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GERONTECHNOLOGY

# A Paradigm Shift for Rehabilitation Robotics

## *Therapeutic Robots Enhance Clinician Productivity in Facilitating Patient Recovery*

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The demand for rehabilitation services is growing apace with the graying of the population. According to the World Health Organization (WHO), senior citizens at least 65 years of age will increase in number by 88% in the coming years. By 2050, the United States' contingent of seniors is expected to double from approximately 40 to 80 million (Figure 1). With this increase comes increased incidence of age-related disorders. The following is an example.

- *Cerebral vascular accident (stroke)*: For every decade after age 55, the relative incidence of stroke doubles [1]. At present, more than 700,000 Americans suffer strokes each year; more than half survive. In the United States alone, close to 5 million stroke victims are alive today [1]. Even higher incidence is observed in other developed countries with older populations (e.g., Japan). There can be some respite from stroke if pharmacological agents are successfully developed to preserve vessel patency, to protect neurons, and to stimulate neosynaptogenesis. However, if that should happen, an increase in stroke survival rates may well increase the number of stroke victims in need of rehabilitation services.

The need for rehabilitation services is even more pressing if we consider neurological diagnoses other than stroke. The following are some examples.

- *Cerebral palsy (CP)*: This is a term used to describe a group of chronic conditions affecting body movement and muscle coordination, which affects 2.8 in 1,000 children born in the United States each year [2]. It is caused by the damage to one or more areas of the brain, usually occurring during fetal development; before, during, or shortly after birth; or during infancy [3]. In addition, studies have shown that at least 5,000 infants and toddlers and 1,200–1,500 preschoolers are diagnosed with CP each year as developmental and motor delays become more apparent.
- *Multiple sclerosis (MS)*: It is the third leading cause of disability in young adults in the United States, with a prevalence of approximately one in every 1,000, with two thirds of these cases occurring in females for an estimated total of 350,000 in the United States. MS is a chronic disease of the central nervous system, and currently there is no cure for it. None of the current immunomodulatory therapies convincingly alters long-term progressive disability. Patients with nontraumatic spinal cord injury (SCI) may well equal this incidence.
- *SCI:* It is the leading cause of disability in young adults in the United States. The incidence of SCI has been estimated to be between 30 and 60 new cases per million of the U.S. population per year, with an estimated prevalence of 250,000 (700–900 per million of population). Almost 80% are males younger than 40 years [4], [5].
- *Parkinson's disease (PD)*: It is a neurodegenerative disorder characterized by bradykinesia, resting tremor, rigidity, and postural reflex impairment. It is one of the most common neurological disorders, with estimates ranging from 500,000 to 1.5 million affected in the United States, and this number will increase over the next 50 years as the average life expectancy increases [6], [7]. The time of onset is typically between 40 and 70 years of age, with peaks in the sixth decade of life. Most commonly, the clinical status of the patient with PD progresses from a relatively modest limitation at the time of diagnosis to an ever-increasing disability over a period of 10–20 years.

There is both a need and an opportunity to deploy technologies such as robotics to assist recovery. This, in essence, constitutes a paradigm shift moving the field of rehabilitation robotics beyond assistive technology that helps an individual cope with the environment to a new class of physically interactive, user-friendly robots that facilitate recovery. Therapeutic robots further the clinicians' goal of facilitating recovery not only by delivering measured therapy but also by affording new ways to evaluate patients' progress. Here, we will focus on this paradigm shift: robots that support and enhance the productivity of clinicians in their efforts to facilitate an individual's recovery.

A recent IEEE publication described the remarkable growth of activities in the rehabilitation robotics in the past few years and our devices deployed in clinical trials (see [9] for details). In addition, the lead author recently edited two special issues presenting a broad spectrum of leading research efforts in rehabilitation robotics: from the clinical perspective in the *Veterans Administration's Journal of Rehabilitation Research and Development* (JRRD), September/October 2006, and from the engineering

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perspective in the *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, September 2007 (IEEE TNSRE). Therefore, rather than attempting to replicate the content of these publications, in this article, we restrict ourselves to a summary of the growing activities with our robots. Most researchers employing rehabilitation robotics have focused on stroke, as this is the single largest cause of permanent disability. We briefly review the published clinical literature in this emerging field and our initial clinical results in stroke. However, we also report our initial efforts that go beyond stroke, broadening the potential population that might benefit from this class of technology by discussing case studies of applications to other neurological diseases. We will also highlight the underexploited potential of this technology as an evaluation tool.

