off between power and weight always emerges [20]. Haptic devices are almost always electrically driven to attain the high control bandwidths required for simulating contact with virtual environments. Unfortunately, motors have very low power-to-weight ratios, which tends to limit the force output and render them suitable only for relatively low-force applications such as movement therapy following stroke. Pneumatic actuators, on the other hand, have high power-to-weight ratios but poor actuator response, rendering them appropriate for exercise therapy but too bandwidth-limited for simulating ADL tasks for functional rehabilitation.

Despite these limitations, recent articles suggest a trend toward using pneumatically powered devices for physical therapy. Examples of these devices include the pneumatic muscle actuator (pMA) exoskeleton, which uses pMA [21], and the "Skil Mate" wearable elbow/forearm exoskeleton, powered by McKibben artificial muscles, being developed for astronaut extravehicular activity [22]. While these devices have excellent power-to-weight ratios, they have relatively very low bandwidth capability (~0.5 Hz) that renders them unsuitable for many types of functional retraining. However, they do show excellent promise as assistive and resistive training devices.

Haptic/Virtual Reality Blending

Adding haptic feedback to VR graphics is often referred to as "augmented" reality and may offer a significant new tool in functional rehabilitation. By creating environments that not only look like real environments but also exert forces like real objects, therapists can retrain patients to do ADL tasks using virtual environments. Physical parameters can be changed in software without building mock-ups, and therapists can obtain quantitative metrics through sensors mounted on the robot.

While VR appears to have great value in training or immersing a nondisabled person performing a remote task, the efficacy of VR therapy for paretic patients is still an area of active research. For example, some data suggest that a training regimen dispensed under the cover of games allows a patient with adhesive capsulitis to tolerate pain better and to exercise a larger ROM beyond the limits achieved without any games. However, whether such a strategy will work for severe-to-moderate stroke patients is unclear.

The largest implementation issue faced by researchers when combining VR and haptics is the need to calibrate the stereoscopic visual feedback with the haptic feedback. This calibration is necessary to ensure that when a user sees herself/himself touching a virtual object, she/he "feels" the object at the same time. If the calibration is not implemented correctly, the user feels disconnected from the virtual environment. The state of the art in combining large-reach haptics and VR technology is exemplified by Yokokohji et al. at Kyoto University, Japan [23]. They used a PUMA 560 robot (Staubli Unimation, Inc, Duncan, South Carolina, no longer in existence) as a haptic device and visual feedback from an LCD (liquid crystal display) as shown in **Figure 5** [23]. Using a technique called "chroma keying," the user views a live video image of his own hand blended with the graphic scene of the virtual environment while manipulating the end effector of the robot. By calibrating the haptic and visual VR, the user

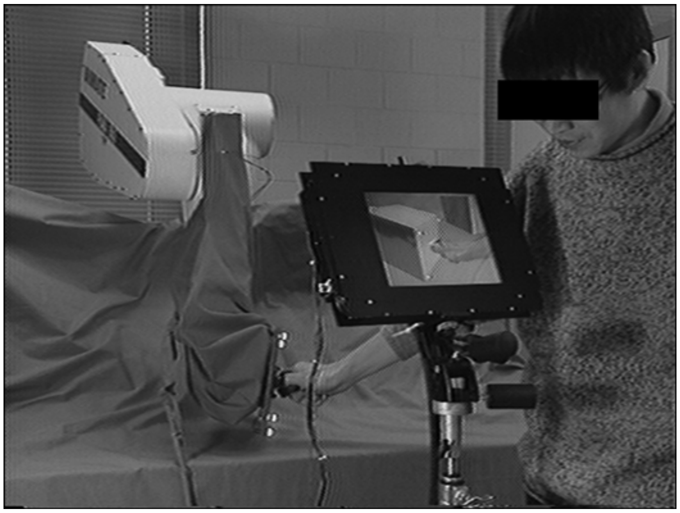

Figure 5.
Blending live video and graphics using “chroma keying” with LCD (liquid crystal display) screen and PUMA 560 haptic display. Reprinted by permission from Yokokohji Y, Hollis RL, Kanade T. What you can see is what you can feel—Development of a visual/haptic interface to virtual environment. Proceedings of the IEEE Virtual Reality Annual International Symposium; 1996; Los Alamitos, CA. New York: IEEE; 1996. p. 46–53. (© [1996] IEEE.)

perceives that his hand encounters the haptic device at the same instant that the video overlay image of the hand touches the virtual object displayed on the LCD screen.

