

Mechanical Design of a Distal Arm Exoskeleton for Stroke and Spinal Cord Injury Rehabilitation

Ali Utku Pehlivan, Ozkan Celik, *Student Member, IEEE*, Marcia K. O'Malley, *Member, IEEE*

Abstract—Robotic rehabilitation has gained significant traction in recent years, due to the clinical demonstration of its efficacy in restoring function for upper extremity movements and locomotor skills, demonstrated primarily in stroke populations. In this paper, we present the design of MAHI Exo II, a robotic exoskeleton for the rehabilitation of upper extremity after stroke, spinal cord injury, or other brain injuries. The five degree-of-freedom robot enables elbow flexion-extension, forearm pronation-supination, wrist flexion-extension, and radial-ulnar deviation. The device offers several significant design improvements compared to its predecessor, MAHI Exo I. Specifically, issues with backlash and singularities in the wrist mechanism have been resolved, torque output has been increased in the forearm and elbow joints, a passive degree of freedom has been added to allow shoulder abduction thereby improving alignment especially for users who are wheelchair-bound, and the hardware now enables simplified and fast swapping of treatment side. These modifications are discussed in the paper, and results for the range of motion and maximum torque output capabilities of the new design and its predecessor are presented. The efficacy of the MAHI Exo II will soon be validated in a series of clinical evaluations with both stroke and spinal cord injury patients.

Index Terms—Exoskeletons, parallel mechanisms, haptic interface design, stroke rehabilitation, spinal cord injury rehabilitation.

I. INTRODUCTION

In the United States, each year about 795,000 people experience a stroke. Stroke has a significant social and economic impact on the United States with a \$68.9 billion total estimated cost for 2009 and is the leading cause of long-term disability [1]. There are approximately 12,000 incidences of Spinal Cord Injury (SCI) in the US each year [2]. With the average age of injury as low as 40.2 years, a much younger population is effected by SCI than by stroke, leading to an estimated yearly direct and indirect costs of \$14.5 billion and \$5.5 billion, respectively [3].

Robotics provides numerous opportunities to improve rehabilitation protocols and to lower therapy expenses [4], [5]. Because of the potential benefits, robotic rehabilitation has been an active field of research for the last two decades. Although various aspects of robotic rehabilitation have been investigated and presented in the literature, a significant effort has been the design of novel rehabilitation robots or devices. Early examples of these robots include the MIT-MANUS [5] and MIME [6], [7], both of which were designed for rehabilitation of the proximal upper extremity

The authors are with the Mechatronics and Haptic Interfaces Laboratory, Department of Mechanical Engineering and Materials Science, Rice University, Houston, TX 77005 (e-mails: aliutku@rice.edu, celiko@rice.edu, omalley@rice.edu)

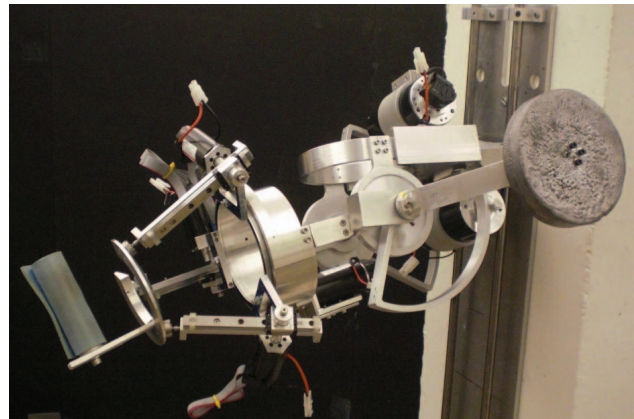


Fig. 1. MAHI Exo II – Elbow, forearm and wrist exoskeleton for stroke and spinal cord injury (SCI) rehabilitation.

joints (shoulder and elbow). Due to the success of these early systems, robotic devices for the rehabilitation of distal joints of the upper extremity have also been developed, such as the MAHI Exoskeleton [8], [9], RiceWrist [10], the wrist module of the MIT-MANUS [11] and wrist rehabilitation devices developed by Hesse et al. [12], to name a few. Most recently, rehabilitation robots with more degrees-of-freedom (DOF) such as Rupert [13], CADEN-7 [14] and ARMin [15] that are capable of actuating shoulder, elbow and wrist joints simultaneously have also been designed.