## Robotic Gym

Figure 2(a) shows the pioneer of its class, the MIT-MANUS for planar shoulder-and-elbow therapy, whose development started in late 1989 [10]. MIT-MANUS, from the Massachusetts Institute of Technology's (MIT) motto "Mens et Manus" (mind and hand), was designed for clinical neurological applications. Unlike most industrial robots, MIT-MANUS was configured for safe, stable, and highly compliant operation in close physical contact with humans. This was achieved using impedance control, a key feature of the robot control system. Here, we opted for a fixed-based design robot (actuators are fixed with respect to a stationary coordinate system) versus an exoskeleton design. [Fixed-based or end-effector designs like MIT-MANUS are simpler, afford significantly faster "don" and "doff" (setup time much smaller) than exoskeleton designs but typically occupy a larger volume. We employ a rule of thumb to guide us in the selection of configuration based on the target range of motion. For limb segment movements requiring joint angles to change by 45° or less, end-effector designs appear to offer better compromises. Conversely, exoskeletal designs appear to offer better choices for larger ranges of motion.] Its computer control system modulates the way the robot reacts to mechanical perturbation from a patient or clinician and ensures a gentle compliant behavior. The machine was designed to have a low intrinsic end-point impedance (i.e., be back-drivable) to allow weak patients to express movements without constraint and offer minimal resistance at speeds up 2 m/s (the approximate upper limit of unimpaired human performance, hence the target of therapy, and the maximum speed observed in some pathologies, e.g., the shock-like movements of myoclonus).

Following the successful clinical trials with MIT-MANUS, a one-degree-of-freedom (DoF) module [Figure 2(b)] was conceived to extend the benefits of planar robotic therapy to spatial arm movements, including movements against gravity. Therapists' suggestions that functional reaching movements often occur in a range of motion close to shoulder scaption are incorporated in the design [11].

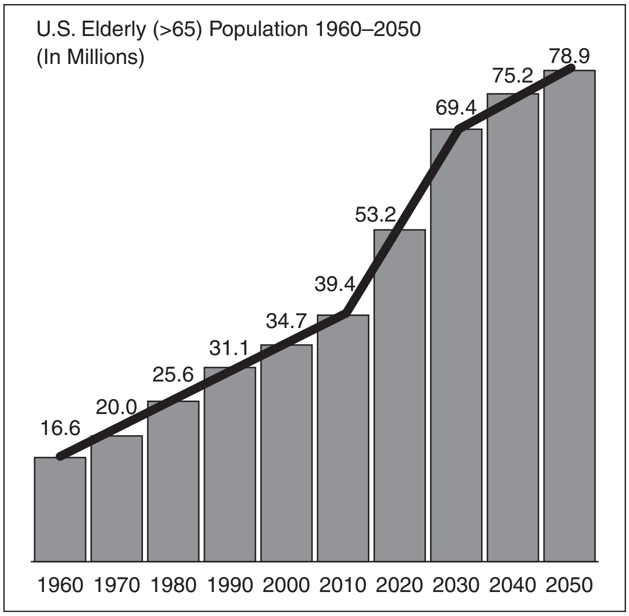


**Fig. 1.** U.S. population older than 65 years (source U.S. Census Bureau (8)).


**Fig. 2.** A gym of robots. (a) The shoulder-and-elbow MIT-MANUS delivering therapy to a child with CP (Spaulding Rehabilitation Hospital). (b) The antigravity module (Baltimore VAMC). (c) A person with PD and deep brain stimulation (DBS) practicing with the wrist robot (University of California San Diego). (d) The integrated system affording whole-arm training (transport of the arm and manipulation of objects, VA Coop Study Randomized Clinical Trial CSP 558). (e) The hand module (without cover). (f) A person with MS during therapy with the anklebot (West Haven VA Medical Center).

To extend the treatment envelope beyond the shoulder and elbow, we designed and built a wrist module for robotic therapy [12]. It features three active DoF, namely, flexion or extension, abduction or adduction, and forearm pronation or supination, and can be operated as a stand-alone unit [Figure 2(c)] or mounted to the end of a shoulder-and-elbow robot [Figure 2(d)]. The most common form of unimpaired upper-extremity movement appears to be a combination of translating the hand (with the shoulder and elbow) to a location in space and orienting the hand (with the wrist) to facilitate object manipulation. We are employing the wrist robot in both configurations to determine what works best and for what type of patient ([13]; VA Coop Study, Randomized Clinical Trial, CSP 558).

The next module required for whole-arm therapy is a hand robot [Figure 2(e)]. Moving a patient's hand is not a simple task because the human hand has 15 joints with a total of 22 DoF. Thus, it was prudent to determine how many DoF are necessary for a patient to perform the majority of everyday functional tasks. Here, our clinical experience with more than 300 stroke patients was invaluable as it allowed us to identify what was most likely to work in the clinic (and what probably would not). Although individual digit opposition (e.g., thumb to pinkie) may be important for the unimpaired human hand, it is clearly beyond the realistic expectations of most of our patients whose impairment level falls between severe and moderate; a device to manipulate 22 DoF is unnecessary (or at least premature). The hand therapy module is a novel design that converts rotary into linear movement and may be used to train grasp and release, with its impedance determined by the torque between the rotor and a free-floating stator [14].

