Forging *Mens et Manus*: The MIT Experience in Upper Extremity Robotic Therapy

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Abstract

MIT's motto is *Mens et Manus,* which translates into "Mind and Hand." It could not be a more appropriate motto for our line of research: using robotics and information technology to forge new or reinforce existing pathways to reconnect the brain to the hand. These reconnections allow an adult who has experienced a stroke or a child with cerebral palsy to improve the quality of their life. This chapter describes our efforts toward this goal since the initial development of the MIT-Manus in 1989. Since then, over 800 stroke patients have enrolled in our multiple studies and we have developed a complete robotic gym for the upper extremity. With the most recent endorsement of the American Heart Association and the Veterans

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Affairs/Department of Defense for incorporating robot-assisted therapy into stroke rehabilitation for upper extremity, we have begun realizing our motto toward tailoring therapy to a particular need.

Keywords
Rehabilitation robotics • Robotic therapy • Upper extremity • Stroke • Cerebral palsy

8.1 Introduction

The use of robotic technology to assist recovery after neurological injury has proven to be safe, feasible, and effective, at least in some forms (e.g., upper extremity) and for some patient populations (e.g., stroke). Nevertheless, there is vast room for improvement. But what is the best way to pursue further improvement? Ultimately, we would like to prescribe customized therapy to optimize and augment a patient's recovery. In this chapter, we review our experience in developing upper extremity robotic therapy and applying it in clinical practice. Based on that experience, we propose the most productive way to refine and optimize this technology and its application. Needless to say, this personal viewpoint will almost certainly neglect or underemphasize important developments; however, that should not be construed as a dismissal of other work but more as a symptom of the explosive growth of research in this field. Despite its inevitable limitations, we trust our perspective may have value.

8.2 The State of the Art

The 2010 American Heart Association (AHA) guidelines for stroke care recommended that: "Robot-assisted therapy offers the amount of motor practice needed to relearn motor skills with less therapist assistance. Most robots for motor rehabilitation not only allow for robot assistance in movement initiation and guidance but also provide accurate feedback; some robots additionally provide movement resistance. Most trials of robot-assisted motor rehabilitation concern the upper extremity (UE), with robotics for the lower extremity (LE) still in its infancy… Robot-assisted UE therapy, however, can improve motor function during the inpatient period after stroke." AHA suggested that robot-assisted therapy for the UE has already achieved class I, Level of evidence a for stroke care in the outpatient setting and care in chronic care settings. It suggested that robot-assisted therapy for UE has achieved class IIa, level of evidence a for stroke care in the inpatient setting. Class I is defined as "Benefit >>>Risk. Procedure/Treatment SHOULD be performed/administered;" class IIa is defined as "Benefit >>Risk, IT IS REASONABLE to perform procedure/administer treatment;" level A is defined as "Multiple populations evaluated: Data derived from multiple randomized clinical trials or meta-analysis" [1].

This is not an isolated opinion. The 2010 Veterans Administration/Department of Defense (VA/DOD) guidelines for stroke care came to the same conclusion endorsing the use of rehabilitation robots for the upper extremity but went further to recommend against the use of robotics for the lower extremity. More specifically, the VA/DOD 2010 guidelines for stroke care "Recommend robot-assisted movement therapy as an adjunct to conventional therapy in patients with deficits in arm function to improve motor skill at the joints trained." For the lower extremity, the VA/DOD states that "There is no sufficient evidence supporting use of robotic devices during gait training in patients post stroke." The VA/DOD suggested that robot-assisted therapy for the UE has already achieved rating level B, "A recommendation that clinicians provide (the service) to eligible patients. At least fair evidence was found that the intervention improves health outcomes and concludes that benefits outweigh

harm." Regarding the lower extremity, the VA/DOD suggested against robot-assisted therapy: "Recommendation is made against routinely providing the intervention to asymptomatic patients. At least fair evidence was found that the intervention is ineffective or that harms outweigh benefits" [2].

These endorsements came on the 21st anniversary of our initial efforts begun in 1989 (with support from the United States National Science Foundation) that led to what became known as "MIT-Manus." It would be difficult to deny the impact of this work on neurorehabilitation, described by our clinical colleagues as "perhaps one of the most important developments in neurorecovery in the last 75 years" (personal communication, Dr. Bruce Volpe). Creating this level of trust required decades of perseverance. The enormity of the challenge cannot be understated. This type of research is the antithesis of the rapid-fire breakthroughs expected in, say, information technologies. It requires slow and painstaking experimental trials and the creation of a large body of experimental evidence to demonstrate progress, but that is essential. Neurorehabilitation depends on neural plasticity and its potential to augment recovery ("good plasticity") or to limit recovery ("bad plasticity"). The central challenge of rehabilitation robotics is to provide tools to manage plasticity, harnessing the "good" and limiting the "bad." It is not simply to automate conventional practices. Primarily due to a lack of tools for measurement and experimental control, many conventional practices lack the support of scientific evidence. As a result, there is no clear design target for the technology nor any reliable "gold standard" against which to gauge its effectiveness. In fact, the biggest hurdle we face in the development of rehabilitation robotics is determining what constitutes best practice.

