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Robotic applications in neuromotor rehabilitation

H. I. Krebs*†, B.T. Volpe†, M.L.Aisen‡, W. Hening⊖, S. Adamovich⊖, H. Poizner⊖, K. Subrahmanyan⊕, N. Hogan*,**

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SUMMARY
Robot-aids or Rehabilitators are our chosen neologism to name a new class of robotic devices that represent a substantially departure from prior applications of robotics in rehabilitation. Rather than use robotics as an assistive technology for a disabled individual, we envision robots and computers as supporting and enhancing the productivity of clinicians in their efforts to facilitate a disabled individual's recovery. In this paper, we attempt a brief overview of our work in what promises to be a ground breaking field. We discuss the concept of robot-aided neuro-rehabilitation as a means to deliver therapy, measure patient performance, and also as a design tool. To illustrate the broad spectrum of neurological diseases that this technology might impact, we will illustrate each case with a different pathology, namely cerebral vascular accident (CVA – also known as stroke), Parkinson's disease (PD), and cerebral palsy (CP).

KEYWORDS: Neuromotor rehabilitation; Robot-aids; Disabled patients.

1. INTRODUCTION

Prediction is at best a chancy business. A contender for the record for short-sighted prophecy may well be the 1943 quotation from Thomas J. Watson, Chairman of the Board of IBM: "I think there is a world market for about five computers." Yet this underestimate may be understandable considering the evolution of computers from the balky, complex numerical engines of mid-century to the ubiquitous high-performance micro-processors of the turn of the millennium. The growth of the computer market (which in turn spurred dramatic improvements in technology) was driven by applications such as word-processing which were not foreseen at the outset but emerged only as users gradually perceived the potential of this tool.

We perceive that the development of robotic technologies to aid recovery and rehabilitation following injury will probably follow a similar evolutionary path. Just as word processors opened the door to markedly increased efficiencies for office workers, robot assistants promise the same for caregivers. While the way this promise will be realized may be very different from anything presently available, it may be possible to catch a glimpse of the ultimate potential of the technology by reviewing some existing applications, and that is our goal in this paper.

In particular, we will discuss the concept of robot-aided neuro-rehabilitation as a means to deliver therapy, measure patient performance, and also as a design tool. To illustrate the broad spectrum of neurological diseases that this technology might impact, we will illustrate each case with a different pathology, namely cerebral vascular accident (CVA – also known as stroke), Parkinson's disease (PD), and cerebral palsy (CP). Our vision differs substantially from prior applications of robotics in rehabilitation. Rather than use robotics as an assistive technology for a disabled individual (i.e. a sophisticated crutch), we envision robots and computers as supporting and enhancing the productivity of clinicians in their efforts to facilitate a disabled individual's functional recovery (Figure 1).

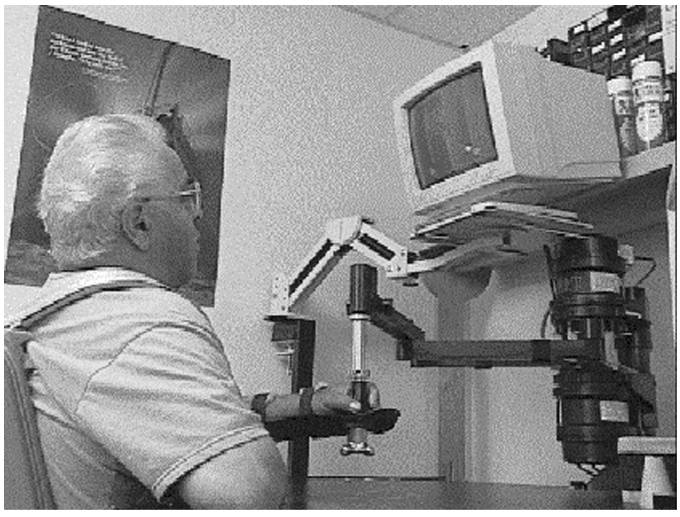


Fig. 1. A recovering stroke patient receiving upper extremity robotic therapy (1995).

* Massachusetts Institute of Technology, Mechanical Engineering Department, Newman Laboratory for Biomechanics and Human Rehabilitation (USA)
** Massachusetts Institute of Technology, Brain and Cognitive Sciences Department (USA)
† Weill Medical College of Cornell University, Department Neurology and Neuroscience, Burke Medical Research Institute (USA)
‡ Veterans Health Administration, Department of Rehabilitation and Development (USA)
⊖ Rutgers University, Center for Molecular and Behavioral Neuroscience (USA)
⊕ Massachusetts Institute of Technology, presently at ESI SAI (USA)

