Restoring ADL Function after Wrist Surgery in Children with Cerebral Palsy: A Novel Bilateral Robot System Design*

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***Abstract*—Cerebral palsy is a leading cause of disability in children and reducing its effects on arm function will improve quality of life. Our goal is to train children with CP after wrist tendon transfer surgery using a robotic therapy system consisting of two robot arms and wrist robots. The therapeutic goal is to determine if the robot training combined with surgery intervention improved functional outcomes significantly more than surgery alone. To accomplish this long-term goal we have developed a Bilateral ADL Exercise Robot, BiADLER aimed at training children with CP in reach to grasp coordination on ADLs. Specifically, the robot will provide active training using an assist-as-needed. This paper presents the design concepts.**

Keywords—cerebral palsy; robot-assisted therapy; wrist orthosis;

I. INTRODUCTION

Cerebral palsy (CP) is a condition that is the most common cause of severe physical disability in childhood[1]. Characteristics signs include spasticity, movement disorders, muscle weakness, ataxia, and rigidity[1]. Static brain lesions appear differently in each individual with CP, and depending on their location and extent, the level of motor impairment will vary [1].

Children with cerebral palsy often have hemiplegia, which in affecting one side of the body more than the other can lead the child to become a “one-handed expert” with their normal functioning arm. In [2], both hemiplegic and normally functioning kids were asked to complete various tasks including touching hand to head, touching hand to mouth, and reaching out to touch a stationary object. Results from this study showed that the hemiplegic kids achieved significantly less supination and greater forward trunk flexion in the hand to head task, less supination and greater forward trunk flexion and shoulder flexion in the hand to mouth task, and significantly less elbow extension in the reach task. Another interesting observation from this study was for bilateral tasks, the movement of the normally functioning limb tended to match the movement of the hemiplegic limb. This could be a result of the brain attempting to maintain the symmetry of bilateral movements by slowing the normal arm down since it is unable to naturally improve the movement of the impaired arm. In addition to reduced range of motion, time to complete the tasks was greater for the hemiplegic kids. These limitations may be attributed to reduced strength, fatigue, and lack of confidence in the movement, which would cause the child to move slower in order to achieve a more accurate movement.

Reaching and grasping function for ADLs may be challenged in different ways due to impairment in shoulder complex, elbow flexors, and wrist complex. For a child with cerebral palsy, wrist motion in the extension and supination directions can prove difficult, and will inhibit their ability to perform everyday tasks. With no cure available for cerebral palsy, current treatment options focus around managing the condition and helping to improve quality of life. These treatments are normally either pharmacologically or therapeutically based, working to improve joint range of motion, strengthen muscles, provide stability, improve motor development, and reduce spasticity [1]. Surgical interventions have also been used and have shown promising results. The goal of surgery is to improve function in the short term. For kids with cerebral palsy, wrist deformity occurs in pronation, flexion, and ulnar deviation, making it difficult to perform all opposing motions (supination, extension, radial deviation)[3]. This can lead to issues with bimanual movements and grasp and release functions [3]. The primary correction of these deformities involves transfer of a wrist flexor (flexor carpi ulnaris) to a wrist extensor (extensor carpi radialis brevis). By performing this transfer over the ulna and not through the interosseous membrane, supination can be improved in addition to extension. As a result of this surgery, certain movement limitations present themselves. The child is unable to perform any passive wrist flexion or resistive wrist extension for 3 months, and cannot passively flex the wrist greater than 45° permanently [3].

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The need after surgery is to recover ADL function, specifically getting the child to achieve coordinated reach-to-grasp function. Our goal is to train children with CP after wrist tendon transfer surgery using a robotic therapy system consisting of two robot arms and wrist robots that can be used with the robot arm. The therapeutic goal is to determine if the robot training combined with surgery intervention improved functional outcomes significantly more than surgery alone.

The use of robot assisted therapy to improve arm function in children with CP is not new. Fasoli et.al. [4] performed a study on hemiplegic CP children focusing on upper extremity rehabilitation using the InMotion2© robot. The goal of the study was to verify the feasibility of introducing robotic therapy as a legitimate means of improving motor skills, and in this respect it was successful. In the study children performed planar motions exclusively. A study by Qiu et.al. [5] focused on the use of virtual reality as a therapeutic intervention using the Haptic Master© therapy robot. The system employed 3-dimensional virtual tasks, providing visual feedback in addition to the force feedback from the robot. The study showed positive improvements for a small subset of patients with mild to moderate hemiplegic CP. Our goal was to develop robot-assisted therapy system that would retrain children with CP on unilateral and bilateral ADLs. The robot would be used after surgery to augment standard therapy. From Shriner's Hospital in Chicago, the time to functional recovery with standard therapy alone varies from 4-6months. We anticipate that since robot therapy often see improvement results within 4 to 8 weeks, adding robot therapy to the standard therapy should reduce the time to recovery. Our design is unique in that is develops a desktop bilateral system of robots for real and virtual ADL practice. The design is inspired by the ADLER robot system that has been shown to improve motor control and ADL function [6,7].

