To appear: Emerging and Accessible Telecommunications, Information and Healthcare Technologies – Engineering Challenges in Enabling Universal Access
(ed) Jack Winters, Charlie Robinson, Richard Simpson, Gregg Vanderheiden, eds. IEEE Press 2002

# Emerging Technologies for Improving Access to Movement Therapy following Neurologic Injury

**David Reinkensmeyer[1], Peter Lum[2], Jack Winters[3]**

**[1]University of California, Irvine**
**[2]Palo Alto VA Rehab R&D Center**
**[3]Marquette University**

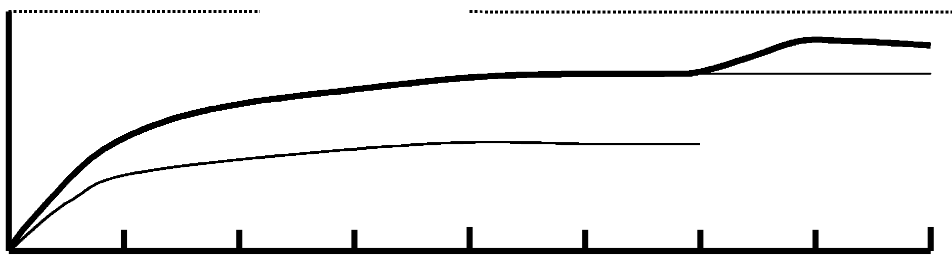
## 1. Introduction

A disturbing paradox has developed between rehabilitation research and practice in the last decade. On the one hand, scientific evidence has accumulated that therapy improves movement recovery following stroke and spinal cord injury. On the other hand, the duration of reimbursed therapy has decreased due to economic pressures on the U.S. health care system. If intensive therapy stimulates recovery, an important goal is to develop technology that allows people with neurologic injuries to practice therapy without always requiring one-on-one interactions with clinicians.

In this chapter, we first discuss key elements of this paradox and how technology may help address those elements. We then review several recent attempts to automate movement therapy for both upper and lower extremity rehabilitation. In conclusion, we pose three questions that we believe will shape the future development and use of this technology.

## 2. Rehabilitation Practice, Rehabilitation Science, and the Need for Therapeutic Technology

The largest inpatient populations within typical comprehensive rehabilitation hospitals are patients with neurologic injuries such as stroke, traumatic brain injury, and spinal cord injury. These patients typically receive intensive movement therapy, if they can tolerate it, from physical and occupational therapists for several hours each day. Over the last decade, however, the length of hospital stay as inpatients has been roughly cut in half, to about 20-30 days. Often it is less, and indeed many individuals do not have access to comprehensive rehabilitative facilities because of barriers such as cost and distance, and end up at facilities that do not specialize in rehabilitative services but do provide some level of therapy each day. Depending on their personal situation, individuals then either go home or to some type of structured environment (e.g. skilled nursing facility), where for a while they typically have access to outpatient care or home care visits (involving nurses or therapists). Typically this will involve therapy about 2-3 times per week. As represented by Figure 1, therapeutic care is then stopped by two to six months, depending on patient progress and financial considerations. At this stage there has been an implicit assumption within the healthcare system that the individual has reached a “plateau,” with there being a residual level of “chronic” impairment that is treated as a fact of life.



As represented by the far right part of the graph in Figure 1, scientific studies in neurorehabilitation now challenge this plateau assumption, and indeed the whole clinical rehabilitative process. As noted nearly a century ago [1], significant recovery following stroke is often possible well after six months with intensive therapy [2]. Some of the most notable and visible evidence comes from studies of Constraint-Induced Movement Therapy (CI Therapy, which refers to a family of therapy techniques that has initially been applied to stroke patients). CI Therapy, initially motivated by the concept of "learned-disuse" of an impaired extremity [3], incorporates constraint of the less-affected extremity (e.g., arm in sling or mitt over hand), with intensive, therapist-supervised movement practice of the more effected extremity. Individuals with mild to moderate impairment following stroke can significantly improve their movement ability even years following the initial insult. Several other studies of intensive movement therapies, including repetitive movement practice [4], robot-assisted therapy [5-7], virtual-reality based therapy [8-10], and locomotion training [11], have shown that significant improvements are possible even years after the initial injury onset. In light of these results, the current scheme of delivering intensive therapy in the early inpatient phase and then transitioning to no supported therapy within six months is likely sub-optimal [12].

Despite this scientific evidence, however, it is unlikely that conventional rehabilitation practice will be restructured to incorporate a longer duration of therapy. The financial pressures on health care providers are intense, and make it difficult to add more therapy unless it can be documented that the therapy reduces long-term care costs. Demonstrating reductions in long term care costs is in turn a difficult undertaking due to the time scale of interest and the complexity of the factors that influence long term outcomes.

Improved technology for automating aspects of rehabilitation may however help align rehabilitation practice with rehabilitation science in the area of movement therapy. For patients who can tolerate additional exercise as inpatients, devices that automate movement therapy could be used relatively unsupervised as an adjunct to regular therapy. Therapy devices could also allow more effective group therapy, allowing the therapist to give one-on-one attention to one patient while another worked with the device under intermittent supervision. Most significantly, emerging devices that could be used at home or at community exercise facilities could allow individuals ongoing access to therapy even years after the cessation of conventional therapy, thereby improving quality of life. Recognizing this potential to enhance access to therapy, there has recently been a surge in research activity focused on devices for automating movement therapy for both the arm and legs.