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2. FIRST OF A KIND

To implement our concept of robot-aided neuro-rehabilitation, we needed a tool that would allow us to control the amount of therapy delivered to a patient, while objectively measuring patient's performance. Robotics can provide this tool. Yet a commercial industrial robot will not suffice for this application. While it can exert forces on the patient's limbs, it shares current limitations of the commercial industrial robot technology. Because of a typical robot's electromechanical design and control architecture, it is intrinsically a position-controlled machine and does not yield easily under the action of external forces. Active force feedback is needed to make the robot respond to the patients' actions, but that approach cannot (see, e.g., Lawrence, 1988) produce the "back-drivability" (low mechanical impedance) required to smoothly and rapidly comply with the patients' actions.[1]

To address the limitation of commercial robots, we started in 1989 to specifically design and build novel low-impedance robots for clinical neurological applications capable of interacting safely and gently with humans. The first of its kind was dubbed MIT-MANUS[2] (Figure 2), after MIT's motto: "Mens et Manus" (mind and hand). Unlike most industrial robots, MIT-MANUS is configured for safe, stable and compliant operation in close physical contact with humans. This is achieved using impedance control, a key feature of the robot control system. Its computer control system modulates the way the robot reacts to mechanical perturbation from a patient or clinician and ensures a gentle compliant behavior. Impedance control[3] has been extensively adopted by other robotics researchers concerned with human-machine interaction (see e.g. the February 1997 issue of IEEE Control System, Special Issue on Robotics, which contains several applications of impedance control). MIT-MANUS can move, guide or perturb the movement of a subject's or patient's upper limb and can record motions and mechanical quantities such as the position, velocity, and forces applied. The present design is portable and meets or exceeds applicable safety standards for operation in a clinical environment. An overview of the robot main characteristics can be found elsewhere.[4] This robot has been used daily for over five years with over 100 stroke patients at the Burke Rehabilitation Hospital (White Plains, NY). A second unit began operation in the fall of 1999 at the Spaulding Rehabilitation Hospital (Boston, MA). Since then other units were installed at the Burke Rehabilitation Hospital (two units: for research and clinical use), at the Baltimore VA Hospital (Baltimore, MD), at the Cleveland VA (Cleveland, OH), and at Helen Hayes Rehabilitation Hospital (West Haverstraw, NY). Our expectation is that these six units will substantially speed up the rate of research and permit us to significantly impact the way rehabilitation medicine is practiced.

Furthermore, in view of our positive results, we renewed our design efforts and are presently designing novel extensions of this technology suitable to provide therapy for spatial movements of the shoulder and elbow, the wrists, the fingers, and the lower limbs, encompassing more human functional abilities

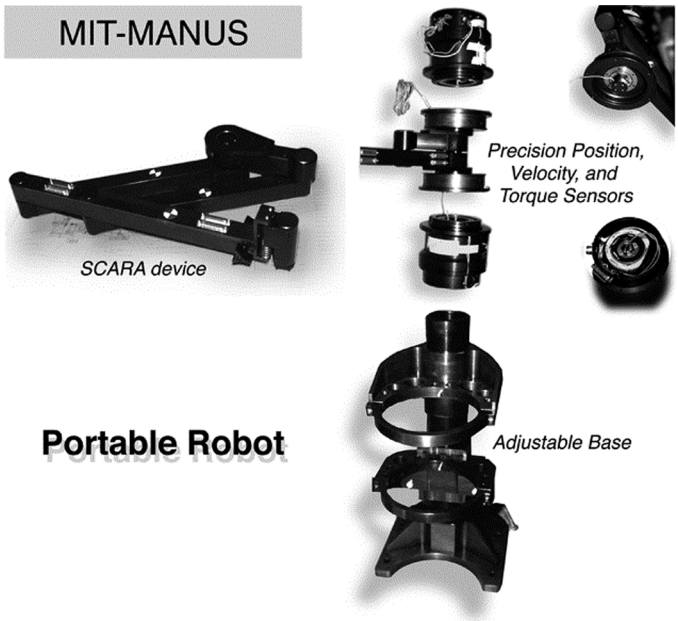


Fig. 2. Exploded view of 2-DOF robot module.

3. DELIVERING THERAPY[5]

In the U.S. health care costs have escalated rapidly over the past three decades, and are projected to surpass 15% of the total GNP in the year 2000, despite significant current efforts to contain and reduce costs. In fact, the Health Care Financing Administration (HCFA) projected health care costs to surpass 16.6% of the total GNP in the year 2007 ($2.1 trillion). Graying of the population will almost certainly aggravate this problem; according to World Health Organization (WHO) in the coming years the population over 65 years old should increase by 88%. This group is particularly prone to suffer a cerebral vascular accident (stroke) since the relative incidence of stroke doubles for every decade after 55 years old further burdening the system. In fact, stroke is the leading cause of permanent disability in the U.S. Between 500,000 and 700,000 Americans per year suffer a stroke; more than half survive; in the U.S. about three million stroke victims are alive today.[6] The economic burden of stroke was estimated to be U$30 billion in 1993, equal to 3% of national health expenditures (American Heart Association, 1993). A similar picture can be drawn for Europe. For example, each year there are over 20,000 new stroke cases in Belgium of a total population of 10 million. Of the 20,000 new stroke cases, the mortality rate is 48.6% within the first eight weeks following the onset of the stroke and of the 51.4% survivor group, 82% will need therapy. Graying of the population is not the only factor pointing to a potential increase in the need for rehabilitation services. Pharmacological agents for neuro-protection under development (e.g., nerve growth factors, better receptor blockers, anti-oxidants, anti-inflammatory agents, and blood-clot dissolving agents) may eventually reduce the severity of stroke and increase the survival rate, yet these advances may also increase the percentage of stroke victims potentially requiring rehabilitation.