Of note, it remains an empirical question whether we should deliver therapy to the whole arm or train individual limb segments. A potential approach to increase the effectiveness beyond our past studies is to develop new whole-arm functionally based therapy approaches that integrate robotic therapy with clinical practice and enhance the carry over of robot-trained movements into functional tasks. Two potential approaches to deliver such a functional training are 1) to train functional tasks with the robot or, alternatively, 2) to train by aiming for impairment reduction at the capacity level, with different robotic modules breaking these functional tasks into components, and leave the carry over of the observed impairment gains from robotic training into functional gains to the therapist. These alternatives are not mutually exclusive, but we must understand the potential and benefit of both approaches to maximize recovery and to begin building a scientific basis for the best rehabilitation practice. For example, it appears that the first approach might lead to better results with mild strokes, whereas the second approach appears to lead to better results for patients with severe to moderate strokes [15], [16], [17]. The modularity of our suite of therapeutic robots, which is a cornerstone of our design philosophy, is uniquely suited to this investigation. It allows us to employ them in a standalone mode to deliver therapy for particular impairments or to integrate the modules to deliver whole-arm functional robotic therapy [Figure 2(d)]. To the best of our knowledge, no other research group can presently pursue this objective because there are no other reconfigurable rehabilitation robots.

The devices described earlier were intended to treat the upper extremity, and as we completed the enabling technology for reconfigurable whole-arm therapy, we initiated the development of lower-extremity devices. Again, we are aiming for maximum reconfigurability and have taken the same modular approach employed for the upper extremity. The first lower-extremity robot module deployed to the clinic has been dubbed the anklebot [9], [18]. The ankle joint is of particular importance because of the prevalence of drop foot, which is a simple name for a complex problem. The foot needs to clear the ground during the swing phase of gait, and it needs to have a controlled landing during heel strike. Lack of proper control during these two phases increases the likelihood of trips and falls. At present, drop foot is typically addressed in the clinic via an ankle-foot orthosis (AFO) that restricts the ankle's range of motion. However, this approach has limitations and offers little hope of reducing the impairment. To address the impairment reduction, we recently introduced to the clinic (at the Center on Task-Oriented Exercise and Robotics in Neurological Disease at the Baltimore Veterans Administration Medical Center and at the West Haven VA Medical Center) a novel ankle robot that allows normal range of motion in all 3 DoF of the foot relative to the shank while walking overground or on a treadmill. Only 2 of these 3 DoF are actuated: plantar or dorsiflexion and inversion or eversion. As with all our devices, we purposely underactuated the ankle robot with fewer DoF than are anatomically present. Not only does this simplify the mechanical design, it allows the device to be installed quickly without problems of misalignment with the patient's joint axes.

### Robotic Therapy: A Paradigm Shift

The infancy of therapeutic robotics is easily demonstrated: a MEDLINE search prior to 1990 will return no articles on therapeutic robotics. Of course, the application of robotics to rehabilitation has a longer history, but as mentioned earlier, the strong and sustained growth of activity in recent years is due to a significant shift away from assistive technology for people with disabilities toward robotic therapies, which use the technology to support and enhance clinicians' productivity and effectiveness as they try to facilitate the individual's recovery. The magnitude of this change goes far beyond the usual ebb-and-flow of activity in technology-related fields. Tracking the approximate number of articles submitted to the International Conference on Rehabilitation Robotics from 1997 to 2007 demonstrates a sharp increase in articles on therapeutic robotics, which rose from 33% to almost 80% of the submitted articles. This is not a minor shift: robotics promises to transform the way physical medicine is practiced.

Although the sharp increase in activities is encouraging, we must highlight the importance of the multidisciplinary effort needed to segregate science from fiction and push the boundaries of the state of the art (please note the large number of coauthors). Sustainable growth of activities in the area of rehabilitation robotics will only be achieved if we engage in serious clinical trials to understand what works and what does not. That said, engineers must recognize the need to bring the technology out of the lab and into the clinic. Successful translational will occur only if we engage clinicians (physicians and therapists) and patients (and their families). Otherwise, much of this flurry of excitement and growth will be transitory in nature (regrettably, not an unprecedented pattern in robotics).

There are a multitude of variables that may influence outcome, and we must determine the interaction or independence among these variables and their actual impact on outcomes. If we can achieve significant inroads in this investigation, we will be able to segregate science from fiction. A very common assumption is that movement therapy works by helping patients relearn motor control (part of the text in this section was extracted from [18]). Although intuitively sensible, this notion may need to be refined. First, normal motor learning does not have to contend with the neuromuscular abnormalities that are common sequelae of neurological injury, including spasticity, abnormal tone, disrupted or unbalanced sensory pathways, and muscular weakness. These deficits appear to involve the peripheral nervous system and might suggest that muscles should be the focus of therapy. Nevertheless, central nervous system plasticity appears to underlie recovery. Thus, recovery may resemble motor learning in some respects, but it is likely to be a more complex process.

Second, normal motor learning is far from fully understood. Topics of ongoing vigorous debate include questions such as: What variables or parameters of action does the brain command and control? How are these encoded and represented in the brain? How are these encodings or representations acquired and retained? What training schedule optimizes acquisition? Is a period of consolidation between training sessions (e.g., sleep) required for long-term retention? All these questions have practical relevance for therapy. For example, if the brain represents action as a sequence of muscle activations, focusing sensorimotor therapy on muscles would seem profitable. However, a large and growing body of evidence indicates that under many circumstances the brain does not directly control muscles; instead, it controls the upper limb primarily to meet kinematic specifications (such as a simple motion of the hand in a visually relevant coordinate frame) that adjust muscle forces to compensate for movement-by-movement variation of mechanical loads, which suggests that focusing on motions rather than muscles may be more profitable. Of course, these are only two of a large number of possible therapy variations. In our research on robotic stroke rehabilitation, we have attempted to assess some of these possibilities.