Consider the example of the failed efforts to automate treadmill training for stroke rehabilitation. Though elegant engineering solutions can be (and have been) applied to automate this process, the essential first step should be to determine whether treadmill training is effective (with or without automation). Unfortunately, recently unveiled results of a National Institutes of Health (NIH)-sponsored large, randomized clinical trial on treadmill training post stroke failed to demonstrate outcomes superior to a simple home exercise program (LEAPS Study) [3]. Thus, at least for stroke, a gait rehabilitation program that is based on treadmill training delivered by therapists (as in the LEAPS study) or robotic devices (such as Lokomat) do not appear to be advantageous [3–5]. Note that this result flies in the face of the "obvious" non-neuro-based benefits of treadmill training, including cardiovascular and greater intensity of gait practice [6]. The message seems clear: we must study the process of neurorecovery as well as the technologies that might augment this process. Otherwise we run the risk of harnessing "bad" plasticity, perhaps to the detriment of patients' recovery.

8.3 An Upper Extremity Gym of Robots

To begin with, we had to invent the technology since the available technologies were inadequate. We developed interactive robots to work with the shoulder and elbow (with and without gravity compensation), the wrist and the hand, as well as combinations of these modules. We further developed exoskeletal robots for neuroscience research (see Fig. 8.1).

8.3.1 Modularity

We chose to pursue a modular approach for several reasons. The foremost was entirely pragmatic: as we intended to introduce new technology to a clinical environment, it needed to be minimally disruptive – i.e., not too big, complex, or intimidating. A secondary reason was our recognition that engineers were unlikely to create optimal technology on the first pass. Though a design to address over 200 degrees of freedom (DOF) of the human skeleton was technically feasible, it would have been large, complex, and – most important – difficult to revise or modify. With a modular approach, individual modules could be refined and optimized without redesign of other modules.

Fig. 8.1 A gym of upper extremity robots. *Top row*: *left panel* shows a person with chronic stroke working with the antigravity shoulder-and-elbow robot, *middle panel* shows a person working with the planar shoulder-and-elbow robot, and *right panel* shows the wrist robot during therapy at the Burke Rehabilitation Hospital. *Middle row*: *left panel* shows the hand module for grasp and release, *middle panel* shows reconfigurable robots. The robotic therapy shoulder-and-elbow and wrist modules can operate in stand-alone mode or be integrated into a coordinated functional unit; *right panel* shows the shoulder-and-elbow and hand module integrated into a coordinated functional unit. *Bottom row* shows the exoskeletal robot for psychophysics. Each robot includes three active DOF affording psychophysical experiments with the shoulder, elbow, and wrist. For this exoskeletal robot, the links must be adjusted to the person's limb segments (using laser pointers). Once arm, forearm, and wrist are properly adjusted, we commence psychophysical experiments assisting or selectively applying perturbation force fields to shoulder, elbow, and wrist (either flexion/extension or abduction/adduction)

8.3.2 Gravity-Compensated Shoulder-and-Elbow Robot

The centerpiece of our effort for the upper extremity became known as MIT-Manus, from MIT's Motto *Mens et Manus* (Mind and Hand). 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. Its computer control system modulated the way the robot

reacted to mechanical perturbation from a patient or clinician and ensured a gentle compliant behavior. The machine was designed to have a low intrinsic end-point impedance (i.e., be backdrivable) to allow weak patients to express movements without constraint and to offer minimal resistance at speeds up to 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). MIT-Manus had two active DOF and one passive DOF. It consisted of a semi-direct-drive, five-bar-linkage SCARA (Selective Compliance Assembly Robot Arm) mechanism driven by brushless motors [7–9]. Since then, several variants were deployed under the commercial name of InMotion2 robot (Interactive Motion Technologies, Watertown, MA, USA).

8.3.3 Gravity-Compensated Shoulder-Elbow-and-Wrist Exoskeletal Robot

From the human–machine, mechanical interface viewpoint, robots can be classified as end-effector or exoskeletal robots. End-effector robots interact with the human via a handshake, i.e., the interaction takes place through a single port. In other words, there is a power flow or exchange only at the tip of the robot. Exoskeletal robots are mounted on distinct human limb segments with more than one interaction port. End-effector robot designs like the 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, fixed-based designs appear to offer better compromises. Conversely, exoskeletal designs appear to offer better choices for larger ranges of motion. That said, in some circumstances the application dictates the configuration. One such case occurs during psychophysical experiments in which we may want to carefully apply and control perturbations to one, but not another, joint and hence we designed a highly backdrivable, 3-active-DOF, gravity-compensated shoulder-elbow-and-wrist exoskeletal robot. Several variants were deployed under the commercial name of InMotion-Exos robot, which in addition to MIT-Manus shoulder-and-elbow capability, affords a selective capability of either wrist flexion/extension or wrist abduction/adduction, as shown in Fig. 8.1 (Interactive Motion Technologies, Watertown, MA, USA). The InMotion-Exos can be configured for uni- or bimanual use.

8.3.4 Gravity Noncompensated Shoulder-and-Elbow Robot

A 1-DOF module was conceived to extend the benefits of planar robotic therapy to spatial arm movements, including movements against gravity. Incorporated in the design are therapists' suggestions that functional reaching movements often occur in a range of motion close to shoulder scaption. That is, this robotic module was designed for therapy to focus on movements within the 45–65° range of shoulder abduction and from 30° to 90° of shoulder elevation or flexion [10]. The module can permit free motion of the patient's arm or can provide partial or full assistance or resistance as the patient moves against gravity. As with MIT-Manus, the system is highly backdrivable.

