Design of *Wrist Gimbal*: a Forearm and Wrist Exoskeleton for Stroke Rehabilitation

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Abstract— In this paper, we present design, implementation and specifications of the *Wrist Gimbal*, a three degree-of-freedom (DOF) exoskeleton developed for forearm and wrist rehabilitation. Wrist Gimbal has three active DOF, corresponding to pronation/supination, flexion/extension and adduction/abduction joints. We mainly focused on a robust, safe and practical device design to facilitate clinical implementation, testing and acceptance. Robustness and mechanical rigidity was achieved by implementing two bearing supports for each of the pronation/supination and adduction/abduction axes. Rubber hard stops for each axis, an emergency stop button and software measures ensured safe operation. An arm rest with padding and straps, a handle with adjustable distal distance and height and a large inner volume contribute to ease of use, of patient attachment and to comfort. We present the specifications of Wrist Gimbal in comparison with similar devices in the literature and example data collected from a healthy subject.

Index Terms— Exoskeletons, rehabilitation robotics, haptic interface design, stroke rehabilitation.

I. Introduction

In the United States alone, approximately 795,000 individuals experience a new or recurring stroke every year, making it the fourth leading cause of death in the country [1]. It is also the leading cause of serious, long term adult disability due to hemiparesis or hemiplegia, and as a result, the direct and indirect cost of stroke in the United States for the year of 2009 was estimated to be $68.9 billion [1]. Based on the concept of neuroplasticity, the brain's ability to reorganize by forming new neural connections [2], [3], numerous studies [4] have found that stroke patients are able to regain motor function with continuous therapy and rehabilitation of extremities affected by hemiparesis or hemiplegia.

Conventional means of rehabilitation for stroke patients involve a one to one interaction with a physiotherapist, and is not only labor intensive, but also does not provide an objective method to determine the patients' motor function recovery rate [5], [6]. In addition to addressing these issues, the inclusion of robot-assisted therapy for stroke rehabilitation allows for patients to undergo different repetitive rehabilitation approaches with the incorporation of various control strategies based on the patient's condition [7]. Another benefit of robotic devices is that they can be programmed to run autonomously for extended amounts of time [5], [8]. This can result in physiotherapists being able to attend to more than one patient at any given time and the

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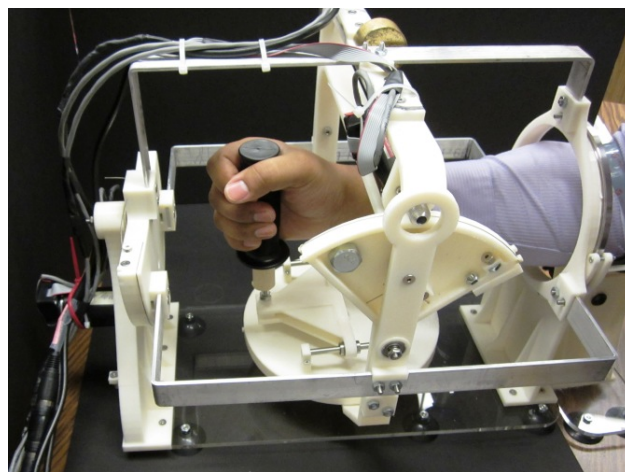

Fig. 1. Wrist Gimbal: a three degree-of-freedom forearm and wrist exoskeleton for stroke rehabilitation.

patient being able to perform these rehabilitation sessions at home without the help of a therapist. These benefits have led to increased interest in development and use of robotic devices to assist rehabilitation of stroke patients.

Initial robots developed for upper-extremity rehabilitation, such as MIT-MANUS [9] and MIME [10], mainly focused on the proximal joints, i.e. shoulder and elbow. Subsequently, distal rehabilitation devices focusing on the forearm and wrist joints were developed, examples of which include the wrist module of MIT-MANUS [11], MAHI Exo I and II [12], [13], RiceWrist and RiceWrist-S [14], [15], the IIT wrist robot [16], SUE [17], the Haptic Knob [18], [19] and the Universal Haptic Drive [20]. In a study on the amount of skill transfer between proximal and distal segments of the arm due to isolated proximal and distal training, Krebs et al. [21] suggested that training the more distal limb segments such as the wrist has a higher skill transfer to the proximal segments. Based on this finding, we have chosen to focus on development of a distal device since it can potentially benefit motor function improvement in both distal and proximal joints.