In the following sections, we will describe the robust results in stroke and present case studies of the effect of robotic therapy on other populations, in particular, CP, MS, and SCI. As these studies are ongoing, we include data from representative samples of convenience (two subjects per condition). Final results including all the cohort of enrolled patients will be published in the near future in clinical journals by some of the coauthors, Fasoli (CP), Lo (MS), and Volpe (SCI), at the completion of these ongoing studies. All protocols reported in this article were approved by the Committee on the Use of Human Experimental Subjects of MIT and by the institutional review board of the respective testing site, and the informed consent was obtained from all participants.

**Table 1. Burke inpatient studies ($n$ = 96).**

| Between-Group Comparisons: Final Evaluation Minus Initial Evaluation | Robot Trained ($n$ = 55) | Control ($n$ = 41) | $P$ Value |
|---|---|---|---|
| Impairment measures (±SEM) | | | |
| Fugl-Meyer shoulder/elbow | 6.7 ± 1.0 | 4.5 ± 0.7 | NS |
| Motor power | 4.1 ± 0.4 | 2.2 ± 0.3 | <0.01 |
| Motor status shoulder/elbow | 8.6 ± 0.8 | 3.8 ± 0.5 | <0.01 |
| Motor status wrist/hand | 4.1 ± 1.1 | 2.6 ± 0.8 | NS |

Mean interval change in impairment and disability (significance $P < 0.05$).

## Robot Therapy: Stroke

Volpe et al. reported the results of robotic training with 96 consecutive inpatients admitted to Burke Rehabilitation Hospital who met inclusion criteria and consented to participate [19]. Inclusion criteria were diagnosis of a single unilateral stroke within four weeks of admission to the study; the ability to understand and follow simple directions; and upper limb weakness in the hemiparetic arm (i.e., a strength grade of 3/5 or less in muscle groups of the proximal arm) as assessed with the standardized Medical Research Council battery. Patients were randomly assigned to either an experimental or control group. The sensorimotor training for the experimental group consisted of a set of video games in which patients were required to move the robot end-effector according to the game's goals. If the patient could not perform the task, the robot assisted and guided the patient's hand. Although the patient groups were comparable on all initial clinical evaluation measures, the robot-trained group demonstrated significantly greater motor improvement (higher mean interval change ± SEM) than the control group on the trained limb segment (shoulder and elbow). In fact, patients in the robot-trained group improved twice as much as patients in the control group for the trained limb segments.

In addition to the inpatient studies (see Table 1), we recruited 117 community-dwelling volunteers in the chronic stage of stroke recovery at the Burke Medical Research Institute, Spaulding Rehabilitation Hospital, and Baltimore VA Medical Center. Prior to engaging in robotic therapy, these patients were assessed on three separate occasions to determine baseline function and to establish a within-subject control. The primary outcome measures were the Fugl-Meyer and the Motor Power score. Our baseline analyses revealed no statistically significant differences among any of the pretreatment clinical evaluations, indicating the stability of chronic motor impairments in this subject group. However, after robotic training, we found significant reductions in motor impairment of the hemiparetic upper limb [20], [21].

In fact, results from many other research groups have shown the same kind of impact. Figure 3 shows the result of a meta-analysis on upper-extremity robotic training trials published up to October 2006 with the first generation of therapeutic robots. A computerized literature search was conducted in MEDLINE, CINAHL, EMBASE, Cochrane Controlled Trial Register, DARE, SciSearch, Doconline, and PEDro, and it returned 173 hits. Only those articles that compared robot training against a control group were included. Studies that compared different forms of robotic therapy and studies on chronic stroke that compared discharge values with admission values were excluded. [In addition, a significant number of hits were eliminated because of poor design. It emphasizes again the need for a truly multidisciplinary effort. Of note, Dr. Bruce Dobkin (University of California, Los Angeles), who is the editor-in-chief of *Neurorehabilitation and Neural Repair*, identified this weakness and established the basic principles to design successful clinical trials that can be accessed at that journal.] The results demonstrated small but statistically significant improvements because of the robot-assisted therapy even when compared head to head with conventional therapy in stroke [22]. Another meta-analysis study, which included studies on chronic stroke that compared discharge values with admission values, indicates a similar positive impact of the technology [23].

Although stroke is the single largest cause of permanent disability in the United States, our interests go beyond stroke: we believe that robotics may prove to be applicable to most neurological disorders and will fundamentally change the process of rehabilitation. To achieve this, we must understand whether delivering movement therapy via robotic assistants will have a genuine impact on other afflictions, and we must understand the distinctive features of each disease. Here, we present our initial results with samples of convenience in CP, MS, and SCI.

