Rehabilitation Robotics: Adapting Robot Behavior to Suit Patient Needs and Abilities

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***Abstract*— Robotics offers one solution to the rising problem of rehabilitating victims of neurological injury and disease. Rehabilitation robots have proven successful in speeding recovery for recent stroke victims, and in reducing impairment and pain for chronic victims who were thought to have little opportunity for improvement. Such robots require high force capability with a closely controlled "feel," requiring low endpoint impedance. For complex robot configurations, a combination of backdrivable hardware design and impedance-reducing controller design may offer the best solution. A novel therapy algorithm that exploits similarities between motor recovery and motor learning adapts robot impedance to patients as they recover. Results of therapy using this algorithm are a substantial improvement over the original robot therapy.**

I. Robot Therapy: Speeding Recovery for Recent and Chronic Patients

THE use of robotic aids in administering physical therapy to sufferers of neurological injury and disease is gaining acceptance as a method of reducing motor impairment and disability. The promise of automated tools is welcome to combat a problem that is widespread and growing; the incidence of stroke, for example, is increasing [1],[2], and there are already almost 5 million stroke survivors in the U.S. alone, as many as 90% of whom require therapy at some point. With an increasing percentage of the population over 65 years of age and rising health care costs, technology to help clinicians improve in effectiveness and efficiency is sorely needed.

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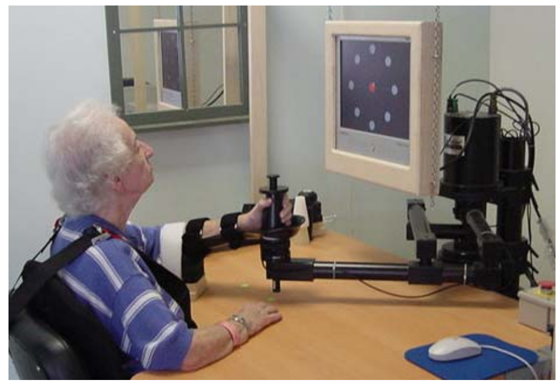

Figure 1. MIT-MANUS robot for shoulder and elbow rehabilitation in the horizontal plane.

Most early uses of robotics for rehabilitation focused on assisting patients in completing tasks that their impairment had compromised. Rehabilitation robotics instead attempts to rid the patients of their impairments, allowing them to live more functional lives. The greater promise of rehabilitative robots comes with greater difficulty: unlike most assistive applications, rehabilitation robots must do more than repeatedly complete a well-understood task; they must closely cooperate with various human subjects; they also must be designed so as to facilitate motor recovery over time. The latter challenge is made particularly difficult by the fact that the mechanisms of motor recovery are not yet fully understood. Therapy robots offer potential help in unraveling this mystery.

MIT-MANUS, our robot for shoulder and elbow therapy in the horizontal plane (Fig. 1), has been used to treat over 250 patients over the last decade [3]. Studies have repeatedly shown that patients benefit from robot therapy; the benefits extend from inpatients immediately following a stroke to outpatients, years after strokes.

In all of our studies, patients followed visual cues from a simple video game that directed them to move their impaired arm toward targets on the screen. The position of the patient's hand was shown on the screen in real time. When patients were not able to move, or moved slower than desired, the robot provided a gentle assisting force. The closer the patient's movement came to the desired trajectory, the less assistance they received.

Results of a pilot study (20 patients) and follow-up study

(56 patients) showed that patients who received one hour of robot therapy daily, four or five days a week, in addition to conventional physical and occupational therapy, showed a reduction in impairment of about 10%, as evaluated by several clinical measures. This is twice the reduction seen in patients who received only conventional therapy, along with "sham" robot therapy [4]-[6].

Perhaps even more promisingly, the effect of robot therapy was studied on outpatients who had suffered stroke one to five years previously. A total of 62 patients received robot therapy three times a week for six weeks, without receiving conventional therapy. Although their impairment level was stable before they started therapy, and in spite of the prevailing belief that most improvements come in the first three months following stroke, robot therapy significantly reduced their impairment and, equally important, their shoulder pain [7]-[9].