In this paper, we present design, implementation and specifications of the Wrist Gimbal (see Fig. 1), a three degree-of-freedom (DOF) exoskeleton developed for forearm and wrist rehabilitation. Our main design goal has been development of a robust, safe and practical device to facilitate clinical implementation, testing and acceptance. The three active DOF of Wrist Gimbal correspond to pronation/supination (PS), flexion/extension (FE) and adduction/abduction (AA) joints.
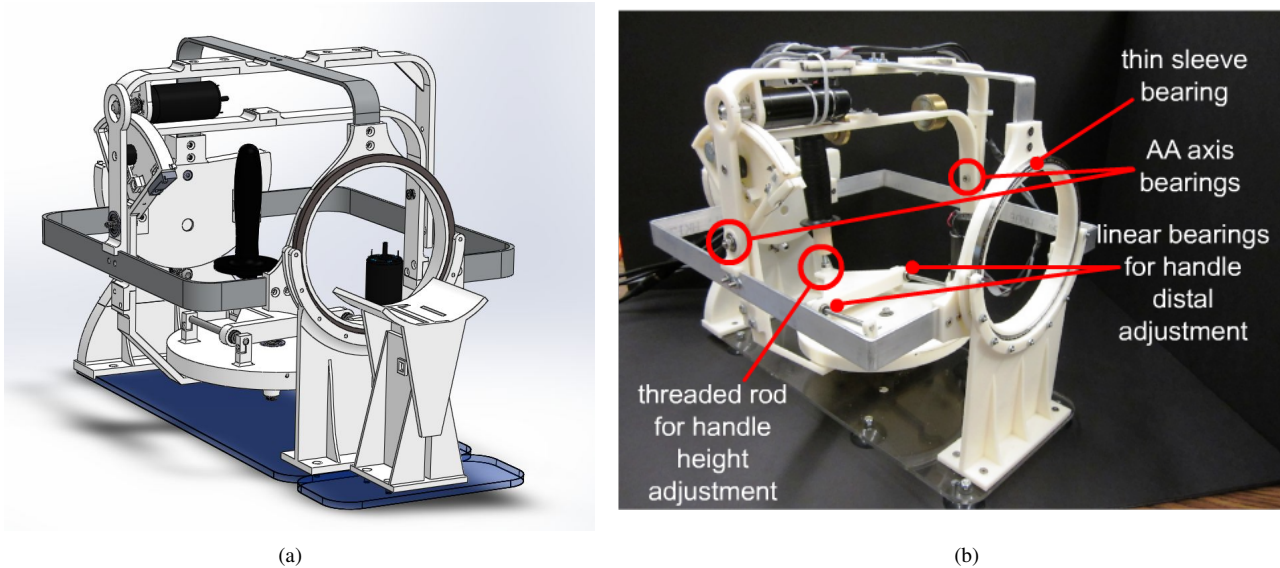
Fig. 2. (a) CAD model of Wrist Gimbal. (b) Manufactured and assembled Wrist Gimbal. Thin sleeve bearing with a six inch inner diameter supports the PS axis at the proximal end. This improves rigidity of the device while allowing easy access and attachment of the patient to the handle. Ball bearings at both ends of the abduction/adduction (AA) axis also contribute to structural rigidity of the device. handle height is adjustable via a threaded rod and nut. The handle also is allowed to freeley move in the distal/proximal direction via linear bearings. These passive DOF allows accurate alignment of device and user's wrist axes of rotation. They also allow easy accommodation of wrists and hands of varying dimensions.

We implemented two bearing supports for each of the PS and AA axes that provide rigidity and mechanical robustness. Rubber hard stops for each axis, an emergency stop button and software measures ensure safe operation. An arm rest with padding and velcro straps, a handle with adjustable distal distance and height and a large inner volume contribute to ease of use and patient comfort. Further specifications of Wrist Gimbal include a cost efficient and practical desktop design that can be easily attached to any flat surface via industrial strength suction cups.

The paper is structured as follows: Section II describes design considerations/goals and how they were achieved. Section III explains the implementation in detail, provides sensor and actuator specifications and control system structure. Section IV summarizes the device's range of motion (ROM) and torque characteristics in comparison with other designs from the literature and presents pilot data from representative therapy scenarios for the device. Section V concludes the paper.

