DISTURBANCES OF HIGHER LEVEL NEURAL CONTROL -- ROBOTIC APPLICATIONS IN STROKE

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Abstract - **We review results of initial clinical trials with 76 stroke patients at the Burke Rehabilitation Hospital. They provide evidence that robot-aided training enhances recovery. We also discuss technology under development, including algorithms for evaluating patients' performance. To conclude, we summarize different modalities of robot-aided therapy. In our initial clinical trials we used a single modality of robot therapy, but since each lesion is unique there is no reason to believe that a "one-size-fits-all" optimal treatment exists. We argue that therapy should be tailored to each patient's needs.**
Keywords - rehabilitation, stroke, robot, adaptive, modality.

I. INTRODUCTION

In "Why Michael Couldn't Hit", Harold Klawans [8] raises an interesting question about brain plasticity: why can a superstar professional athlete in a particular sport, say basketball, only achieve mediocre competence in another sport, say baseball? In principle, it is the same hardware recruiting similar capabilities: the same skeleton and muscles, the same nervous system, with similar eye-hand coordination and similar body-balance control. Yet on the scale of professional sports competence, the same hardware that achieves absolute wonders and perfection in one environment is less impressive in another. One might argue that all that is required is minor tuning of the motor control system to adjust to the subtleties of the new game. If a minor tune-up would suffice, a year of intensive practice and training should achieve that goal, yet in general, it does not. In other words, MJ was not an exception to this rule. It appears that the motor control system gets "hardwired" to perform one task seamlessly, but not another. There is strong evidence that there are particular periods of massive organization and re-organization of the motor control system. In humans, these "windows of opportunity" occur primarily during child development and adolescence. Outside these windows of opportunity, plasticity still occurs, albeit of a much smaller and subtle proportion. In summary, MJ may have lost his window of opportunity to hardwire baseball.

But what about an adult "broken" brain following a stroke? It appears that after a severe stroke that for example, wipes out a fourth of a survivor's brain, a massive re-organization takes place. In other words, there may be a "window of opportunity" that might allow us to maximize motor neuro-recovery following a stroke. Short of direct neural transplants, this period might afford the biggest chance of recovering function. Our efforts have been concentrated on applying robotics and information technology to determine how to augment therapy, harness plasticity, and increase the productivity of clinicians so that this window (if it exists) might be fully exploited.

In this paper, we review results obtained in the initial clinical trials with 76 stroke patients at the Burke Rehabilitation Hospital. We provide evidence that robot-aided training enhances recovery; and that this effect is not due to a general physiological improvement — in fact, it appears to be limb- and muscle-group specific. We discuss existing technology and new technology under development, including algorithms for evaluating patients' performance. Finally, we summarize the different modalities of robot-aided therapy that we are investigating. In the initial clinical trials we used a single modality of robot therapy, but since each lesion is unique there is no reason to believe that a "one-size-fits-all" optimal treatment exists.

II. CLINICAL RESULTS

Cerebrovascular accident (CVA) is the leading cause of disability in the United States. Almost 600,000 people in the U.S. experience a stroke each year, and nearly 4.5 million stroke survivors in America experience some degree of disability (American Heart Association, 2001). The effects of stroke can be devastating, resulting in deficits of cognitive, affective, sensory, and motor functions.

Although individuals with stroke commonly experience some degree of spontaneous recovery, they often receive intensive occupational and physical therapy to enhance recovery of function. Common movement-related impairments include decreased passive range of motion, weakness, hyperactive reflexes, and in-coordination. Typical therapeutic activities include manual stretching of a patient's limb to improve passive range of motion, assisted movement through specific reflex-inhibiting patterns to reduce hyperactive reflexes, and graded coordination or strengthening exercises. Progress is often evaluated subjectively, with the therapist making hands-on or visual judgments about a patient's isolated motor control or functional use of the affected limb [4]. We propose that robotic technology can facilitate the rehabilitation process through precise measurement of movement kinematics and forces, and by providing opportunities for graded, goal-directed motor action.

