A Modular Low-Clearance Wrist Orthosis for Improving Wrist Motion in Children with Cerebral Palsy

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***Abstract*— Children with Cerebral Palsy (CP) often exhibit impairments in the coordination of the grip and lift phases of arm movements that directly impact their ability to perform activities of daily living (ADLs). The application of assistive robotic therapy to children with spastic hemiplegic CP has shown that augmented movement training can lead to improved functional outcomes and improved arm kinematics. Assistive robotic therapy of the wrist has been shown to help improve motor skills in stroke patients, but the devices employed are often large and obtrusive, focusing on a repeated motion rather than a task-based itinerary. Here, we propose a lightweight low clearance wrist orthosis for use in children with Cerebral Palsy that actuates pronation/supination and flexion/extension of the wrist.**

I. Introduction

Cerebral palsy is a neurological condition that is the most common cause for severe physical disability in childhood [1]. Characteristic signs include spasticity, movement disorders, muscle weakness, ataxia, and rigidity. Difficulty holding and detecting objects develop as a result of abnormal stereognosis, diminished 2-point discrimination, and diminished proprioception. With no cure available for cerebral palsy, current treatment options focus around managing the condition and helping to improve quality of life. Treatments can be pharmacologically or therapeutically based, or can involve surgical intervention. They work to improve joint range of motion, strengthen muscles, provide stability, improve motor development, and reduce spasticity [1]. Surgery corrects physical deformities that limit the ability to complete grasp and release functions by transferring a wrist flexor to a wrist extensor, improving range of motion in extension and supination [2].

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The idea of assisting improvement in wrist motion through robotic means has been explored extensively with stroke therapy. Devices such as RiceWrist [3,4] and Wrist Robot [5], have been developed for stroke therapy using an exoskeleton approach with a rigid structure, matching the anatomic positions of the wrist joints. A handle is employed for the user to grasp as they are performing wrist movements. The InMotion2 [6] and NJIT-RAVR [7] have demonstrated the feasibility of applying robot-assisted therapy to a juvenile population with Cerebral palsy. The structures of these devices remain similar to their stroke therapy relatives, with emphasis is placed on the virtual task environment designed to maintain the user's attention. The design of these devices can limit physical interaction with objects, making the implementation of task-based therapies to improve activities of daily living (ADLs) problematic. The goal of this research is to create a robotic device for task-based therapies to improve ADLs that is minimally obtrusive and maintains a low profile while allowing the hand to remain open for the manipulation of therapy objects.

II. Methods

A. Structure and Design

Since the proposed device is intended for use on children with cerebral palsy in a task-based therapy environment, special attention was taken to keeping the device lightweight and safe, while providing it with a low clearance to the therapy environment and allowing the hand to remain free to grasp and release objects. The system is designed to monitor and provide corrective torques about the wrist as needed, based on generated task-relevant movement profiles. Corrective torques can be applied in support of pronation, supination, flexion, and extension, with the remaining degrees of freedom monitored passively.

The full system consists of a passive 3 DOF arm and a 4 DOF wrist orthosis with 2 actuated DOFs, mounted to a wooden tabletop therapy environment (Fig. 1). A task board is included with the tabletop where therapy objects can be placed. Each object has a shape-specific slot, allowing the location of objects to be fixed across successive trials and facilitating comparisons between task-based therapy sessions. The passive arm has a revolute-revolute-prismatic (RRP) configuration, allowing 3-dimensional positioning within the workspace. The orthosis interfaces with the passive arm through a series of aluminum links that allow passive yaw (180°) and pitch (120°) of the orthosis for orientation. Pronation and supination are initiated through a

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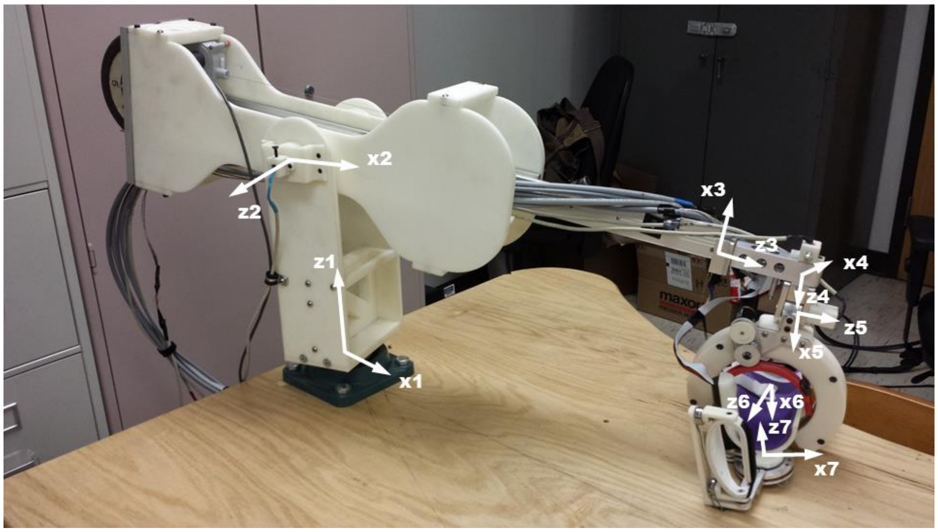

Figure 1. Orthosis and passive arm with rotational reference frames. The z-axes represent the axis of rotation, while translation from one joint to the next occurs along either the x or z-axis.