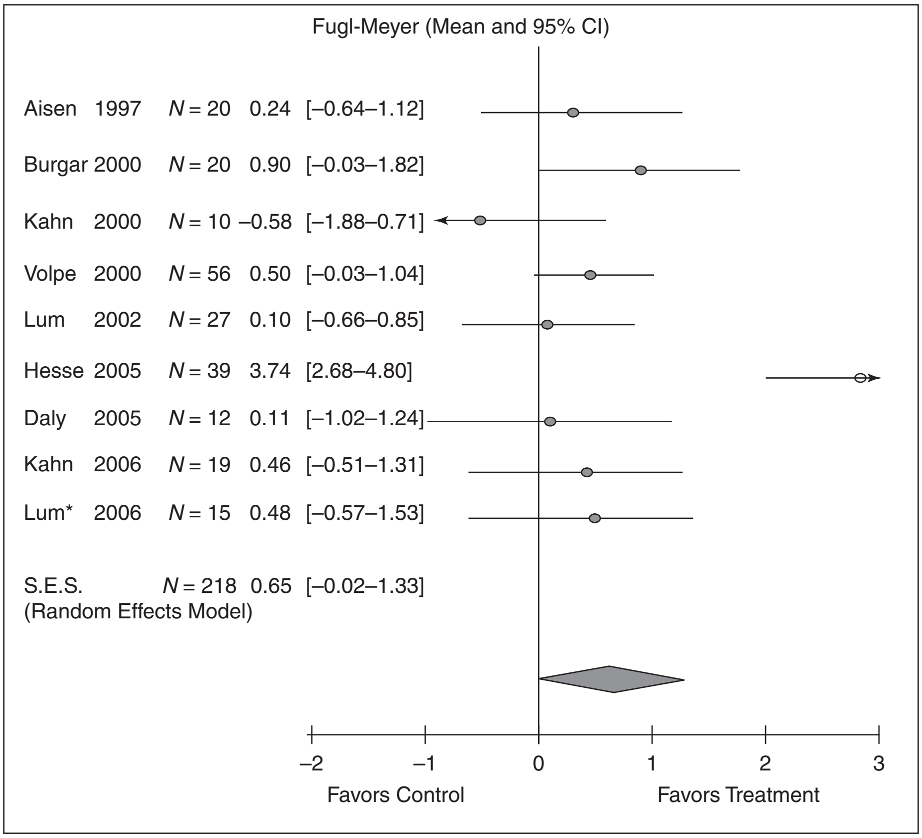


**Fig. 3.** Meta-analysis of robot-assisted therapy trials on motor recovery following stroke.

### Robot Therapy: CP

We engaged children 4–12 years old having hemiplegic CP in 16 robotic sessions of task-specific training with the MIT-MANUS. Hemiplegic CP is the most common syndrome in children born at term and is second in frequency only to spastic diplegia among preterm infants [24]. Children with hemiplegia typically have impaired sensory mechanisms [25], decreased motor control and muscle weakness [26], and spasticity. Typical therapy for children with hemiplegia is often based on motor learning, in which varied experiences that promote task-specific training are used. Motor learning strategies that incorporate practice, repetition, and context are commonly used in the current therapy practices. Enrolled children received two sessions of robotic therapy per week at Spaulding Rehabilitation Hospital, with an emphasis on repetitive reaching exercises for the paretic shoulder and elbow. These 16 one-hour therapy sessions, and clinical evaluations that measured changes in motor impairments, were administered over a 12–14-week period. Clinical assessments included the Modified Ashworth Scale, Fugl-Meyer Assessment (with specific scoring established for this pediatric population), and the Quality of Upper Extremity Skills Test (QUEST).

**Table 2. Spaulding CP studies.**

| Changes Admission to Discharge (Child ID) | Modified Ashworth Scale (/35) | Fugl-Meyer Assessment Upper Extremity (/66) | Quest (/100) |
|---|---|---|---|
| PII_02 | −2.75 | 4.5 | 7.1 |
| PII_03 | −2.5 | 6.0 | 7.7 |

Here, we are showing the results with two of the 12 children enrolled in this pilot study.

The initial results for the first two children are shown here (Table 2). Findings suggest that 16 h of robotic therapy with the MIT-MANUS can have a positive impact on reducing tone and motor impairment in the paretic arm to the order of 7–9%.

### Robot Therapy: MS

Specific gait abnormalities have been observed in ambulatory MS patients [27]–[29], including those with even minimal impairment as measured by the Expanded Disability Status Scale (EDSS $< 2$, [27]). These gait abnormalities have generally included reduced velocity, reduced stride length, increased double support time, and gait asymmetry. Rehabilitation for the purpose of improving or sustaining motor function is not a part of usual care for the chronic phases of MS. Studies employing inpatient rehabilitation have shown that rehabilitation in this setting can help to restore function in relapsing-remitting patients with nonremitting deficits [30]. However, the potential role and efficacy of outpatient rehabilitation have not been fully explored. There are no current interventions directed at correcting ankle impairment. The current solution is to fit an AFO, which helps to ensure that the foot clears the ground and also fixes the ankle and thus induces compensatory movements at the knee and hip to accommodate this loss of articulation.

