UPPER EXTREMITY EXOSKELETONS FOR ROBOT-AIDED REHABILITATION
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UPPER EXTREMITY EXOSKELETONS

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Neurological injuries, including stroke and spinal cord injury, typically result in significant motor impairments. These impairments negatively impact an individual's movement coordination, in turn affecting their ability to function independently. It is well understood that intensive motor rehabilitation is necessary to restore functional use of the impaired limbs. For example, recent research in stroke rehabilitation has emphasized a need for more effective therapy than the current standard of care. A key motivation for effective therapy is to restore stroke survivors' independence and reduce the cost of therapy and care, with one objective being the restoration of arm functions so that individuals can again perform normal activities of daily living.

Intensively repetitous motion training has proven to restore some motor function after neurological injuries. This training is often labor-intensive and costly. By enabling therapists to train their patients intensively through consistent, repeatable movements, robotic rehabilitation systems offer a cost-effective solution requiring less labor and effort. These systems have demonstrated therapy outcomes comparable to those of intensive training without robotic aid. This means that it is possible to reduce the amount of labor for the therapist without sacrificing therapy effectiveness. Given the potential for robotics to positively affect the delivery of rehabilitation, researchers have focused efforts to optimize rehabilitation through the development of hardware and control algorithms.

The design of upper limb robotic therapy devices has been a topic of research for over two decades. Early devices were end-effector based, and guided the motion of a patient's hand to desired positions. These devices focused on rehabilitation of elbow and shoulder movement, typically immobilizing the patient's wrist to ensure that the desired arm motions were produced. Hardware and software designs emphasized the safety of the robotic devices, using control methods specifically designed to ensure safe interaction forces between the user and the device. Later devices aimed to expand the capabilities of robotic therapy devices by targeting the wrist and hand as well. However, when the end-effector based device targets many degrees of freedom, the redundancy of the human arm makes it possible for patients to compensate for impaired motion of one joint by using a different set of joints to complete a given task (for example, compensating for impairment in the wrist with extra shoulder and elbow motion). Therefore, exoskeleton type devices have been developed to isolate the motion of individual joints. These devices tend to have higher complexity and reduced range of motion as compared to endpoint manipulators, but they target more selectively the desired joint(s), and they enable more precise data collection about the motion of the patient's limb. Recent designs have focused on systems that match the full range of motion of the targeted joints, aiming towards actuated systems that have both high torque output, to assist patients with muscle tone, and low intrinsic impedance, to minimally perturb independent arm movements. Satisfying all of these requirements while simultaneously maintaining a high priority on patient safety is still an active area of research.

Recently, the focus of robotic therapy research has shifted towards improving treatment methods. It has long been known that motor learning is more effective if the learner is actively engaged in the learning process. This general feature of motor learning holds true in stroke and spinal cord injury therapy as well. Active

FOR ROBOT-AIDED REHABILITATION

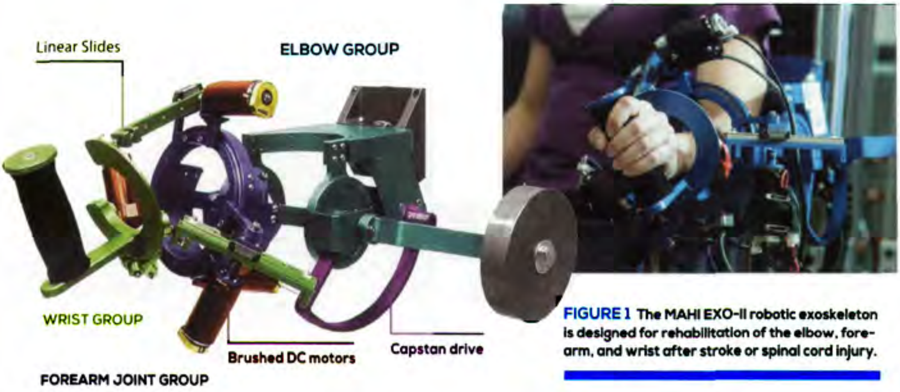


FIGURE 1 The MAHI EXO-II robotic exoskeleton is designed for rehabilitation of the elbow, forearm, and wrist after stroke or spinal cord injury.

therapy, in which the patient is actually attempting to move his or her own arm, results in greater improvements to motor function than passive therapy. Therefore, robotic therapy efforts are moving towards systems that encourage active patient participation by continually challenging the patient to the edge of his or her abilities.