Expanding and Improving Robot Therapy

The results of this work have thus far been encouraging. However, our studies have consistently shown that robot therapy reduces impairment in the limbs specifically targeted by the robot; the benefits do not generalize. Patients improved in clinical measures addressing the shoulder and elbow, but not the wrist and hand [5]-[8].

The lack of generalization shows a need for additional robotic devices that target other types of movement, and other limbs. To that end, we have developed robots to target vertical arm movements [10], wrist motion [11], and hand or grasp motion [12]. Additional robots are in development, including several to target the lower limbs.

As we develop more specialized devices with more degrees of freedom (DOFs), the technical challenges of rehabilitation robotics become more significant. Although the devices look very different, all share some of the same basic needs and challenges.

II. Fundamental Engineering Challenge: Interacting with High Forces, Low Impedance

Robots are inherently well-suited to certain aspects of physical therapy. Where repetition and consistency are needed, robots excel, and these are indeed important parts of a therapy regime. Robots can help the patient make thousands of moves in a session, and can continue indefinitely without tiring. Thus they can free the physical therapist to supervise multiple patients or to focus on individual patient needs. Robots far exceed any human's ability to deliver therapy consistently, ensuring that each patient receives the appropriate interaction for each and every move. With motion and force sensors, robots can provide quantitative feedback that far exceeds human measuring capabilities, offering vast potential for accurate and repeatable measures of performance and impairment.

While robots are a natural fit for physical therapy in the ways described above, a significant technical gap remains between typical (e.g. industrial) robots and the types of custom machines needed for this application. The most profound engineering challenge, and the most distinctive feature of the family of robots we use for therapy, is the balancing of high force capabilities and low mechanical endpoint impedance. Achieving robot behavior appropriate for therapy requires explicitly addressing the mechanical interaction between robot and human, and designing robot and controller for high-force, low-impedance interaction.

Determining robot requirements

The force requirements for a therapy robot are dictated primarily by the need to help move the patient's limbs, possibly against muscle co-contraction. For example, for arm therapy in a tabletop plane, a continuous force requirement of around 45 N was determined [13]. For vertical arm motion, a similar requirement included the effects of gravity for upward force [10].

The endpoint impedance requirements derive from a slightly less obvious, but in our view equally important, need. Early evidence seems to confirm our belief that motor recovery is connected to motor learning (some evidence is described in the following section), and thus the process of retraining patients to move must be treated as a learning process. It is not sufficient to simply move the patient's limb repeatedly; the patient must be actively engaged, attempting to move, and able to see the result of his own attempts, just as an infant learns motor skills. Thus the patient must be capable of easily moving the robot, and the robot must have low endpoint impedance (be backdrivable). While the robot must be able to "get out of the way," it must also at times provide a stiff interface to guide or resist the patient. In general, the robot must act like a damped spring, and the stiffness of this spring must be adjustable. The robot must be able to provide endpoint impedances across a span ranging from apparently "zero" impedance to a strong stiffness, where "zero impedance" and "strong stiffness" are defined on the basis of the body part that the robot assists. For the arm device, the following parameter ranges were selected: 0 to 2 N/mm stiffness, 0 to 1 N static friction, and 2/3 to 4/3 kg inertia [13].

Controlling Interaction

By design, controlled therapy robots have dynamics comparable to those of the system with which they interact. This contrasts with motion controlled robots, which seek to impose motion and be much "stiffer" than their environment, and force controlled robots, which seek to impose force and be much "softer" than their environment. In either case, these assumptions permit the neglect of the environment in controller design, as the closed-loop dynamics of the robot are not significantly altered by interaction. For *interactive robots* such as therapy robots, interacting with the environment substantially alters the system dynamics, and must be considered in analyzing stability. Furthermore the performance of a therapy robot is defined not in terms of its ability to follow a trajectory, but instead by its ability to provide a desired "feel" at the endpoint (for example, the feel of a spring and damper).

Stability and performance are both addressed directly when *impedance control* is used for controller design [14]. Impedance control regulates the behavior of the robot at the point where it interacts with the environment. Specifically, mechanical impedance, often denoted as *Z*, is defined as the force the robot returns in response to the port velocity:

$$Z = \frac{F}{\dot{x}} \tag{1}$$

F is the endpoint force, and $\dot{x}$ the endpoint velocity.