II. MECHANICAL DESIGN

A. Kinematic configuration and structural rigidity

Wrist Gimbal has a three DOF serial kinematic configuration, with all revolute joints, similar to RiceWrist-S [15] and IIT wrist robot [16]. Serial kinematic configurations have the advantage of leading to simpler mechanical structures, which facilitates manufacturing and reduces points of potential failure, hence also reducing the amount of required maintenance. However, serial configurations usually do not yield as rigid structures as parallel configurations. Structural rigidity is desired in rehabilitation robots under impedance control to improve accuracy of forces or torques generated at the handle. To still obtain a rigid device with a serial

configuration, we have used ball bearing supports at two ends of both the PS and the AA axes. For the PS axis, which is the outermost DOF, a standard ball bearing is used at the distal end. A thin sleeve bearing with an inner diameter of six inches supports the proximal end while allowing a large clearance for patient's hand to be inserted into the device, as illustrated in Figs. 1, 2(a) and 2(b). Regular ball bearings are used to support the AA axis at both ends, as depicted in Figs. 2(a) and 2(b). The FE axis is supported by a single ball bearing. This does not, however, pose a problem for structural rigidity, since the FE axis comprises the innermost DOF that is closest to the end effector (handle).

B. Alignment of wrist axes with device axes

Facilitating accurate alignment of anatomical joint axes of rotation with the device joint axes of rotation is an important design consideration for exoskeletons. Axis misalignments can cause user discomfort and even pain, especially during movement [22], [23]. For wrist and forearm exoskeletons, all three DOF intersects at the wrist center and the device wrist center has to match the anatomical wrist center as closely as possible. Wrist Gimbal addresses this issue by making use of a handle whose height can be passively adjusted and fixed via a threaded rod and two nuts, as depicted in Fig. 2(b). The handle has a flat surface for the hand to rest on at its bottom, which keeps the wrist in alignment with the device's PS and AA axes, when handle height is properly adjusted. The handle attaches to the FE platform via two linear bearings, as shown in Fig. 2(b), which allows placement of the wrist in the device at a position optimal for FE axis alignment. These linear bearings also function as a relief point that allows slight movements of the handle with respect to the robot, in case of any minor misalignments

TABLE I

SPECIFICATIONS OF SENSORS, ACTUATORS AND CABLE DRIVE TRANSMISSION GEAR RATIOS USED IN WRIST GIMBAL.

Axis	Peak Output Torque (mNm)	Sensor Resolution with Quadrature (deg)	Remarks
Forearm Pronation/Supination	191*15=2865	0.012	Actuator: Maxon Motor RE40
			Encoder: Avago HEDL 5540 500CPR
			Cable drive gear ratio: 15:1
Wrist Flexion/Extension	110*16=1760	0.01125	Actuator: Maxon Motor RE35
			Encoder: Avago HEDL 5540 500CPR
			Cable drive gear ratio: 16:1
Wrist Adduction/Abduction	110*16=1760	0.01125	Actuator: Maxon Motor RE35
			Encoder: Avago HEDL 5540 500CPR
			Cable drive gear ratio: 16:1

that can be unavoidable. A similar linear bearing approach was used in [15] and [16] for similar purposes. Differing from the previous designs, we preferred to use two bearings to improve rigidity and proper transmission of controlled torques to the handle. These mechanisms employed to aid proper and convenient alignment of the device and user joint axes also function as a means for the device to easily accommodate users with various arm and hand dimensions.

III. DEVICE IMPLEMENTATION AND SPECIFICATIONS

A. Materials and manufacturing

We used a 3D printer (uPrint Plus) to manufacture a majority of the mechanical parts out of ABSplus material. ABSplus is a light and durable plastic that is well suited for functional rapid prototyping. The material thickness throughout the device was carefully selected and adjusted to reduce both the cost and the inertia of the device as much as possible, without compromising structural rigidity and integrity. Support surfaces or ribs were incorporated into the design to achieve a desirable balance for this trade-off. We have also used aluminum bars to build a lightweight and sturdy main frame for the device. The capstans for the cable drive transmissions were also manufactured out of aluminum.