One example of promoting more active engagement is the notion that the rehabilitation robot should change its behavior and physical interactions with the user based on real-time assessment of patient capability. Adaptive robotic training protocols called "assist-as-needed" algorithms focus on providing the minimal amount of robotic assistance necessary for a patient to complete a movement, thus requiring significant effort from the patient. These algorithms range from simple controllers designed to gently guide the patient's hand along a particular path, to more complex, interactive algorithms that estimate the current ability of the patient and apply just enough assistive force for the patient to complete the desired movement.

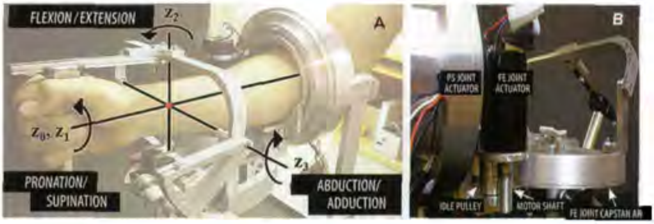
CASE STUDIES IN THE DESIGN OF UPPER EXTREMITY EXOSKELETONS

As an example of exoskeleton type upper limb rehabilitation robot systems offering adaptive assist-as-needed control, we consider the MAHI EXO-II and the RiceWrist-S, two upper limb exoskeletons for rehabilitation after neurological injury developed in the Mechatronic and Haptic Interfaces (MAHI) Laboratory at Rice University.

The MAHI EXO-II[1], shown in **Figure 1**, is an exoskeleton with four active DOF, including elbow flexion-extension (F/E), forearm pronation-supination (P/S), wrist F/E and radial-ulnar (R/U) deviation, and one passive DOF (shoulder abduction and adduction for the user's comfort). The basic kinematic structure of the wrist portion of the exoskeleton is a 3-revolute-prismatic-spherical (RPS) mechanism with additional degrees of freedom (both active and passive) for the more proximal joints of the upper limb. The elbow DOF consists of a revolute joint that is actuated by a brushed motor attached via nylon coated cable to a capstan arc. The forearm DOF also consists of a revolute joint actuated by a DC motor and cable drive.

Figure 2 shows the RiceWrist-S—an improvement of the design of the wrist module of the MAHI EXO-II, recently presented in reference 2. This design uses a serial, spherical mechanism with cable-drive actuation to address limitations of the parallel mechanism design of the MAHI EXO-II wrist module, namely limited range of motion and torque output capabilities in wrist

FIGURE 2 **The RiceWrist-S. (A) Schematic of the anatomical axes of the wrist joint. (B) Cable routing mechanism for the RU joint: power is transferred from the motor shaft to the transmission rod via a steel cable. The transmission rod drives the RU joint capstan arc that is coupled with the handle support. (C) Cable routing mechanism for the FE joint: an idle pulley is employed to transfer actuation to the FE joint capstan arc via a steel cable**



flexion/extension and radial/ulnar deviation. The design achieves the goals of 1) covering the complete workspace of the human wrist, 2) providing high torque output that enables both assistance and resistance training, and 3) introducing minimal friction, gravitational and inertial loading in the haptic display of forces to the user. To minimize reflected gravitational and inertial loading and provide acceptable torque output, DC motors are located remotely and connected to the respective output shaft through aluminum capstan arcs. The system also features a customized force sensing handle, used for assessment of grip force before and after the therapy session.

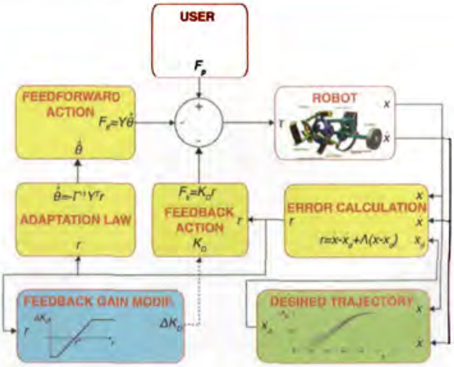


FIGURE 3 **AAN controller block diagram. Blocks used for the adaptive controller are with a yellow background, while blocks introduced for the rehabilitation robotics application are shown in blue and green. The dashed line represents a non-continuous transfer of signals (the feedback gain is changed only between different tasks).**