To address this problem, we are employing the Anklebot in a pilot study at the West Haven VA Medical Center. Here, we report a case study of a sample of convenience of two subjects who had progressive disease and were ambulatory with cane assistance (Table 3). Both subjects had prominent drop foot and were engaged in a protocol similar to a driving simulator. Seated subjects practiced a block of 320 plantar-dorsiflexion movements, followed by another block of 320 inversion-eversion movements in a temperature-controlled environment. This protocol included twice-a-week training sessions for a total of 12 sessions of approximately 45 minutes duration per session. Outcomes were measured at baseline and at discharge and included the timed 25-ft walk (T25FW), the 6-min walk (6MW), isometric strength for ankle flexion or extension and inversion or eversion, muscular fatigue as tested with sustained hold, and accuracy. Here, accuracy was defined as the score patients achieved in the driving simulator training game. Patients were asked to move their ankle unassisted in plantar-dorsiflexion or inversion or eversion and pass the vehicle through incoming randomly positioned gates. For every successful maneuver through a gate, the patient scored +10 points. For every collision with the walls, patient lost $-10$ points. Maximum score was 800. In addition, kinematic data were collected by the Anklebot (see Figure 4).

Of particular interest in this pilot study is the impressive change in torque production at the ankle and the improvement in movement accuracy (tested in the same temperature-controlled environment) for these persons with MS after the 12 training sessions. The training protocol does not include a gait-specific task. Nevertheless, we observed a carry over to characteristics of gait with a general improvement in the distance covered in a 6MW and the time for a 25FW, even though walking had not actually been trained.

**Table 3. West Haven VA Medical Center MS studies.**

| Average of Two Subjects | Pre-Anklebot | Post-Anklebot | Change |
|---|---|---|---|
| T25FW (s) | 9.6 | 8.49 | 11.50% |
| 6MW (min) | 256 | 285 | 11.30% |
| Ankle plantarflexion (N $\times$ m) | 3.74 | 27.9 | 645% |
| Ankle dorsiflexion (N $\times$ m) | 0.4 | 14.3 | 3475% |
| Movement accuracy (dorsi-plantarflex) | 560 | 780 | 39.30% |

Here, we are showing the results with two of the six subjects enrolled in this pilot.

## Robot Therapy: SCI

Emergency medical and surgical services have decreased mortality rates after traumatic SCI, which results in almost 10,000 new survivors of traumatic SCI per year in the United States. New treatments are desperately needed for the subacute stage. Currently, methylprednisolone is used as an effective treatment, which has been delivered in high doses within eight hours of injury (as a bolus and then continued for the first 24 h) [33] with other potential candidates [32]. Improved gains in function and, importantly, gains in independence have been made primarily via assistive devices. Nevertheless, it is possible that therapeutic robotics may have a place in reducing impairment. On the basis of preclinical information that plasticity occurring in the spinal cord is possible, we attempted to influence the functional abilities of patients with chronic traumatic SCI by using robotic protocols that have been effective in patients with stroke. We screened 39 persons with SCI who were admitted to Burke Rehabilitation Hospital during the period of 2002 to 2006. Of those, nine fell within the incomplete C4–C6 lesion category. We trained these subjects with the shoulder-and-elbow robot for 18 sessions over six weeks with one arm, followed by another 18 sessions of training with the other arm. We evaluated these subjects using the Fugl-Meyer and Motor Power scales, and we present here a case study of a representative sample of convenience of two of these subjects (Table 4).

For these patients, we recorded changes greater than 10% in the Fugl-Meyer Assessment and 20% in the Motor Power scales. Note especially that while we trained one arm at a time, both limbs simultaneously improved by comparable amounts.

## Robot-Based Evaluation

The results discussed earlier were limited to standard clinical scales and did not take full advantage of the robot's capabilities to quantify patient performance.