From a mechanical design point of view, rehabilitation robots can be classified into two groups: end-effector based robots and exoskeletons. MIT-MANUS [5], a two degree-of-freedom (DOF) planar manipulator with a workspace in the horizontal plane, is an example to the end-effector based robots. Based on an industrial 6 DOF PUMA robot, MIME [7] constitutes another example to end-effector based designs. Although end-effector based robots provide training capability encapsulating a large portion of the functional workspace, they do not possess the ability to apply torques to specific joints of the arm. Exoskeletons, on the other hand, are designed to resemble human anatomy and their structure enables individual actuation of joints. Examples to upper-extremity rehabilitation exoskeletons include 5 DOF MAHI Exoskeleton [8], 5 DOF Rupert [13], 6 DOF ARMin [15] and 7 DOF CADEN-7 [14]. Recently, rehabilitation engineering research has increasingly focused on quantitative evaluation of residual motor abilities in an effort to obtain an objective evaluation of rehabilitation and pharmacological treatment effects [16]. Exoskeletons offer the advantage of precisely

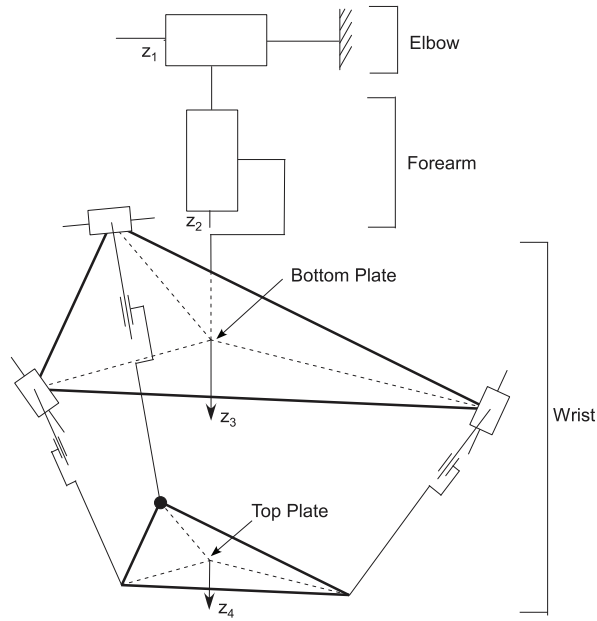


Fig. 2. Kinematic structure of MAHI Exo II – A 3-RPS (Revolute-Prismatic-Spherical) platform constitutes the wrist degrees-of-freedom of the robot and is in serial configuration with forearm and elbow degrees-of-freedom.

recording and monitoring isolated joint movements of the arm and wrist and hence is a better-suited design option versus end-effector based designs for this purpose.

In this paper, we present design of MAHI Exo II (see Fig. 1), an elbow, forearm and wrist exoskeleton designed and manufactured for rehabilitation of stroke and SCI patients. The mechanical design builds upon its predecessor, MAHI Exo I [8], [9] and has a total of 5 DOF. Main design improvements include resolving the problems caused by universal-revolute joints at the wrist ring of the previous design and a practical solution for changing the side of the counter-balance weight to enable attachment of both left and right arm to the device. Further improvements include lowering the cost of the device and an additional passive DOF for adjustment of shoulder abduction/adduction angle for comfort and ease of attachment to the device.

The paper is structured as follows: Sections II-A–II-C describe and illustrate the mechanical design of the wrist, forearm and elbow joints of the device in detail, Section III compares the device’s range of motion and torque capabilities with the prior design and with values from the literature. Section IV concludes the paper.