This paper discusses our design and development strategy for a bilateral robot system, Bilateral ADL Exercise Robot (BiADLER) that would assist children with CP on unilateral and bilateral ADL coordination. The unique goal is to develop an ADL training system that can provide assistance-as-needed for reach, wrist pronation/supination and wrist/flexion/extension.

II. BILATERAL ROBOT DESIGN REQUIREMENTS AND SPECIFICATIONS

A. Design Criteria

Initially the design criterion for this system was amassed through several collaborative design meetings with the technical and physical therapy staff of Shriners Children's Hospital. It was there that the needs of our target population were better understood while the vision and goals for the system's design were laid. The resultant primary study requirements were as follows:

- The age of children with CP is to be between 7-14 years.
- Therapy team wanted to use many of the established activities of daily living but adjust their functional context to better suit children.
- To achieve the full range of tasks, a horizontal as well as a removable vertical workspace was desired.
- The robotic system is to help control and guide the position and orientation (flexion/extension and supination/pronation) of the child's hand for use in grasp/release exercises.
- Because the therapy would be comprised of grasp tasks and many of the subjects would more than likely have spasticity that would make the difficult to get the thumb out of the palm, the palm and hand in general needs to remain as unobstructed a possible while maintaining active assistance in wrist orientation.
- Since the majority of the population have shoulder (proximal) strength and poor distal strength, the robot must implement an assist as needed strength training paradigm for arm positioning and an assist-as-needed orientation control paradigm.
- In order to keep all of the subjects across the age range seated flat footed and comfortable in a torso restraint while interacting with both workspaces, the chair as well as the table height would be fully adjustable.
- Along with data collection, organization, analysis, presentation of data outcomes, the system must implement a GUI that allows easy set-up and adaptive control algorithms for training.

B. Environment Design Objective

Once all of the requirements were compiled, the main design objectives were defined. It was decided that the system would consist of two robotic arms that would interface with the subjects through an orthosis style end-effector. Though the system would have a bi-lateral configuration, it would only assist uni-laterally; with one robotic arm being active whiles the other remains passive (*Fig. 1*).

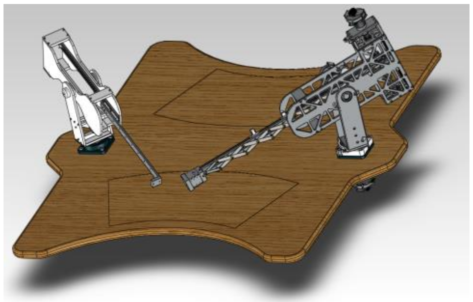

Fig. 1: CAD Design for Robotic Arms & Double Sided Workspace.

Since our subject population would be comprised of both right and left handed impairments, the system would have to be double sided allowing for the physical relocation of the subjects from one side to the other depending on their handedness. This would require a mirrored workspace with mid-line placement of the robotic arms so they could operate equally in both. Because we were looking at footprint constraints for the implementation of this system, a positioning structure for the robot that had revolute-revolute-prismatic (RRP) degrees of freedoms. There are two robots in the resulting system. The "active" robot is to be used with the impaired arm; it has 5 active degrees of freedom (DOF) and 2 passive DOF, 3 active positioning degrees of freedoms RRP, and 1 active orientation degrees of freedom, and 1 active wrist flexion/extension. The “passive” robot has the same position structure and orientation RRR to enable measurement of less impaired arm.

C. Device (therapy environment and tasks)

Construction of the system began with a single sided version of the Therapy Environment (*Fig. 2*). Here a standard office chair was modified, reinforced, and fitted with a butterfly style torso restraint harness. V-contoured rails and a rolling caddy with over-under V-groove wheels were then welded up out of aluminum to save on weight, making the eventual rolling of the seated environment from one side of the table to the other as easy as possible. Screw clamps on each side of the caddy allow the subjects to be locked in place once they were positioned at the table. The original 4 inch height adjustment of the office chair was maintained while a spring loaded pop-pin mechanism allows the chair to be locked into the forward, 90º right, or 90º left positions (for therapy or entering/exiting the chair on either side). The entire rolling chair assembly bolts to the base of a ConSet motorized height adjustable table with threaded knobs that allow for tool-less docking.