Mechanical impedance is a property of the robot alone, regardless of the environment. Proper selection and ideal implementation of impedance can (in principle) guarantee stability with certain environments and provide desired feel.

The technical challenge of rehabilitation robotics is in creating devices that meet specifications as described above. Such devices differ from traditional robots by offering a broad range of endpoint impedance that includes sufficiently low impedance for a patient to backdrive the robot with ease. Therapy robots also differ from haptic devices, which typically offer very low endpoint impedance, and a broad range of such impedances, but which saturate at unacceptably low forces. In applications with complex geometries, this problem has only been satisfactorily solved using a combination of mechanical design and control assistance.

Achieving robot requirements via hardware and control

1) Direct-drive

Direct-drive electromechanical mechanisms have certain appealing characteristics that help to meet the unique requirements of rehabilitation robotics. The absence of transmission elements eliminates a problematic source of friction and undesired dynamics, and greatly simplifies the implementation of interaction controllers. Electromagnetic motors are generally very heavy, and increase dramatically in weight as force requirements increase. Thus it is advantageous that they be kept stationary.

MIT-MANUS (Fig. 1) is a two DOF direct-drive SCARA (Selective Compliance Assembly Robot Arm) robot that has been in use in clinics for over a decade. The five-bar parallel linkage is driven within a tabletop plane by two large brushless DC servomotors. Vertical loads are borne by the robot's structure, not its actuators. The use of only a limited workspace (38 cm by 46 cm) within the robot's total range of motion results in fairly uniform inertia properties across the workspace. Relatively large motions in the workspace translate to small rotations at the actuators, so that actuator friction and inertia appears minimally at the endpoint. The result is a robot with force capabilities meeting the 45 N specification, with coulomb friction less than 2 N, viscous damping less than 4 N/(m/s) and inertia less than 1.7 kg, slightly exceeding specification [15].

The use of relatively simple robot hardware with minimal low- to mid-frequency dynamics permits the use of relatively simple control algorithms. Because the MIT-MANUS hardware meets the specifications for low endpoint impedance, *simple impedance control* meets the requirements for robotic therapy [14]. This approach consists of driving an intrinsically low-friction mechanism with force- or torque-controlled actuators, and using motion feedback to increase output impedance. A generic model of an interactive robot in joint space yields the following equation of motion:

$$I(\Theta)\ddot{\Theta} + C(\Theta,\dot{\Theta}) + D(\dot{\Theta}) = T_a + T_e \tag{2}$$

Θ is a vector of robot joint angles, *I* is the (possibly configuration dependent) inertia matrix, *C* denotes nonlinear inertial coupling torques, *D* is a vector of intrinsic robot dissipative torques, T_a represents actuator torques and T_e the environment torques. A simple impedance control law is:

$$T_a(\Theta,\dot{\Theta}) = K_j(\Theta_o - \Theta) + B_j(\dot{\Theta}_o - \dot{\Theta}) \tag{3}$$

This takes the form of a proportional-derivative controller, where the proportional gain matrix K_j defines the stiffness and the derivative gain matrix B_j the damping. Θ_o represents a virtual trajectory, the desired robot position. (This controller would result in configuration-dependent endpoint stiffness and damping; the actual controller includes a well-defined nonlinear transformation and is omitted here for simplicity.) Because the sensors and actuators are collocated, this controller is extremely robust, resulting in a robot that is stable when interacting with a broad range of environments. Using this controller, MIT-MANUS is able to stably represent stiffness in excess of 2000 N/m[15]. Endpoint impedance differs from desired only by the robot's inertial and frictional properties, which are nearly negligible in the context of this application.

The direct-drive, simple impedance control approach works effectively because the SCARA configuration offers a low-impedance design for two planar degrees of freedom. For more complex configurations, direct drive designs are difficult to find, especially designs that do not have an unreasonably small ratio of workspace size to package size.

2) Serial configurations

When the geometric constraints of more complex rehabilitation robots preclude direct-drive systems, serial configurations are a potential solution. Serial robots, common in industrial systems, require actuators for certain DOFs to be carried by the links that move other DOFs. The mass of the moving actuators not only becomes a burden on

Figure 2. Vertical module, mounted to MIT-MANUS.