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At present, physical and occupational therapy provide the standard and presumably beneficial form of treatment for these impairments, but it is labor-intensive and expensive. Until recently, health care providers have reduced rehabilitation costs primarily by shortening inpatient stays. Once the practical limit of abbreviated inpatient stays is reached, further efficiencies will be attainable chiefly by addressing clinical practices themselves. While skilled therapists can achieve good results with even rudimentary equipment, the maximum effectiveness of their existing "toolbox" is rapidly being reached. To increase productivity new tools are needed. Our research suggests that robotics and information technology can provide an overdue transformation of rehabilitation clinical practice from its present basis in manual operations to a more technology-rich operation. This situation creates a pressing need and an opportunity, both of which motivate our work. The need is for new therapeutic strategies to increase productivity while optimizing the quality of care; the opportunity is to take advantage of recent dramatic advances in technology – especially in robotics, sensing, information processing and telecommunications – to meet this need.

In what follows, we will present some of the results obtained during eight years of clinical trials delivering therapy to stroke survivors.* The goal of these clinical trials was to test the critical hypothesis: *if exercise therapy influences brain recovery.* Our goal was to determine if robot-aided therapy was well tolerated by patients and if training had any meaningful value in neuro-recovery following a stroke. If positive, this result would open a plethora of opportunities for robotics supporting and enhancing the productivity of clinicians while delivering higher quality of care to stroke patients. We pioneered the application of robotics as a therapist-aid in the clinical setting in a pilot study with 20 stroke patients (supported by the Burke Medical Research Institute). This trial was conducted using MIT-Manus (built with National Science Foundation support). Results were promising and showed that robot therapy is safe, tolerated by patients and produces a significant, measurable benefit.[7] This benefit was not limited to an ephemeral improvement that vanished once patients were discharged. In fact, a recall of these 20 stroke patients, three years after hospital discharge, showed that the benefits were sustained.[9] While these results must be interpreted with care due to the limited number of subjects and the inhomogeneity of the patients, a replication study has confirmed the results of the pilot study.[10]

In what follows, we will present the composite results of two trials with 76 patients (initial study with 20 patients[4,7,9] – replication study with 56 patients[10]). These 76 sequential hemiparetic patients were enrolled from 1995 to early 1999. Patients were admitted to the same hospital wards and assigned to the same team of rehabilitation professionals. They were enrolled in either a robot-aided sensory-motor therapy group (RT, N=40) or in a group receiving standard therapy plus "sham" robot-aided therapy (ST, N=36). Both groups were described in detail elsewhere.[4,7,9,10] Patients and clinicians were blinded to the treatment group (a double-blinded study). Both groups received conventional therapy; the RT group received an additional 4–5 hours per week of robot-aided therapy consisting of peripheral manipulation of the impaired shoulder and elbow correlated with audio-visual stimuli, while the ST group had an hour of weekly robot exposure.

The sensory-motor motor training for the RT group consisted of a set of "video-games" and typically lasted for six weeks. 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. The robot was controlled by an impedance controller, which produced a constant isotropic end-point stiffness and damping. Coupled to our highly back-driveable design, the stability of this controller is extremely robust to the uncertainties due to physical contact.[3,11] The training for the ST group was similar to the RT group. Half of the one hour session consisted of playing the video games with the unimpaired arm and half the session with the impaired arm while the robot passively supported the arm and provided the video-game visual feedback (position feedback). If the patient could not perform the task, he/she used the unimpaired arm to assist and complete the game (self-ranging), or the clinician assisted.