Our research to date has shown that repetitive, goal-directed, robot-assisted therapy can be effective in reducing motor impairments in the affected arm after stroke [1,11,16,17]. Table 1 summarizes the outcome of seventy-six stroke patients exhibiting a unilateral lesion who were enrolled in the initial clinical trials, which lasted

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Abstract

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approximately 5.5 weeks per patient. Patients were randomly assigned to an experimental and a control group. The experimental group received an hour per day of robot-aided therapy exercising the shoulder and elbow. The control group received an hour per week of "sham" robot-aided therapy with the same video games. The results of the initial studies, as measured by standard clinical instruments, showed statistically significant difference between the experimental and control group for shoulder and elbow (the focus of the exercise routines), but no differences for wrist and fingers (which were not exercised). This result suggests a local effect with limited generalization of the benefits to the unexercised limb or muscle groups. If this is the case, we must extend our robots to exercise different groups of muscles and limb segments.

Group	F-M (/66)	MP (/20)	MS1 (/40)	MS2 (/42)
	Δ 1	Δ 1*	Δ 1*	Δ 1
RT (40)	9.25	3.99	8.15	4.16
ST (36)	7.1	2.0	3.42	2.64

Table 1. Change during Acute Rehabilitation (76 patients): Experimental (RT) vs. Control (ST) Group - Δ1: score change from hospital admission to discharge; F-M is the Fugl-Meyer Scale; MP is the Motor Power; MS1 is the Motor Status Score for Shoulder & Elbow, and MS2 is the Motor Status Score for Wrist & Fingers; $p < 0.05$ for statistical significance (*).

III. ROBOTIC TECHNOLOGY

The centerpiece of our ongoing research program is MIT-MANUS, a novel robot specifically designed and built for clinical, neurological applications [6,9]. Because the mechanical system was designed to have a low intrinsic end-point impedance, with extremely low inertia and friction (i.e. it is highly "back-drivable"), MIT-MANUS is able to move smoothly and can rapidly comply with a patient's motor actions [9,11]. The robot sensors permit accurate and essentially continuous measurement of the key variables relevant to motor behavior, namely position, velocity, and forces applied. The present module has two degrees-of-freedom (DOF) that can move a patient's shoulder, elbow, and hand in a horizontal, gravity-eliminated plane. During therapy, the person's hemiparetic arm is placed in a customized arm support that is attached to the end-effector (i.e. handle) of the robot arm. As the patient moves the robot's handle toward a designated target, a video screen in front of them provides visual feedback of the target location and movement of the robot handle. If the person is unable to move the arm, the robot guides the hand to the target in much the same way as a therapist provides hand over hand assistance during conventional therapy.

Considering the limited benefits to the unexercised limb or muscle groups, we are extending our robot-aids to exercise different groups of muscles and limb segments. We

are presently developing robots to add spatial motion capabilities to MIT-MANUS, and novel robots for wrist, fingers, and legs [2,5,12,18]. Figure 1 depicts some of our robots, all developed under the same design philosophy striving at intrinsic low end-point impedance.

Fig.1. A Gym of Robots. The top left corner shows a recovering stroke patient receiving upper extremity robotic therapy with MIT-MANUS. The lower left corner picture shows the wrist robot and the right figure shows the spatial module (to be added to the tip of MIT-MANUS).

IV. EVALUATION TOOLS

We believe that robotic technology can enhance conventional practice of rehabilitating neurologically-based impairments in many ways. Treatment intensity, including the number of movement repetitions, can be closely monitored and controlled. This treatment information can be used in conjunction with robot evaluation data to examine the specific effects of robot-assisted therapy on motor behavior. The performance indices derived from robot data can measure changes in the kinematics or forces elicited during movement that may not be detected by standard clinical evaluations. We are presently developing different performance indices to evaluate patients' ability and have organized them into two categories based on the type of human-machine interaction: unconstrained and constrained.

We had been using variations of the first set of performance indices (unconstrained) in psychophysical experiments with unimpaired subjects as well as patients. These indices are hand path displacement, the lateral deviation from a straight line between start and target positions, mean squared aiming deviation, the correlation between observed movement and a minimum jerk motion of

the same duration, the mean squared difference between the observed and minimum jerk movements, and the number and overlap of submovements. Because these measures require patients to be able to independently move their arm, albeit in a gravity-compensated environment, they have severe limitations when dealing with hemiplegic or severe hemiparetic stroke patients, who initially can not reach the movement targets.