## 3. Rehabilitation of Arm Movement

Of the 600,000 people who survive a stroke in the U.S. each year, over 300,000 incur chronic arm impairment. Several robotic therapy devices, or "rehabilitators", have been developed to automate therapy for the arm following stroke. In initial clinical trials, these devices have been used to address several fundamental questions, including:

- Will movement recovery improve if conventional therapy is supplemented with robotic therapy?
- What are the relative benefits of robotic and conventional therapy?
- What are the elements of robotic and conventional therapy that stimulate movement recovery?

### 3.1 Clinical Results with Arm Rehabilitators

*MIT-MANUS:* The first robotic system to receive extensive clinical testing was the MIT-MANUS, a two degree-of-freedom (DOF) robot manipulator that assists shoulder and elbow movement by moving the hand and forearm of the patient in the horizontal plane [13]. A unique design feature is low intrinsic end-point impedance (i.e.: back-driveability), which allows the device to measure free movements as well as to guide a weak limb in "hand-over-hand" therapy. Video games with visual, auditory and tactile feedback engage the patients in the therapy. For more than 5 years, clinical testing has been underway predominantly at the Burke Rehabilitation Hospital (White Plains, NY). The testing protocol has been guided by how the device is likely to be used clinically, as an adjunct to regular therapy that provides patients with extra sensory motor stimulation that they would not normally receive if the device were not available. A recent report described results with 56 subacute patients who completed the training protocol. In addition to their regular therapy, experimental subjects received five one-hour sessions a week (25 total sessions) with MIT-MANUS beginning 23 days after stroke onset. Controls received one hour of "sham" therapy a week, in which the subject used the less-impaired limb in the robot, or the robot interacted passively with the more-affected limb. When compared to controls, the experimental subjects had greater gains in proximal arm strength, reduced motor impairment of the shoulder and elbow, and greater recovery of functional independence [14]. The two groups were still statistically different in terms of motor impairment at a 3-year follow-up [5].

*MIME:* The MIT-MANUS results provide convincing evidence that supplemental robotic therapy can improve recovery, but they do not address whether robotic treatment offers unique advantages to conventional therapy, or at least is no less effective than conventional methods. Answering this question has been the driving motivation behind the MIME project at the Veterans Affairs Palo Alto Rehabilitation Research and Development (RR&D) Center [15, 16].

The MIME system consists of a robot manipulator (Puma 560) that applies forces to the paretic limb through a customized forearm and hand splint. The robot's six DOF allow the forearm to be positioned within a large range of positions and orientations in three-dimensional space. A six-axis sensor measures the forces and torques between the robot and the paretic limb. Four modes of robot-assisted movement have been developed. In passive mode, the subject relaxes as the robot moves the limb toward a target with a predetermined trajectory. In active-assisted mode, the subject triggers initiation of the movement with volitional force toward the target and "works with the robot" as it moves the limb. In active-resisted mode, the robot provides a viscous resistance in the direction of the desired movement and spring-like forces in all other directions as the subject attempts to reach toward the target. In bimanual mode, the subject attempts bimanual mirror-image movements while the robot assists the affected limb by continuously moving the affected forearm to the contralateral forearm's mirror-image position and orientation. During bimanual mode, the two forearms are kept in mirror-symmetry by a position digitizer, which measures the movement of the contralateral forearm and provides desired coordinates for the robot motion controller.

The goal of the initial clinical testing was to compare the effectiveness of a therapy program of robotic manipulation with an equally intensive program of conventional therapy techniques [16]. Twenty-seven chronic stroke subjects received 24 one-hour sessions over two months. Subjects in the robot group practiced shoulder and elbow movements while assisted by MIME. Subjects in the control group received conventional treatment, based on NeuroDevelopmental Therapy methods, that targeted proximal upper limb function, and five minutes of exposure to the robot in each session. When compared to conventional treatment, robot-assisted movements had advantages in terms of clinical and biomechanical measures. The robot group had statistically larger improvements in a clinical motor impairment scale after one month of treatment, and also after two months of treatment. The robot group had larger gains in strength and larger increases in reach extent after two months of treatment. At the six-month follow-up, the groups were no longer different in terms of the motor impairment scale, however the robot group had larger improvements in a scale that measures functional independence in ADL.

*The ARM Guide:* The MIT-MANUS and MIME studies generated strong evidence supporting the benefits of robotic therapy, but left open what the essential elements of the robotic therapy were. For example, it may be that the repetitive movement attempts by the patient, rather than the mechanical assistance provided by the robotic device, were the primary stimuli to recovery. This question is being addressed using a device called the ARM Guide in a clinical trial being conducted at the Rehabilitation Institute of Chicago in collaboration with the University of California at Irvine.

The ARM Guide is a singly actuated, three DOF device designed to mechanically assist in reaching movements [17]. Since reaching movements typically follow straight-line trajectories, the device uses a linear bearing to guide reaches by the subject. The linear bearing can be oriented at different yaw and pitch angles to allow reaching to different workspace regions. Like MIT-MANUS and MIME, the device can assist or resist in movement, and can measure hand movement and force generation. The device is statically counterbalanced so that it does not gravitationally load the arm.