Yokokohji et al.’s approach of blending live video and graphics highlights one of the key problems with combining haptic and video feedback. In most work, the “real” world of the user and the “virtual” world of the object are separate and do not interact directly with each other. Although the users control the virtual hand, it is not their own hand that they see interacting with the virtual object. This indirect control gives users the impression that they are using a manipulator to move an object at a remote site rather than actually being immersed in the virtual world.

Few researchers have tried to blend human-scale haptics with fully immersive virtual environments. Virtually complete immersion was achieved by Buoguila et al. at the Tokyo Institute of Technology (Tokyo, Japan) using their cable-driven Big SPIDAR robot, which is attached to four corners of a 3 m cubic frame [24]. Stereographic imagery is projected on a 120 in. screen and observed through liquid-crystal-shuttered glasses while the user interacts with an object suspended by cables. Because the robot consists of thin cables, the system maintains the transparency of the working space and does not occlude the projection screen. However, the stereoscopic calibration for this system has proven to be exceedingly difficult.

Engineers at Ford Motor Company are attempting to create full parallax views of automobile models by using holography [25]. Besides creating a true three-dimensional (3-D) virtual image, holography also circumvents the occlusion problem typical of viewing an image on a flat screen. When their large 6-degree-of-freedom (DOF) haptic device (which currently uses a head-mounted display) is integrated with the holographic system, it may produce a very realistic 3-D system. However, holographic movies are still limited to only a few frames per second, which is inadequate for real-time implementation [26].

Interactive Control

By design, high-bandwidth interactive rehabilitation robots have dynamics comparable with those of the system with which they interact. They contrast with low-bandwidth motion-controlled robots, which seek to impose motion and are assumed to be much “stiffer” than the environment with which they interact. High-bandwidth rehabilitation robots also contrast with force-controlled robots, which seek to impose force and are assumed to be much “softer” than their environment. Both low-bandwidth motion-controlled robots and force-controlled robots permit the neglect of the environment in controller design, because the closed-loop dynamics of the robot are not significantly altered by interaction. But for rehabilitation robots, interacting with the environment substantially alters the system dynamics and must be considered in analyzing stability. Furthermore, the performance of a rehabilitation robot is defined not in terms of its capability to follow a trajectory, but instead by its capability to provide a desired “feel” at the endpoint [27].

Stability and performance are both addressed directly when impedance control is used for controller design [28]. Impedance control regulates the behavior of the robot at the point where it interacts with the environment. Mechanical impedance is a property of the robot alone, regardless of the environment. Proper selection and ideal implementation of impedance can guarantee stability with certain environments, as well as desired feel. For example, a programmer could specify a “virtual” spring connecting the patient’s hand to a position that moved along a nominal trajectory. When the patient’s motion is close to nominal, the robot exerts little force. Conversely, when the patient’s hand strays, the robot pushes or pulls it back to the nominal motion; the farther the patient strays, the greater the force the robot exerts.

The challenge for rehabilitation robot developers is to create devices that offer a broad range of endpoint impedance that includes sufficiently low impedance for a patient to backdrive the robot with ease. This quality differs from traditional factory robots, which have high impedance; it also differs from haptic devices, which typically offer a broad range of impedances but saturate at comparably low force. The controller modulates the way the robot reacts to mechanical perturbation from a patient or clinician and ensures a gentle, compliant behavior. Note that impedance control does not specify a unique motion but an entire family of motions and shares the burden of producing motion with the patient. Importantly, it allows the patient to make movement errors but attempts to minimize the magnitude of those errors and thus is considered key to "adaptive" or "performance-based" rehabilitation [5,29].

