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Rehabilitation Robotics: an Academic Engineer Perspective

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Abstract— In this paper, we present a retrospective review of our efforts to revolutionize the way physical medicine is practiced by developing and deploying rehabilitation robots. We present a sample of our clinical results with well over 600 stroke patients, both inpatients and outpatients. We discuss the different robots developed at our laboratory over the past 20 years and their unique characteristics. All are configured both to deliver reproducible interactive therapy and also to measure outcomes with minimal encumbrance, thus providing critical measurement tools to help unravel the key remaining question: what constitutes "best practice"? While success to date indicates that this therapeutic application of robots has opened an emerging new frontier in physical medicine and rehabilitation, the barrier to further progress lies not in developing new hardware but rather in finding the most effective way to enhance neuro-recovery. We close this manuscript discussing some of the tools required for advancing the effort beyond the present state to what we believe will be the central feature of research during the next 10 years.

I. Introduction

The 2010 American Heart Association guidelines for stroke care and the Veterans Administration/Department of Defense guidelines for stroke care endorsed the use of rehabilitation robots for the upper extremity but not for the lower extremity [1]. Later in 2010, the Veterans Administration and Department of Defense did the same [2]. These guidelines were issued based on clinical evidence provided by multiple clinical trials and not wishful thinking. For the upper extremity, we and others have tested multiple variations [see for example [3]] with perhaps the most important result coming out in the spring of 2010 when the results of the ROBOTICS Study were published in the New England Journal of Medicine [see CSP558 [4]]. For the lower extremity, results employing robotic devices have been far less promising. As an example, the larger studies employing the Lokomat (Hocoma, Zurich, Switzerland) achieved statistically significant worse results when compared to those produced by usual care [5][6]. One might speculate that perhaps the technology was trying to facilitate the "wrong" aspects of gait neuro-recovery. In fact, contrary to our initial expectations, the major hindrance to the development and deployment of robots for therapy is not engineering, but the lack of strong evidence supporting many current rehabilitation practices. In many cases, conventional practices lack the support of empirical evidence or any other scientific basis. 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 to determine what constitutes best practices. Take the example of the failed efforts mentioned above to automate treadmill training for stroke rehabilitation; the premise perhaps should be first to determine whether treadmill training is effective (with or without automation), noting that clinical results are full of surprises. Recently unveiled results of an NIH sponsored large randomized clinical trial on treadmill training post-stroke did not lead to superior results when compared to a simple home exercise program (LEADS Study). Thus, at least for stroke, a gait rehabilitation program that encompasses exclusively concepts of spinal cord central pattern generators delivered by either therapists (treadmill training such as LEAPS) or robotic devices (such as the Lokomat) do not appear to be advantageous. Hence we need to investigate both the process of gait neurorecovery as well as better technology that can effectively assist gait rehabilitation, otherwise we might run the risk of "poisoning the waterhole." While this fact might discourage our colleagues from industry, for the academic engineer, this challenge is an unprecedented opportunity: robots provide an ideal platform for objective, reproducible, continuous measurement and control of therapy. In the following pages, we review our initial evidence-based clinical results, describe the different devices we have developed, discuss robot-assisted evaluation approaches and explain some neuroscience concepts that are likely to shed light and constitute the basis of neuro-recovery,

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II. Clinical Results

A. Inpatients

The first rehabilitation robotics clinical results included 20 patients who were randomly assigned to a) an experimental group that, in addition to their standard care, trained daily during weekdays for 20 sessions for an additional hour of robot-mediated therapy with the MIT-Manus, a robot developed for neuro-rehabilitation [7] or b) to a control group that, in addition to their standard care, received one hour per week of robot exposure and required self-ranging with the MIT-Manus. Results demonstrated that the robot group improved twice as much as the control group in the limb segments that were exercised [8]. Similar results were obtained by others and are summarized in different meta-analysis [see [3]].

B. Chronic Stroke

We followed inpatients for over 3 years and observed that contrary to what was previously thought and reported in several epidemiological studies, there is further opportunity to deliver therapy even several years post-injury [9]. Therefore, we ran a series of studies with community dwelling persons with chronic stroke. Here we show an example of people that have passed through our studies. Note the shift to the right on cumulative distribution curve from admission to discharge indicating improved outcomes. Similar results were observed in the Veterans Administration run multi-site, randomized clinical trial ROBOTICS (CSP-558). Of note and contrary to our studies, ROBOTICS involved patients with multiple strokes representing a cohort of disabilities and impairments that are ignored among the stroke general population [3].

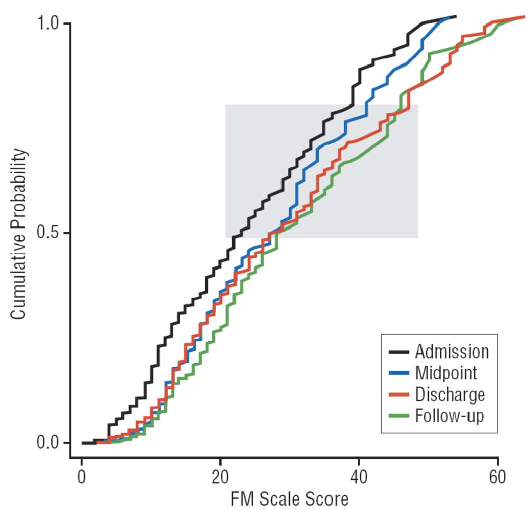

Fig.1. Changes in Outcomes with Robotic Therapy. The composite shows changes for 248 stroke patients at the Burke Rehabilitation Hospital for both inpatients and chronic patients enrolled from 5 days post-stroke to 11.3 years after the injury [10].