To address this limitation we developed the second set of indices (constrained). These indices are the mean magnitude of interaction forces in and out of plane of movement, the mean speed, the mean power exchanged between robot and patient, the mean holding radius for a given perturbation force, the maximum range of movement against a given impedance, and the shoulder flexion, extension, abduction, adduction maximum static forces [13]. Note that our highly back-drivable robot designs afford a unique ability to measure the process of neuro-recovery. For example, consistent with the conjecture that apparently continuous movements are actually composed of a sequence of submovements or segments, we were able to identify in twenty patients recovering from a single cerebral vascular accident (stroke), the apparent submovements that comprised a continuous arm motion in an unloaded task. Kinematic analysis demonstrated a submovement speed profile that was invariant across patients with different brain lesions, and provided experimental verification of the detailed shape of primitive submovements. We propose as a working hypothesis that this kind of "quantization" is a basic feature of human motor behavior, and used it to develop a robot-aided assessment procedure [7,10].

Indices such as hand path displacement or the number and overlap of submovements will provide accurate measures of how directly and smoothly an individual moves his or her arm when reaching toward a target, that are repeatable from one evaluation session to the next. We are presently correlating findings from robotic evaluation data with standard clinical evaluations, in order to identify the performance indices that best measure motor performance throughout the rehabilitation process. This is a first step in developing reproducible, reliable and valid robotic measures that will initially complement and may ultimately replace subjective clinical scales. We also expect robotic evaluation data to be valuable when examining patterns of motor learning and recovery, and when predicting functional motor outcomes. The performance indices derived from this data can be used in conjunction with functional brain imaging to examine the relationships between neural reorganization and motor action. In addition, kinematic and force measures derived from robotic evaluation data can more precisely measure the effects of different therapy approaches on motor performance after a disabling event. These measures will enable us to more closely examine the relationships between neural processing, motor recovery, and functional outcomes. The effects of different forms of practice (e.g. blocked vs. random) and varied treatment intensities (e.g. altering duration, number of repetitions, or

frequency) also can be readily monitored by the robot. It will lead to the development of more scientifically based theories of motor re-learning and rehabilitation practice.

V. MODALITIES OF ROBOT-ASSISTED THERAPY

There is no reason to believe that a "one-size-fits-all" optimal treatment exists. Instead therapy should be tailored to each particular patient's needs. Robot-assisted therapy can be delivered in a variety of ways to reduce motor impairment and enhance functional motor outcomes. Goal-directed therapeutic "games" can be designed to address motor impairments including poor coordination, impaired motor speed or accuracy, decreased grasp or dexterity, and diminished strength, as well as addressing cognitive or perceptual impairments. Depending on the survivor's impairment and lesion, robotic aids can provide passive, active-assistive, active, and active-resistive exercises. They can also deliver therapeutic approaches with no equivalent experience in nature [14]. We expect the understanding of what constitutes the most appropriate therapy to become an intensively active topic of research.

Naturally the desired outcome of rehabilitation is not merely a reduction of impairment, but an improvement in functional abilities and participation in daily life tasks. Currently, robot-assisted therapy is primarily administered in isolation from other rehabilitation efforts, with little emphasis on the practice of trained movements during daily functional tasks [1,3,9,11,15]. Research studies have indicated that the use of imagery-based tasks and the presence of objects during goal-directed tasks can significantly enhance movement kinematics during reach, in persons with and without CVA [19]. Based on this research, we are developing a therapeutic practice model that uses imagery-based, simulated tasks during robotic therapy sessions and is directed toward the carryover of robot-trained movements during functional activities. The intent is that this functionally-based robotic therapy may improve the generalization of learned motor skills, and thereby enhance functional motor performance.

One innovative modality of robotic therapy developed recently in our lab is the inclusion of specific, movement-related feedback and game adaptation. The stroke rehabilitation therapy we administered during our initial clinical trials was a fixed, repetitive exercise cued by a video display. It consisted of a series of point-to-point moves, which appeared to be well suited for patients with very limited movement ability. As displayed in Figure 2, the effect of the stiffness of the current impedance controller can be visualized as a potential energy field about a desired position. During therapy, this desired position moves from the starting position (*) to the end position (**).