In an ongoing clinical trial, sixteen chronic stroke subjects have received 24 therapy sessions over two months. Subjects in the robot group have received mechanically assisted reaching exercise with the ARM Guide. For this group, the subject initiates movement, and the ARM Guide completes the movement along a smooth trajectory through the arm's full passive range if the subject is unable. Subjects in the free reaching group have performed unassisted, repetitive reaching exercise, matched in the number of repetitions and target locations with the robot group. All subjects have been evaluated using a set of clinical and biomechanical measures of arm movement. As in the MIT-MANUS and MIME studies, the subjects who have received therapy with the ARM Guide have shown significant improvement in the clinical and biomechanical measures [7, 18]. However, the amount of improvement in the free reaching group has been comparable.

One interpretation of these preliminary results is that the action of repetitively attempting to move, rather than the mechanical assistance provided by the ARM Guide, was the primary stimulus to arm movement recovery. Such a hypothesis is consistent with other repetitive movement exercise paradigms that improve upper extremity movement ability following brain injury [4, 19, 20]. Another possible explanation is that the particular form of active assistance provided by the ARM Guide is sub-optimal, and that other devices with their own versions of active assistance may demonstrate a benefit over unassisted exercise. For example, the MIT-MANUS device can assist planar motion rather than constraining motion to a linear path, and this may be therapeutically beneficial. The MIME device can assist in 3D movements besides straight-line movements and in bimanual therapy, and again, these features may be therapeutically beneficial. A third possible explanation is that the subject group in the ARM Guide group spans a range of impairment levels and stroke types, and mechanically assisted movement will benefit particular subsets of stroke patients. For example, severely impaired subjects may benefit motivationally from the mechanical assistance.

### 3.2 Other Emerging Technologies for ARM Rehabilitation

Several other systems are being developed to automate therapy for the arm and hand following stroke. In this section we review a few examples that demonstrate how virtual reality, low-cost technology, and the Internet are being incorporated into automated therapy systems.

*GENTLE/S*: The GENTLE/S is a project sponsored by the European Commission to evaluate robot-mediated therapy for neuro and physical rehabilitation following stroke [21]. In this project, a three DOF robot called Haptic Master has been used to implement three exercise modes similar to MIME's unilateral modes. A novel feature of the system is that the robotic exercise is integrated with virtual environments. For example, one virtual environment is a room that patients interact with by moving objects from one location on a table to another. The Haptic Master assists the movement patterns needed to complete the tasks. Compared to user interfaces that provide feedback in terms of video games or abstract 2-D presentations of interaction forces, a user interface based upon a Virtual Environment could improve patient motivation for using the system. This is relevant given evidence that highly repetitive exercises may be needed for improved recovery.

*SEAT:* At the Veterans Affairs Palo Alto RR&D, the SEAT project is investigating device-based bimanual therapy in the context of a wheel-steering task [22]. This project builds upon previous work that identified the potential of instrumented and powered devices that assist the paretic limb during bimanual tasks [23, 24]. SEAT includes a full driving simulation and a motorized steering wheel. Sensors on the steering wheel measure the forces imposed upon the wheel from each hand. In addition to modes that assist the impaired limb, a unique "constrained" mode forces the more-affected limb to perform the task. In this mode, the subject attempts to steer normally with both limbs, but the wheel can only be rotated by the more-affected limb, and not by the less-affected limb. Preliminary testing has shown that during turns in which the more-affected limb is moving against gravity, more positive torque is applied to the wheel by the more-affected limb in "constrained" mode than when the motor only supplies the restoring torque associated with a normal steering environment. It has been suggested that this is a device-based form of CI Therapy, and could be a means improving performance of an important functional task without direct supervision from therapists.

*ARC-MIME:* The ARC-MIME project at the Rehabilitation Technologies Division of Applied Resources Corporation is an attempt to develop a commercial device that merges concepts from MIME and the ARM Guide. Since a large portion of the movement patterns used in the MIME therapy are based upon straight-line reaching movements, it was realized that a linear slide similar to the ARM Guide could accommodate a significant portion of the movement patterns used in the MIME treatment. In addition, since a linear guide allows only one DOF of movement, it can be operated more safely than the PUMA-based MIME, and also can be produced at significantly reduced cost. With NIH SBIR Phase I support, a prototype device was built that functionally resembles two ARM Guides, one for each limb. The MIME control software was ported to ARC-MIME, so all of the MIME modes are available, including the bimanual mirror-image mode. In initial testing, four chronic stroke subjects exercised in both MIME and ARC-MIME in the same session. When the movement patterns were matched, the forces directed toward the targets by the paretic limb were not significantly different for the two devices, although there were some differences in the forces lateral to the target. Nevertheless, it was concluded that subjects interact in ARC-MIME in a similar fashion to MIME, and so the clinical gains seen in the MIME training should also be reproducible with ARC-MIME. With NIH SBIR Phase II funding, further development and clinical testing are proceeding.