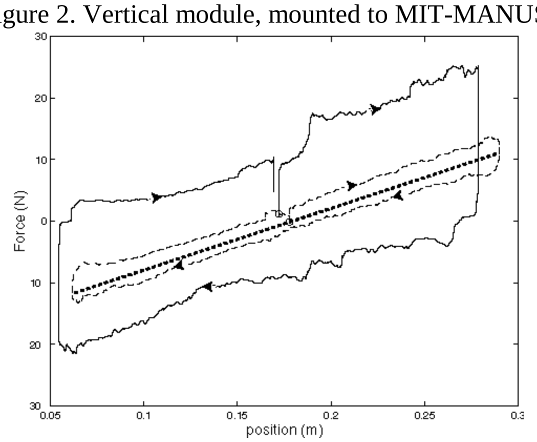

Figure 3. Vertical module representation of 100 N/m virtual spring. Simple impedance controller (solid), force-feedback impedance controller (light dashed), and ideal (heavy dashed) behavior shown.

the driving actuators, but also substantially increases endpoint inertia. To combat both problems, some type of gearing is almost always used to boost the force/weight ratio of the moving actuators. Gearing, however, invariably adds friction and reflects actuator damping and inertia to the endpoint with the square of the gear ratio. With high friction and high gear reduction, it is not uncommon for a geared transmission to lose backdrivability altogether.

When serial robots are used for interactive robots, it is essential that friction be minimized and a relatively small gear ratio be chosen, such that the system is backdrivable and has inherent endpoint impedance reasonably close to the targeted behavior. Advanced impedance control techniques can then be used to augment performance, reducing the *apparent* endpoint impedance.

For example, a robot module (Fig. 2) was added to MIT-MANUS to provide 36 cm of vertical endpoint motion in addition to the existing planar motion. The module uses a rotary motor and a custom-made low-friction screw transmission. The screw package, a Rollnut (Norco, Inc.) design, approaches pure rolling contact between nut and screw. The nut translates over 19 mm for every turn of the motor. The resulting package is backdrivable and has around 10 N of friction and inertia around 5.5 kg. The completed module has a mass of 7.7 kg [10].

In order to bring the endpoint impedance closer to the desired value, a simple impedance controller was augmented with a proportional force feedback loop to minimize errors between the intended output force and the actual output force, as dictated by the desired endpoint impedance. For this single-DOF case, a robot model with inertia M, friction F_f that depends on position and velocity, as well as force due to gravity mg, subject to actuator force F_a and interaction force F_e produces the equation of motion:

$$M\ddot{z} + F_f(z,\dot{z}) + mg = F_a + F_e \tag{4}$$

Here, the simple impedance controller has the form:

$$F_a = F_{pd} = -K(z - z_o) - B(\dot{z} - \dot{z}_o) \tag{5}$$

K is the desired endpoint stiffness, B the desired damping, z the endpoint position and z_o the virtual trajectory. The augmented impedance controller with force feedback is:

$$F_a = K_f(F_{pd} + F_e) \tag{6}$$

K_f is the force feedback gain. The resulting equation of motion, with control law substituted in, is:

$$\frac{M\ddot{z}}{1+K_f} + \frac{F_f(z,\dot{z})}{1+K_f} + \frac{mg}{1+K_f} + B(\dot{z} - \dot{z}_o) + K(z - z_o) = F_e \tag{7}$$

The apparent parameters reflect a reduction of the intrinsic mass, friction, and gravity by a factor of K_f plus one. This compensator is used in the vertical module with a gain of 5, resulting in a substantial reduction in inertia and friction, as shown in Fig. 3, which shows the results of a simple hand-actuated test on the system with a simple impedance controller and a force feedback controller simulating a virtual spring. Extensive testing showed that the system is stable with all expected environments when the force feedback compensator is used.