8.3.5 Wrist Robot

To extend treatment beyond the shoulder and elbow, we designed and built a wrist module for robotic therapy [11]. The device accommodates the range of motion of a normal wrist in everyday tasks, i.e., flexion/extension 60°/60°, abduction/adduction 30°/45°, pronation/supination 70°/70°. The torque output from the device is capable of lifting the patient's hand against gravity, accelerating the inertia, and overcoming most forms of hypertonicity. As with all of our exoskeletal designs, we purposely underactuated the wrist

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. In this case, the axes of the wrist's ulnar-radial and flexion-extension joints do not intersect, and the degree of nonintersection varies between individuals [12]. If robot and human had the same number of DOF but these were not co-aligned, motion might evoke excessive forces or torques. By allowing the human joint more DOF than the robot, excessive loads are avoided. Ease of use is another critical consideration in all our designs. We consider it a major determinant of success or failure in the clinical rehabilitation environment. The wrist robot must be attached to or removed from the patient (donned or doffed) within 2 min. Finally, the wrist-robot module can be operated in isolation or mounted at the tip of the shoulder-and-elbow, gravity-compensated robot. Hence, it enables a combination of translating the hand (with the shoulder-and-elbow robot) to a location in space and orienting the hand (with the wrist robot) to facilitate object manipulation.

8.3.6 Hand Robot

Moving a patient's hand is not a simple task since the human hand has 15 joints with a total of 22 DOF; therefore, 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 over 800 stroke patients was invaluable in that it allowed us to identify what was most likely to work in the clinic (and what probably would not). Though 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). Our hand therapy module is a novel design that converts rotary into linear movement using a single brushless DC electrical motor as a free-base mechanism with what is traditionally called the stator being allowed to rotate freely [13]. The stator (strictly, the "second rotor") is connected to a set of arms, while the rotor is connected to another set of arms. When commanded to rotate, the rotor and stator work like a double crank and slider mechanism, in opposing configuration, where the crank is represented by a single arm and the slider is the shell or panel which interacts with the hand of the patient (see Fig. 8.1). The hand robot is used to simulate grasp and release with its impedance determined by the torque evoked by relative movement between stator and rotor. A torsional spring (connected in geometric parallel) is available to compensate for a patient's hypertonicity (inability to relax). The hand robot is capable of providing continuous passive motion, strength, sensory, and sensorimotor training for grasp and release; it can be employed in stand-alone operation or mounted at the tip of the planar robot.

8.4 Harnessing Good Plasticity to Augment Recovery

8.4.1 Clinical Evidence for Inpatient Care

Volpe et al. reported composite results of robotic therapy with 96 stroke inpatients admitted consecutively to Burke Rehabilitation Hospital in White Plains, NY [14]. All participants received conventional neurological rehabilitation during their participation in the study. The goal of the trial was to amass initial evidence to test whether movement therapy had a measurable impact on recovery. Consequently, we provided one group of patients with as much movement therapy as possible to address a fundamental question: does goal-oriented movement therapy have a positive effect on neuromotor recovery after stroke? Note in passing that, at the time of these studies, the answer to this question was far from clear.

Patients were randomly assigned to either an experimental (robot-trained) or control (robot-exposure) group. Individuals in the robot-trained group were seen for five 1-h sessions each week and participated in at least 25 sessions of

Table 8.1 Burke inpatient studies ($N = 96$) mean interval change in impairment and disability (significance $P < 0.05$)

Between-group comparisons: final evaluation minus initial evaluation	Robot trained ($N=55$)	Control ($N=41$)	P-value
Impairment measures (± sem)			
Fugl-Meyer shoulder/elbow (FM-se)	6.7 ± 1.0	4.5 ± 0.7	NS
Motor power (MP)	4.1 ± 0.4	2.2 ± 0.3	<0.01
Motor status shoulder/elbow (MS-se)	8.6 ± 0.8	3.8 ± 0.5	<0.01
Motor status wrist/hand (MS/wh)	4.1 ± 1.1	2.6 ± 0.8	NS
Disability evaluation			
Functional independence measure (FIM)	32.0 ± 5.0	25.5 ± 6.5	NS

sensorimotor robotic therapy for the paretic arm. Patients were asked to perform goal-directed, planar reaching tasks that emphasized shoulder-and-elbow movements with their paretic arm. MIT-Manus' low impedance guaranteed that the robot would not suppress attempts to move. When a patient could not move or deviated from the desired path or was unable to reach the target, the robot provided gentle guidance and assistance dictated by an impedance controller [15]. This robot action (which we dubbed "sensorimotor" therapy) was similar to the "hand-over-hand" assistance that a therapist often provides during conventional therapy. It is interesting to note that this form of "assistance as needed," which has been a central feature of our approach from the outset (and a challenge for our robot designs), has recently been adopted and promoted by other groups [16, 17].

Individuals assigned to the robot-exposure (control) group were asked to perform the same planar reaching tasks as the robot-therapy group. However, the robot did not actively assist the patient's movement attempts. When the subject was unable to reach toward a target, he or she could assist with the unimpaired arm, or the technician in attendance could help to complete the movement. The robot supported the weight of the limb while offering negligible impedance to motion. For this control group, the task, the visual display, the audio environment (e.g., noise from the motor amplifiers), and the therapy context (e.g., the novelty of a technology-based treatment) were all the same as for the experimental group, so this served as a form of "placebo" of robotic movement therapy. Patients in this group were seen for only 1 h per week during their inpatient hospitalization.

The study was "double blinded" in that patients were not informed of their group assignment and therapists who evaluated their motor status did not know to which group patients belonged. Standard clinical evaluations included the upper extremity subtest of the Fugl-Meyer Assessment (FM, maximum score = 66); the MRC Motor Power score for four shoulder-and-elbow movements (MP, maximum score = 20); and the Motor Status Score (MSS, maximum score = 82) [18–20]. The Fugl-Meyer test is a widely accepted measure of impairment in sensorimotor and functional grasp abilities. To complement the Fugl-Meyer scale, Burke Rehabilitation Hospital developed the Motor Status Scale to further quantify discrete and functional movements in the upper limb. The MSS scale expands the FM and has met standards for inter-rater reliability, significant intraclass correlation coefficients, and internal item consistency for inpatients [21].