Internet Time Delay

Extending impedance control to telerehabilitation requires care. The challenge arises from the time delay introduced in the control loop by the network. The time delay of Internet communications is highly variable and can be well over hundreds of milliseconds, even with the highest bandwidth. In some applications, haptic telerehabilitation requires bilateral, force-reflecting teleoperation, which means the forces and motions of one robot are communicated to the other robot and vice versa. Again, if left uncompensated, time delays can induce unstable interaction between the two robots.

A significant amount of previous research has been done in teleoperation with time delay but mostly for compensating the delay in visual feedback. The solution has typically been to provide the user with a "predictive graphics display" to command the arm while performing a task rather than using the delayed "live" video feed from the robot [30]. However, this scheme only works as well as the graphics can predict what the actual robot will do, and any discrepancy between the modeled graphical environment and the real world could potentially cause problems.

Predictive force feedback is much harder to implement because it is even more susceptible to modeling error than predictive graphics displays. Just a small error in the position of a remote object can cause a huge discrepancy in the force experienced at the near end by the haptic device. When the load being confronted at the remote site is another person, as is the case in telerehabilitation, the load is virtually impossible to predict. Thus, predictive haptic displays have not emerged as a viable solution in remote rehabilitation.

The leading solution to the time-delay problem was originally presented in work by Anderson and Spong [31] using wave-scattering theory. They proved that stability could be guaranteed by structuring the interface with the remote data communication system so that robot-to-robot interaction was equivalent to a (virtual) passive transmission line. More recently, the wave-variable approach was extended to eliminate undesirable wave reflections and achieve high-performance bilateral teleoperation in the presence of substantial time delays, on the order of seconds [32]. It is important to note that this solution requires impedance control featured in several rehabilitation robots to ensure gentle, stable interaction with the patient. Imaida et al.'s work on teleoperation [33] offers a good overview of these and other time-delay compensation techniques.

The wave variable approach was used successfully in a cooperative beam experiment conducted over the Internet between Interactive Motion Technologies, Inc, and the Georgetown University Imaging Science and Information Systems (ISIS) Center (Washington, DC) [15]. During the test, time delays of up to 110 ms were observed and produced borderline instability without compensation. However, under wave-variable control, the system was quite robust with little deterioration in performance. Packet loss was found to be less than 1 percent at transfer rates of 100 Hz when UDP transmission was used. However, as the time delay increased, the virtual mass at the haptic interface also increased, which caused the handle to have a heavier feel.

While all of these approaches yield successful time-delay compensation, they also have their limitations. Many introduce unwanted damping or inertia at the haptic interface, which is a real detriment to the realism of the simulation. However, these effects are often quite subtle until the time delay increases above a few tenths of a second. Given the increasing bandwidth, speed, and improved routing of the Internet, time delays may shrink to acceptable levels a decade hence.

Patient Safety

In recent years, robots have made substantial inroads in the medical field. Devices such as *da Vinci* [4], Gentle/S [34], and the InMotion2 robot (MIT) [35] have provided clinicians with new tools for treating patients. Ironically, these treatment devices might also pose a significant hazard to the patient. While the robot must be capable of operating upon or assist the patient, it must also consider the safety of the patient and enforce all necessary safety precautions.

For robots interacting with the human, the most important feature of the controller is the uncertainty of physical contact. The stability of most robot controllers is vulnerable when contacting objects with unknown dynamics. Dynamic interaction with highly variable and poorly characterized objects (e.g., patients or therapists who are neurologically impaired) could destabilize the robot. By employing an impedance controller as described in the previous subsection, even inadvertent contact with points other than the robot endpoint will not destabilize the controller. This feature is essential for safe operation in a clinical context.

Rehabilitation robot developers will need to integrate further safety considerations into their designs. In perhaps no other application will the danger be more acute than for robotic exoskeletons that essentially encapsulate the human. The basic system does not inherently address the needs of safety, because its design can only identify certain basic failure modes. However, the electromechanical subsystems, the software subsystems, and the control subsystem all need to be examined for determining overall patient safety.

