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Mechanical Design of RiceWrist-S: a Forearm-Wrist Exoskeleton for Stroke and Spinal Cord Injury Rehabilitation

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***Abstract*— Robotic rehabilitation of individuals with neurological lesions from stroke or spinal cord injuries is promising in that robots can provide intensive therapy and enable quantitative and objective assessment of motor impairment. Robotic devices for the upper extremity have primarily focused on the proximal joints, with only a few devices designed specifically for forearm and wrist rehabilitation, which is critical for the restoration of independence in activities of daily living. Previous robotic systems have neglected degrees-of-freedom at the wrist, or have offered limited range of motion or torque output capability. In this paper, we present the kinematic design of a serial mechanism, the RiceWrist-S, for forearm and wrist rehabilitation, and compare its range of motion and torque output capabilities to a previously reported parallel mechanism and to requirements developed from assessment of daily activities. The RiceWrist-S design meets or exceeds targets for range of motion and torque in all degrees of freedom.**

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

I. Introduction

Each year in the United States, about 795,000 people experience a stroke. Stroke is the leading cause of long-term disability and has a significant social and economic impact on the United States with a $68.9 billion total estimated cost for 2009 [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 estimated yearly direct and indirect costs of $14.5 billion and $5.5 billion, respectively [3].

Rehabilitation of patients with impairments due to neurological lesions mostly includes task-oriented repetitive movements which can improve muscle strength and movement co-ordination in these patients [4]. The goal of rehabilitation is to induce brain and spinal cord plasticity and to improve functional outcomes, and to fulfill this goal, therapy has to be intensive with long duration and high repetition numbers [5]. Considering these factors, classical rehabilitation has obvious limitations. First of all, classical rehabilitation is labor intensive and as a consequence expensive, so the duration of the training sessions is generally shorter than the required amount, the main factor that impedes achievement of the optimal therapeutic outcome [6]. Because consistency of training depends on the performance of the therapist, classical rehabilitation is further limited.

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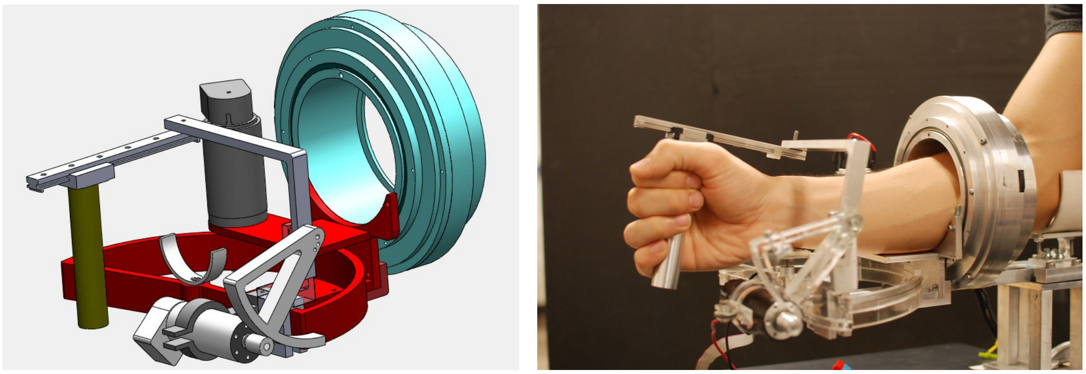
Rehabilitation robotics is a branch of robotics which aims to eliminate most of the disadvantages of classical rehabilitation. Utilizing robotics for rehabilitation increases the number of training sessions with consistent repetitions and reduces personnel cost by enabling the opportunity to assign one therapist to train two or more patients [7]. Robotics also enables the performance evaluation of patients during therapy, and objective and quantitative assessment after therapy [8], which is not possible with classical rehabilitation. In addition, virtual reality implementations can provide a unique medium where therapy can be provided within a functional and highly motivating context [9], and consequently the intensity of the therapy can be increased.