Although the robot-exposure (control) and robot-treated (experimental) groups were comparable on admission, based on sensory and motor evaluation and on clinical and demographic scales, and both groups were inpatients in the same stroke recovery unit and received the same standard care and therapy for comparable lengths of stay, the robot-trained group demonstrated significantly greater motor improvement (higher mean interval change ± sem) than the control group on the MS-se and MP scores (see Table 8.1). In fact, the robot-trained group improved twice as much as the control group in these measures. Though this was a modest beginning, it provided unequivocal evidence that movement therapy of the kind that might be delivered by a robot had a significant positive impact on recovery.

8.4.2 Clinical Evidence for Chronic Care

The natural history of motor recovery of the paretic upper limb after stroke reveals a dynamic process that has traditionally been described by a period of flaccidity that is followed by changes in tone and reflex, as well as the frequent development of synkinesis or associated movement disorders. This synkinesis is characterized by involuntary, composite movement patterns that accompany an intended motor act [22]. Complete motor recovery, when it occurs, will unfold rapidly. However, the more commonly observed partial recovery, with broad variability in final motor outcomes, unfolds over longer periods [23, 24]. That said, the current state of knowledge regarding motor recovery post stroke indicates that the majority of gains in motor abilities occur within the first 3 months after stroke onset, and that over 90% of motor recovery is complete within the first 5 months [25]. We were able to recall one third of the 96 stroke inpatients mentioned earlier 3 years after discharge. We observed that both groups continued to improve after discharge from the hospital and after 5 months post stroke. Our data suggest that previous results limiting the potential of chronic patients' recovery were based on the effects of general rather than task-specific treatments during the recovery period post stroke. Recently, the Veterans Affairs completed the VA-ROBOTICS study (CSP-558), a landmark multisite, randomized clinical trial in chronic stroke of upper extremity rehabilitation robotics employing our gym of robots (planar shoulder-and-elbow, antigravity, wrist, and hand robots) [26].

The VA-ROBOTICS study vanquished for good the old conjecture that an adult brain was hardwired and static. It demonstrated that even for persons with multiple strokes, severe strokes, and many years post stroke, there is a real opportunity for meaningful improvement. At follow-up, 6 months after completing the intervention, the robot group demonstrated sustainable and significant improvement over the usual-care group on impairment, disability, and quality of life. The results are even more impressive if we consider the results of the complete program of robotic treatment rather than an analysis that focused on the first half of the study (see Fig. 8.2). In a nutshell, while the results at 12 weeks show that the difference between the first half of the robotic treatment group and usual care was slightly over 2 Fugl-Meyer points (as the therapists were learning how to use the robots), once the therapists were proficient in using the technology, the difference between the second half of the robotic treatment group and usual care was almost 8 points in the Fugl-Meyer assessment (the total robotic group versus the total usual care showed a 5-point change).

It is quite important to stress that VA-ROBOTICS enrolled moderately to severely impaired chronic stroke patients, and over 30% of these patients had multiple strokes. As such, the group represented a spectrum of disability burden that many studies have avoided and, in our research, represented the majority of the cases (65% of the volunteers were enrolled). Thus, even if the positive changes in the robotic therapy group might appear modest, the persistent statistically significant improvement at the 6-month follow-up evaluation suggests improved robustness and perhaps an incremental advantage that prompted further improvement even without intervention.

In this era of cost containment, cost-benefit analysis is essential, and in this case, it provided an important result. As expected, active interventions added cost beyond the usual care offered in the VA; for example, the extra cost of the robotic equipment plus an additional therapist cost the VA $10,000 per patient for 36 months. However, when we compared the total cost, which included the clinical care needed to take care of these veterans, there were no differences between active intervention and usual care. The usual-care group cost the VA roughly the same $15,000 per patient because that group used the rest of the VA health care system three times more often than the active intervention groups. In other words, for 36 weeks of care, the robotic group cost the VA $10,000 for robotic therapy and $5,000 for clinical care. For 36 weeks of care, the usual-care group cost the VA approximately $15,000. This suggests better care for the same total cost. These results were quite unexpected, and a full economical analysis is under way by the VA; we will have to wait for the detailed economical analysis to get further