*EMG-Induced Stimulation Therapy.* In the robotic therapy systems discussed above, the endpoint of a manipulator is coupled to the hand or forearm, with forces transmitted and positions passed through this mechanical interface. Conceptually, the manipulator mimics aspects of hands-on physical therapy, but with the added benefit of being able to obtain quantitative information across the interface. This requires external power and a controller, and doesn't directly impact on muscle activity. An alternative approach is to electrically stimulate muscle. This concept has been has been around for centuries, mostly applied to paralyzed individuals, and basic functional neuromuscular stimulation (FNS) has been an active area of research since the 1960s [25]. The area of neural prostheses is outside the realm of discussion; suffice it to say that while considerable progress has been made (e.g., for how to best stimulate and condition muscles), there have also been challenges, especially related to control algorithms. One strategy that bypasses such problems is EMG-induced Stimulation Therapy. One commercial system (AutoMove) explicitly targets stroke therapy, and was FDA-approved in 1997. Rather than attempt proportional EMG control as with high-end arm prosthetics systems, it uses sensitive detection of a very weak voluntary EMG signal to cause a much larger FNS drive to the muscle that by default lasts for 5 seconds. It normally is used to target weak muscles such as wrist extensors. A typical therapy session consists of several 5-second contractions followed by 20 seconds of rest, continued for about 20 min. An advantage is that it takes advantage of human power and control, and is modular and fully ready for home use. While this product would seem to target muscle strengthening rather than coordination, the evidence suggests significant enhancement not only of strength in the local muscle(s) and increased range of motion in the related joint, but also in measures related to function (e.g., Fugl-Meyer) and independence (FIM) [26, 27].

*Virtual Reality-Based Neurorehabilitation*. The cornerstones of Virtual Reality (VR) technologies are "interactivity" and "immersion". VR was originally motivated by applications such as military training simulators and space telerobotics and more recently high-end gaming industry and telesurgery [28]. VR systems for movement therapy are just beginning to be developed [29]. In developing these systems, the burden of proof rests with producing evidence that therapy in a virtual world is better than "real world" therapy at preparing individuals to function in the real world. One possible advantage of VR is that it can augment a therapy environment, for example by overlaying novel computer-generated audiovisual displays or by using haptic devices to provide novel sensory input.

For example, in one recent study, two chronic stroke subjects with hemiparesis practiced placing a virtual envelope in a virtual mail slot depicted on a computer display. An electromagnetic tracking device measured and displayed the subject's actual arm movement [8]. The computer display showed the desired movement trajectory, derived from an unimpaired subject, which could be used as a virtual, animated "teacher" to demonstrate the desired movement to the subjects. The teacher animation could also be adjusted in speed, paused at any point, or displayed as a trace. Training in the virtual environment for sixteen treatment sessions reduced reaching errors during real-world performance by 50%. Using a similar enhanced virtual feedback approach, four subjects with acquired brain injury were trained to pour a cup. The subjects also showed transfer to real-world performance [10].

Novel haptic interfaces for use in VR therapy have been developed by Burdea and his colleagues [9, 31, 32]. For their hand rehabilitation system they have used two interfaces: a Cyberglove (Virtual Technologies, Inc.) with 18 embedded sensors and their Rutgers Master II-ND (RMII) force feedback glove (US patent 5354162, 1994) with 14 sensors and four small pneumatic actuators that can apply forces up to 16 N. This unique glove and system (US patent 5429140, 1995) requires an air compressor (100 Psi) for power and their Haptic Control Interface to control fingertip forces and compute joint angles (to actuators crossing thumb, index, middle, ring). The glove applies forces to the hand to simulate different therapeutic equipment, and to perform passive range of motion or strengthening exercises. The display shows a rigid body image of the hand rather than a cursor. For therapy, the system currently uses four VR exercise programs that were developed using a commercially available graphics library (WorldToolKit). Each program targets one aspect of hand movement, namely range, speed, fractionation and strength, within the context of simple games for which the patient performs a number of trials of a particular task. Three subjects with chronic stroke improved hand movement ability by using the system daily regularly over two weeks [9]. This same research group has also developed a six degree-of-freedom Stewart platform coupled to the foot to provide ankle therapy, so far targeted to orthopedic and stroke applications [32, 33].

*Java Therapy:* Java Therapy is a low-cost, high accessibility system for facilitating repetitive movement therapy developed at U.C. Irvine with support from the Microsoft Corporation [34]. This system is called “Java Therapy” because of its heavy use of the Java programming language. Users log on to the system using the Web, perform a customized program of therapeutic activities, and receive quantitative feedback of their rehabilitation progress. A remote supervising caregiver can then monitor progress, make changes to the exercise program, and provide information and encouragement. The system can be used with a variety of input devices for monitoring movement, including a low-cost, force-feedback joystick that is also capable of assisting or resisting in movement like more sophisticated robotic therapy devices. Because the system uses mass-manufactured input devices, Web infrastructure, and Java applets, it is relatively affordable, accessible, and adaptable. Data from home-based usage by a chronic stroke subject have been presented that demonstrate the feasibility of using the system to direct a therapy program, mechanically assist in movement, and track improvements in movement ability [35].

*Constraint-Induced Therapy:* A therapy technique that may be amenable to automation is Constraint-Induced Therapy. As mentioned above, CI therapy has been demonstrated to substantially improve upper extremity recovery of patients with mild to moderately severe chronic strokes, but remains labor intensive [36]. The therapy involves promoting use of the more-affected upper extremity for 90% of waking hours by constraining the less-affected extremity for two or three consecutive weeks with a resting hand splint and sling or other device that prevents movement of the hand and wrist for activities of daily living. The patients receive a type of training termed "shaping" for 7 hours/day (with rest intervals) for all weekdays during this period (massed practice) [37]. Shaping involves highly repetitive movements and tasks with the difficulty graded in small increments by the trainer. A device that allows subjects to perform the shaping training without direct supervision could make CI-therapy accessible for the vast number of stroke subjects who might benefit from the treatment. Subjects could receive CI therapy at home and a therapist could treat three or four patients at one time in the clinic, thereby substantially reducing the cost of the therapy. However, it is an open question whether compliance with such an intensive training protocol is possible without direct one-on-one attention and encouragement from therapists and trainers. A new research project at the VA Palo Alto RR&D Center, supported by a grant from the Department of Veterans Affairs, will explore these issues.