The results of clinical studies involving robotic rehabilitation protocols support the idea of implementing these devices in treatment of stroke and SCI patients. Due to the clinical demonstrations of its efficacy in restoring function for upper extremity movements and locomotor skills primarily in stroke populations, robotic rehabilitation has gained significant traction in recent years. Although a number of 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. It is fair to say that nearly all the activities of daily living (ADL) (eating, drinking, cleaning, dressing, etc.) involve upper extremity movements. So, for a stroke, spinal cord injury or any other brain injury patient, rehabilitation of upper extremities is crucial for restoring the functionality to be able to achieve ADL. In the following section a brief presentation of the widely used hardware design methods in upper extremity rehabilitation robotics is made.

II. Background

From a mechanical design point of view, rehabilitation robots can be classified into two groups: end-effector based robots and exoskeletons. MIT-MANUS [10] and Mirror Image Movement Enabler (MIME) [11] constituted examples of 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 of upper-extremity rehabilitation exoskeletons include 5 DOF MAHI Exoskeleton [12], 5 DOF Rupert [13], 6 DOF ARMin [6] and 7 DOF CADEN-7 [14]. Recently, rehabilitation engineering research has increasingly



(a) (b)

Fig. 1. (a) CAD model of the RiceWrist-S complete assembly. (b) Manufactured RiceWrist-S complete assembly with motors and handle.

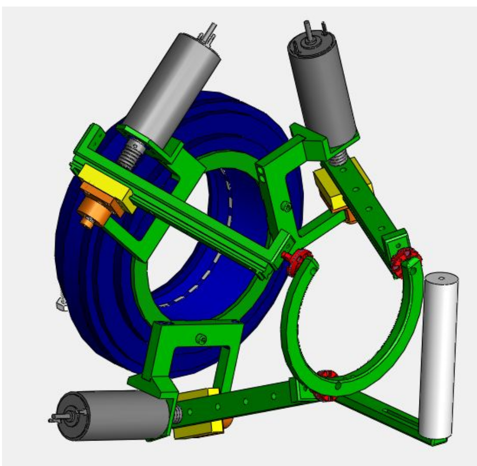


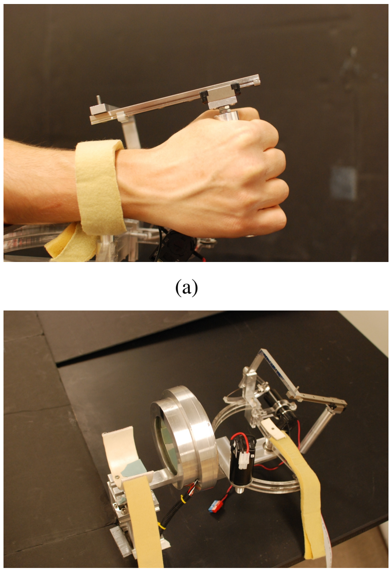
Fig. 2. RiceWrist – The previous design employs a 3-RPS (revolute-prismatic-spaherical) parallel mechanism at the wrist module.

focused on quantitative evaluation of residual motor abilities in an effort to obtain an objective evaluation of rehabilitation and pharmacological treatment effects [8]. Exoskeletons offer the advantage of precisely recording and monitoring isolated joint movements of the arm and wrist and hence are a better-suited design option versus end-effector based designs for this purpose.

Among exoskeletal rehabilitation robots, another classification in terms of mechanical design can be made: grounded and ungrounded robots. Ungrounded robots can be worn by the patient like a costume and are attached only to the body of the patient. These kinds of devices, such as the X-Arm 2 [15], enable the patient to have more naturalistic movements and allow large workspace capabilities during the movements. However, despite their better movement capability, ungrounded robots can offer limited torque output capability. Because the devices are carried by the patients during the rehabilitation sessions, they have to be lightweight, which limits the chosen actuator sizes and hence the torque output. On the other hand, grounded robots, such as MAHI Exoskeleton [12], ARMin [6] and CADEN-7 [14], because of their structure, provide more flexibility in actuator selection. Also, grounded robots offer design simplicity compared to ungrounded robots [12].