Any safety-critical design should begin with a preliminary hazard analysis to determine failure scenarios that could harm the patient [36]. Following this assessment, the designer needs to determine how many simultaneous component failures can be tolerated for the system to remain "fail-safe," i.e., be able to detect a failure and either hold a safe position without exerting any force or power-down if a failure occurs. Then, a fault-tree analysis can be conducted to determine what component failures lead to what conditions. This process is iterative and can often lead to additional sensors for redundancy or new computer boards for monitoring. While this procedure does place additional burden on the design process, it is necessary to ensure a safety-critical design with a tolerable level of risk.

TOWARD BILATERAL TELEREHABILITATION

In the previous section, we examined the major hurdles faced by design engineers for telerehabilitation systems. Although several unilateral systems have been built to date with modest degrees of success, what inroads have been made into bilateral systems where time-delay compensation and built-in safety become paramount concerns? In this section, we define and examine two variations on bilateral rehabilitation, interactive and cooperative, using the MIT-Manus robot as an example platform. Known commercially as the InMotion2 robot, the MIT-Manus was developed at MIT in the early 1990s as a prototype for stroke therapy [37].

Interactive Telerehabilitation

We use the term "interactive telerehabilitation" to describe the situation in which both patient and therapist interact with each other in a graphical virtual environment but have no direct force-feedback interaction with each other. However, both are still interacting with their virtual environments via force feedback. This is typical of gaming with force feedback over the Internet such as the Internet air hockey game shown in **Figure 6**, in which the handle of the robot functions as the "striker." Each player will feel a force impulse when he or she strikes the puck, but the two players cannot push against or "check" each other.

Games more directed at therapeutic interventions are based on studies showing that desired characteristics of the therapeutic context (i.e., use of imagery-based tasks, object parameters) can significantly influence movement kinematics during reach, in persons with and without CVA [38]. Movement was improved (i.e., was faster and smoother) when persons reached for actual objects or engaged in simulated, imagery-based tasks rather than

Figure 6.
Internet air hockey on InMotion2 robot can be used for interactive telerehabilitation.

rote exercise [39–41]. In this vein, we have been developing functionally based rehabilitation video games.

In "Breakfast at Tiffany's," shown in **Figure 7**, we are developing a game in which the subject interacts with the therapist (represented by Tiffany) and she/he may be cued to transport the limb to grasp and move a plate or reach for and grasp a virtual bagel and place it on the plate. Furthermore, depending on the patients' therapy needs, game tasks may also call for grasping a bread knife and cutting the bagel (bimanual activity), reaching for and opening a jar of jam (bimanual), transporting the limb to grasp and move a coffee cup closer, pouring coffee and milk, and dropping sugar cubes into the coffee. Such activities induce the practice of reach and grasp that patients would use during "real-life" activities.

Note that when using this game, we require more DOF than shown previously in **Figure 6**. We must integrate our robot modules into a "single" device—shoulder and elbow, wrist, and hand, as shown in **Figure 8**. This case exemplifies the importance of one of MIT's core design specifications: modularity. Modularity can confer significant advantages such as device configurability tailored to specific impairments, improved resource utilization given that modules may be decoupled for stand-alone use, and an expandable hardware architecture that can readily accommodate new modules, third-party modules, and upgraded modules.

Cooperative Telerehabilitation

We use the term "cooperative telerehabilitation" to describe the situation in which the therapist and patient interact directly with each other over the Internet, both visually and kinesthetically. Here, bilateral rehabilitation is fully implemented. The Georgetown University ISIS Center has assembled two InMotion2 robots into a telerehabilitation test bed to study the feasibility of conducting remote assessment and therapy over the Internet using the architecture previously described in the "Bilateral Systems" section. In this scenario, both the therapist and patient robots are considered "clients" that are independently interacting with the virtual object, considered the "servers." The VOG applies the sensed "interaction" forces from the clients and then calculates the resultant motion of the object. The motion of the object at each "contact" point is then transmitted back to each client where it is tracked by a controller.