III. REHABILITATION ROBOTICS

Our approach was to tackle a difficult and common clinical problem, stroke rehabilitation for the upper limb, using the best available technology. In this case, we had to invent the technology, since in 1989 there were no available alternatives. The centerpiece of this effort became known as MIT-MANUS, from MIT Motto's Mens et Manus (Mind and Hand). MIT-MANUS is a robot designed for clinical neurological applications [7]. 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 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 to 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). We employed the same set of design principles in all of our designs. Figure 2 shows our robots for upper and lower extremity.

Fig.2. MIT Gym of Robots [7, 11-17]. Top row on the left shows the MIT-Manus to promote neurorecovery of the injured brain and control of the shoulder-and-elbow and on the right the anti-gravity to promote training of the shoulder against gravity. On the 2nd row on the left we show the wrist robot which affords training of the 3 degrees of freedom of the wrist and forearm and at the right, the hand module for grasp and release. The 3rd row on the left shows the combination of shoulder-and-elbow robot with the wrist module mounted at the tip of first affording training for both transport of arm and object manipulation. On the right, the sketch of the alpha-prototype of the MIT-Skywalker for gait training. On the bottom row, we show pediatric populations working with the MIT-Manus and our pediatric anklebot that afford training in dorsi/plantarflexion and inversion/eversion.

IV. Assessment

Robotics can also provide exquisite tools to evaluate motor recovery. They can 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, assurance of patient compliance with treatment regimens, and maintenance of patient records. Here we will present two examples. The first example demonstrates how we can characterize inter-limb joint coordination in stroke patients. The ability to reach appropriately for an object or to move objects requires proper inter-joint coordination. 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 inter-limb joint movement [18]. The second example demonstrates that a set of kinetic and kinematic robot-mediated metrics may be used to estimate clinical scales. Here the clinical scales are the Fugl-Meyer Assessment (FMA) and the Motor Status Score scales (MSS). The robot-based metrics include the ability to move straight towards a target, the mean and peak speed of the movement, smoothness of the movement, the ability to draw a circle, and the degree of independence of the shoulder and elbow while drawing the circle [19].

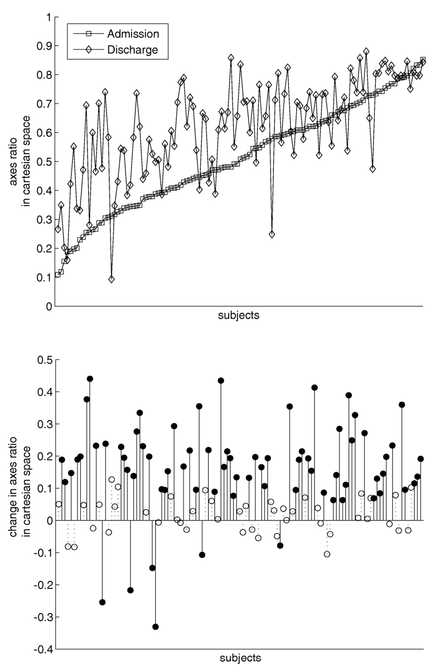

Figure 3: Axes ratio values for 111 chronic stroke patients at admission and discharge. Subjects were sorted according to the value of axes ratio at admission. On the x-axis subjects' labels have been omitted for clarity. Note that an axis ratio equal to 1 indicates a circle. On the bottom, changes in axes ratio metric over the course of therapy for each subject are shown. Filled circles and open circles indicate changes that are statistically significant ($p < 0.05$) and not statistically significant, respectively.

$$FMA = -4.58 - 11.63*[Aim] + 37.04*[Deviation] - 29.30*[MeanSpeed] + 62.55*[PeakSpeed] + 83.96*[Smoothness] + 1.72*[Duration] + 2.98*[EllipseRatio] - 17.28*[Joint\ Ind.]$$

$$MSS = -29.64 - 2.96*[Aim] - 16.12*[Deviation] - 230.22*[MeanSpeed] + 161.99*[PeakSpeed] + 184.74*[Smoothness] + 3.36*[Duration] - 16.55*[EllipseRatio] - 35.85*[Joint\ Ind.]$$

V. Modeling

Experience with over 600 stroke patients has suggested a working model of recovery similar to implicit motor learning. Most strokes preserve the patient's understanding of task goals, but leave an inability to perform the task — even simple tasks. As with implicit learning, recovery occurs without awareness of the learned information. We incorporate this concept in one innovative modality of robotic therapy introduced in 2002. We developed a performance-based, progressive assist-as-needed algorithm, which continuously challenges the patient. We achieved this goal by modifying both the time allotted for the patient to make the move and also the primary stiffness of the impedance controller that guides the movement towards the target. We varied these parameters based on the patient's performance and variability. The goal is to challenge the patient to move as fast as possible and provide as little as possible guidance towards the target. This approach did prove to lead to best clinical results so far.

VI. Conclusion

In this paper, we present a retrospective review of our efforts to revolutionize the way physical medicine is practiced by developing and deploying rehabilitation robots. We present a sample of our clinical results with well over 600 stroke patients, both inpatients and outpatients. We discuss the different robots developed at our laboratory over the past 20 years and their unique characteristics. While success to date indicates that this therapeutic application of robots has opened an emerging new frontier in physical medicine and rehabilitation, the barrier to further progress lies not in developing new hardware but rather in finding the most effective way to enhance neuro-recovery. We close this manuscript discussing some tools needed to complete the cycle for advancing the effort beyond the present state and determine how to optimize and tailor therapy to a particular patient's need, which we believe is the central feature of research during the next 10 years.

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