II. DESIGN DESCRIPTION

The basic kinematic structure of the five degree of freedom MAHI exoskeleton (Exo I) is depicted in Fig. 2. The exoskeleton is comprised of a revolute joint at the elbow, a revolute joint for forearm rotation, and a 3-RPS (revolute-prismatic-spherical) serial-in-parallel wrist. The first two DOF correspond to elbow and forearm rotations. Out of two rotational and one translational (distance of bottom plate from top plate) DOF of the 3-RPS platform, the two

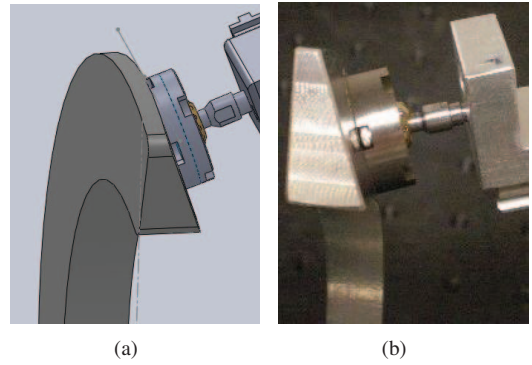


Fig. 3. (a) CAD model of the wrist ring with inclined surface to increase wrist range of motion. (b) Manufactured inclined wrist ring attached to the spherical joint.

rotational DOF correspond to wrist flexion/extension and abduction/adduction. The fifth DOF accounts for minor misalignments of the wrist rotation axes with the device, which may become a problem especially during movement. The new design, while maintaining the basic kinematic structure and grounded nature of the original design, introduces a number of significant design improvements based on the deficiencies of the previous design. The issues and the proposed solutions are presented in detail below, grouped under wrist, forearm and elbow subsections.

A. Wrist Mechanical Design

Based on the results of pilot clinical testing of spinal cord injury (SCI) patients with MAHI Exo I, the most important deficiency of the design in the wrist part was identified as the mechanical singularities introduced by the wrist ring connector joints. Because of these singularities, at certain configurations, patients’ wrist movements were not being satisfactorily recorded for evaluation. The main reason for the problem was that universal-revolute joints were incapable of providing the intended spherical joint characteristics at some specific configurations of the 3-RPS mechanism. Consequently, we have replaced the universal-revolute joints with Hephast-Seiko SRJ series high precision spherical joints. Although these spherical joints resolved the problems due to the universal-revolute joints, they led to a decrease in range of motion (ROM). To improve the ROM, we used an inclined surface design on the wrist ring (see Fig. 3(a)). This design also contributed to a considerable reduction of friction and backlash and resulted in a wrist mechanism with significantly more rigid and smooth operation compared to MAHI Exo I. Besides all of these advantages offered by the use of spherical joints and the inclined wrist ring design, the overall ROM was still slightly reduced in comparison with MAHI Exo I. A comparison in terms of ROM for both designs for various joints is given in Table I in Section III. Nevertheless, the new design is still capable of spanning 100% of wrist abduction/adduction ROM and 63% of wrist flexion extension ROM during activities of daily living (ADL).

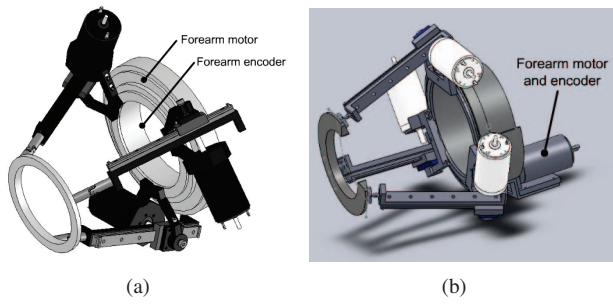


Fig. 4. (a) Forearm mechanical design CAD model for MAHI Exo I. Forearm encoder ring ran along the circumference of the forearm and was prone to misalignment errors. A frameless brushless motor inside an aluminum encasing actuated the joint. (b) Forearm mechanical design CAD model for MAHI Exo II. Current design employs a Maxon DC motor with cable drive mechanism, and the encoder is coupled to the motor shaft at the bottom end (not shown in this model).