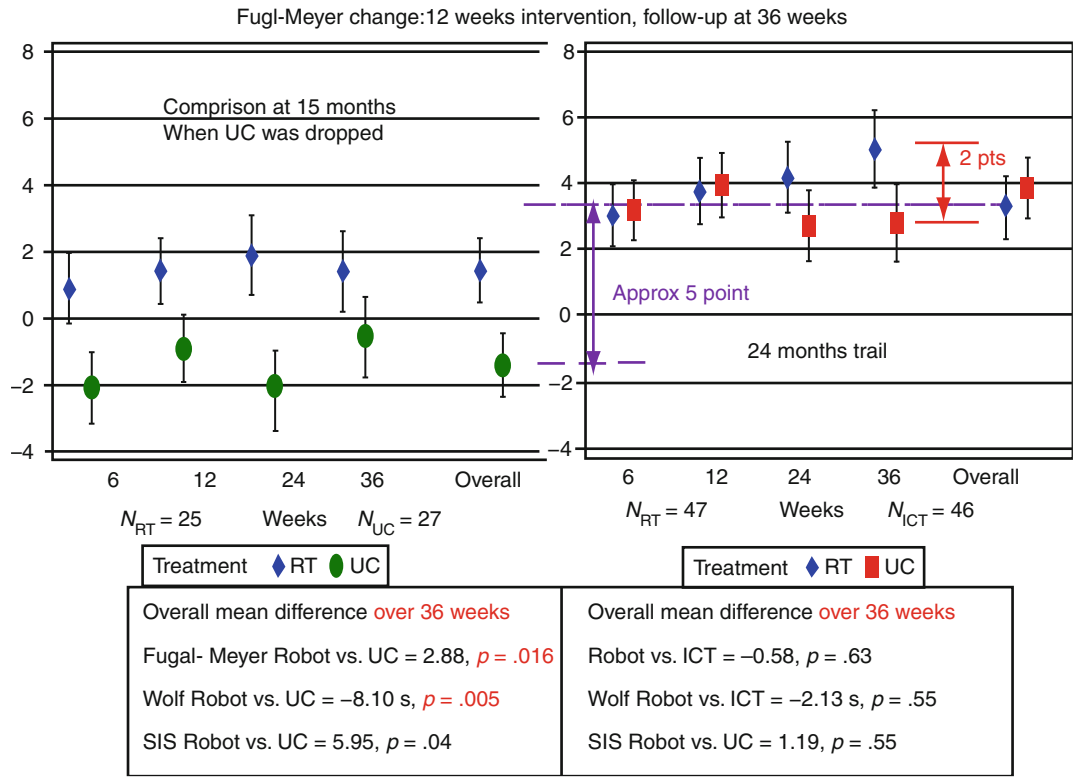

Fig. 8.2 Changes over time in the VA-ROBOTICS. Training lasted for 12 weeks with an additional 6-month follow-up after completion of the intervention. The *left panel* shows the comparison of the first half of the robot group with the usual care (first half as therapists learned how to employ the system). The *right panel* shows the comparison of the complete robot group with the Intensive Comparison Training (both groups executed 1,024 reaching movements with the paretic arm in an hour session). *Arrows* indicate the changes between usual care and robot group and between robot group and ICT at 36 weeks evaluation

information. Nevertheless, the preliminary results warrant guarded optimism.

Summarizing briefly, there is now objective evidence that in the "real" therapy world away from the clinical research environment, robotic therapy that involves an interactive high-intensity, intention-driven therapy based on "assist-as-needed" motor learning principles leads to better outcomes than usual care in chronic stroke (and probably even bigger impact for acute/subacute stroke).

8.4.3 Clinical Evidence Contrary to Common Clinical Perceptions

While appropriate robotic therapy has been demonstrated to augment recovery, we still don't know how to tailor therapy to meet a particular patient's needs. We do not know the optimal dosage. What is the minimum intensity to promote actual change? Is too much therapy detrimental? Should we deliver impairment-based or functionally based approaches? To whom: severe, moderate, mild stroke patients? Should therapy progress from proximal to distal or the other way around? Should we train subcomponents of a movement, such as reaching in a compensated environment and raising the arm against gravity, or train the complete spatial movement against gravity? Should we assist-as-needed, resist, or perturb and augment error? Who might be the responders who benefit most from these interventions? How should we integrate robotic gyms with therapy practice?

Our ignorance could not be more evident than when testing a common perception among

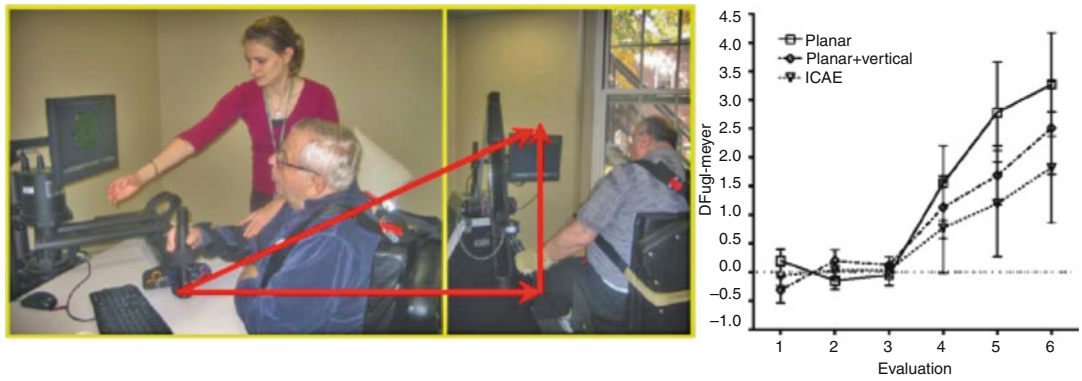

Fig. 8.3 Component training and spatial composition. The FMA changes at each point (mean, STD) with ICAE standing for intensive conventional arm exercise. Baseline demonstrates stability and no difference among groups. Changes from baseline to final and follow-up showed a significant benefit for both robotic groups

clinicians that training must involve spatial movement. While Lo and colleagues demonstrated that a combination of planar, vertical, wrist, and hand robot training improves both arm impairment and functional recovery, as well as quality of life, the added value of antigravity/spatial training was not addressed in that study. Though therapists long held the belief that training must be spatial, investigations comparing training in gravity-compensated and noncompensated environments had not been performed. To address this question, in a randomized clinical trial, we compared a combination of antigravity and planar robot training with planar training alone and compared its effectiveness to a control group who received intensive conventional arm exercise (ICAE) [27]. We hypothesized that planar robot training combined with robot-assisted reaching outside the constrained gravity-compensated horizontal plane would be superior to gravity-compensated planar robot therapy alone. We also hypothesized that a 6-week program of robot-assisted motor training would be more efficacious than ICAE across impairment, function and activity measures (half duration of the duration of VA-ROBOTICS).