## 4. Rehabilitation of Gait

### 4.1 Devices for Automating Body Weight Supported Locomotion Training

Recent research has suggested that the spinal cord has a remarkable capacity to learn. For example, the lumbar spinal cord of the cat can be trained to step [38-47] in the absence of supraspinal input. The key characteristics of the training are partial unloading of the limbs and assistance of leg movements during stepping on a treadmill. Based on animal studies, several laboratories and rehabilitation centers world-wide have developed "body weight supported" (BWS) locomotion training as a treatment therapy for humans following spinal cord injury, stroke, and other neurological disorders that impair locomotor ability [48-56]. The findings from several independent studies indicate that BWS training improves stepping, including both treadmill and overground walking, in spinal cord injured and stroke-impaired humans [22, 49, 51, 53, 55-59]. Under the supervision of researchers at UCLA, an NIH-funded, multi-center, clinical trial is currently being conducted to determine whether BWS locomotion training should become a treatment standard.

Implementing BWS locomotion training as an accessible treatment would be difficult, however, for several practical reasons. BWS locomotion training is labor intensive, requiring two to three therapists to manually assist the patient's legs and torso during each training session. Assisting in leg motion can be exhausting for the therapists. In addition, the assistance provided, and thus the pattern of sensory input to the spinal cord, can vary greatly between trainers and sessions. Recognizing this need, two European research groups and a major U.S. healthcare provider have developed robotic devices for automating BWS training in humans.

*MGT:* The Mechanized Gait Trainer (MGT) is a singly-actuated mechanism that drives the feet through a gait-like trajectory [60]. The device consists of two foot plates connected to a doubled crank and rocker system. An induction motor drives the cranks via a planetary gear system. The rear ends of the foot plates follow an ellipsoid-like movement. Different gears can be incorporated to vary stride length and timing. The planetary gear system also moves the patient harness in a locomotion-like trajectory through two cranks attached to suspension ropes. The torque generated by the motor is sensed and displayed on-line to provide a biofeedback signal to the patient. The MGT has been used to train two patients who were two months post-stroke [60]. The patients received four weeks of gait training with the device, consisting of five 20-minute sessions per week. The patients improved significantly in their overground walking ability.

*Lokomat:* The Lokomat is a motorized exoskeleton worn by the patients during treadmill walking [61]. This device has four rotary joints that accommodate hip and knee flexion/extension for each leg. The joints are driven by precision ball screws connected to DC motors. Parameters such as the hip width, thigh length, and shank length can be manually adjusted to fit individual patients. The weight of the exoskeleton is supported by a parallelogram mechanism that moves in the vertical direction and is counterbalanced by a gas spring. The hip and knee motors can be programmed to drive the legs along gait-like trajectories. Several spinal cord injured patients have tested the device [61]. The device was able to drive gait-like patterns in the patients, reducing the labor burden on the therapists who were assisting in the step training.

*Autoambulator*: HealthSouth, the nation's largest provider of rehabilitative healthcare services, has developed a robotic device for automating locomotion training called the "Autoambulator" [62]. The device is intended to replicate a normal walking pattern. Although few details on the device design are available, the patient is supported by a hoist, and his or her legs are secured in a pair of aluminum rotating arms located above a treadmill. Vital signs, knee, thigh and side torques, speed, weight, wiring voltage are automatically monitored after the treadmill begins to move.

### 4.2 Other Emerging Technologies for Gait Rehabilitation

As for arm therapy, virtual reality is also being incorporated into gait therapy. For example, at the VA Palo Alto RR&D Center, the SOR (stepping-over-responses) project is investigating the potential benefits of virtual reality for improving the ability of stroke subjects to step over obstacles. It is hypothesized that training subjects to walk over objects will also improve their gait patterns. To use the system, a subject wears a head-mounted display as he or she walks on a treadmill while holding onto handrails if needed. Simulated obstacles of various heights and lengths are presented to subjects superimposed over a real-time lateral view of the subject walking. An image capture system measures the foot position, and collisions between the virtual object and the foot are detected. Vibrotactile feedback is presented to the heel or toe of the foot involved in a collision depending upon which part of the foot collided with the object.

In preliminary clinical testing, 21 chronic stroke subjects were randomized to a test group that received the VR training or a control group that stepped over real foam objects. All subjects received 6 one-hour sessions over two weeks. Both groups had significant improvements in obstacle clearance, walking speed, stride length, and the distance covered in a 6-minute walk test. There was a non-significant trend in favor of the VR group in all of these parameters. Improvements were also retained at a two-week follow-up. Training subjects with this VR system is expected to be safer than conventional training, and provide more rapid, precise and novel feedback to the patient, which could facilitate more effective movement strategies.

## 5. Future Directions

Clearly, there is a rapidly developing array of tools for automating some aspects of movement therapy following neurologic injury. We conclude by presenting three important questions that will shape the development and use of this technology:

*What are the key stimulants to movement recovery, and how can they be enhanced with technology?* Currently it is unclear what the essential components of a successful therapy program or technology are. Some of the many possibilities are enhancing proprioceptive input, repetitive practice, care in grading therapy difficulty, and quantitative or novel feedback of movement performance. Movement therapy technology provides the tools necessary to selectively control many of these components and then to measure their effects. Identifying the essential components of therapy will in turn allow therapy technology to be improved in a rational, systematic fashion.