The potential energy field of the adaptive impedance controller is also shown in Figure 2. While the stiffness of the previous controller tends to impede the patient from moving ahead of the desired point, the proposed controller allows capable patients to reach the target unassisted. During the proposed therapy, the time allotted for the

patient to make the move and the stiffness of the impedance controller are varied based on the patient's ability. In this way the therapy continuously adapts to challenge the patient.
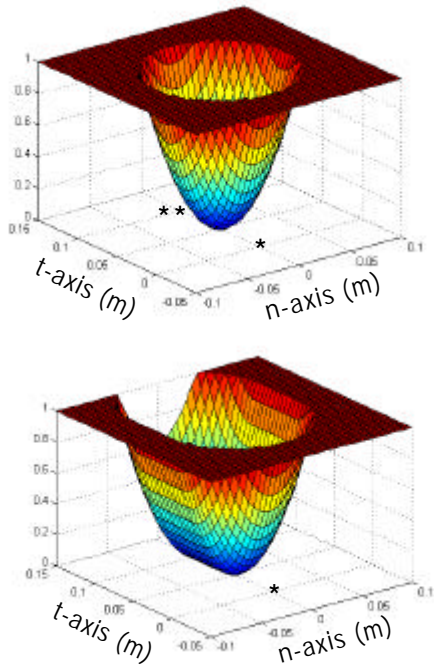

Fig.2. Impedance Controllers. The top plot shows the potential energy of the controller employed during the initial trials. The bottom plot shows the potential energy for the novel adaptive controller.

In an effort to keep patients motivated during therapy sessions, a video display provides the patient with positive reinforcement during the session. Changes in patient performance are indicated both by the height of the bars and their color. These performance measures grade the patient's ability to initiate movement (PM1), to move from the starting position to the target (PM2), to aim their movement along the target axis (PM3), and to reach the target position (PM4). PM1 records how many times the patient initiated the "game" by moving the arm above a modest velocity threshold. PM2 is used to adjust the time allotted for the move. PM3 is used to adjust the impedance controller stiffness. While PM4 records the maximum distance the patient moved along the target axis.

The PM2 and PM3 measurements must evaluate a patient's performance during each move. Figure 3 depicts the most promising candidates for PM2, the ability to move (top row), and for PM3, the ability to aim (bottom row) obtained from a representative patient between admission and discharge. The first column depicts kinetic measurements, whereas the second column is kinematic.

The kinetic measurement for PM2 is the average power along the target axis (PM2a), and the kinematic

measurement is the average deviation from the minimum jerk trajectory (PM2b).

$$PM2a = \frac{1}{N}\sum_{i=1}^{N}[F_t(i)V_t(i)] \qquad (eq.1)$$

$$PM2b = \frac{1}{N}\sum_{i=1}^{N}[t(i)-t_{m.j.}(i)] \qquad (eq.2)$$

where F_t is the force along the target axis, V_t is the velocity along the target axis, t is the distance along the target axis, and t_{mj} is the prescribed minimum jerk trajectory of the desired position. Note that the representative patient data shows that from admission to discharge these numbers become less negative, indicating that the patient contributes more power and motion to complete the task.

The kinetic measurement for PM3 is the average absolute power normal to the target axis (PM3a), and the kinematic measurement is the root-mean-square deviation along the normal to the target axis (PM3b).

$$PM3a = \frac{1}{N}\sum_{i=1}^{N}|F_n(i)V_n(i)| \qquad (eq.3)$$

$$PM3b = \sqrt{\frac{1}{N}\sum_{i=1}^{N}n(i)^2} \qquad (eq.4)$$

where F_n is the force normal to the target axis, V_n is the velocity normal to the target axis, and n is the distance normal to the target axis. Both measures for PM3 show that the patient's ability to aim improved between admission and discharge.
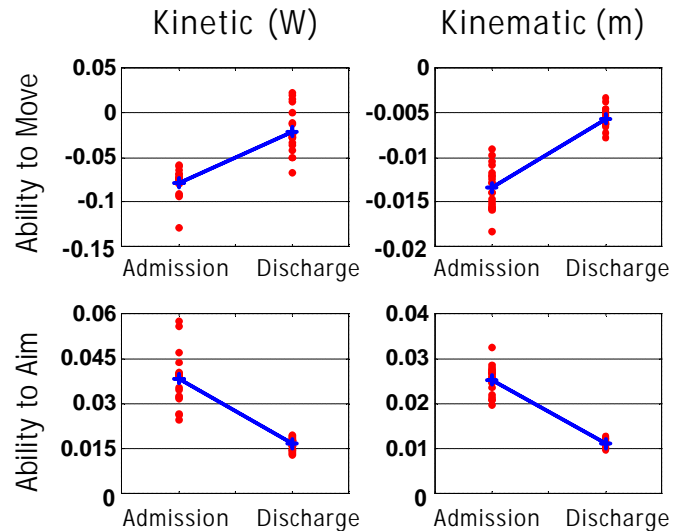

Fig.3. The Most Promising Candidates for PM2 and PM3.