A standard assessment procedure was performed by the same "blinded" therapist every other week to assess all patients during rehabilitation and during the recall post-hospital discharge (robot-aided therapy group and control group). Each patient's motor function was assessed by standard procedures including the Motor Power for shoulder and elbow (MP), the Motor Status Score for shoulder and elbow (MS1), and the Motor Status Score for wrist and fingers (MS2). Table I presents the results with these 76 patients.[6]

The Fugl-Meyer (F-M) and Motor Status Score for wrist and fingers (MS2) show no statistically significant difference between groups. The MS1 and MP for shoulder and elbow (focus of the training) show a statistically significant improvement, the experimental group responding to therapy with about twice the score improvement of the control group over a comparable period. Our replication study confirmed and strengthened our initial pilot study.[7] Note that results for the additional 56 patients were of the same order of magnitude as the ones in initial study.[10] A feature of these results is that although the MS1 is capable of detecting a significant advantage of robot therapy for shoulder and elbow, the MS2 for wrist and fingers shows no significant difference between experiment and control groups. This

Table I. Change during Acute Rehabilitation (76 patients): Experimental (RT) vs. Control (ST) Group – Δ1: score change from rehabilitation hospital admission to discharge; one-way t-test that RT>ST with $p<0.05$ for statistical significance (*).

Group	F-M	MP	MS1	MS2
	Δ1	Δ1*	Δ1*	Δ1
RT (40 patients)	9.25±1.36	3.99±0.43	8.15±0.79	4.16±1.16
ST (36 patients)	7.1±1.20	2.0±0.32	3.42±0.62	2.64±0.78

* For an overview on other groups developing robotic applications to support the productivity of clinicians in their efforts to facilitate a disabled individual's recovery, see references [6] and [8].

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result suggests that the benefit of robot-administered sensory-motor training (and perhaps human-administered sensory-motor training, too) is specific to the muscle groups or limb segments exercised and does not generalize broadly. This result motivated us to develop novel extensions of this technology suitable to provide therapy for other limb segments.

4. PRECISION INSTRUMENT

Robotic technology for neurological rehabilitation offers the potential benefit of new measurements – and deeper insight – into the process of recovery from neurological injury or pathology. Consider the example of Parkinson's disease (PD), which is a chronic, progressive, degenerative movement disorder that affects 85 to 187 in every pool of 100,000 people (race related ratio) and has a prevalence of 1,800 per 100,000 for those over 65 years of age.[12,13] It is characterized by bradykinesia (slowness in movement), tremor, rigidity, akinesia, and postural instability (righting ability).[12] In recent years, numerous studies have found that PD patients may show deficits in learning. Combined with information about basal ganglia neuronal connections and activity, this led some investigators to suggest that one of the key functions of the basal ganglia is assisting learning.[14,15] However the specific nature of any learning deficit in PD patients remains relatively under explored. As the noted neurologist Gordon Holmes recognized long ago*: "One of the great disadvantages which clinical investigations suffer is difficulty in recording and measuring observations

* G. Holmes, "The cerebellum of man", *Brain* **62**, 1–30 (1939) p. 10.