DYNAMIC CHARACTERIZATION OF REHABILITATION ROBOTS

Before any clinical implementation can take place, a thorough analysis of a robot's performance is necessary to validate it as a suitable platform for rehabilitation. The MAHI EXO-II and RiceWrist-S have capabilities comparable to other state-of-the-art serial wrist exoskeletons$_3$. In comparison to the RiceWrist-S, the parallel mechanism of the MAHI EXO-II offers lower inertia, viscous coefficient, and static friction, but has reduced torque output and workspace. Both devices offer favorable static friction characteristics, both in magnitude and as a percentage of maximum continuous torque output, and a relatively constant magnitude of friction throughout the workspace enables effective compensation via feed-forward techniques. Both the inertial and viscous friction characteristics of the devices are suitable for administering high quality therapy; however, future designs would benefit from the use of advanced composites in the distal elements of the exoskeleton, along with a less inertial method for elbow DOF gravity compensation. Closed-loop bandwidth tests showed that the devices have capabilities to match healthy human movement.

Table 1 summarizes the range of motion and torque requirements for activities of daily living (ADL). Where the workspaces of our devices exceed the necessary ranges, we use redundant software and hardware stops to ensure the safety of the patient. We present the experimentally determined performance characteristics of the MAHI EXO-II and RiceWrist-S in **Table 2**, including static friction, inertia, viscous friction, and closed-loop position bandwidth. Note that the torque values listed are the maximum torque values.

	RANGE OF MOTION (*deg*)			TORQUE (*Nm*)		
Joint	ADL	ME-II	RW-S	ADL	ME-II	RW-S
Elbow F/E	150	90	—	3.5	7.35	—
Forearm P/S	150	180	180	0.06	2.75	1.69
Wrist F/E	115	65	130	0.35	1.45	3.37
Wrist R/U	70	63	75	0.35	1.45	2.11

TABLE 1 **Range of motion and torque characteristics of the MAHI EXO-II and RiceWrist-S**

SUBJECT ADAPTIVE, ERROR TOLERANT THERAPY

A crucial area of rehabilitation robotics involves the definition of a therapeutic protocol, capable of maximizing recovery and promoting neural plasticity. Here, "protocol" refers to the combination of movement type, visual interface, number of repetitions, sequence, number and type of joints addressed and, most important, the mechanical action applied by the robot. In this regard, preliminary evidence gathered to date (primarily for stroke rehabilitation) demonstrates that maximum therapeutic benefit is obtained when the implemented control algorithms promote the participant's active engagement in their therapy. Addressing these needs, we have contributed to the development of controllers that enable the so-called assist-as-needed (AAN) paradigm to be used for robot-aided rehabilitation therapy[4].

The main novelty of our implementation of AAN control is the resulting ultimately bounded stability property that allows errors within a known bounded region, as opposed to asymptotic stability, which corresponds to errors approaching zero. We aim to obtain this global property motivated by studies of human motor control that show that error is likely to be a driving signal for motor learning. Through this scheme, we do not provide assistance to minimize errors, but rather we tolerate error and manipulate the error bound in a performance-adaptive way. The developed controller, whose block diagram is depicted in **Figure 3**, consists of three main components: i) an adaptive controller based assistance scheme, ii) a performance-based feedback gain modification algorithm, and iii) an online trajectory recalculation.

The control action is given by:

$$F_r = F_{ff} - K_D r = \hat{G}(x) - \hat{F}_p(x) - K_D r,$$

where $\hat{G}$ is the estimate of the gravitational term, $\hat{F}_p$ is the estimate of interaction forces, K_D is a feedback gain matrix, and $r = \dot{x} - \dot{x}_d + \Lambda(x - x_d)$ is the error term, calculated through the combination of position and velocity errors. Through the assumption of linear parameterization of the feedforward contribution, we define:

$$F_{ff} = Y\hat{\theta}$$

where Y is a regressor matrix containing known functions of the state x, and $\hat{\theta}$ is a vector that contains the parameter estimates. To model the feedforward contribution, we use the superposition of Gaussian radial basis functions with amplitude θ, evenly distributed in the n-dimensional robot workspace. Through the use of the adaptation law $\dot{\hat{\theta}} = -\Gamma^{-1} Y^T r$, we could demonstrate that the controller is uniformly ultimately bounded, i.e. the error is guaranteed to stay within a certain bound that can be modulated through proper selection of the feedback gain. The other blocks exploit this particular feature of our control approach.