B. Forearm Mechanical Design

The improvements for the forearm joint include increasing the torque output while reducing the mechanism complexity and cost. In the previous design, Applimotion 165-A-18 frameless and brushless DC motor actuator with MicroE Systems Mercury 1500 encoder were used to drive the forearm joint. Although this design enabled implementing the desired mechanism in a limited space, it mainly suffered from low torque output. In the new design, a high torque DC motor (Maxon RE40), with cable drive mechanism is implemented. Use of cable drive mechanism is justified by backdrivable and zero-backlash nature of it and by the considerable reduction in cost. In the new design, desired range of motion is unaltered with an approximately 35% increase in torque output (see Table I), for under the fourth of the cost of the prior design. Another consideration for the new design was eliminating the complexity of the mechanism, more specifically eliminating the issues that emerged due to the misalignment of the optical encoder. In the previous design, the optical encoder was embedded in the forearm joint with the frameless brushless motor, as depicted in Fig. 4(a), and was vulnerable to dislocations especially during attaching an arm in or out of the exoskeleton. Misalignments in the encoder grating ring required the disassembly of the forearm mechanism and a significant effort to satisfy the μm level tolerance. Consequently, instead of having the sensor and the actuator be open to effects that would lead to misalignments, in the new design they have been kept out of interference with the arm during attachment or detachment, as shown in Fig. 4(b). This solution also enabled easy access to the encoder and the motor in case of a malfunction.

C. Elbow Mechanical Design

The primary goal in the new design for the elbow part was to implement a mechanism that allows both left and right arm therapy. In MAHI Exo I, a Kollmorgen U9D-E pancake DC motor with a cable transmission system was fixed on one side of the elbow mechanism and a counterweight was attached through a moment arm to the motor shaft to provide passive gravity compensation for the forearm assembly. Because the

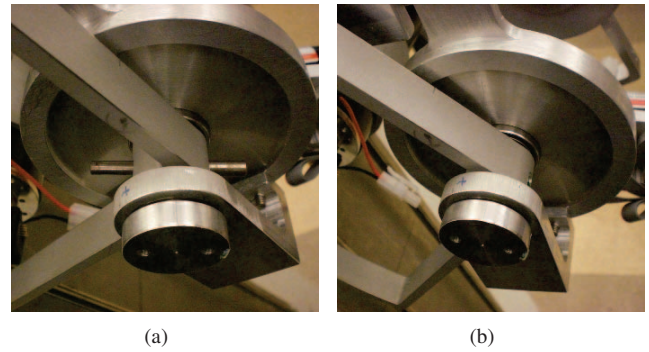


Fig. 5. (a) A tapered pin connects the capstan to the elbow shaft on both sides. (b) The tapered pin can be easily removed to allow driving the elbow joint from the other side. By changing the side of the counterweight, the device can be used for the desired arm.

counterweight and elbow motor would be between patient and mechanism as shown in Fig. 6(a) for left arm attachment, this configuration only allowed right arm therapy. To overcome this issue, a new design which employs two high torque DC motors (Maxon RE65) with cable drives is developed. Main consideration for the new design was to implement a mechanism that will enable one to change the transmission from one side to the other easily and quickly. For this reason coupling/decoupling of the capstans with the driving motor shaft is provided via easily mountable/removable taper pins, as shown in Figs. 5(a), 5(b). Consequently, changing the transmission from one side to other only requires enabling desired capstan mechanism and mounting the counterweight to the corresponding drive shaft.

New elbow actuation design also led to a considerable improvement in the torque output. Although the initial design was well within the useful range for training and rehabilitation applications, the torque output for the elbow joint was further increased to enable locking of the elbow joint in specified positions for isolated wrist or forearm training. A large capstan with 15:1 transmission ratio allowed a 238% increase in torque output as compared to MAHI Exo I (see Table I).

One of the most important points to take into account during the mechanical design of a rehabilitation robot is to ensure that the system does not cause any discomfort or safety hazard for the user during the movement [17]. For this reason, a tilting mechanism (as a passive DOF) is implemented to enable the patients to have a better posture during the training/rehabilitation sessions, as illustrated in Figs. 6(b), 6(c).