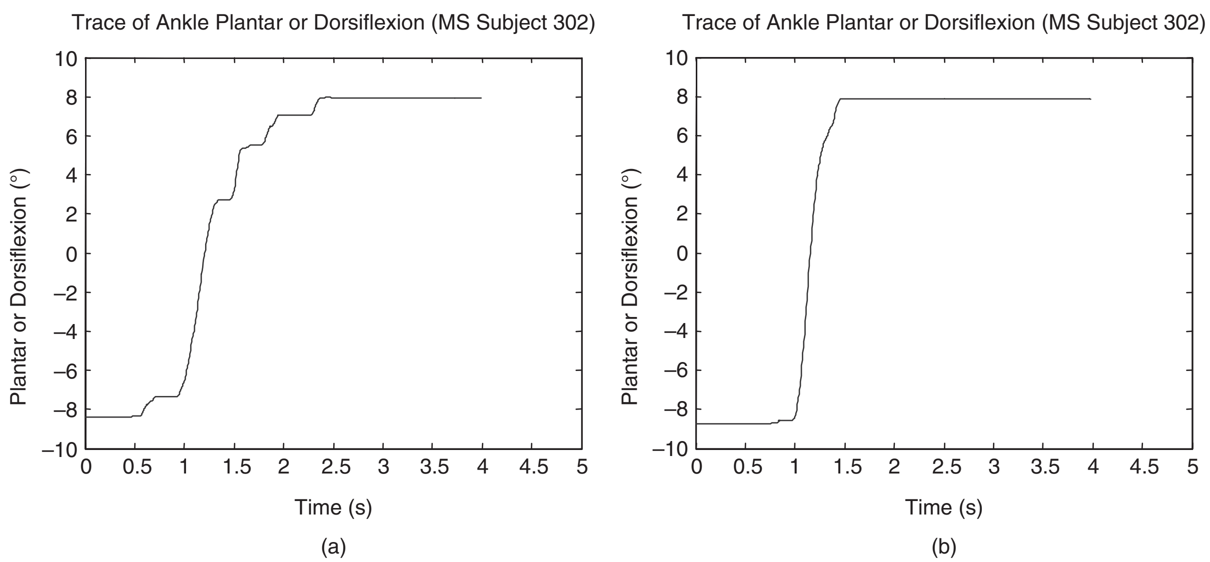


**Fig. 4.** Unconstrained ankle movement. (a) The traces of MS subject's ankle movement at admission. (b) At discharge.

Rehabilitation robotics can not only introduce new efficiencies into certain routine therapy activities but also provide a rich stream of objective data to assist in patient diagnosis, customization of therapy, adaptation of the way the robot is controlled during therapy [33], assurance of patient compliance with treatment regimens, and maintenance of patient records. Robotics can also ease the transition to fully electronic medical records. Here, we will present two examples. The first example demonstrates how we can characterize interlimb joint coordination in stroke patients. The ability to reach appropriately for an object or to move objects requires proper interjoint coordination. The second example demonstrates that even a simple metric (the deviation from a straight line) can detect differences between the effectiveness of surgical (implantation of deep brain stimulators) and medical (pharmacological) therapies in PD. Thus, such robot-based evaluations can potentially add a new and additional tool to the process of deciding when to consider the option of surgical implantation.

## Robot-Based Evaluation: Stroke and Interjoint Coordination

The evaluation games employing the shoulder-and-elbow MIT-MANUS included drawing circles, stars (point-to-point movements), squares, diamonds, and navigating through windows [34]. Some games required predominantly shoulder motion, whereas others required predominantly elbow motion. Additional games required the coordination of both shoulder and elbow. For example, the axis ratio of the ellipse fitted to a subject's attempt to draw a circle provides a metric of the ability of subjects to coordinate interlimb joint movement. We found that subjects were able to draw better circles over the course of 18 sessions of the robotic therapy program. Figure 5 shows the changes in the axis ratio for 16 subacute inpatients attempting to draw circles (see [35] for more details of this metric and results with 117 chronic stroke volunteers). This result demonstrates that the sensorimotor point-to-point training appears to facilitate coordination and generalize to tasks not explicitly trained.

## Robot-Based Evaluation: PD and Deep Brain Stimulation

Deep brain stimulation (DBS) is the most common surgical procedure for patients with PD. Although DBS has been shown to have a positive effect on PD symptoms, the specific nature of its effects on motor control is not yet understood. We previously introduced the use of a wrist robot to study the effects of stimulation on motor performance and learning [36]. Here, we present some results from PD patients with implanted stimulators, tested with and without stimulation, and compare them to results from PD patients without stimulators, tested on and off medication. The subjects performed point-to-point reaching movements with their wrist. We scored the movements based on their accuracy and compared the scores from the four conditions: stimulation on, stimulation off, on medication, and off medication.

The results from 12 subjects diagnosed with PD are reported here. Five subjects had implanted stimulators (mean age $74.2 \pm 4.9$ y) and seven subjects did not (mean age $69.7 \pm 7.6$ y). The subjects with stimulators were tested both on and off stimulation while continuing to follow their normal medication regimen. The subjects with no stimulators were tested both on and off medication. The United Parkinson's Disease Rating Scale (UPDRS) was used to provide a measure of the clinical severity of each subject at the time of testing. The clinical state of all subjects improved on the UPDRS when given their therapy, be it surgical or medical. We note that the severity of subjects in the DBS group was similar to that of subjects in the medication group, both on and off therapy (UPDRS DBS-ON = 28.1; DBS-OFF = 38.6; Medication-ON = 27.1; Medication-OFF = 36.4; total possible score = 108; higher scores reflect more impaired performance). Subjects were presented with

**Table 4. Burke SCI studies.**

| Changes from Admission to Discharge | Fugl-Meyer Assessment (/66) | Motor Power (/70) |
|---|---|---|
| Limb 1 | 6.66 | 13.8 |
| Limb 2 | 9.33 | 15.5 |

Here, we are showing the results with two of the nine subjects enrolled in this pilot.