The size, weight, force/torque output and required control effort for a robotic system are either directly or indirectly affected by the actuation type of the system. Hydraulic, pneumatic and electric actuation are three main actuation types used in robotics. In upper extremity rehabilitation robotics, though, hydraulic actuators are rarely used because of disadvantages such as oil leakage, necessity of wide space and return oil line [16]. Pneumatic actuators offer a high power-to-weight ratio which makes them ideal for light weight applications (for example ungrounded robots). But their highly nonlinear dynamics and low bandwidth make their control challenging and inappropriate for virtual reality application [12]. Electrical actuation is the most commonly used type amongst upper extremity rehabilitation robot applications. Electric actuators, although they possess lower power-to-weight ratio, allow advanced control applications which include virtual reality implementations. Because grounded robots enable one to use larger and heavier motors, electrical actuators are the most prevalent for these devices.

A transmission system enables one to transmit the motion from the actuator to the specific part of the system, and while doing that the provided torque/force values can be increased, while the speed of the motion is decreased. Considering that we are dealing with patients with neurological impairments, it is fair to say that upper extremity rehabilitation robots usually operate at low speeds, so high operation speed is not a crucial design specification for these devices. Torque/force output of a rehabilitation robot, on the other hand, can be considered as one of the performance metrics of the system. Gear and cable drives are the two most frequently used transmission types in rehabilitation robotics. Gear drives are easy to implement but introduce backlash and friction to the system. Both backlash, by causing instability, and friction, by impeding backdrivability, obstruct virtual reality/haptic implementations. A cable, on the other hand, allows backdrivability and is a backlash-free transmission system. So, although it increases the design complexity, cable drive transmissions are frequently used in haptic devices [17].



(a)

(b)

Fig. 3. (a) The handle is coupled through a linear joint to the system. By this way a passive degree-of-freedom is provided to prevent misalignments of the robot joints with the biological joints. (b) Straps at the forearm and wrist are adjustable to coincide the robot joints with the biological joints.

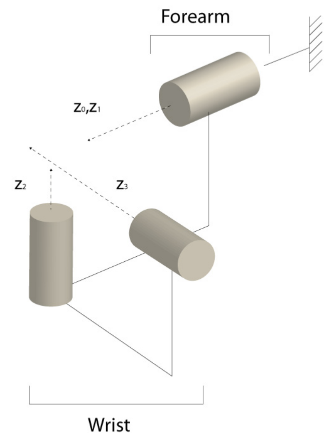


Fig. 4. Representation of the kinematic structure of RiceWrist-S.

III. Approach

RiceWrist-S (Fig.1) is a grounded, exoskeletal device which uses electrical motors for actuation and cable drives for transmission. To achieve better resemblance to human anatomy and ability of individual actuation of joints, an exoskeletal design is employed. Actuation has been achieved with electric motors, rather than pneumatic actuators, to have a larger bandwidth and consequently have the ability to convey high frequency forces and better sense of touch. Also, RiceWrist-S employs cable drives to ensure backdrivability and zero backlash. The system, because of the load of electric motors, is grounded.

In contrast, the RiceWrist (Fig. 2), the predecessor of RiceWrist-S, employs a 3-RPS (revolute-prismatic-spaherical) parallel mechanism at the wrist module. Although parallel mechanisms offer better rigidity, decreased inertia, and isometric force distribution throughout the workspace, the workspace capabilities are limited as compared to serial mechanisms. In the RiceWrist-S design we employ a serial mechanism in order to better match the functional workspace of human wrist.

According to Schiele et al. [18], besides matching the complete functional workspace of a human limb and being able to activate individual joints, a truly ergonomic rehabilitation robot also must not cause any safety hazards for the operator while preventing misalignments of the robot joints with the biological joints. In the previous design, because the two rotational and one translational degree of freedom were coupled on the end effector of the parallel mechanism, any isolated movement for the rotational degrees of freedom (which correspond to the wrist movement of the patient) inevitably resulted in a change in the translational degree of freedom. Because wrist axes of patient were supposed to coincide with the rotation axes of the end effector of the parallel mechanism, any change in the translational degree of freedom caused misalignments of the robot joints with the biological joints. In order to keep the robot joints aligned with the human joints, with the serial configuration the wrist joints are decoupled in the new design. Furthermore, a strap at the wrist and a strap at the forearm have been employed, and a passive degree of freedom has been provided at the wrist in the RiceWrist-S (Fig. 3). In order to ensure safety of the operator, mechanical stops have been implemented for the joints with a ROM beyond human ROM.