In particular, the feedback gain modification algorithm analyzes performance in the previous tasks, and changes the feedback gain for the next task by comparing the error in the observed movement profiles with the variability of healthy subjects' movements during unperturbed movements. Instead of increasing the feedback gain until the error is minimized, we decrease the feedback gain until the measured error is within an acceptable range defined as repeatability error in similar tasks executed by healthy subjects (r^* variable in the block diagram). This algorithm creates a continuous and dynamic challenge to the user, reducing the amount of robotic assistance when movements are characterized by below-physiologic error levels. When instead the assistance is excessively decreased, resulting in the user lagging behind the desired trajectory, the feedback gain is increased to provide additional support.

As a final step in the formulation of our subject-adaptive therapeutic protocol, we include a performance-adaptive desired trajectory generation algorithm. The algorithm is used to avoid the transfer of forces that resist the subject's movement, in the case when the subject is actually performing better than the previously defined nominal trajectory. We implement an explicit on-line recalculation routine that guarantees that the desired trajectory is both continuous and time-differentiable, and does not lag the subject's movement. Through the online trajectory recalculation algorithm, we also modulate the time allocated to complete a task if the subject was ahead of the desired trajectory in the previous task. Through the combination of the feedback gain modification algorithm and the desired trajectory definition and recalculation algorithms, the subject is continuously challenged to perform more repetitions, increasing his effort in the therapeutic protocol. Clinical evaluation of this protocol is currently underway in Houston, in collaboration with our clinical partners at TIRR-Memorial Hermann Hospital and UTHealth.

	STATIC FRICTION (*Nm*)		INERTIA (*kgm*^{2})		VISCOUS FRICTION (*Nms/rad*)		CLOSED-LOOP POSITION BW (*Hz*)	
Joint	**ME-II**	**RW-S**	**ME-II**	**RW-S**	**ME-II**	**RW-S**	**ME-II**	**RW-S**
Elbow F/E	0.95	—	0.27	—	0.12	—	2.8	—
Forearm P/S	0.14	0.22	0.026	0.026	0.017	0.43	4.2	3.5
Wrist F/E	0.11	0.20	0.002	0.012	0.028	0.085	13.3	6.0
Wrist R/U	0.11	0.21	0.003	0.005	0.023	0.14	10.6	8.3

TABLE 2 Dynamic characteristics of the MAHI EXO-II and RiceWrist-S

DEMONSTRATING EFFICACY

The clinical evaluation of our exoskeleton-based upper limb rehabilitation robots has been conducted primarily with individuals with incomplete spinal cord injury (SCI). We first evaluated our MAHI EXO-II wrist module for rehabilitation of the upper limbs (UL) of two tetraplegic persons with incomplete SCI[5]. Two pilot experiments were conducted. First, we demonstrated that we could administer treatment to the left UL of a tetraplegic subject during seven therapy sessions with the device. The subject's feedback and the investigator's observations were used to enhance the robotic device and the corresponding graphical interface. Then, a second tetraplegic subject underwent ten three-hour training sessions administered by a physical therapist. Efficacy of the treatment was evaluated using both clinical assessments often conducted by physical therapists in a rehabilitation setting and robotic measures of motor impairment that quantify the characteristics of movements using data collected from the exoskeleton during movement execution with the device unpowered and backdriven by the subject. At the conclusion of this pilot study with our exoskeleton, the subject was able to more quickly complete basic activities of daily living with the treated limb. The smoothness of the individual's unassisted movements in each degree of freedom was also evaluated pre- and post-therapy and showed significant improvements.

Based on these promising pilot results, we conducted a more extensive case study with the full MAHI EXO-II device[6], with robotic training provided to both upper limbs of a participant with chronic incomplete SCI. For this participant, the right UL was more affected, such that she was unable to initiate or sustain independent movement. The left UL was less affected by the injury, and as a result, she was able to initiate movements independently. We observed gains in performance only for the more engaging control mode (only used with the less affected limb), and these findings are in agreement with the literature noting the need for patient engagement and simultaneous intent of movement with sensorimotor feedback in order to realize treatment gains. The extension of this study to a population of 10 SCI survivors has recently concluded, with results currently undergoing analysis for publication.