A battery of tasks, similar to the ADLER [6] system, will be implemented. Subjects will perform selfcare tasks such as eating and drinking, and games tasks that emphasize grasping and orientation of objects after reaching to pick them up. Bilateral tasks such as reach to stack objects bilateral and reaching to complete two handed games will be utilized. A GUI will control task environment.

Fig. 2: Active Prototyped System Configuration. Positioning portion seen with Hapticmaster Gimbal

D. Device (robotic arms)

Since the system consists of one passive and one active assist robotic arm, the design of each is quite different (*Fig. 3*). The passive system will have 6 non-controlled DOFs RRPRRR and is mostly SLS Rapid Prototyped construction with a lightweight aluminum prismatic joint assembly. Since this is the passive half of the system, and will serve solely for position measurement, it is only outfitted with resistive elements. Rotary potentiometers are being used to measure revolute joints and a linear potentiometer is used for the prismatic joint.

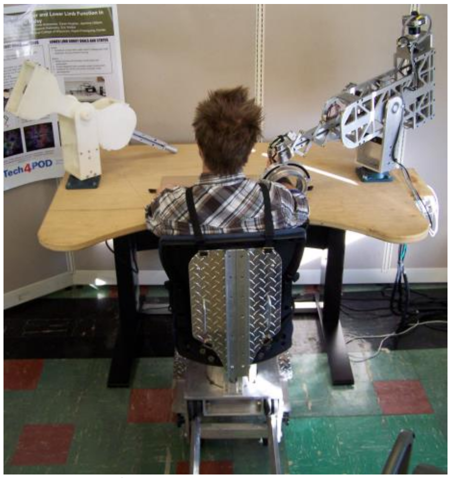

Fig. 3: Prototypes of Active and Passive Robotic Arms

The active robot has 7 DOFs RRPRRRR with only 5 of those degrees of freedom being controlled. The robot is an all-aluminum chassis with both revolute joints being driven by Maxon EC90 Flat motors with identical Planetary Gearheads providing the speed reduction and torque required. For the prismatic joint, a third Maxon EC90 Flat motor fitted with a different Gearhead ratio drives a ball screw which actuates the telescopic scissor assembly. Figure 4 shows a closer look at the position structure. Table I lists the Denavit-Hartenberg (D-H) parameters that define the frame arrangement for the positioning structure. Table II summarizes the mass properties for the active robot system. The orientation design is described in section III.

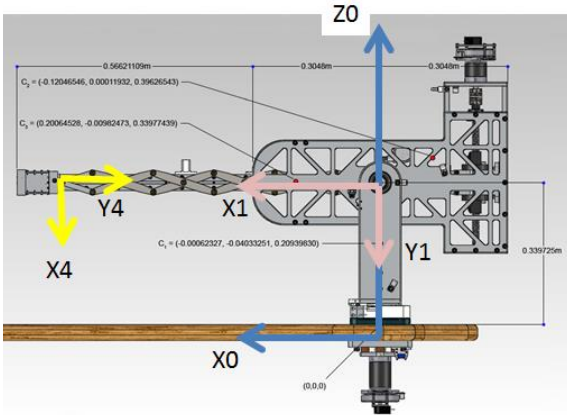

Fig. 4: Active Robot Positioning Structure.

TABLE I. D-H PARAMETERS POSITIONING STRUCTURE

Name	Joint Angle	Link Offset	Link Length	Link Twist
shoulder	θ1	d1=0.34m	a1=0	α1= -pi/2
elbow	θ2+pi/2	d2=0	a2=0	α2= pi/2
scissors	0	d3=d3+0.305 m	a3=0	α3= -pi/2

TABLE II. PROPERTIES OF POSITIONING STRUCTURE

	Mass	ROM for joints
Link 1	5.6 kg	$\theta 1$= +/-90 degrees
Link 2	8.79 kg	$\theta 2$= +45/-90
Link 3	5.52 kg	d3 = 0 to 0.56m

III. BIADLER ORIENTATION STRUCTURE: WRIST ORTHOSIS

A. Range of Motion and Torque Assistance

In creating a wrist orthosis to improve functionality for a child with cerebral palsy, many requirements must be established relating the user, device, tasks, and environment to each other. The user of the device will fall into the 7-14 year old age group, be hemiplegic, and has a level of impairment that still allows functionality of the affected limb. Based on data collected, wrist diameters for children in this age group ranged from 3-7 cm, requiring the size of the device to be at least this large to accommodate all users, especially the older ones that are more fully developed. The children using the device will have undergone surgical procedures previously, so range of motion in flexion will be set at 45° while maximum extension will be set at 70°, as previously established by Masia et.al.[7]. Total rotation of the wrist (pronation/supination) will be set at 160°[8] but the device can still be successful by providing a range of rotation of only 100°[3]. Gupta and O’Malley reported that just over 5 Nm was the peak torque capability of the wrist in all three planes of motion, and since this value was incorporated into their design, we found it sufficient to use this output in our design as well[3].