*Can the benefits of the technology be made to outweigh its costs?* Many of the devices described in this chapter require relatively sophisticated equipment. To become truly accessible, this equipment must be designed in such a way that a company can afford to produce it while rehabilitation clinics and individual users can afford to buy it. Incorporating technologies that are mass manufactured for other applications may help. Careful consideration will need to be given to the cost of equipment as well as its capability.

*Can automated therapy techniques be made foolproof enough to be truly accessible?* Current technologies for automating therapy typically involve donning a device and accessing a software interface. Can the human-machine and human-computer interfaces be made simple enough that the system can be used without assistance from therapists? In addition, can technologies be designed well enough so that they are not misused to promote harmful movement patterns? Ultimately, the acceptance of new technology for therapy will depend not only on its restorative benefits and cost-effectiveness, but also on its simplicity of use and robustness to misuse.

## References

[1] S. Franz, M. Sheetz, and A. Wilson, "The Possibility of Recovery of Motor Function in Long-Standing Hemiplegia," *JAMA*, vol. 65, pp. 2150-2174., 1915.

[2] E. Taub, N. Miller, T. Novack, E. Cook, W. Fleming, C. Nepomuceno, J. Connell, and J. Crago, "Technique to improve chronic motor deficit after stroke," *Arch Phys Med Rehabil*, vol. 74, pp. 347-354, 1993.

[3] S. Wolf, D. Lecraw, L. Barton, and B. Jann, "Forced use of hemiplegic upper extremities to reverse the effect of learned nonuse among chronic stroke and head-injured patients," *Exp Neurol*, vol. 104, pp. 125-32, 1989.

[4] C. Butefisch, H. Hummelsheim, P. Denzler, and K. Mauritz, "Repetitive training of isolated movement improves the outcome of motor rehabilitation of the centrally paretic hand," *Journal of the Neurological Sciences*, vol. 130, pp. 59-68, 1995.

[5] B. Volpe, H. Krebs, N. Hogan, L. Edelsteinn, C. Diels, and M. Aisen, "Robot training enhanced motor outcome in patients with stroke maintained over 3 years," *Neurology*, vol. 53, pp. 1874-6, 1999.

[6] P. S. Lum, H. F. M. Van der Loos, P. Shor, and C. G. Burgar, "A robotic system for upper-limb exercises to promote recovery of motor function following stroke," *Proceedings Sixth Int. Conf. on Rehab. Robotics*, pp. 235-239, 1999.

[7] L. Kahn, Z. M, R. WZ, and R. DJ, "Effect of robot-assisted and unassisted exercise on functional reaching in chronic hemiparesis," *Proceedings IEEE Engineering in Medicine and Biology Conference, Istanbul, Turkey*, 2001.

[8] M. Holden, E. Todorov, J. Callahan, and E. Bizzi, "Case report: virtual environment training improves motor performance in two stroke patients.," *Neurology Report*, vol. 23, pp. 57-67, 1999.

[9] D. Jack, R. Boian, A. Merians, M. Tremaine, G. Burdea, S. Adamovich, M. Reecce, and H. Poizner, "Virtual reality-enhanced stroke rehabilitation," *IEEE Trans. Neural Systems & Rehab. Engng*, vol. 9, pp. 308-318, 2001.

[10] M. Holden, A. Dettwiler, T. Dyar, G. Niemann, and E. Bizzi, "Retraining movement in patients with acquired brain injury using a virtual environment," in *Medicine Meets Virtual Reality 2001*, J. D. e. a. Westwood, Ed.: IOS Press, 2001, pp. 192-198.

[11] H. Barbeau, D. A. McCrea, M. J. O'Donovan, S. Rossignol, W. M. Grill, and M. A. Lemay, "Tapping into spinal circuits to restore motor function," *Brain Research. Brain Research Reviews*, vol. 30, pp. 27-51, 1999.

[12] P. Bach-y-Rita, "Theoretical and Practical Considerations in the Restoration of Functions Following Stroke," *Topics in Stroke Rehab*, in press.

[13] H. I. Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans. Rehab. Eng.*, vol. 6, pp. 75-87, 1998.

[14] B. Volpe, H. Krebs, N. Hogan, L. Edelstein OTR, C. Diels, and M. Aisen, "A novel approach to stroke rehabilitation: robot-aided sensorimotor stimulation," *Neurology*, vol. 54, pp. 1938-44, 2000.

[15] C. G. Burgar, P. S. Lum, P. C. Shor, and H. F. M. Van der Loos, "Development of robots for rehabiltitation therapy: the Palo Alto VA/Stanford experience," *Journal of Rehabilitation Research and Development*, vol. 37, 2000.

[16] P. S. Lum, C. G. Burgar, S. P.C., M. Majmundar, and M. Van der Loos, "Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper limb motor function following stroke.," *Arch. Phys. Med. Rehabil.*, in press.

[17] D. J. Reinkensmeyer, L. E. Kahn, M. Averbuch, A. N. McKenna-Cole, B. D. Schmit, and W. Z. Rymer, "Understanding and treating arm movement impairment after chronic brain injury: Progress with the ARM Guide," *Journal of Rehabilitation Research and Development*, vol. 37, pp. 653-662, 2000.

[18] L. E. Kahn, M. Averbuch, W. Z. Rymer, and D. J. Reinkensmeyer, "Comparison of robot-assisted reaching to free reaching in promoting recovery from chronic stroke," in *Integration of Assistive Technology in the Information Age*, M. Mokhtari, Ed. Amsterdam: IOS Press, 2000, pp. 39-44.