III. RESULTS AND DISCUSSION

The ranges of motion and maximum achievable torque outputs for the elbow, forearm and wrist joints based on the mechanical design improvements outlined in the previous section are summarized in Table I. Same parameters are given for the previous design (MAHI Exo I) and for activities of daily living (ADL) as reported by Perry et al. [14] for comparison.

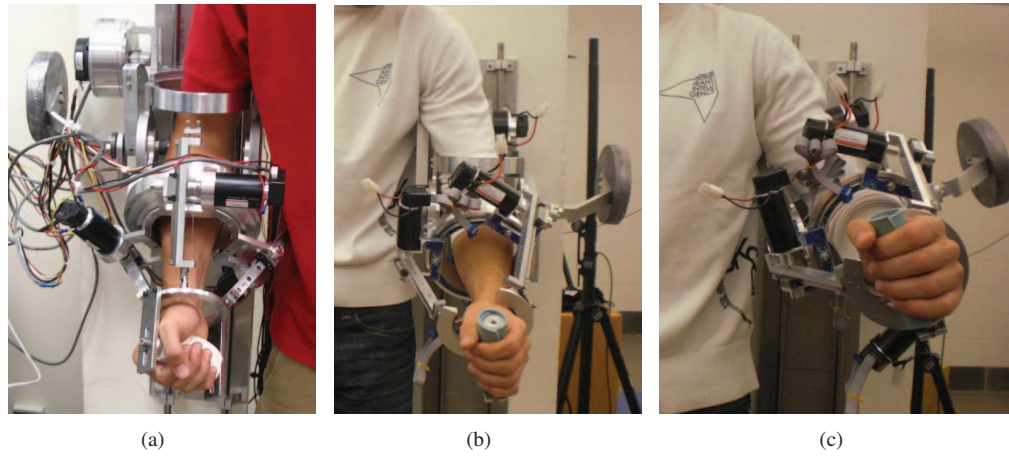


Fig. 6. (a) In MAHI Exo I, elbow motor and counterweight fixed on one side allowed only rehabilitation of the right arm. (b) In MAHI Exo II, counterweight can be attached on either side to allow both left and right arm therapy. (c) A passive DOF that tilts the whole device in the coronal plane provides improved patient comfort and posture during therapy.

TABLE I

ACHIEVABLE JOINT RANGES OF MOTION (ROM) AND MAXIMUM CONTINUOUS JOINT TORQUE OUTPUT VALUES FOR MAHI EXO I AND MAHI EXO II. MAXIMUM JOINT ROM AND TORQUE VALUES FOR 19 ACTIVITIES OF DAILY LIVING (ADL) AS EXTRACTED FROM [14] ARE ALSO GIVEN FOR COMPARISON.

Joint	ADL		MAHI Exo I		MAHI Exo II	
	ROM (deg)	Torque (Nm)	ROM (deg)	Torque (Nm)	ROM (deg)	Torque (Nm)
Elbow Flexion/Extension	150	3.5	90	4.91	>90	11.61
Forearm Pronation/Supination	150	0.06	180	1.69	>180	2.30
Wrist Flexion/Extension	115	0.35	85	2.92	72	1.67
Wrist Abduction/Adduction	70	0.35	85	3.37	72	1.93

Both MAHI Exo I and II are capable of providing a ROM exceeding or only slightly below the ROM of ADL for forearm pronation/supination and wrist abduction/adduction. MAHI Exo I covers 74% of wrist flexion/extension ROM of ADL while MAHI Exo II covers 63% of it. For the elbow, both designs cover approximately 60% of ADL ROM, from a fully extended posture to a right angle at the elbow. For the joints with a ROM beyond human ROM, both hardware and software stops are implemented for safety.

In terms of torque output capability, both versions of the exoskeleton provide more than sufficient torque to replicate torques involved in ADL, for all four DOF. MAHI Exo II has a much higher elbow maximum continuous torque output than MAHI Exo I, but less torque output at the wrist DOF. This is mainly due to use of lighter DC motors (Maxon RE35, 340 g) in MAHI Exo II, as compared to DC motors used in MAHI Exo I (Maxon RE40, 480 g). MAHI Exo II torque output at the forearm DOF is also improved 36% compared to the previous design. The improvements in forearm and elbow torque output serve to enable locking these joints at desired positions in software to allow isolated training of remaining unlocked joints. Despite the decrease in torque output at the wrist joints, the wrist motors are still capable of providing this locking property.