An example of a cooperative rehabilitation task is depicted in **Figure 9** [15]. The patient and therapist "pick up" opposite ends of a shelf sitting across a pair

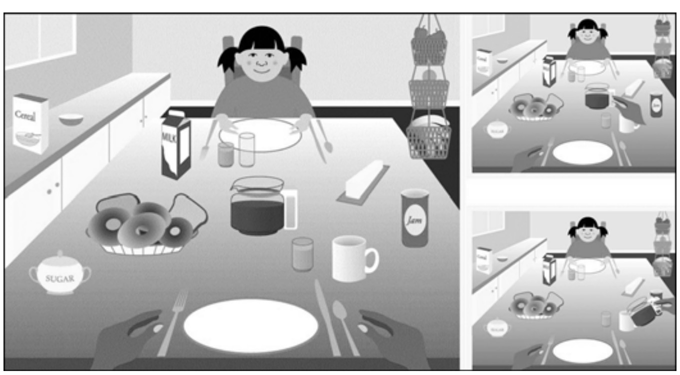

Figure 7.
"Breakfast at Tiffany's" is example of interactive telerehabilitation where patient (near end) and therapist (far end) reach and grasp objects in shared virtual environment but do not directly contact each other.

(a)
(b)

Figure 8.
Robot modularity: **(a)** wrist robot in stand-alone operation or **(b)** integrated to planar shoulder-and-elbow InMotion2.

of sawhorses by grasping their robot handles, which coincide with their ends of the shelf. The mass, length, and inertia of the shelf can be adjusted to correspond to different materials using a graphical user interface on the therapist's computer. The gravity vector points in the sagittal plane of the operator so that she/he is pushing away when lifting the shelf. As the shelf is "lifted," the side that is lower will begin to feel more of the weight, thus stimulating the patient to maintain the beam in a horizontal position. Also, if one side tugs on the shelf, then the other side feels it, thus encouraging a cooperative strategy to lift the object. This scheme proved successful in preliminary experiments conducted over the Internet between Interactive Motion Technology, Inc, and the Georgetown University ISIS Center.

FUTURE TRENDS

What might the components of a telerehabilitation system include in a decade from now? Two critical pieces of information that might shape the future direction in rehabilitation robotics, in general, and telerehabilitation, in particular, are whether (1) multidimensional robots are needed or if a modular approach will suffice and (2) high-bandwidth backdrivable interactive robots are essential or if an enhanced version of the continuous passive motion (CPM) machine will suffice. Research efforts at MIT continue to embrace the design philosophy that modularity and high-bandwidth backdrivable robots are essential, while efforts at Georgetown University embrace multidimensional robots and an enhanced version of the CPM machine. Our shared vision includes advancements in VR (graphics) technology, such as 3-D displays and holography, and increases in Internet bandwidth to reduce the time delay in remote rehabilitation. Here, we review some recent trends in haptic devices, functional rehabilitation, and home-based therapy.

Exoskeletons: The New Haptic Engine?

Wearable robotics, or exoskeletons, have been under development for VR applications for almost two decades. Exoskeletons can provide a more natural haptic interface for physical therapy because they allow contact between the patient and the robot along the entire length of the limb, as a therapist might do. In addition, exoskeletons will allow more surround-feel environment for VR training, an area in which they have already been prodigiously employed.

The Maryland-Georgetown-Army (MGA) Exoskeleton is a collaboration between Georgetown University and the University of Maryland (College Park, Maryland) to develop a robotic device for shoulder rehabilitation [42]. The exoskeleton, shown in **Figure 10**, is electrically powered and builds on advances in actuator/drive technology for developing a lightweight but powerful design. It has five joints, each powered by a brushless direct current motor through a harmonic drive train capable of exerting up to 92 N•m of torque at the shoulder. Encoders mounted on the motors and a suite of force sensors at the

Figure 9.
Cooperative beam task uses OpenInventor™ 3-D graphics (Silicon Graphics Inc, Sunnyvale, California) displayed on stereographic goggles and force-feedback from InMotion2 robot to represent virtual environment.