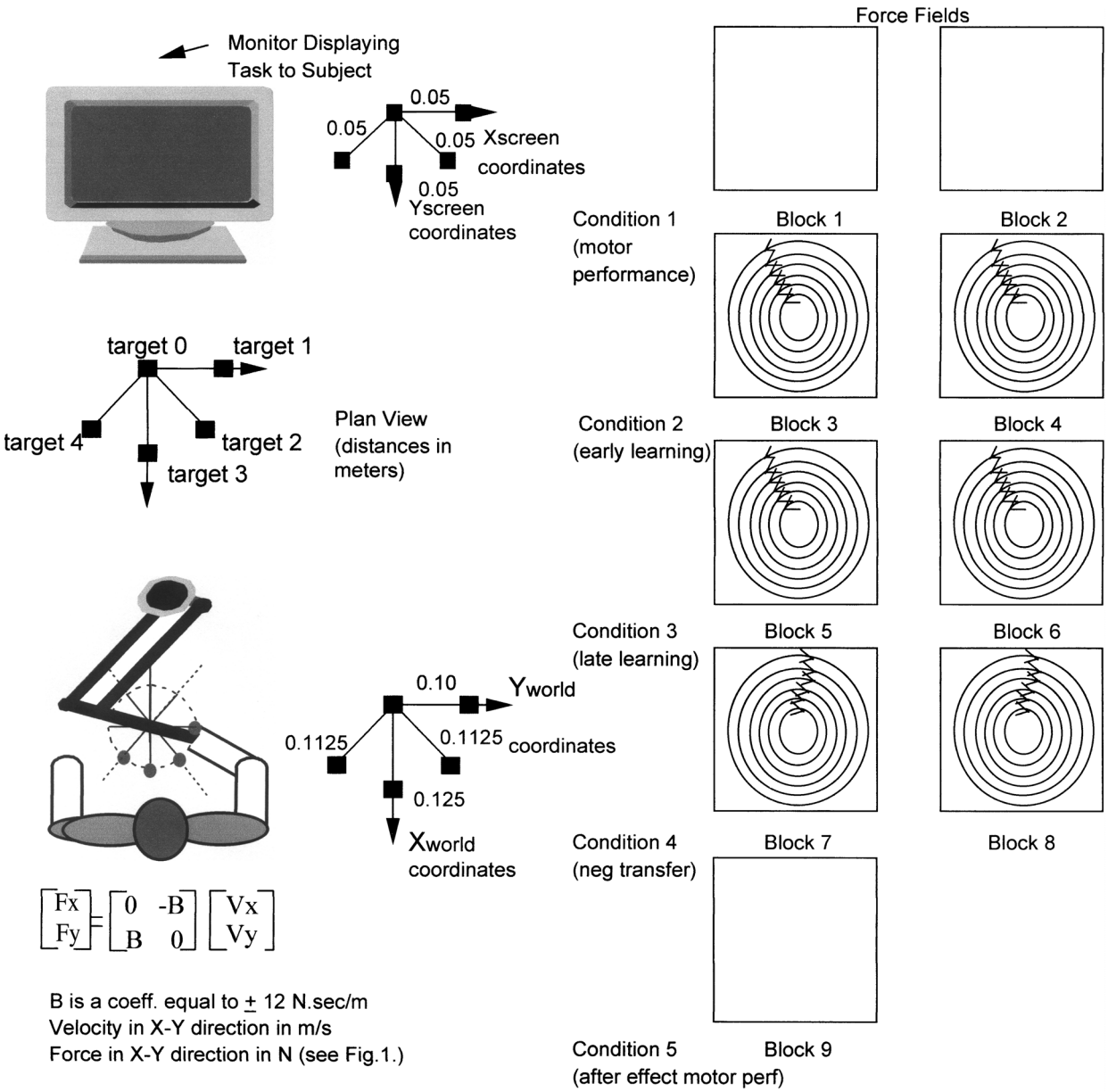


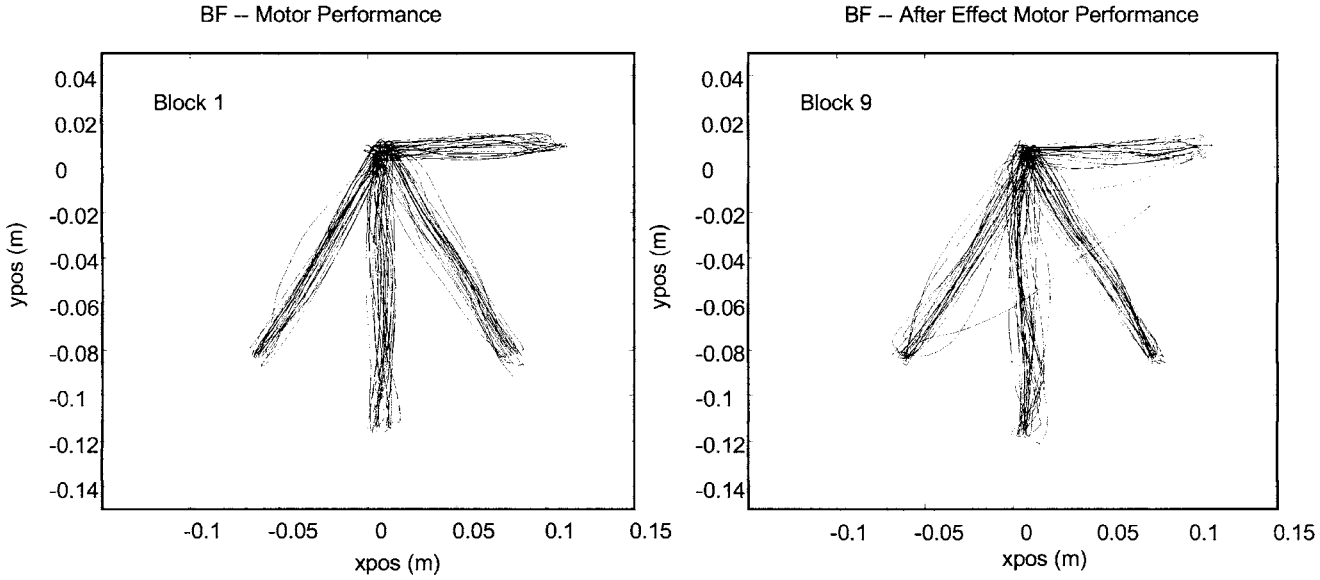
Fig. 3. General Arrangement and Force Fields in Different Conditions. Subject while sitting, moved the robot end-effector with his/her right hand in a point-to-point task in a virtual haptic environment with different force fields for each condition. During blocks 1, 2, and 9 no perturbation forces were applied. In contrast, in blocks 3 through 6 a force-field perturbation is applied, while in blocks 7 and 8 the force-field characteristic is reverted. Note that the hand coordinates were different from the visual coordinates in order to compensate for the rectangularity of the monitor.