IV. Design Details

The exoskeleton is comprised of a revolute joint for forearm rotation and two revolute joints at the wrist part which correspond to wrist flexion/extension and wrist radial/ulnar deviation. Because the human joints are aligned with the joints of the device, the measurement of arm position is reduced to the solution of kinematics of the exoskeleton. The kinematics of the exoskeleton will be investigated next.

A. *RiceWrist-S Kinematics*

Figure 4 depicts the basic kinematic structure of 3-DOF RiceWrist-S. Coordinate frame $\{0\}$ represents the newtonian frame (ground), and frame $\{1\}$, frame $\{2\}$ and frame $\{3\}$ are fixed to the forearm, wrist flexion/extension and wrist radial/ulnar deviation joints respectively. The joint axes z_1, z_2 and z_3 intersect and the Denavit-Hartenberg (D-H) parameters are given in Table 1.

Joint	rot(x)	tr(x)	rot(z)	tr(z)
Forearm	0	0	θ_1	0
Wrist F/E	$-\frac{\pi}{2}$	0	θ_2	0
Wrist R/U	$\frac{\pi}{2}$	0	θ_3	0

TABLE I

Link parameters for the Forearm and Wrist joints

TABLE II

SENSOR AND ACTUATOR SPECIFICATIONS

Axis	Peak Output Force/Torque (Nm)	Peak Stall Force/Torque (Nm)	Sensor Resolution (deg)	Remarks
Forearm Supination/Pronation	5.08	1.694	0.002	Actuator : Applimotion 165-A-18 Transmission: Direct-Drive Encoder : MicroE Systems Mercury 1500
Wrist Flexion/Extension	38.4	2.805	0.012	Actuator :Maxon Motors RE-40 (148877) Transmission: Cable-Drive (15:1) Encoder : Avago HEDS 5540
Wrist Radial/Ulnar Deviation	12.24	1.058	0.015	Actuator :Maxon Motors RE-30 (310009) Transmission: Cable-Drive (12:1) Encoder : Avago HEDS 5540

where θ_1, θ_2 and θ_3 are rotation angles correspond to the forearm pronation/supination, wrist flexion/extension and wrist radial/ulnar deviation respectively. Consequently the transformation matrices between frame $\{0\}$ and frame $\{1\}$; frame $\{1\}$ and frame $\{2\}$; and frame $\{2\}$ and frame $\{3\}$ are given as

$$^{0}T_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$^{1}T_2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_2 & -\cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$^{2}T_3 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

and hence, the transformation between frames $\{0\}$ and $\{3\}$ is

$$^{0}T_3 = ^{0}T_1\, ^{1}T_2\, ^{2}T_3 \quad (4)$$

As stated above, the forearm and wrist joints of the operator are aligned with the robot joints during the operation and hence the measurement of the orientation of frame $\{3\}$ with respect to frame $\{1\}$ in terms of *zxy*-Euler angles, γ, α, and β corresponds to measurement of the forearm pronation/supination, wrist flexion/extension and wrist radial/ulnar deviation respectively. It should be noted that, because wrist flexion/extension joint is mechanically restricted to operate in a specified workspace to correspond to human ROM, Euler angle α is between $60^\circ \geq \alpha \geq -60^\circ$. Hence the forearm and wrist radial/ulnar deviation joints never align during the operation, and the workspace is singularity-free.

B. Actuation and Sensing

The system is designed as a high fidelity haptic device to have the ability of inclusion of virtual reality applications in the training sessions. Considering their capacity of conveying high frequency forces (to successfully render sense of touch) and negligible nonlinearities in their dynamics, electrical actuators are employed in the system. At the forearm joint a frameless and brushless DC motor actuator with direct drive is used to implement the desired mechanism in a limited space. At the wrist part, high torque DC motors are used with cable drives with 15:1 and 12:1 transmission ratios for wrist flexion/extension and wrist radial/ulnar deviation joints respectively.