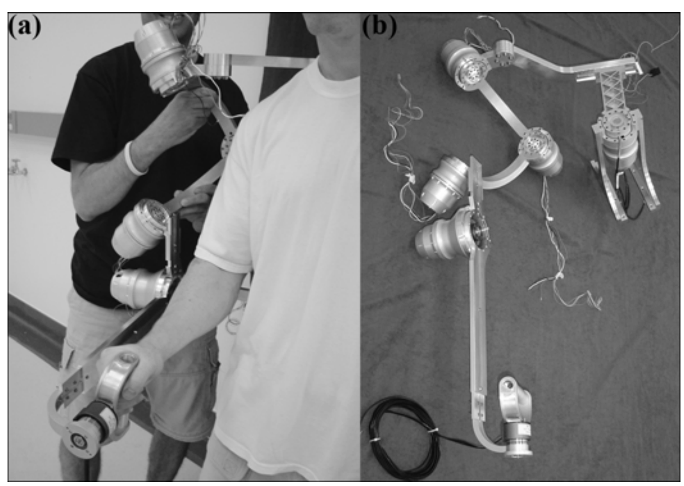

Figure 10.
MGA (Maryland-Georgetown-Army) Exoskeleton: **(a)** being checked for fit on subject during assembly and **(b)** complete hardware configuration.

shoulder, elbow, and wrist provide input to the control system to realize desired rehabilitation protocols.

The MGA Exoskeleton can be used for assessing arm strength, speed, and ROM with onboard sensors and can function as both a resistance trainer and VR tool for rehabilitation. Operation of the device can be monitored by a computer-controlled safety system based on an architecture developed for a robotic flight experiment aboard the Space Shuttle [36]. The exoskeleton is currently undergoing hardware integration and testing.

Functional Rehabilitation: Protocol of the Future?

In randomized control trials for persons with both acute and chronic impairments after stroke, persons treated with a robotic rehabilitation protocol have demonstrated significant reductions in impairment of the exercised limb [8,43–50]. These gains in motor capacities (e.g., voluntary control) agree with a prominent theme of current research into recovery, which posits that activity-dependent plasticity underlies neurorecovery. However, the desired outcome of rehabilitation services includes both reductions in motor impairments and an improved ability to successfully participate in ADL. While we have seen reductions in motor impairment, no specific attempts were made during these studies to help the person link the movements practiced during robotic therapy to motor actions while performing tasks.

To increase the effectiveness of robotic therapy, we envision new functionally based approaches that will integrate rehabilitation robotics with clinical practice and enhance the carryover of robot-trained movements during functional tasks. We expect that treatment protocols, properly targeted to emphasize a sequence and timing of sensory and motor stimuli similar to those naturally occurring in ADL, could facilitate carryover of the observed gains in motor abilities and thereby confer greater improvements in functional recovery.

The aforementioned results from randomized control trials were based on a "bottom-up" approach, which assumed that improvements in underlying capacities (e.g., force production, isolated movement) would enhance motor function during activities and tasks [51]. Functionally based rehabilitation robotics will be guided by a "top-down" rehabilitation approach, in which a person's identified goals for task performance are used along with evaluation data for establishing a treatment plan. Rehabilitation robotics will not only provide remediation for impairments at the capacity level (e.g., forces produced, voluntary motor control) but also allow task-specific, intensive therapy for impaired abilities (e.g., reaching or grasping) that underlie task performance. One goal of this work is to blend both approaches and to begin building a scientific basis for the "best" rehabilitation practice. Researchers can thus expect to better understand how interventions directed toward one level of performance (i.e., abilities) influences functioning at other levels (e.g., developed capacities, activities, and tasks).

Home-Based Therapy: The Next Frontier?

Reductions in healthcare reimbursement place constant demands on rehabilitation specialists to reduce the cost of care and improve productivity. Service providers have responded by shortening the length of patient hospitalization. Thus a healthcare delivery system that did not fully understand the best regimens for inpatient rehabilitation therapy is now increasingly promoting outpatient rehabilitation (administered in less than one-third of the time) to a sicker population in which there is a more limited ability to prescribe and deliver therapy, monitor patient compliance, and assess outcomes. This changing environment creates a need for a continuum of care in these discontinuous settings (e.g., rehabilitation hospitals, skilled nursing facilities, outpatient clinics, health maintenance and well spaces, and the home).