We have also validated the RiceWrist-S as a tool to deliver robotic rehabilitation therapy through a case study with a subject affected by chronic incomplete (AIS level C) SCI at the C3-5 level[2]. The subject, a 45-year-old male, participated in ten sessions of robot-assisted arm training over twenty days, approximately four times per week. At each session, the subject's movements were evaluated with the robot programmed to apply no forces, but only measure the subject's visually cued, point-to-point movements. After evaluation, the subject was visually cued to execute the same movements, with the robot providing active resistance, by means of a velocity-dependent resistive force field. The *analysis of robotic data measured during the* evaluation sessions supports the hypothesis that robotic training increased movement smoothness, as assessed through two metrics, the Movement-Arrest-Period-Ratio (MAPR), which quantifies the amount of time movements are above a threshold velocity, and the Normalized Sum of Jerk (NSOJ), which directly assesses the jerk of the executed movements. Although

ABOUT THE AUTHORS

Fabrizio Sergi received his Ph.D. degree in biomedical engineering from Università Campus Bio-Medico di Roma, in Rome, Italy, and is currently a postdoctoral research scientist in the mechanical engineering department at Rice University. His research interests span multiple aspects of human-robot interaction, including the design and subject-adaptive control of high-performance robots for rehabilitation and human augmentation and the use of robots as scientific tools to investigate motor learning. He is *a member of the American Society* of Mechanical Engineers.

Amy Blank received a Ph.D. in mechanical engineering from the Johns Hopkins University in 2012. She is currently a postdoctoral research associate at Rice University in the department of mechanical engineering. Her research interests are in theory and application for design, modeling, and control of robotic manipulators and human-robot interaction. Specific areas of interest include upper-limb prosthetics and rehabilitation, biologically inspired robotic sensing and control strategies, variable-impedance robot control, and user feedback for prosthesis control and teleoperation.

Marcia O'Malley received her mechanical engineering Ph.D. in 2001 from Vanderbilt University. She is an associate professor of mechanical engineering and computer science at Rice University. In addition, she is director of rehabilitation engineering at TIRR-Memorial Hermann Hospital. Her research addresses the issues that arise when humans physically interact with robotic systems, with a focus on training and rehabilitation in virtual environments. In 2008, she received the George R. Brown Award for Superior Teaching at Rice University. She is a Fellow of the American Society of Mechanical Engineers.

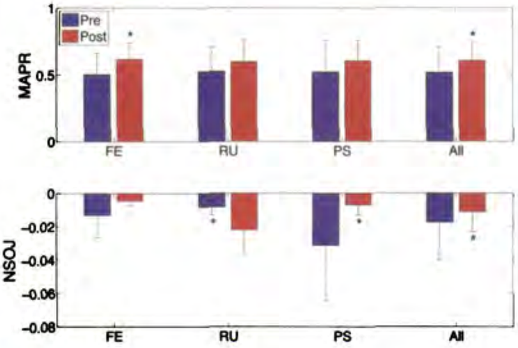


FIGURE 4 **Bar plot describing the two measures of smoothness computed during the first (Pre) and last (Post) session of therapy with the RiceWrist-S, representing mean and standard deviation of the movements for each degree of freedom during evaluation. Asterisks indicate statistical significance ($p<0.05$).**

not every DOF-specific comparison showed a statistically significant difference, the pre-therapy vs. post-therapy comparison involving the combination of movements in all directions demonstrated a statistically significant increase of smoothness of subject's reaching movements, as shown in **Figure 4**.

NEXT STEPS

Robotic exoskeletons designed for rehabilitation of the upper limb after neurological injury aim to promote neural plasticity and recovery of motor coordination through high intensity and high repetition of reaching movements. The design of these devices requires consideration of the therapeutic application in terms of range of motion, torque requirements, and dynamic performance that ensures safe patient-robot interactions. Further, the development of these systems must consider the control algorithms that govern the nature of the patient-robot interaction. The importance of engaging the patient in therapy has been clearly demonstrated through studies of both active and passive movements assisted by robotic systems, and therefore recent research has focused on the ability of robotic systems to engage the patient using assist-as-needed strategies. Assist-as-needed strategies have moved towards adaptive controllers that estimate patient effort and impairment in real time based on movement data collected by the robot, thus changing the level of assistance provided even during a single movement. Though feasibility and positive functional gains have been shown for many of these methods that encourage patient engagement, it is still unclear which methods are most appropriate for different situations and levels of patient impairment. While small clinical studies have demonstrated the viability of robotic rehabilitation after neurological injury, carefully controlled, large-scale clinical studies are needed to compare available treatment methods across patient populations and to determine how the efficacy of the methods depends on the characteristics of specific patients. The results of such studies will enable therapists to optimize treatment methods for restoring upper-limb function after neurological injury in patients with a variety of needs and abilities. ■

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