B. Motors, amplifiers and encoders

The implementation of Wrist Gimbal included mounting of three Maxon DC brush motors on corresponding platforms to actuate each DOF. The motors transmit torque to the device handle through cable drive mechanisms which amplify the torque output of the motors by their respective gear ratios. Each motor is controlled by a Maxon ESCON 50/5 servoamplifier configured to operate in current mode and powered by a single 48V power supply. Avago optical encoders with 500 counts per revolution (CPR) resolution mounted directly onto the DC motors allow for accurate measurement of the angular position of the device handle. Table I summarizes the specifications of the DC motors, encoders and gear ratios used in the Wrist Gimbal.

The DC motors were selected based on three considerations. First, the motors were required to meet and exceed the torque requirements in performing activities of daily living (ADLs) in each DOF (see Table II). The second consideration

was the mass of each of the motors, which was an important parameter in ensuring static balance of the device as much as possible upon assembly, and in keeping the inertia low to improve device backdrivability. Third, the output torque values for each DOF relative to each other in other wrist devices in the literature was considered. The RiceWrist [14] has a torque output of 1.69 Nm, 1.37 Nm and 1.59 Nm for the PS, FE and AA joints, respectively; or a ratio of $1.2:1:1.2$. The same ratio for MIT-MANUS wrist extension [11] is $1.4:1:1$. For Wrist Gimbal, this ratio has a similar value of $1.7:1:1$. The AA and the FE motors were selected to have the same torque output since the amount of torque required to perform ADLs for these DOF are comparable (see Table II). The PS motor torque output was significantly greater than the other two motors because it acts as a base platform for which the other two DOF are built on, thereby actuating a larger inertia.

C. Data acquisition and control

We used a Quanser Q8-USB data acquisition board together with Matlab/Simulink and Quanser QuaRC software for data acquisition and control system development for Wrist Gimbal. Control algorithms were set to run at a 1 kHz loop rate. We implemented proportional and proportional derivative position controllers for initial testing of the device. The initial testing included observing position trajectory tracking performance with step, ramp and sinusoidal reference trajectories for all DOF, which was found satisfactory. Additional control scenarios were developed to test performance of the device under representative therapy tasks. One such control scenario was a passive control mode, in which the device did not generate any force feedback, but was rather used to record the natural movement trajectories of the user for all joints. Another control scenario induced viscous force fields, with adjustable viscous damping values. In this resistive control scenario, the device generated resistive torques that opposed movement of the user, via implementation of virtual linear dampers in the control algorithm. Example movement trajectories and torque profiles were captured under the passive and resistive control modes as the device was used by a healthy subject, and are presented in the Section IV-B.

COMPARISON OF THE RANGE OF MOTION (ROM) AND TORQUE CAPABILITIES OF WRIST GIMBAL WITH THE REQUIREMENTS TO PERFORM
ACTIVITIES OF DAILY LIVING (ADLS) AND WITH OTHER SIMILAR REHABILITATION DEVICES. VALUES FOR ADLS ARE EXTRACTED FROM [24].