B. Mechanical Structure

Structure is key in this design since many of the tasks the user will be asked to perform involves moving the hand around and bringing it close to the face and head. Therefore, safety will need to remain a priority in any design concept. Other requirements include being lightweight, comfortable, durable, and size adjustable. Most wrist rehabilitation devices developed to this point have been large and bulky, focusing on the improvement in motion rather than the use of the hand[7,8-12]. The goal is to minimize size as much as possible while still allowing the device to function as needed. To create durability and rigidity of the device, a lightweight metal, like aluminum, appears to be the best option. Other devices using this material have successfully been able to maintain their structural integrity after prolonged use. Plastics provide a low-weight and low-cost option, but are brittle, may have trouble holding other electrical components, and are not electrically conducive to the device. A tougher metal like stainless steel would provide strength and electrical conductivity, but can be heavy. Too much weight in the device could result in a reduction of the user's ability to move easily.

C. Current Prototype Design

Our current orthosis design incorporates two independently operating actuators utilizing cable drives to generate movement for pronation/supination and flexion/extension (fig. 5). The structural assemblies for these motions are attached to a trough with a telescoping design to provide support for the forearm and stability to the rest of the system. The full orthosis will be attached to the Bi-Adler robot arm through an L-shaped bracket and square connector that allow passive motion in flexion/extension and radial/ulnar deviation in order to position the wrist within the workspace based on the desired task that needs to be performed. Similar robotic therapy devices have utilized a gimbal design for the orthosis end effector, including the HapticMaster, whose othosis we have used as a temporary option as we develop our own. While effective in actuating wrist and forearm rotation, the heavy and bulky nature of its physical structure requires more force to create movement, putting greater stress on the robot positioning arm. The full circular design also inhibits the ability of the user to make contact with the therapy surface, which is necessary to perform the activities of daily living asked of the user. Our gimbal employs a horseshoe-shaped gimbal structure, allowing closer contact to be made with the therapy surface, and lighter design, limiting the amount of material needed to support the functionality of the orthosis.

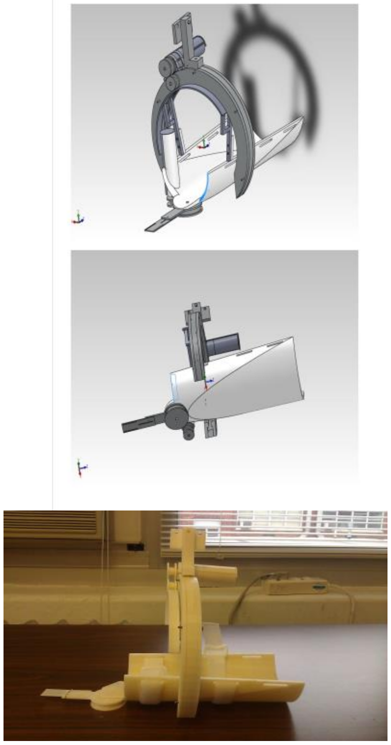

Figure 5: Orthosis Design Concept

Actuation of pronation/supination uses an open gimbal design, allowing closer contact to the table top surface where the tasks are initiated. The gimbal is made up of three pieces, two external and one internal, which connect to form an inner track. A bushing surface will be established within the track to allow for free, frictionless movement for pronation and supination. Actuation of flexion/extension is accomplished using a link assembly that attaches to the bottom of the hand and is secured by two straps wrapping through the links and around the hand. The first hand link is incorporated with a spindle that will rest over the same anatomical axis that's used for flexion and extension. Table III summarizes the D-H parameters for the orientation and wrist flexion and extension. Table IV the inertial and ROM parameters.