Simulations were conducted to determine how the performance measures varied with the desired range of robot command variables and assumed patient variation. The controller time allotted for a move from the starting position to the desired target was varied between 1.5 and 4.5 seconds. To assist patients with their aim, the stiffness of

the impedance controller was varied from 50 to 350 N/m along the direction normal to the target axis. It was also assumed that the patients' move time would lie in between 1.5 and 4.5 seconds, and their maximum deviation along the normal to the target axis would be from 0.01 m to 0.07 m.

The final selections for PM2 and PM3 are displayed in Figure 4. PM2, the ability to move, was defined as a function of both PM2a and PM2b. Thus, both kinetic and kinematic information of the patient's move is contained in this performance measure. In particular, the positive values represent the average deviation from the commanded minimum jerk trajectory when the patient is moving ahead of the assist, and the negative values represent the average power delivered from MIT-MANUS to the patient during assisted moves. PM3, on the other hand, was defined as a function of PM3b only, the RMS normal deviation of the patient. PM2 required both kinetic and kinematic measures in order to discriminate when the patient leads or lags the desired minimum jerk trajectory of the controller.
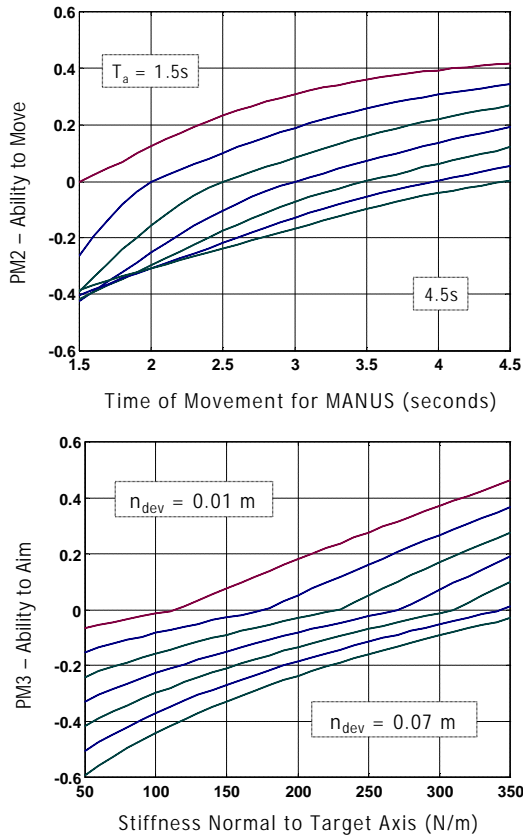

Fig.4. Adaptive Performance Indices: Calibration Curves

Several observations can be made concerning PM2 and PM3. As the parameters increase, the performance measures also increase monotonically along each line of constant patient parameters. Note, when PM2 equals zero, the patient move time equals the commanded robot move time, and when PM3 equals zero, each value of maximum patient normal deviation corresponds to a value of controller

stiffness. MIT-MANUS is able to track the patient's move time by using a simple control law such as:

$$T_m[k+1] = T_m[k] + \lambda \cdot PM2[k] \qquad \text{(eq.5)}$$

where $T_m[k]$ is the desired controller move time during the kth game, and λ is the gain from PM2 to T_m.

This tracking algorithm is a good first step, but we are not simply interested in tracking the patient's performance, but intend to challenge them to improve their performance or, at the very least, motivate them to maintain it. During the initial N games, the control system will operate in a tracking mode to identify how well the patient is able to complete the task. Recall, when the controller parameters are changed, the zero PM occurs at a different value of patient performance. In order to help account for this, a secondary performance measure was introduced that serves as an indication of patient variability. The performance level (PL) is defined to be

$$PL = \begin{cases} -1 & PM < -0.01 \\ 0 & -0.01 \le PM \le 0.01 \\ +1 & PM > 0.01 \end{cases} \qquad \text{(eq.6)}$$

The value of PL indicates whether the patient performed worse or better than their baseline performance. A value of 0 is also available to denote when the patient performed approximately the same.