[19] J. Liepert, H. Bauder, W. Miltner, E. Taub, and C. Weiller, "Treatment-induced cortical reorganization after stroke in humans," *Stroke*, vol. 31, pp. 1210-6, 2000.

[20] R. J. Nudo, B. M. Wise, F. SiFuentes, and G. W. Milliken, "Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct," *Science*, vol. 272, pp. 1791-1794, 1996.

[21] F. Amirabdollahian, R. Loureiro, B. Driessen, and W. Harwin, "Error correction movement for machine assisted stroke rehabilitation.," in *Integration of Assistive Technology in the Information Age*, vol. 9, *Assistive Technology Research Series*, M. Mokhtari, Ed. Amsterdam: IOS Press, 2001, pp. 60-65.

[22] E. Protas, S. Holmes, H. Qureshy, A. Johnson, D. Lee, and A. Sherwood, "Supported treadmill ambulation training after spinal cord injury: a pilot study," *Archives of Physical Medicine and Rehabilitation*, vol. 82, pp. 825-31, 2001.

[23] P. S. Lum, S. L. Lehman, and D. J. Reinkensmeyer, "The bimanual lifting rehabilitator: a device for rehabilitating bimanual control in stroke patients," *IEEE Transactions on Rehabilitation Engineering*, vol. 3, pp. 166-174, 1995.

[24] P. S. Lum, D. J. Reinkensmeyer, and S. L. Lehman, "Robotic assist devices for bimanual physical therapy: preliminary experiments," *IEEE Transactions on Rehabilitation Engineering*, vol. 1, pp. 185-191, 1993.

[25] R. Stein and H. Peckham, *Neural Prosthesis*, 1992.

[26] G. Kraft, Fitts, and Hammond, "Techniques to Improve Function of the Arm and Hand in Chronic Hemiplegia," *Arch. Phys. Med. Rehabil.*, vol. 73, pp. 220-7, 1992.

[27] G. Francisco, J. Chae, H. Chawla, S. Kirshblum, R. Zorowitz, G. Lewis, and S. Pang, "Electromyogram-Triggered Neuromuscular Stimulation for Improving the Arm Function of Acute Stroke Survivors: A Randomized Pilot Study," *Arch. Phys. Med. Rehabil.*, vol. 79, pp. 570-575, 1998.

[28] G. Burdea and P. Coiffet, *Virtual Reality Technology,*. New York.: John Wiley and Sons, Inc., 1994.

[29] M. Holden and E. Todorov, "Use of virtual environments in motor learning and rehabilitation," in *Handbook of Virtual Environment Technology*, K. Stanney, Ed.: Lawrence Erlbaum Assoc, in press, pp. ch. 54.

[30] "National Institute on Disability and Rehabilitation Research Homepage. (2000). At: http://www.ed.gov/offices/OSERS/NIDRR/#LRP."

[31] G. Burdea, V. Popescu, V. Hentz, and K. Colbert, "Virtual reality-based orthopedic telerehabilitation," *IEEE Trans on Rehab Eng*, vol. 8, pp. 430-432, 2000.

[32] J. Deutsch, J. Latonio, G. Burdea, and R. Boian, "Post-stroke rehabilitation with the Rutgers Ankle system --a case study," *Presence*, vol. 10, pp. 416-430, 2001.

[33] M. Girone, B. Burdea, M. Bouzit, and J. Deutsch, "Orthopedic rehabilitation using the Rutgers Ankle interface," in *Virtual Reality Meets Medicine 2000*: IOS Press, 2000, pp. 89-95.

[34] D. Reinkensmeyer, C. Painter, S. Yang, E. Abbey, and B. Kaino, "An Internet-based, force-feedback rehabilitation system for arm movement after brain injury," *Proceedings of CSUN's 15th Annual International Conference, "Technology and Persons with Disabilities", March 20-25, 2000, Los Angeles, CA*, vol. http://www.csun.edu/cod/, 2000.

[35] D. Reinkensmeyer, C. Pang, J. Nessler, and C. Painter, "Java Therapy: Web-Based robotic rehabilitation," in *Integration of Assistive Technology in the Information Age*, vol. 9, *Assistive Technology Research Series*, M. Mokhtari, Ed. Amsterdam: IOS Press, 2001, pp. 66-71.

[36] E. Taub and S. L. Wolf, "Constraint induced movement techniques to facilitate upper extremity use in stroke patients," *Topics in Stroke Rehabil*, vol. 3, pp. 38-61, 1997.

[37] E. Taub, G. Uswatte, and R. Pidikiti, "Constraint-induced movement therapy: a new family of techniques with broad application to physical rehabilitation -- a clinical review," *Journal of Rehabilitation Research and Development*, vol. 36, pp. 237-51, 1999.

[38] H. Barbeau and S. Rossignol, "Recovery of locomotion after chronic spinalization in the adult cat," *Brain Research*, vol. 412, pp. 84-95, 1987.

[39] M. Belanger, T. Drew, J. Provencher, and S. Rossignol, "A comparison of treadmill locomotion in adult cats before and after spinal transection," *J. Neurophysiology*, vol. 76, pp. 471-491, 1996.

[40] R. de Leon, N. London, R. Roy, and V. Edgerton, "Failure analysis of stepping in adult spinal cats," *Progress in Brain Research*, vol. 123, pp. 341-8, 1999.