TABLE III. D-H PARAMETERS POSITIONING STRUCTURE

Name	Joint Angle	Link Offset	Link Length	Link Twist
Pitch-like	θ4	d4=0	a4=0.145	α4= pi/2
Pro/Sup	θ5+pi/2	d5=0	a5=0	α5= -pi/2
Yaw-like	θ6	d6=0	a6=0.0545	α6= 0
Wrist flex/ext	θ7	d7=0	a7=0	α7= 0

TABLE IV. PROPERTIES OF ORIENTATION STRUCTURE

Gimbal Specifications		
Specification	***Value***	***Units***
Internal Diameter	14	cm
External Diameter	18	cm
Trough Length	23.2	cm
Joint 4 ROM	-90/90	degrees
Pronation/Supination ROM, Joint 5 (ACTIVE)	80/80	degrees
Joint 6 ROM	-45/45	degrees
Wrist Felx/Ext Joint 7 ROM (ACTIVE)	-45/70	degrees
Desired Wrist Torque	5	Nm
Desired Pronation/Supination Speed	80	rpm
Actuator Torque	19.6	mNm
Actuator Speed	31,900	rpm
Gear Reduction (from gearhead)	29:1	
Gear Reduction (from gimbal)	14.4:1	
Link Assembly Specifications		
Hand Link Length	8.0786	cm
Adjustable Link Length	6	cm
Flexion/Extension ROM	45/70	degrees
Desired Wrist Torque	5	Nm
Actuator Torque	19.6	mNm
Actuator Speed	31,900	rpm
Gear Reduction (from gearhead)	29:1	
Gear Reduction (from stage 1 pulley)	2.5:1	
Gear Reduction (from stage 2 pulley)	4:1	

IV. BIADLER CONTROL DESIGN

This system is operated out of a Matlab developed GUI that interfaces with the robotic systems through a Real-Time TargetPC (*Fig. 6*). The TargetPC is out-fitted with Data Acquisition and Quadrature Encoder cards as well as the CAN Bus controller card used to communicate with the 5 Maxon EPOS2 70/10 closed loop position/speed/current motor controllers during robotic operation. There also exists a parallel USB communications bus us primarily for programing and troubleshooting the controllers. Additionally 3 levels of safety have been integrated into the system to help protect the subjects from harm. The first is at the disposal of the technician operating the system and would be located in software. The software stop signals a system pause, where by the arm position locks and is released only when the signal is cleared. The second is at the disposal of the subject in the form of an E-Stop button that functions as a system halt. This button bypasses the software and triggers a hardware level position lock that can only be released by re-setting the E-Stop switch. The third is only available the operating technician and is a power kill switch that will cut power to the motors in the event that software and hardware were not responding.

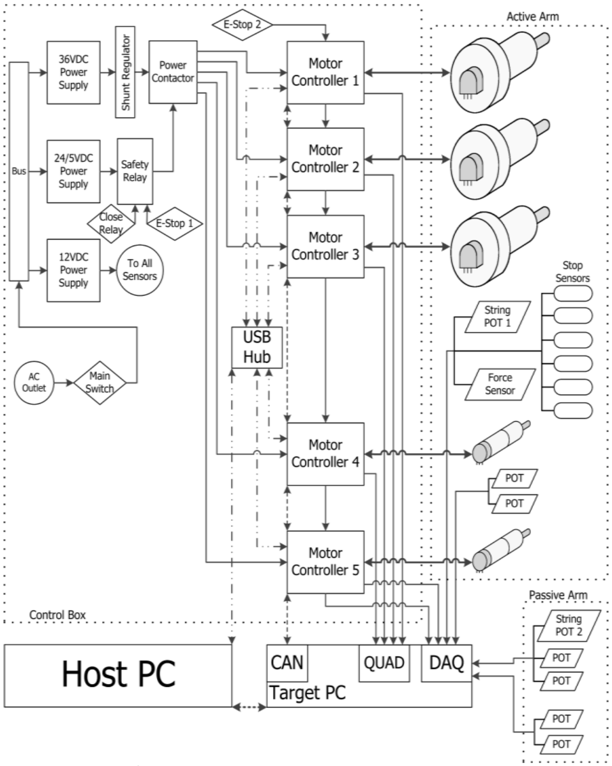

Fig. 6: Simplified System Block Diagram

A. Control Design

In employing a control strategy for the device, both position control and force control will need to be implemented to obtain the desired output from the device. Several techniques have been used in similar devices, giving a wide range of ideas to go off of in developing our own control system. The ADLER GUI and training strategies will be used as a stepping off point for control of the system with changes being made for platform differences [6]. The system uses a PID control to implement the low-level controllers and will have a variety of supervisory strategies to control arm and hand movements [12-14].

V. CONCLUSIONS

We presented a new therapeutic design for training children using a bilateral ADL exercise robot. The concept was presented and current development was described. Next steps are the finalization supervisory control strategies and testing with target population. The advantages of this design over existing systems aimed at CP children is that it is a bilateral desktop system that will support reaching as well as grasping tasks. The design is tuned to support the retraining of wrist motions that are targeted by the wrist tendon surgery. Hand retraining uses Functional Electrical Stimulation.

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