The last N+ games in a session will be grouped into sections of 3 games each. During each of these sections, the desired controller move time and the controller stiffness will remain constant. By considering the average PM and the sum of the PL values ($-3 \le PL_{sum} \le 3$), the controller will adapt to patients' performance and variability, and challenge them to continue to improve. The proposed performance-based adaptive algorithm can be stated as follows:

$$T_m|_{k+1,k+2,k+3} = T_m[k] + \lambda \cdot a(PL_{sum}) \cdot PM2_{ave}$$

$$\text{where} \quad a(PL_{sum}) = \begin{cases} 0.5 & PL_{sum} = -3 \\ 0.25 & PL_{sum} = -2 \\ 0.125 & PL_{sum} = -1 \\ 0.125 & PL_{sum} = 0 \\ 0.25 & PL_{sum} = +1 \\ 0.5 & PL_{sum} = +2 \\ 1 & PL_{sum} = +3 \end{cases} \qquad \text{(eq.7)}$$

The desired effect of challenging the patient to improve while keeping them motivated will be accomplished, in part, by the asymmetry in the definition of $\alpha(PL_{sum})$. When patients do consistently better than their previous performance, $\alpha(PL_{sum})=1$, and when patients do consistently worse, $\alpha(PL_{sum})=0.5$. Thus, the algorithm uses information related to patient variability to dictate how much of an increase or decrease of the parameter there will be during the next 3 games. The asymmetry challenges improving patients to improve further, but makes the task easier, to a lesser extent, when patient performance is worsening.

So far, we have discussed only the approach to adapt the time for movement completion. An analogous approach is used to adapt the stiffness normal to the target axis.

Figure 5 displays a hypothetical case of a therapy session lasting for 20 repetitions. The first row is the patient simulation parameters, the second row is for MIT-MANUS, and the third row displays the PM2 and PM3 values displayed to the patient after games 5, 9, 14, and 19. In this session, a (simulated) patient tries to improve his/her aiming skills, but, as a result, moves more slowly. Since the performance has improved with respect to aim, the controller stiffness is decreased, providing less guidance and challenging him/her to further improve. Although patient's preferred move time has slowed to almost 3.8 seconds, MIT-MANUS completes the move in approximately 3.4 seconds. Therefore, the algorithm allows him/her to slow down from the original performance, but attempts to motivate the patient to do better than current performance. The displays are given as percentages and are defined by:

$$PM\% = \left\{ \begin{array}{c} 80 \text{ After Game 4} \\ 80 + c_1 \sum PL + c_2 PM_{ave} \end{array} \right\} \qquad (eq.8)$$

In this expression, c_1 and c_2 are scaled to limit patient display between approximately 70 and 90%. Recall that the purpose of the visual display is to provide positive reinforcement to the patient throughout the session.
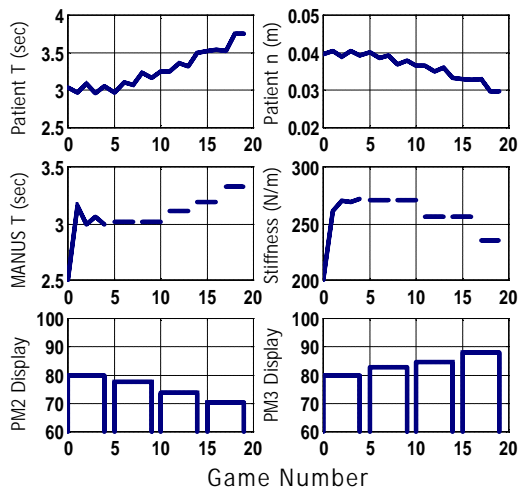

Fig.5. Simulation of the Adaptive Algorithm for a Therapy Session lasting for 20 repetitions.

VI. CONCLUSION

In closing, robotic technology provides many unique and unprecedented opportunities to not only increase the intensity of rehabilitation programs, but to precisely and objectively measure changes in motor performance that result from intervention. It allows persons with motor impairments the opportunity to engage in rigorous, goal-directed movement activities that are often more motivating and rewarding than contrived repetitions of "real-life" tasks. It provides the clinician opportunity to deliver therapy optimally tailored to the particular patient's needs, obviating pre-conceived ideas that a "one-size-fits-all" modality can suffice. We look forward to the development of new robotic tools for rehabilitation, and to further examining the effects of robotic technology on functional motor recovery.

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