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accurately by such methods as physiologists employ". It is our view that the use of robotic technology can help remedy this problem, and allows clinical disorders to be characterized not only at the qualitative level, but also at the quantitative level. We are examining whether PD patients have a learning deficit, particularly a deficit in procedural motor learning. To that end, PD patients and age-matched controls were asked to execute point-to-point movements in a "virtual mechanical environment" generated by MIT-Manus. The visually-evoked and visually-guided task is similar to the one used in our neuroimaging studies[16,17] and it consisted of moving the robot end-effector from its initial position towards a target, in a point-to-point movement. The target set had a fixed number of positions in a horizontal plane as shown in Figure 3.

Trials consisted of the subject moving a screen cursor controlled by the robot end-effector between a homing target and 4 outward targets (1–4) which were randomly presented. The inward homing target 0 was presented following each of the outward targets. Every outward target was presented an equal number of times. Movements were aggregated in blocks. Each block consisted of a total of 80 movements. Note that the hand coordinates were different from the visual coordinates in order to compensate for the rectangularity of the monitor. The subject sat in a chair in front of the robot and monitor, and grasped a handle with his/her right hand. The subject was instructed to move the end-effector to the presented target within 0.8 sec. The color of the target changed for the subsequent 0.8 sec, and a new target was presented. Since the monitor screen was positioned perpendicular to the subject's line of sight, moving the handle towards the subject corresponded to the cursor moving downward on the screen. The subject's movement was performed predominantly with the arm and forearm.

We compared the learning rate of subjects while they learned to manipulate the novel force field. The results suggest that PD patients exhibit a deficit in the rate of procedural motor learning.[18] To illustrate the potential of this approach to measure patients' performance, consider the important question of whether fatigue will significantly influence the results. To answer that question, we compared performance in the final block without imposed force (block 9) with the subject's performance at baseline levels (block 1 and 2). The results for a control subject are shown in Figure 4. The left plot shows the movements during baseline (block 1) and the right plot shows the movements during the final block (block 9) with the inset table presenting each



Group	Index (means) / Condition	Displacement (m)	Lateral Deviation (m)	Correlation Coefficient	Speed-mjrk Difference
Parkinson	Motor Perf.	0.1158	0.0049	0.9021	0.0019
Patients	After-Effect	0.1111	0.0047	0.9020	0.0019
Age-Matched	Motor Perf.	0.1234	0.0039	0.9251	0.0020
Controls	After Effect	0.1216	0.0038	0.9155	0.0019

Fig. 4. Comparison of the mean-values of the different indices during Motor Performance (blocks 1 & 2) and during After-Effect Motor Performance (block 9). The plots show the hand path trace movements of subject BF during block 1 (left plot) during block 9 (right plot). Fatigue appears not to be a limiting factor in our protocol, since in no instance was the Motor Performance statistically significant different than the After-Effect Motor Performance (ANOVA $p<0.05$ for significance) [18].

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condition's average using different performance indices. Note that at face value the left and right panels look qualitatively similar. In addition, we can quantify the results to guarantee that fatigue was not an effect. In that analysis, we used different performance indices to measure patients' performance as shown in the figure's table inset. There is no statistically significant difference between these blocks on any of the four measures, and hence we conclude that for our experimental protocol, fatigue was not a confounding effect (for more details see reference [18]).

5. DESIGN TOOL

According to the United Cerebral Palsy Association, 500,000–700,000 individuals in the U.S. demonstrate one or more symptoms of cerebral palsy. Forty percent of all cases are attributed to lack of oxygen or injury during birth, twenty-five percent of all cases are result of prenatal causes such as virus, x-rays, drugs, anemia, poor nutrition or premature delivery, and of the remaining cases, the causes are unknown. Clinically, CP is associated with neuro-motor dysfunction, psychological dysfunction, as well as convulsions and behavior disorders of organic origin. The neuro-motor dysfunction can strike both voluntary and involuntary movements, and it includes one or a combination of clinical symptoms such as spasticity, rigidity, athetosis, and ataxia. Children with spastic and rigid hemiplegia or quadriplegia make up the largest group.

In a not so unusual scene, parents of a bright 9 years-old boy diagnosed with athetoid cerebral palsy and associated symptoms of spasticity knocked at our lab in search of a computer-interface for their son. Brief description of athetoid cerebral palsy consequence includes hyperextension of the fingers and constant motion. The parents claimed to have done an extensive search and trial of commercially available products. They claimed dissatisfaction with all tested products. The child has only gross motor skills in the upper extremities and requires maximal assistance with all activities of daily living including dressing and feeding. Nevertheless, they correctly perceived the enabling and liberating possibilities of personal computers and the internet empowering their child.