The main goals of the redesign have been enabling the use of the exoskeleton for therapy of both arms and resolving the backlash and singularity issues related to the universal-

revolute joints at the wrist ring. To achieve the first goal, two separate DC motors (Maxon RE65) as shown in the complete assembly in Figs. 7(a) and 7(b) were used. The elbow joint is driven by only one of the motors at a given time, in such a way that the active capstan does not get in the way, specifically between the upper arm and the torso of the patient during elbow movements. Changing of the configuration for using the device for one arm from a configuration for the other arm is handled via installing/removing of a taper pin (see Fig. 5(a)) and attaching the counterweight onto the side opposite to the patient. Taper pins provided a practical yet still zero-backlash solution to capstan-shaft coupling and decoupling. The second goal was achieved via use of high precision spherical joints, which led to a slight decrease in ROM after including an inclined wrist ring design that allowed making most use of the available ROM envelope for the spherical joints.

In comparison with other rehabilitation robots, MAHI Exo II poses several advantages. First, parallel design of the wrist provides increased rigidity and torque output; decreased inertia; and isometric force distribution throughout the workspace, as compared to a serial configuration. Also, the alignment of the biomechanical axes of joint rotation with the controlled DOF of the RiceWrist makes it possible to constrain movement of a desired joints. This is particularly important in rehabilitation, where the therapy exercises may focus on a particular joint.

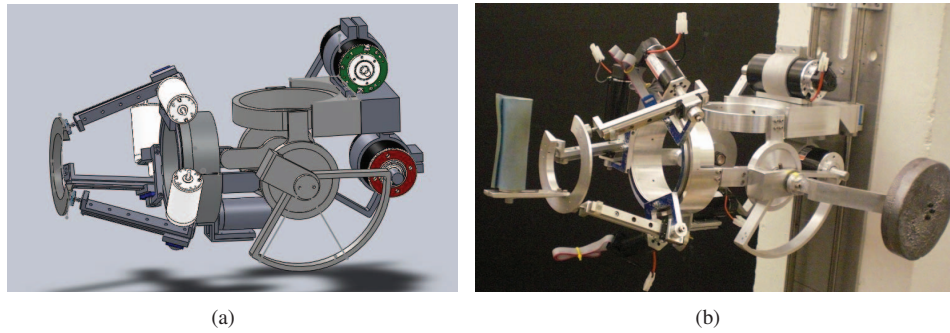


Fig. 7. (a) CAD model of the MAHI Exo II complete assembly. (b) Manufactured MAHI Exo II complete assembly with motors, handle and counterweight attached.

The new design offered additional benefits in comparison with MAHI Exo I. One benefit was lowered cost due to use of all DC brush motors for all actuators, by replacing the frameless brushless DC motor on the forearm and the pancake DC motor on the elbow joint of the earlier version. Another improvement was the additional passive DOF that allowed tilting of the whole device in the coronal plane which significantly added to patient comfort, posture and ease of attachment/detachment.

IV. CONCLUSION

We have presented details of the mechanical design of the MAHI Exo II, a robotic exoskeleton for upper extremity rehabilitation after stroke, spinal cord injury, and related movement disorders. The exoskeleton is comprised of a revolute joint at the elbow, a revolute joint for forearm rotation, and a 3-RPS (revolute-prismatic-spherical) serial-in-parallel wrist. The design maintains the basic kinematic structure and grounded nature of its predecessor, the MAHI Exo I, while offering key design improvements such as reduction of backlash and singularities, increased torque output in some degrees of freedom, improved wearability by allowing the device mount to be abducted at the shoulder, and streamlined interchange between left and right arm configurations. Future work will involve the development of enhanced control modes to allow additional treatment options for the therapist, and clinical evaluation of the device for patients with stroke and spinal cord injury affecting upper extremity motor coordination.

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