An example of a commercial product for home-based therapy is the KMI Hand Mentor, developed by Kinetic Muscles, Inc (Tempe, Arizona) [52]. The Mentor uses "air muscle" power and was developed specifically for retraining stroke patients to grasp everyday objects such as keys and utensils while in their homes. Accompanying visual feedback and intermediate goals are used to encourage the patient to try harder tasks. The company has recently embarked on a project to develop an "Upper Extremity Trainer" that combines wrist, elbow, and shoulder motion for stroke rehabilitation.

Toward the goal of providing a continuum of care, we sought to create a scenario that would allow us to provide not only therapy but also fun activities in a multiplayer game environment, a more civilized version of Doom™, Quake™, or Counter-Strike™. The potential benefits of combining telerehabilitation with multiuser training are extensive, but which aspects of this emerging technology will work best in practice are as yet unclear. Two reasons exist for this optimism. First, technology for multiplayer games in which players interact in real time through the Internet has emerged relatively recently to become one of the fastest-growing sectors of the computer/video game market. Second, the prodigious size of this highly competitive market rapidly reduces the cost of technology developed for computer/video games.

CONCLUSIONS

Clearly, many challenges, both technical and economic, still lie ahead if we are to realize home-based robotic telerehabilitation. Technical challenges include the development of complex multidimensional robots capable of simulating more task-oriented home therapy. While devices such as the InMotion2 Robot are a good start, they can neither realize the full 3-D motion of the upper limb nor exert the forces that might be encountered while performing ADL.

In addition, compensating for or nulling the concomitant increase in mass and friction in these haptic devices is by no means a bygone conclusion. All control systems have their limitations, and multiple control approaches might be required for different regimens. Impedance control, for example, works best when simulating spongy contact and light damping, while admittance control is superior for simulating high inertia and heavy damping.

Furthermore, compensating for potentially large and variable time delays needs further work. The wave variable approach, as well as others that were discussed, is a good first-cut, but all have their drawbacks. When wave variables are used, for example, increasing time delay manifests itself as large perceived mass at the haptic interface—which might not be a good thing.

Issues related to coordinating the haptic and visual feedback still need to be addressed. The coordination is critical to realistic simulation, or the patient will become confused and the virtual environment will cease to feel "immersive." In addition, visual technology is as much of a moving target as the robotic technology—if we solve the coordination of VR goggles, what will happen when holography comes along? In addition, we will want to use the Internet to transmit real-time audio and video between the patient and the therapist. The real-time aspect will be essential for realizing full bilateral configurations used in cooperative therapy.

In addition, the economic challenges should not be underestimated. We believe a strong market exists for home-based rehabilitation, but the reduction of reimbursements is a major milestone that must be conquered, otherwise telerehabilitation will remain aloof. Only then will commercial off-the-shelf (COTS) therapy devices become a reality and widespread deployment in homes and clinics a possibility. Naturally, the cost of rehabilitation devices currently being tested in clinics (often tens of thousands of dollars) will need to drop by at least an order of magnitude, but mass production of devices alone could reduce these costs significantly.

Software development will also be key. A significant portion of project cost, sometimes more than half, is related to software development. Therefore, even if the cost of the initial hardware prototype drops, the software cost will not. While the total development cost will get amortized over more units if COTS therapy is realized, it will remain the dominant cost. Therefore, the development of new software tools and perhaps open-source libraries for exercise regimens will also be a key to reducing the cost of home-based therapy.

In summary, we believe that home-based telerehabilitation has a bright, albeit hazy, future. It will be part of the continuum of care, delivering high-quality therapy and care from bedside in the acute facility, to the rehabilitation hospitals or skilled nursing facilities, to the outpatient clinics or health maintenance and wellspaces, and to the home. It is not far fetched to imagine the baby-boomers in the driver's seats of multiplayer games everywhere, starting in their retirement communities—the teens will only follow suit!

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