|	Forearm Pronation/Supination		Wrist Flexion/Extension		Wrist Adduction/Abduction	
	ROM (deg)	Torque (Nm)	ROM (deg)	Torque (Nm)	ROM (deg)	Torque (Nm)
ADL	150	0.06	115	0.35	70	0.35
Wrist Gimbal	**180**	**2.87**	**180**	**1.77**	**60**	**1.77**
RiceWrist-S	180	1.69	120	2.81	70	1.06
MIT-Manus Wrist Robot	180	1.69	135	1.20	45	1.20
MAHI Exo II	>180	2.30	72	1.67	72	1.93
Universal Haptic Device	90	20.00	90	20.00	90	20.00
Supinator Extender (SUE)	90	2.71	90	2.71	-	-
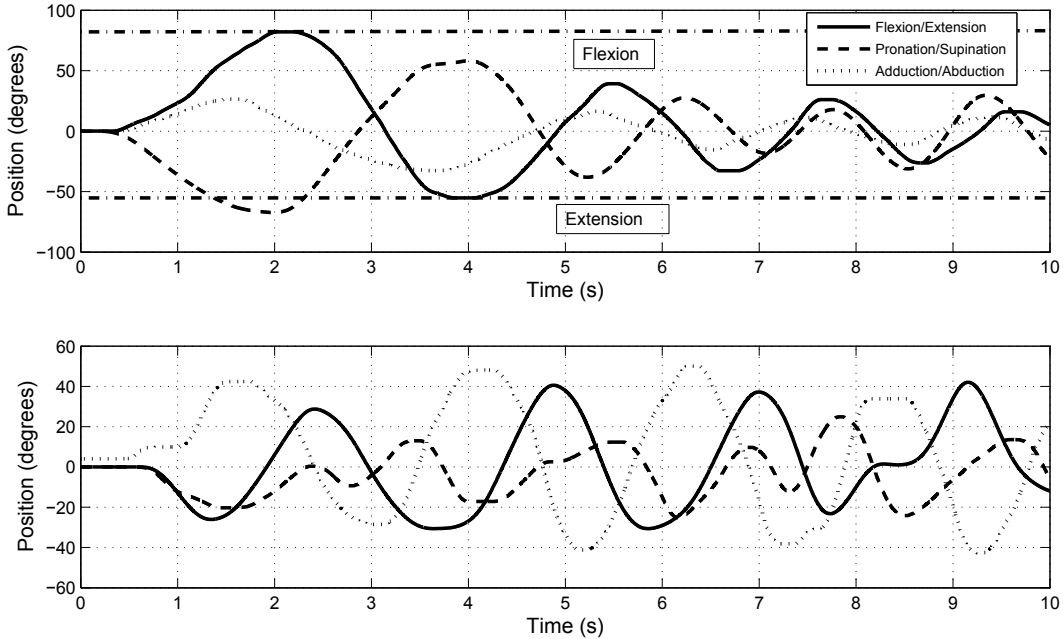
Fig. 3. One example scenario where Wrist Gimbal may be employed in a clinical setting is using it as an evaluation tool for range of motion (ROM). The first plot shows example data from a healthy subject completing representative isolated wrist and forearm movements. The flexion/extension ROM can be estimated from the data collected as indicated by the horizontal lines. The lower plot reports a similar scenario where all joints were moved concurrently to comprise a composite movement.

D. Safety

One of the major concerns for incorporating robotic devices in clinical setting is human safety. Several safety features were implemented on Wrist Gimbal to ensure safe operation and use of the device. These safety features include: (i) Mechanical rubber hard-stops for each axis of rotation to prevent movements beyond the design limits, (ii) An easily accessible emergency stop button which deactivates all amplifiers, (iii) Saturation blocks in developed controllers to limit the amount of torque output of each of the DC motors.

IV. RESULTS AND DISCUSSION

A. Comparison with other devices in literature

Two important characteristics of robotic devices built for rehabilitation purposes are their range of motion (ROM) and torque capabilities for each DOF to ensure that it meets or exceeds the minimum requirement to perform activities of daily living (ADLs). Various wrist devices have been built as rehabilitation devices for stroke or spinal cord injury patients and Table II provides a comparison of the ROM and torque output for the forearm pronation/supination, wrist flexion/extension and wrist adduction/abduction for various wrist and forearm devices reported in the literature. The table also allows for a direct comparison between the various devices and the requirements to perform ADLs. Table II shows that in comparison to other devices, Wrist Gimbal has a desirable large workspace as defined by the ROM for the three DOF of the device. This allows for stroke patients to be able to practice a wider variety of range of movements and a broader range of stroke patients with different motor function abilities to benefit from the device since movements of some patients might be constrained within a subset of the entire ROM.
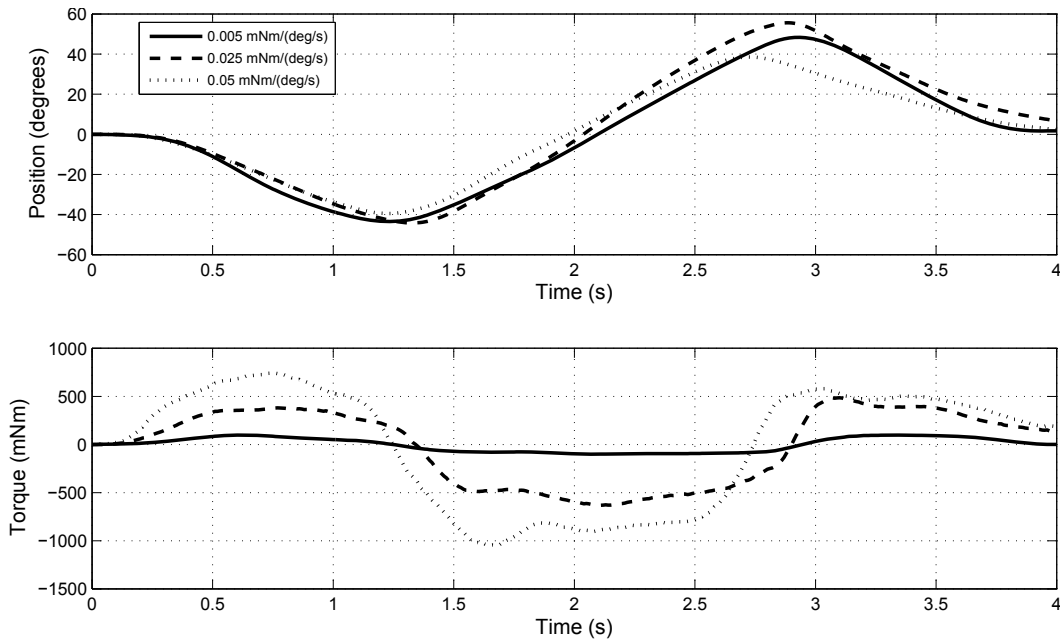
Fig. 4. In a second example scenario, Wrist Gimbal employed resistive fields that opposed user movement with adjustable rates of viscous friction. The first plot shows pronation/supination movement trajectories of a healthy subject. For each trajectory, a different viscous damping value was implemented. The second plot shows that implementation of increasing damping values demanded increasing amounts of torque by the user to complete the same movement.