One of us (K. Subrahmanyan) decided to build a computer interface for the child. In addition to the interface design per se, we had to address the problem of mechanical manipulation. Manipulation is defined in the broad sense as operating the manipulator's end-effector (e.g., robot tip or human arm) to interact with tools and/or the environment to achieve a desired task. Manipulation requires that the manipulator is mechanically coupled to the object being manipulated and any useful classification of manipulation must consider mechanical work exchange. In fact, all significant results on couple stability of robots have as its cornerstone the concept of passivity (see e.g. references [3, 11, 19, 20]. Passivity is defined as:

$$\int_0^T \vec{f}(t) \cdot \vec{v}(t)\, dt > 0, \forall t > 0$$

where $\vec{f}(t)$ represents all admissible force histories (effort) and $\vec{v}(t)$ represents the corresponding velocity histories (flow). Although interaction with passive objects covers a useful range of applications, there are many important situations (such as the use of power tools) where the environment may be active. To our knowledge, no general, sufficient condition for coupled stability exists for interaction between manipulators with active objects.[21]

We had to design a control strategy for coupled stability between a manipulator (haptic computer interface) interacting via a single port to an active (non-passive) environment (CP individuals). While we can not apply stability criterion valid for a passive environment, on a conceptual level, if the stability is considered alone, the criterion should aim at "absorbing" all the energy introduced by the environment. The extreme case corresponds to an "infinite" damper. Performance consideration requires that we "relax" this criterion. Drawing on the power consumption, we defined our controller design strategy for the haptic computer interface interacting at a single port with a non-passive, non-modelled environment (the CP subject), as:

– a controllable damper tuned to the lowest output impedance that showed passive behavior while in use by the particular CP individual performing a representative task, i.e., at any time instant during the task execution, power is being absorbed by the manipulator (computer interface).

To determine the proper value of output impedance, we ran a set of trials in which the child sat facing the robot in his electric wheelchair with his usual corrective seating devices to improve trunk posture. The subject's left hand was fitted with a customized wrist splint and the fingers were placed around the handle of the robot and held in place with Velcro straps. The task consisted in moving the robot end-effector tracing a virtual square (square side 0.1m) displayed in the computer monitor positioned slightly above the robot as illustrated. The virtual square was chosen to simulate the use of a typical computer program: visually-evoked and –guided, occupying the workspace center. Furthermore it required the coordination of both shoulder and elbow movements (gross motor skills). The planned sequence of tests consisted of repeating the task with increasing isotropic end-point damping (0, 12, 24, 36 N-sec/m). The subject was informed that he was being timed.

Figure 5 shows the results for different damping values of 0, 12, 24, and 36 Ns/m. Plots on the left column show a plan view of the subject's hand movement. Plots on the right column show the movement's power vs time, where power is given by the dot product of the interaction port force and velocity. Results suggested that damping improves subject's performance and we could estimate the damping range for a haptic computer interface for the particular subject. To recap, according to our design strategy, the manipulator should be passive through out the task. Power vs time records suggest that for this case the ideal damping constant is within the 18 to 24 Ns/m range, and we arbitrarily settle to a damping of 20 Ns/m. As a sanity check, for this damping range, we compared exerted forces with guidelines of the US Air Force for anthropometric force estimates during repetitive tasks. For a weak female, the maximum

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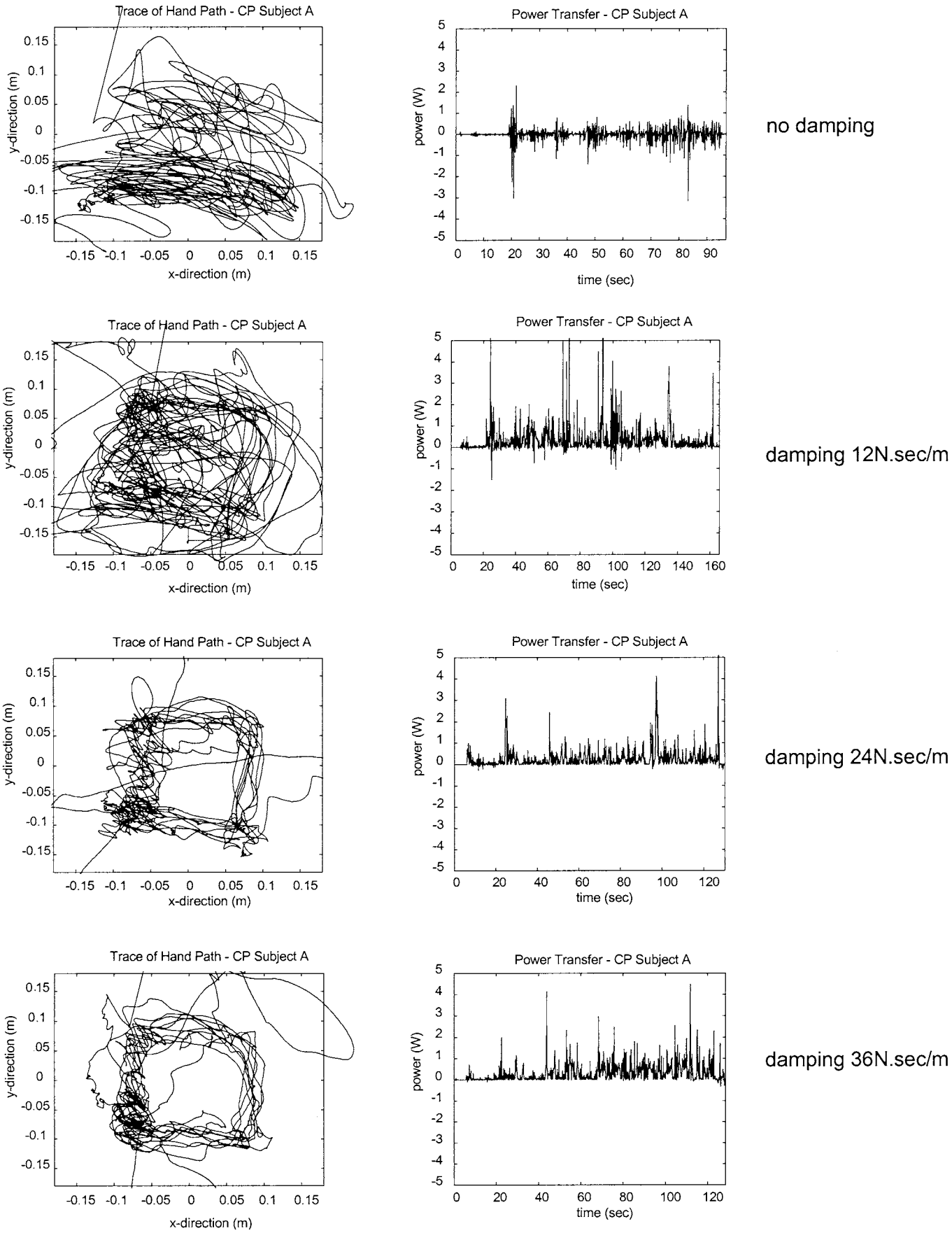