All interventions were provided by the same therapist for 6 weeks: 1 h, three times a week for a total of 18 sessions. Robot therapy included the use of two different robots employed in the VA-ROBOTICS study. Robot-assisted planar reaching was performed with a 2-active-degrees-of-freedom (DOF) InMotion2 shoulder–elbow robot. The combined-robot group (planar + vertical) used the planar shoulder–elbow robot for gravity-compensated horizontal reaching followed by the 1-DOF InMotion-linear robot in its vertical position for reaching against gravity. The robots provided assistance with a performance-based algorithm, adapting forces as needed to challenge or assist movement. This algorithm, introduced in 2002, continuously challenges the patient by modifying (a) the time allotted for the patient to make the move and (b) the primary stiffness of the impedance controller that guides the movement. The better the patient performs, the more she or he is challenged to move quicker and receive less guidance; the controller updates its characteristics at each completion of multiples of five games [15]. In addition, the robots' compliant and backdrivable behavior allowed for expression of movement outside a rigid trajectory. The intensive conventional arm exercise (ICAE) sessions were time matched with the robotic sessions. The rate of movement repetition was not precisely matched to the robot, but overall intensity was much greater than with a conventional exercise program. (Fig. 8.3)

On the primary outcome, all three groups showed modest gains from baseline to final training without significant differences. The two robotic groups, however, showed significant within-group changes not seen in the ICAE control group, both at the end of treatment and after

a retention period. Remarkably, contrary to clinicians' expectations, the combined-training group was not superior to the gravity-compensated robot training group. In fact, the planar (gravity-compensated) robot training subjects showed the greatest change.

Independence in everyday living activities includes the ability to execute reaching motions at any given moment despite the opposition of gravity. In this investigation, the robot interventions were primarily differentiated by the presentation of two different types of reaching in a horizontal and in a vertical plane (gravity-compensated and noncompensated) versus reaching in a single (gravity-compensated) horizontal plane. It was hypothesized that a combined robotic training program would enhance recovery by increasing task challenge and generalization of reaching to more than one context. However, the successive presentation of arm activities with different environmental and motor demands did not lead to better overall group outcomes.

One interpretation of these results is that the motor system may use two distinct internal models for whole arm antigravity reaching and gravity-compensated planar reaching, and our blocked training in close succession interfered with motor consolidation [28, 29]. This interpretation is supported by a prior robotic study that found gravity, noncompensated vertical reaching promoted further recovery in chronic stroke beyond that resulting from gravity-compensated planar reaching if it followed, rather than abutted, gravity-compensated planar reaching, i.e., 6 weeks of planar reaching training followed by 6 weeks of antigravity training [10]. Whether motor memories require an interval to consolidate (Caithness G) or whether practicing the whole arm movement is necessary to promote optimal recovery [30] is a complex question that this study design cannot answer. However, given the findings, it is clear that further investigation of alternative sequencing of the two robot therapies is warranted. Perhaps combining these two robotic therapies on alternating days or weeks would provide a better recovery based on impairment and functional measures. Perhaps each domain may require a different schedule. Identifying the best sequence and presentation of therapies that make different demands on the patient is clearly an important empirical question, a necessary step toward using robotic therapy to optimize stroke recovery. However, it is equally clear that basing therapy programs on intuitively reasonable, preconceived but untested ideas will not suffice.

8.4.3.1 Which Processes Underlie Neuro-recovery?

A common assumption is that sensory-motor therapy works by helping patients to "relearn" motor control [31]. Though intuitively sensible, this notion may need to be refined. In the first place, 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. Thus recovery is likely to be a more complex process than learning. Secondly, 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? These deep questions have practical relevance for therapy. For example, if the brain represents action as a sequence of muscle activations, it would seem profitable to focus sensory-motor therapy on muscles. 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 extremity primarily to meet kinematic specifications (such as simple motion of the hand in a visually relevant coordinate frame), adjusting muscle activity to compensate for movement-by-movement variation of mechanical loads. That would suggest it may be more profitable to focus sensory-motor therapy on motions rather than muscles and on motor learning rather than muscle strengthening. In our research on robotic stroke rehabilitation, we have attempted to assess some of these possibilities and have developed adaptive treatment algorithms to incorporate such ideas.

Our performance-based adaptive algorithm uses nonlinear impedance control to implement a "virtual slot" extending between the start and goal positions during reaching movements [15]. Lateral deviation from the desired trajectory was discouraged by the stiffness and damping of the slot sidewalls. Desired motion was assisted by moving the back wall of the slot along a minimum-jerk virtual trajectory so that the slot progressively "collapsed" to a "virtual spring" centered on the reaching movement goal position. However, motion along the "virtual slot" (well aimed and faster than the nominal desired trajectory) was unimpeded.

A request to move was signaled by a target in the visual display changing color. If the patient failed to trigger the robot within two seconds, the robot began to act (i.e., the back wall of the "virtual slot" closed on the goal position). To trigger the robot, the patient had to move the handle (in any direction) at a speed above a modest threshold value. Even severely impaired patients with a paretic arm could trigger the robot – although trunk motion was discouraged by restraining seatbelts, in practice, sufficient trunk motion was possible to move the handle and trigger the robot; no particular instruction was given but to try to reach the target. Though ultimately inappropriate trunk motion is to be discouraged, this mode of triggering the robot encouraged severely impaired patients to participate actively rather than passively allow the robot to drive the arm.