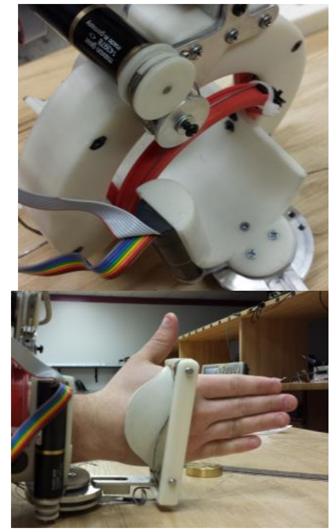

Figure 2. (Top) Actuation system for pronation and supination. A cable and pulley system is used to couple the motor shaft to a protruding raceway (red). (Bottom) Hand brace with mounted load cells. The fingers and thumb are unconstrained to facilitate grasping and manipulation of objects.

turntable bearing (American Precision Group™ AT04535) mounted to a trough where the forearm rests. Actuation of pronation and supination is driven by a cable and pulley system coupled to a brushless DC motor (Maxon™ EC22 motor with GP22C planetary gearhead) through an external raceway attached to the turntable bearing (Fig. 2). The DC motor can provide up to 5 Nm of torque continuously about the wrist [3]. Flexion and extension are facilitated by an aluminum spindle located beneath the wrist joint and linked to a brace that supports the hand just below the metacarpals (Fig. 2). The brace design enables the application of flexion/extension torques while leaving the hand open for grasp and release tasks. Actuation is accomplished by similar means through a cable and spindle coupled to a second DC motor/gearhead combination (Maxon™ EC22 motor with GP22C planetary gearhead).

Safety was emphasized in the design by positioning the motors to prevent user contact with the moving elements, and direct heat transmission away from the user. Mechanical stops were added to limit the ranges of motion of the actuated joints (±70° for flexion/extension and pronation/supination [8]). An emergency stop button was wired to the electrical power system to enable the user to abort actuation of the wrist by cutting power to the motors.

B. Feedback and Control

The orthosis is fully sensorized to provide real-time feedback as the device is operated. Single-turn potentiometers on the passive joints and two digital encoders on the actuated joints are used to provide joint-space position information. The hand brace is outfitted with two tension and compression miniature load cells (Omega™ LC201) to provide force data during movement. This information is used to overcome the inertia of the motor/gearhead by commanding a compensating torque from the motors. Fig. 3 shows a communication flow diagram between the peripheral devices in the system. The main control box houses the electronic components including a digital positioning controller for each motor (Maxon™ EPOS2 70/10). The controllers drive the motors and monitor their performance via Hall effect sensors and digital encoders. The controllers receive commands from the

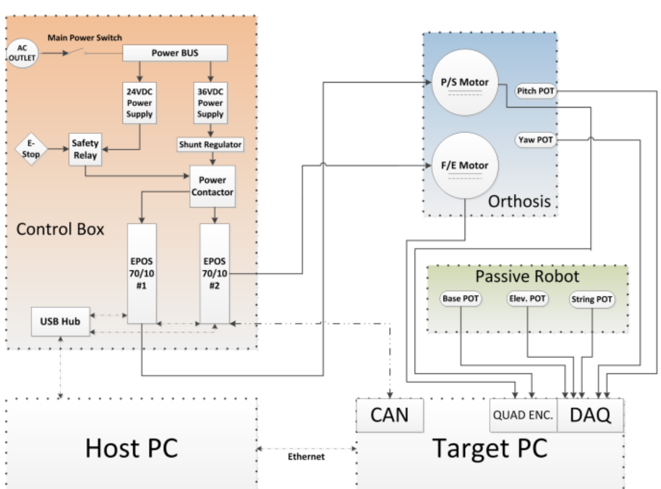

Figure 3. Flow diagram for communication between system elements

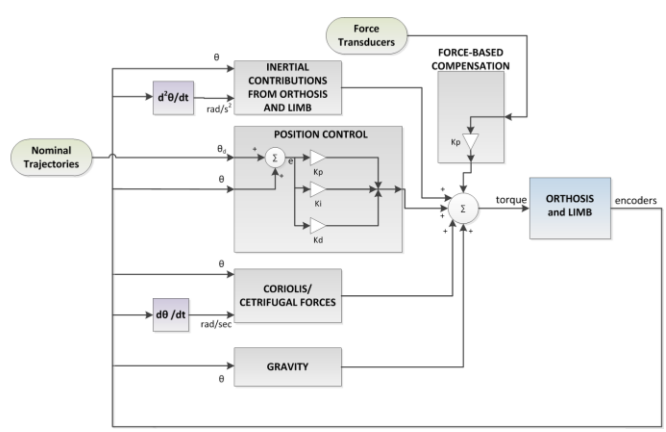

Figure 4. Orthosis position and force feedback control

control algorithm using a CAN communication line running from the target computer and an Ethernet network connection established between the target and host computers.