Fig. 5. Hand path trace and power flow for CP subject. The figure shows the results for different damping values of 0, 12, 24, and 36 Ns/m. Plots on the left column show a plan view of the subject's hand movement. Plots on the right column show the movement's power vs time.

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force recommended over an extended period should not exceed 28 N in shoulder abduction.[22] The CP subject never exceeded half of this force value. An interface was built by one of us (K.Subrahmanyan) for the child's and our "ad-hoc" control design strategy proved to improve the subject's ability to perform the task and interact with cyberspace.

6. CONCLUSION[23]

In keeping with caution against raising premature and/or unrealistic clinical expectations, we presented a few snap-shots of the potential of the concept of robot-aided neurorehabilitation. We are particularly keen on the its use as a means to deliver therapy and measure patient performance, as a tool to support and enhance the productivity of clinicians in their efforts to facilitate a disabled individual's functional recovery.

If pressed to take a stand, we feel quite optimistic that robot technology has evolved to the point that it should now be feasible for robots to mingle with humans, supporting or participating in activities of daily human living. This will require the machines to be reliably stable and safe in close physical contact with humans. Impedance control is the enabling technology upon which the proposed research is founded. It was proposed by one of us (Hogan) as a general approach to controlling physical interaction between a robot and objects in its environment, ensuring robust stability and compliant behavior.

There are at least two reasons why robot aids for neuro-rehabilitation provide a natural path to evolving practical personal robotic technology. The first is that they require the challenges of close physical contact with non-modeled objects (i.e. humans) to be confronted squarely (and solved!). The second, perhaps less obvious, is that in these rehabilitation applications the interaction between robot and human (i.e. patient) naturally occurs under close supervision, i.e., by the clinical team. This helps to ensure safety, builds human confidence in the technology and provides a rich source of feedback to improve the technology.

A strong argument can be made that history (e.g., that of desktop computers) shows that an effective way to realize the promise of a new technology is to deploy it as soon as market conditions permit and let the user communities that emerge drive the evolution of new applications and technology refinements. Putting robotic tools in a clinical environment not only develops human-centered robots with an immediate clinical application, it provides an effective way to identify what works and what doesn't when robots and humans interact.

In the near-term future we envision a range of natural extensions of this technology to encompass more human functional abilities. For example, we are developing robot modules suitable to provide activity therapy for spatial movements,[24,25] the wrists,[26] the fingers,[27] and the lower limbs. We also plan to use this technology to establish the practicality and economic feasibility of clinician-supervised, robot-administered therapy, including classroom therapy, as well as of home-based self-therapy.

Placing human-centered robots in the clinical environment opens up a plethora of opportunities for new and better studies of the brain and body, how they work together, how they respond to injury and how they recover from it; we have already propose d several such studies but we have barely scratched the surface. But more important, as the initial results with stroke patients had shown, ultimately this kind of technology might have a positive outcome at what really matters: minimizing the impairment of the survivors.

ACKNOWLEDGEMENTS

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