Secondly, the revised algorithm continuously monitored the patient's performance. By combining records of the kinematics of actual patient motion and the kinetics of mechanical interaction between robot and patient, five performance measures were computed: we graded (a) patients' ability to initiate movement, (b) patients' movement range or extension toward the reaching movement target goal, (c) amount of mechanical power that the robot exerted to assist the hand toward the target, (d) the smoothness of the movement, and (e) the aiming/deviation from a straight line connecting the center to the reaching goal. These measures were used to adjust the parameters of the controller during a therapy session. For the first five cycles through the eight goal positions, the time allotted for a movement (the duration of the nominal minimum-jerk trajectory) and the stiffness (impedance) of the "virtual slot" sidewalls were adjusted to approximately track the patient's current performance and need for guidance. This was important as patient performance typically declined between the end of one therapy session and the beginning of the next as commonly seen in motor learning (acquisition of a skill and its retention). For every subsequent five cycles of the game, the controller parameters were adjusted based on the patient's performance and its variability during the previous batch of moves. The intent here was not just to track patients' performance but also to challenge them to improve. As patients aimed better, the stiffness of the "virtual slot" sidewalls was decreased, requiring better accuracy (and vice versa). As patients moved faster, the time allotted for movement was decreased, requiring faster movements (and vice versa). The speed threshold to trigger the robot was also adjusted to 10% of the peak speed of a minimum-jerk trajectory of that duration. Consequently, if nominal movement duration increased, the speed of motion required to trigger the robot decreased (and vice versa). Thus, the motor ability required to trigger the robot and move to the target was less demanding for more impaired patients and more demanding as performance improved. Again, this was intended to encourage active participation of even the most impaired patients and yet continuously challenge patients as they recovered.

Thirdly, to provide motivation, positive reinforcement, and knowledge of results, the revised algorithm provided specific, movement-related feedback in the form of a simple graphical display consisting of five displays reflecting patient's performance in the last batch of five repetitions [32]. Each readout was determined by the five performance measures discussed earlier. The therapist could elect to hide displays that were not meaningful for a patient to avoid discouraging patients who could not yet move well without boring patients who could.

This performance-based progressive therapy algorithm provided support for patients to progress from complete hemiplegia to normal arm

Table 8.2 Motor impairment outcomes of performance-based progressive robotic therapy

Severity	Impairment measure (mean ± sem)	FM SEC (max = 42)	% change	MP (max = 70)	% change
Moderate	Before treatment	17.0 ± 1.3		37.2 ± 2.5	
N = 12	After treatment	22.5 ± 1.3*	32%	45.4 ± 1.7*	22%
CNS > 4; NIHSS < 15	Follow-up (3 months)	24.5 ± 0.9*	44%	46.5 ± 1.9*	25%
Severe	Before treatment	8.2 ± 0.7		17.3 ± 1.8	
N = 16	After treatment	10.9 ± 0.9*	33%	23.7 ± 2.0*	52%
CNS < 4; NIHSS > 15	Follow-up (3 months)	12.5 ± 0.9*	37%	26.3 ± 2.2*	52%

FM SEC Fugl-Meyer, shoulder–elbow component, *MP* motor power, *CNS* Canadian Neurological Scale, *NIHSS* National Institutes of Health Stroke Scale
*Denotes significant change, $P < 0.001$

movement. The ability to initiate a movement was stressed for severely impaired patients, helping to ensure appropriate timing of afferent and efferent signals. Movement range is an important clinical measure of function but also rewards hypertonic patients for relaxing their arms, allowing the impedance controller to move their hands closer to the target. The amount of power that the robot exerted encourages a patient to attempt to do more of the movement. Finally, smoothness and aiming (deviation from a straight path) quantify the trade-off between speed and accuracy that is characteristic of unimpaired movement and probably most important for patients with moderate to mild impairment.

This adaptive algorithm was evaluated in multiple studies including VA-ROBOTICS. Here, we recount the typical changes observed in chronic stroke patients as reported elsewhere [33]. All patients were evaluated six times: three times in a 2-month period prior to the start of therapy to assess baseline stability (phase-in phase), then at the midpoint and at the discharge from robotic therapy (18 1-h sessions of robotic training, three times a week for 6 weeks), and finally at a follow-up evaluation session 3 months after training. Evaluators were blinded to the protocol used for treatment.

The first three evaluations showed no significant changes on any of the impairment scales, verifying that subjects were indeed at the chronic phase of their recovery in which no spontaneous improvement was observed. Subsequent evaluations showed that the adaptive protocol evoked a statistically significant improvement in motor performance which was maintained at the 3-month follow-up (see Table 8.2). More important for our understanding of recovery, the *magnitude* of the improvement achieved with this adaptive algorithm was many times greater than that achieved with our previous robotic therapy. The only change was the robot control scheme; the same robot assisted with the same set of reaching movements during the same number of sessions. A treatment protocol, which adapted to the patient in order to present a continuous challenge substantially, enhanced recovery.

An important and informative detail is that this enhancement of recovery was achieved with *fewer* repetitions. Because the adaptive protocol adjusted the time allotted for a movement and allowed long movement durations as needed, fewer repetitions could be accomplished in a 1-h therapy session. Under this adaptive protocol, patients typically made just over 12,000 movements over the course of treatment. Under the previous hand-over-hand sensory-motor protocol, patients made just over 18,000 movements in the same number of sessions.

This confirms that, although the process of recovery may share some features of motor learning (such as specificity), the relationship between learning and recovery may be subtle. Though movement is beneficial, movement alone is not sufficient; active involvement of the patient is essential. Though repetition may be beneficial, repetition alone is not sufficient; the benefits of robotic therapy do not exclusively derive from the high "dosage" of movement delivered but from the interactive nature of the therapy protocol.