If the force feedback gain K_f in (6) is made too large, instability results when the system is coupled to certain environments. This is because the system becomes non-passive [16]. If the system is passive, it can interact stably with all other passive systems. Colgate has shown, however, that a system under proportional force feedback becomes non-passive when the feedback gain exceeds 1 [16]. The screw-driven vertical module operates stably with a higher gain because the environment with which it interacts, the human arm, has limited stiffness and is not as destabilizing as other passive environments. Still, passivity severely limits performance. This is why the compensator can only be used for performance *augmentation*, and the robot hardware itself must be intrinsically backdrivable.

Newman has derived a passive compensator, known as a Natural Admittance Controller (NAC), that greatly reduces apparent friction while keeping inertia close to its intrinsic value, the *natural admittance* [17]. Such a compensator was implemented and greatly reduced friction.

The endpoint inertia is the initial problem with serial robots for interaction, and is the most difficult characteristic to eliminate artificially. Gearing and control via NAC substantially ameliorates the problem, but does not eliminate it. We are presently exploring new control techniques that exploit knowledge of the limited impedance characteristics of expected robot environments to improve performance while still achieving guaranteed stability.

Robotics for rehabilitation poses a significant technical challenge in robot and control design: to develop robots that can stably transmit high forces to their environment while exhibiting the desired endpoint behavior, including low-impedance behavior. Tailoring the endpoint impedance to suit the recovering patient is essential to increasing the rate of recovery, as is shown in the following section.

III. Rehabilitation as Relearning: Algorithm Improvements

Research to date has shown that repetitive task-specific, goal-directed, robot-assisted therapy is effective in reducing motor impairments in the hemiplegic arms of stroke patients [4],[7],[18]. Indeed, therapeutic games can be designed to address a wide range of motor impairments, including impaired motor speed or accuracy, poor coordination, diminished strength, etc. In essence, the rehabilitative process is one that assists patients to relearn their motor skills impaired due to their brain injury. Depending on the patient's impairment level, robotic games can provide passive, active-assisted, active, and active-resistive exercises. An active topic of research in stroke rehabilitation is determining what constitutes the most appropriate therapy for each patient because it is unlikely that one type of therapy will address all motor impairments.

In an attempt to tailor therapy to each patient's individual needs, a performance-based progressive algorithm was developed that specifies control system parameters based on patient performance [18]. By providing the patients with specific movement-related feedback and by varying the amount of robotic assistance based on their performance, the game attempts to reward the patients' efforts and to motivate them to actively participate in the therapy and improve their performance. During a therapy session consisting of 20 games, patients are shown a bar graph that displays four "scores" after games 5, 10, 15, and 20. The first bar represents the patient's ability to initiate robot-assistance by passing a velocity threshold. The second bar displays the patient's ability to move to the target, whereas the third bar displays the ability of the patient to aim along the target axis. Lastly, the ability of the patient to reach the desired target location is shown by the fourth bar. Both the height and color of the bars are varied to indicate changes in patient performance.

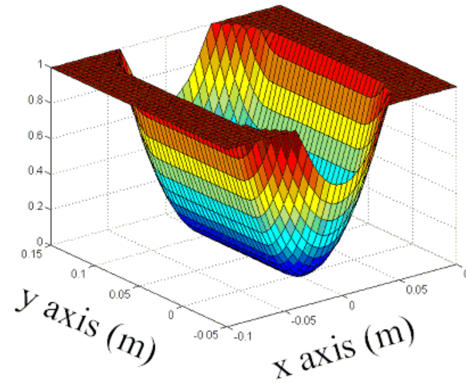

Figure 4. Potential Energy Field of Novel Impedance Controller at Beginning of Movement. Line Segment Along y-axis Will Become a Point at (0,0.1)

Underlying the progressive algorithm is a novel impedance controller that varies the level of assistance the robot will provide to patients based on their abilities to move to the target and aim along the target axis (Fig. 4). Similar to our past therapeutic games, the robot assists the patient in making minimum-jerk movements [19] from a center target to eight equally spaced radial targets and back. The minimum-jerk trajectory, $y_{m.j.}$, is defined by the following polynomial:

$$y_{m.j.} = l_m \left[10\left(\frac{t}{t_m}\right)^3 - 15\left(\frac{t}{t_m}\right)^4 + 16\left(\frac{t}{t_m}\right)^5 \right] \quad (8)$$