Sensor resolution is a factor that affects the range of frequencies of forces, and in turn the quality of the rendered sense of touch, that can be displayed through the haptic interface [20]. In order to achieve a high fidelity haptic device, high resolution optical encoders have been employed in the system. Table II presents the actuator and sensor specifications.

V. RESULTS

Rosen et al. [19] performed a pilot study to determine the kinematic and dynamic requirements of an exoskeleton arm for functional use. In their study, human arm motions were recorded during 19 ADL, which included eating, drinking, general reaching tasks, functional tasks and hygiene related tasks, by using a motion capture system. Torque values were calculated using both a modeling simulation package (Cosmos/Motion, Solidworks) and an analytical approach (Autolev, Online Dynamics). The resulting maximum torque and ROM values required for ADL have been taken as the target specifications in the development of RiceWrist-S. The ROM and maximum achievable torque outputs for the forearm and wrist joints are summarized in Table III. Same parameters are given for the previous design (RiceWrist) and for activities of daily living (ADL) as reported by Rosen et al. [19].

The new design fulfills its main goal, to meet the required workspace capability for ADL for all three DOF. While the ROM capability at the wrist radial/ulnar deviation joint DOF is slightly under the capability of the previous version, the ROM value for the wrist flexion/extension DOF is increased by approximately 70%.

In terms of torque output capability, both versions of the exoskeleton provide more than sufficient torque to replicate torques involved in ADL, for all three DOF. The decrease in the torque output at the wrist radial/ulnar deviation DOF,

TABLE III
ACHIEVABLE JOINT RANGES OF MOTION (ROM) AND MAXIMUM CONTINUOUS JOINT TORQUE OUTPUT VALUES FOR RICEWRIST AND RICEWRIST-S. MAXIMUM JOINT ROM AND TORQUE VALUES FOR 19 ACTIVITIES OF DAILY LIVING (ADL) AS EXTRACTED FROM [19] ARE ALSO GIVEN FOR COMPARISON.

Joint	ADL		RiceWrist		RiceWrist-S	
	ROM (deg)	Torque (Nm)	ROM (deg)	Torque (Nm)	ROM (deg)	Torque (Nm)
Forearm Pronation/Supination	150	0.06	180	1.69	180	1.69
Wrist Flexion/Extension	115	0.35	72	1.37	120	2.805
Wrist Abduction/Adduction	70	0.35	72	1.59	70	1.058

compared to the previous design, is due to the employment of a relatively smaller actuator to decrease the inertia of the system. The new design achieves approximately 100% increase in torque output at the wrist flexion/extension joint.

VI. DISCUSSION

In order to achieve the activities of daily living (such as self hygiene, self feeding, dressing etc.) one needs to use the distal parts of his/her arm (forearm, wrist) in coordination with proximal parts (elbow, shoulder), because most daily life activities require coordinated multi-joint movements [21]. However, most of the previous works are either concentrated solely on the rehabilitation of the proximal part of the arm, or joints at distal part are excluded. RiceWrist-S on the other hand focuses on distal joints (forearm and wrist). Furthermore the chosen design approaches and the kinematic structure of the mechanism give certain advantages to the RiceWrist-S compared to the few number of devices which focus on distal joints of upper extremity. For example the cable drive transmission makes RiceWrist-S a better candidate for virtual reality implementations compared to the wrist module of MIT-Manus which employs a gear drive mechanism [22]. The kinematic structure of the system allows combined movement therapy besides isolated movement therapy compared to the arm trainer [23] which allows only one DOF isolated movements.

In addition to improvements in ROM and torque output, the new design decreased the device cost drastically compared to the previous design. In the previous design at the parallel wrist module, the links were connected to the top platform via high precision spherical joints. With the new design, the serial mechanism for the wrist module eliminated the use of the spherical joints. Additionally, the actuation at the wrist was achieved with two DC-motors instead of three.

VII. ACKNOWLEDGEMENTS

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