8.4.3.2 Robot-Mediated Assay

First proposed over a decade and a half ago, devices for robot-aided neuro-rehabilitation are increasingly being incorporated into stroke patients' care programs. In addition to delivering high-intensity, reproducible sensorimotor therapy, these devices are precise and reliable "measuring" tools that can be expanded with multiple sensors to record simultaneously kinematic and force data. These measurements are objective and repeatable and can be used to provide patients and therapists with immediate measures of motor performance. Reducing the time to evaluate improvement or deterioration may offer new opportunities for designing therapeutic programs and ultimately for increasing the efficiency of patients' care. Across multiple regression models, we demonstrated that robot-based metrics can reliably estimate the clinical scales [34] with good correlations during training and validation ($R>0.7$). For example, we can estimate the Fugl-Meyer assessment (FMA) quite accurately for chronic stroke from the MIT-Manus kinematic metrics via:

$$\begin{aligned}\mathrm{FMA} = {} & 4.58 - 11.68 \times [\mathrm{AIM}] \\ & + 37.04 \times [\mathrm{Deviation}] \\ & - 29.30 \times [\mathrm{MeanSpeed}] \\ & + 62.55 \times [\mathrm{PeakSpeed}] \\ & + 83.96 \times [\mathrm{Smoothness}] \\ & + 1.72 \times [\mathrm{Duration}] \\ & + 2.98 \times [\mathrm{EllipseRatio}] \\ & - 17.28 \times [\mathrm{JoinIndependence}]\end{aligned}$$

where the metrics were extracted from unconstrained reaching movement toward targets presented in eight positions equally spaced around a 14-cm radius circle and back to the center, namely, the deviation from the straight line connecting the targets, aiming, movement mean and peak speed, movement smoothness (ratio of mean to peak speed), and movement duration; or the metrics were extracted from unconstrained circle drawing where the patient's hand was initially positioned at 3 o'clock and at 9 o'clock (right or left to the workspace center) and she or he was asked to draw clockwise and counterclockwise circles starting and ending at the same point, namely, the axes ratio (ratio of the minor to major axes of the best-fitting ellipse) and the joint angle correlation (degree of independence of the shoulder-and-elbow movements) [35].

Robot measurements can potentially outperform human-administered clinical scales and are limited only by the performance of the robot sensors. For example, MIT-Manus can measure positions with a resolution of 0.1 mm. The reliability of human-administered clinical scales has often been questioned; for example, Sanford reported an interrater variability of +/− 18 points on a 95% confidence interval for the total Fugl-Meyer scale, pointing out that small patient improvements will not be able to be identified by the score [36]. Krebs found up to a 15% discrepancy between therapists when evaluating the same patient for the upper extremity FMA scale [37]. Gregson estimated an interrater agreement of 59% for the MAS [38]. The MAS is considered a reliable clinical scale by some [38] but totally unreliable by others [39]. Besides having questionable reliability, human-administered clinical scales are also time-consuming. In contrast, robot measurements can potentially provide therapists and patients with immediate feedback. Real-time scoring cannot only greatly reduce the amount of time required for evaluations of patients' motor improvements but it is also becoming a key need for the new robot-aided neuro-rehabilitation scenarios. These include systems that continuously adapt the amount and type of delivered therapy based on patient's motor abilities [15, 40].

8.5 Discussion

We reiterate the observations (some of which we have made previously) to emphasize our perception of the state of the art. The available evidence demonstrates unequivocally that some forms of robotic therapy can be highly effective, even for patients many years post stroke. At the same time, other forms of robotic therapy have been singularly ineffective. The contrast is starkest when we contrast upper extremity and lower extremity therapy.

Of course, these differences might arise from the contrasting neuro-mechanical complexity of upper extremity reaching and grasping versus lower extremity locomotion, the former being "simpler" in some sense. However, that is a difficult case to make. While the mechanical complexity of locomotion is undeniable (it involves "hybrid" dynamics, a combination of discrete switching and continuous dynamics, one of the most challenging frontiers of robotics and control technology), locomotor behavior is very "old" in phylogenetic terms; it does not require a lot of "brain" to generate functional locomotion. In contrast, the prodigious versatility of "ordinary" human manipulation is very "new" in phylogenetic terms. It seems to require a highly ramified central nervous system and may even be a unique characteristic of human behavior.

We submit that the contrasting effectiveness of upper and lower extremity therapies arises from neural factors, not technological factors. Though, no doubt, it might be improved, the technology deployed to date for locomotor therapy is elegant and sophisticated. Unfortunately, it may be misguided, providing highly repeatable control of movement but ultimately doing the wrong thing. The technology we have deployed to date for upper extremity therapy is straightforward, though nontrivial, but it is firmly based on an understanding of how upper extremity behavior is neurally controlled and derived from decades of neuroscience research. The limitations of lower extremity robotic therapy lie not in the robotic technology but in its incompatibility with human motor neuroscience.

Of course, our knowledge of neural control of human movement is far from complete, and it is continually revised as new knowledge is gained. Thus, there remains ample opportunity to improve upper extremity robotic therapy. To draw an analogy, the state of robotic rehabilitation technology loosely resembles that of aviation in the late 1920s. Heavier-than-air flight had been reliably demonstrated and some applications (i.e., military) had been explored, but the lasting benefits of this technology were about to be realized. Contrasting the piston-engine biplanes of the 1920s with turbine-powered modern airliners may help to comprehend the magnitude and future potential of robotic therapy.

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