[41] R. D. de Leon, J. A. Hodgson, R. R. Roy, and V. R. Edgerton, "Locomotor capacity attributable to step training versus spontaneous recovery following spinalization in cats," *J. Neurophysiology*, vol. 79, pp. 1329-1340, 1998.

[42] R. D. de Leon, J. A. Hodgson, R. R. Roy, and V. R. Edgerton, "The retention of hindlimb stepping ability in adult spinal cats after the cessation of step training," *J. Neurophysiol.*, vol. 81, pp. 85-94, 1999.

[43] V. R. Edgerton, R. R. Roy, R. de Leon, N. Tillakaratne, and J. A. Hodgson, "Does motor learning occur in the spinal cord?," *Neuroscientist*, vol. 3, pp. 287-294, 1997.

[44] V. R. Edgerton, R. R. Roy, J. A. Hodgson, R. J. Gregor, and C. P. de Guzman, "Recovery of full weight-supporting locomotion of the hindlimbs after complete thoracic spinalization of adult and neonatal cats," in *Restorative Neurology, Plasticity of Motoneuronal Connections*. New York: Elsevier Publishers, 1991, pp. 405-418.

[45] J. A. Hodgson, R. R. Roy, R. de Leon, B. Dobkin, and V. R. Edgerton, "Can the mammalian lumbar spinal cord learn a motor task?," *Med. Sci. Sports Exerc*, vol. 26, pp. 1491-1497, 1994.

[46] R. G. Lovely, R. J. Gregor, R. R. Roy, and V. R. Edgerton, "Effects of training on the recovery of full weight-bearing stepping in the adult spinal cat," *Exp. Neurol*, vol. 92, pp. 421-435, 1986.

[47] R. G. Lovely, R. J. Gregor, R. R. Roy, and V. R. Edgerton, "Weight-bearing hindlimb stepping in treadmill-exercised adult spinal cats," *Brain Research*, vol. 514, pp. 206-218, 1990.

[48] M. Visintin, H. Barbeau, N. Korner-Bitensky, and N. Mayo, "A new approach to retrain gait in stroke patients through body weight support and treadmill stimulation," *Stroke*, vol. 29, pp. 1122-8, 1998.

[49] V. Dietz, M. Wirz, G. Colombo, and A. Curt, "Locomotor capacity and recovery of spinal cord function in paraplegic patients: a clinical and electrophysiological evaluation," *Electroenceph. and Clin. Neurophys*, vol. 109, pp. 140-153, 1998.

[50] V. Dietz, M. Wirz, A. Curt, and G. Colombo, "Locomotor pattern in paraplegic patients: training effects and recovery of spinal cord function," *Spinal Cord*, vol. 36, pp. 380-90, 1998.

[51] B. H. Dobkin, S. Harkema, P. Requejo, and V. R. Edgerton, "Modulation of locomotor-like EMG activity in subjects with complete and incomplete spinal cord injury," *J. Neuro. Rehab*, vol. 9, pp. 183-190, 1995.

[52] L. Finch and H. Barbeau, "Hemiplegic gait; new treatment strategies," *Physiotherapy Canada*, vol. 38, pp. 36-41, 1986.

[53] J. Fung, J. E. Stewart, and H. Barbeau, "The combined effects of clonidine and cyprheptadine with interactive training on the modulation of locomotion in spinal cord injured subjects," *J. Neurol. Sci.*, vol. 100, pp. 85-93, 1990.

[54] S. J. Harkema, S. L. Hurley, U. K. Patel, P. S. Requejo, B. H. Dobkin, and V. R. Edgerton, "Human lumbosacral spinal cord interprets loading during stepping," *J. Neurophysiology*, vol. 77, pp. 797-811, 1997.

[55] A. Wernig, A. Nanassy, and S. Muller, "Laufband (treadmill) therapy in incomplete paraplegia and tetraplegia," *J. Neurotrauma*, vol. 16, pp. 719-726, 1999.

[56] A. Wernig, S. Muller, A. Nanassy, and E. Cagol, "Laufband (treadmill) therapy based on "rules of spinal locomotion" is effective in spinal cord injured persons," *Eur. J. Neurosci.*, vol. 7, pp. 823-829, 1995.

[57] H. Barbeau, K. Norman, J. Fung, M. Visintin, and M. Ladouceur, "Does neurorehabilitation play a role in the recovery of walking in neurological populations?," *Annals of the New York Academy of Sciences*, vol. 860, pp. 377-92, 2000.

[58] A. L. Behrman and S. J. Harkema, "Locomotor training after human spinal cord injury: a series of case studies," *Physical Therapy*, vol. 80, pp. 688-700, 2000.

[59] M. B. Gardner, M. K. Holden, J. M. Leikauskas, and R. L. Reginald, "Partial body weight support with treadmill locomotion to improve gait after incomplete spinal cord injury: a single subject experimental design," *Physical Therapy.*, vol. 78, pp. 361-374, 1998.

[60] S. Hesse and D. Uhlenbrock, "A mechanized gait trainer for restoration of gait," *Journal of Rehabilitation Research and Development*, vol. 37, 2000.

[61] G. Colombo, M. Joerg, R. Schreier, and V. Dietz, "Treadmill training of paraplegic patients with a robotic orthosis," *Journal of Rehabilitation Research and Development*, vol. 37, 2000.

[62] "http://www.healthsouth.com/hsus/HSUS/EN_US/corporate/abouths/pressroom/autoambulator.jsp."