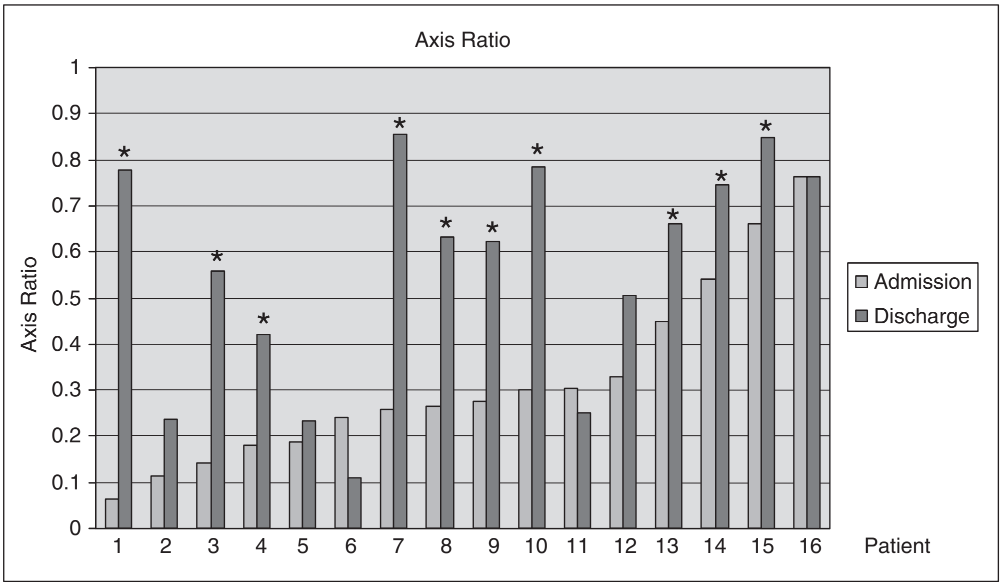


**Fig. 5.** Axis ratios for admission and discharge for each subject. Subjects were sorted according to the value of axis ratio at admission (subject labels have been omitted for clarity). Bigger positive changes from admission to discharge correspond to subjects with lower axis ratios at admission. Note that an axis ratio equal to one indicates a perfect circle. * indicates statistically significant change from admission to discharge ($P < 0.05$).

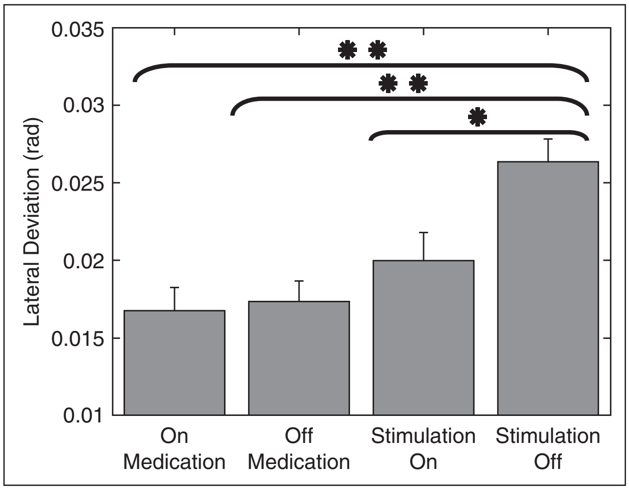


**Fig. 6.** Mean values of lateral deviation across experimental groups and conditions. Whisker bars represent standard errors. A significant difference exists between the mean of the subjects tested off stimulation and the other three group means (*$P < 0.05$; **$P < 0.01$).

one center target and eight peripheral ones [Figure 2(c)]. After an initial practice set, subjects performed a set of 80 reaching movements to a randomly selected peripheral target within a time window of 1.6 s and then moved back to the center position. We found that the subjects with stimulators turned off had the highest mean deviation from the straight line connecting the center and the peripheral target (Figure 6). When stimulation was turned on, these subjects deviated significantly less ($P < 0.05$). The performance of subjects without stimulators was not significantly affected by medication. Subjects with stimulators turned off deviated significantly more than subjects without stimulators, whether on or off medication ($P < 0.01$).

## Conclusions

In this article, we presented an overview of the remarkable growth in the activities in the area of therapeutic robotics and of experiences with our devices. We presented mounting evidence that robotics can be used as a general tool to harness brain plasticity and promote recovery, and this improvement, at least for stroke, is on average sustainable in the long run for both subacute and chronic cases (see [37] for subacute and [20] for chronic stroke). We emphasized that the same kind of technology may have a broader impact beyond stroke therapy, with the preliminary evidence of its value for CP, MS, and SCI being quite promising, even though these diseases impair very different parts of the central nervous system. Nonetheless, significant challenges face us in the next five to ten years. First, we must determine, among the multitude of variables that may influence outcome, the level of interaction or independence between these variables and their actual impact on outcomes. Second, movement therapy in general might only do so much, and we need to investigate the potential impact of the combination of different modalities of therapy (e.g., robotics, pharmacological, electrical stimulation). Only then we will be successful in the quest to optimize therapy to meet particular patient needs. We must pursue this challenge in a truly multidisciplinary fashion armed with tools that not only facilitate and augment therapy delivery but also augment present clinical evaluation scales with robot-based evaluation tools.

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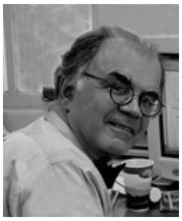

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