where l_m is the length of movement (equal to 0.1 in Fig. 4), t_m is the duration of movement, and t is time elapsed since the movement was initiated. The command forces are defined as

$$F_{c,x} = -kx - b\dot{x} \quad (9)$$

$$F_{c,y} = \left\{ \begin{array}{c|c} -k_{bw}\left(y - y_{m.j.}\right) - b\dot{y} & y < y_{m.j.} \\ 0 & y_{m.j.} \le y \le l_m \\ -k\left(y - l_m\right) - b\dot{y} & y > l_m \end{array} \right\} \quad (10)$$

where k is the controller stiffness, k_{bw} is the "back wall" stiffness (i.e., the stiffness that assists movement towards each target, not aim), and b is the controller damping.

During the therapy, the time allotted for the patient to make the move, t_m, and the primary stiffness of the impedance controller, k, are varied based on the patient's performance and variability, but the "back wall" stiffness, k_{bw}, is held constant. The controller allows capable patients to reach the target unassisted because the robot is backdrivable, and $F_{c,y} = 0$ in the range $y_{m.j.} \le y \le l_m$. By using a performance-based, progressive algorithm, the game continuously challenges the patient by varying t_m and k based on the patient's performance (see [18] for a detailed description of algorithm). For instance, t_m is reduced if the

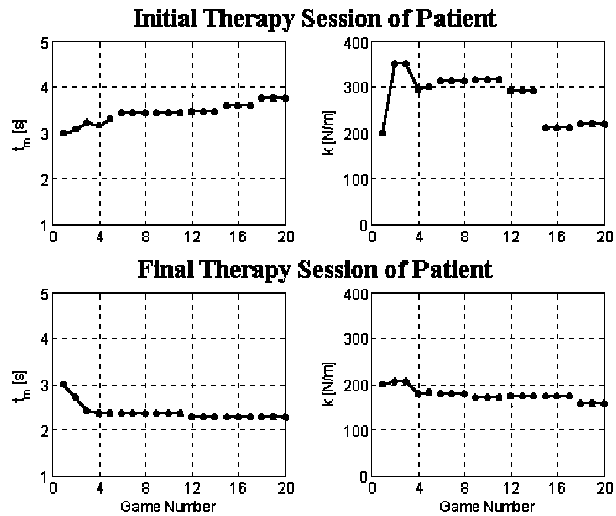

Figure 5. Controller Parameters Specified By Performance-Based Progressive Game: Move Time, t_m, and Stiffness, k.

patient reaches the target before the "back wall" of the controller, and increased if the patient is unable to move as quickly as the robot. Similarly the controller stiffness will increase if the patient needs assistance aiming along the target axis, but will decrease if patient is aiming well.

Initial findings from a study of chronic stroke patients (brain injury occurred at least 8 months prior to initial clinical assessment) have been promising [8]. Although previous studies had demonstrated that most rehabilitative gains occur within the first three months after the stroke occurred [20], both moderate and severe chronic stroke patients experienced a significant reduction in impairment. For the first time with task-specific robot training, there was also a significant reduction in disability with moderate patients. That is, not only was impairment reduced, but patients also gained functional use of their limb. The controller parameters for a patient's initial and final treatment sessions highlight this reduction in impairment (Fig. 5). After six weeks of therapy, the specified controller move time at the end of the session went from ~3.75s to ~2.25s, and the controller stiffness went from ~215N/m to ~155N/m. One interesting observation from the initial therapy session is that the patient was moving slower during games 12-14, but was able to improve aiming ability substantially. This is shown by the slight increase in t_m during games 15-17, but a substantial reduction in k.

IV. Conclusion

Early work in rehabilitation robotics has shown substantial promise in reducing impairment for both recent and chronic victims of stroke. Devices for such therapy require that the fundamental problem of providing high forces over a range of relatively low endpoint impedance be addressed. This problem has most successfully been addressed through a combination of backdrivable hardware design and force feedback control. A pilot study suggests that motor recovery is a learning process, and that tailoring therapy to more closely match a patient's abilities can drastically improve the benefits of therapy. These advances bring robot therapy even closer to being a valuable tool to alleviate demand on clinicians and help the millions of victims of stroke and neurological injury.

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