B. Healthy subject data for representative therapy scenarios

Aside from the range of motion and torque capabilities of the device, two main control strategies were implemented to assist in the rehabilitation: passive and resistive control strategies. Using the passive control, the patient can freely practice wrist movements using the device without any assistive or resistive forces. This operation mode can be used to objectively measure the range of motion of the patient before and after treatment [25]. The plots in Figure 3 shows the recorded movements of a healthy subject performing isolated (single axis) and composite (three axes) movements on the device. For a right-handed subject, a positive value for the position in the plot represents flexion, supination and adduction while a negative value represents extension, pronation and abduction. In a clinical setting, the range of motion for each axis of rotation could be measured by noting down the maximum and minimum displacement that can be achieved by the stroke patient; this is shown in the first plot in Figure 3 for the flexion/extension axis. Since most activities of daily living (ADLs) require use of more than one axis of rotation, the assessment of the range of motion of a patient can also be done for composite movements as shown in the lower plot in Figure 3. If desired, these assessments can be automated by developing a graphical user interface (GUI) for the therapist. Development of such GUIs is among our plans for future work.

The second control strategy implemented, the resistive control strategy, can be used in the clinical setting to vary the task difficulty level –amount of resistive force– for stroke patients in performing specific movements based on their motor function capabilities. Figure 4 shows the position trajectory (upper plot) and resistive torque exerted at the device handle (lower plot) using this control strategy. In these plots, a healthy subject was instructed to perform a repetitive movement utilizing the pronation/supination joint while different viscous friction coefficients were implemented in each trial. From these plots, it can be observed that while similar movement trajectories were performed, the amount of resistive torque exerted at the device handle varied significantly depending on the viscous friction coefficient implemented, allowing movement exercises under adjustable resistive fields.

The mentioned passive and resistive control strategies are just two simple example scenarios illustrating how Wrist Gimbal can be utilized in stroke therapy. The device and the control software development platform for it allows implementation of a wide variety of control scenarios. These scenarios include isolated or composite movement exercises, active assistance, error augmentation and adaptive therapy tasks; and are among our plans for future directions. Additional future directions of work include development of GUIs for selection of and adjustment of parameters for these scenarios, and testing the effectiveness of the device in therapy sessions with stroke patients. Nevertheless, the results obtained in the reported control modes demonstrated that design and implementation of Wrist Gimbal achieved the design goals and considerations.

V. CONCLUSION

We have presented details of the design and implementation of Wrist Gimbal, an exoskeleton for upper extremity rehabilitation after stroke. Wrist Gimbal is comprised of a serial kinematic structure with three revolute joints corresponding to forearm rotation, wrist flexion/extension and

wrist abduction/adduction. The design focused on developing a mechanically robust, safe and easy to use device in a clinical setting. Initial testing of the device was conducted with a healthy subject. Future work will involve the development of additional passive, resistive and assistive control strategies involving virtual reality environments and a graphical user interface.

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