Real-time control of the orthosis is performed using the MATLAB Simulink™ environment. The torques applied by the orthosis are based on the equations of motion for the robot

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) \quad (1)$$

where M(q) is the inertia matrix created from the joint dynamics, C(q, q dot) provides vectors for the contributions of Coriolis and centrifugal forces based on joint position and velocity, and G(q) is the vector contribution of gravitational forces based on joint position. The developed position controller uses negative feedback from the encoder outputs to generate corrective torques to reduce the error between the desired and actual wrist position. A feed forward component is included in the torque control law to calculate the torque needed to move the orthosis along its desired path such that

$$\tau = M(q)\ddot{q}_d + C(q,\dot{q})\dot{q}_d + G(q) + K_v\dot{e} + K_p e + J^T(q)F \quad (2)$$

where K_p is the proportional gain for position control while K_v represents the derivative gain. This formulation, referred to as the "augmented PD control law", was selected to reduce computational demands and reduce delays in the closed-loop response [9]. Force feedback was incorporated through an additional term, where J is the Jacobian matrix for the actuated joints and F is the forces read from the load cells.

C. Normative Trajectory Development

Task-relevant actuation of the wrist is determined in real-time by comparing the subject's task specific movement profile with a desired (normative) movement profile obtained from age-matched control subjects performing the tasks without any assistance from the system. Variability in the movement profiles across subjects is used to provide graded actuation and correction of movements that deviate from the normative range of movement. Nominal trajectory profiles are obtained from different approach directions to account for variations in subjects' initial trajectory (i.e. approach), which can impact the subsequent task-based kinematics. The resulting trajectories are incorporated into the control model, and used by the position controller to compare against the recorded position of the joint and calculate the output torque. Due to the inability to control the approaches taken by the subject's shoulder and elbow toward the therapy object, a series of trajectories are made available for each task, and the appropriate one is accessed based on the kinematic proximity to the object.

D. Pilot Testing of Normative Trajectories

Movement profiles were recorded for a healthy male, adult subject (age 27) performing a cup-to-mouth task. Ten iterations of the task were recorded in 15 second intervals using the subject's dominant arm. For each trial run, the cup was placed in the same spot, and the subject began each task from a predefined "home" position. The subject was told to perform the task with a speed and an approach that felt most natural to them. Data was recorded from the actuated joint encoders and force transducers, giving position and force information related to the task. Mean and standard deviation across trials was calculated for each instant of the movement profile.

III. Results

Fig. 5a and 5b illustrate the change in position over the course of the task. The greatest variability in position for pronation and supination occurred where joint orientation either changed direction or slowed down (t=6.3 sec, $\sigma=\pm 12.7°$, t=7.5 sec, $\sigma=\pm 11.6°$, t=8.9 sec, $\sigma=\pm 10.4°$). The largest variations in flexion and extension occurred during joint angle maxima (t=5.7 sec, $\sigma=\pm 6.3°$, t=7.4 sec, $\sigma=\pm 9.3°$, t=9.0 sec, $\sigma=\pm 7.4°$). Fig. 5c and 5d show the corresponding forces produced at the hand brace, as illustrated in fig. 2. Variations in force were largest when maximums for tension and compression were recorded (tension: t=5.8 sec, $\sigma=\pm 2.1$ N, t=7.4 sec, $\sigma=\pm 3.8$ N; compression: t=7.1sec, $\sigma=\pm 4.4$ N).

IV. Discussion

The final design of the orthosis showcases a lightweight and simple, yet powerful device. The low force outputs seen in the pilot data suggest the orthosis will not be subjected to operating forces that might structurally damage it. No clearance issues were encountered when grasping and lifting the cup off the tabletop, suggesting that the low clearance of the device is suitable for other types of grasping and object manipulation tasks.

The pilot data presented illustrates the patterned trajectory profiles that can be expected from a therapy task like bringing a cup to the mouth. For this task, we see the wrist using varying degrees of pronation exclusively, alternating from flexion to extension, and back to flexion throughout this process. This profile is expected for a drinking task as the wrist is used to tilt the cup to the mouth in order to drink. Variations in flexion and extension of the wrist throughout the movement are used to maintain positional control of the cup in parallel to the table. Though the data was collected for one subject only, the fact that greater variability was seen at points where the wrist changed direction and reached a maximum point in the trajectory suggests that an individual may not perform a task the exact same way every time. Areas of greater variability may also be a consequence of the small sample size, and may become less prevalent as the number of included samples is increased.

The force plots (Fig. 5c,d) show the top load cell featuring primarily tension while the bottom load cell shows primarily compression during the performance of the drinking task. This provides verification that the physical configuration of the load cells can be used to differentiate force production about the actuated degrees of freedom at the wrist. The simultaneous occurrence of tension at the top

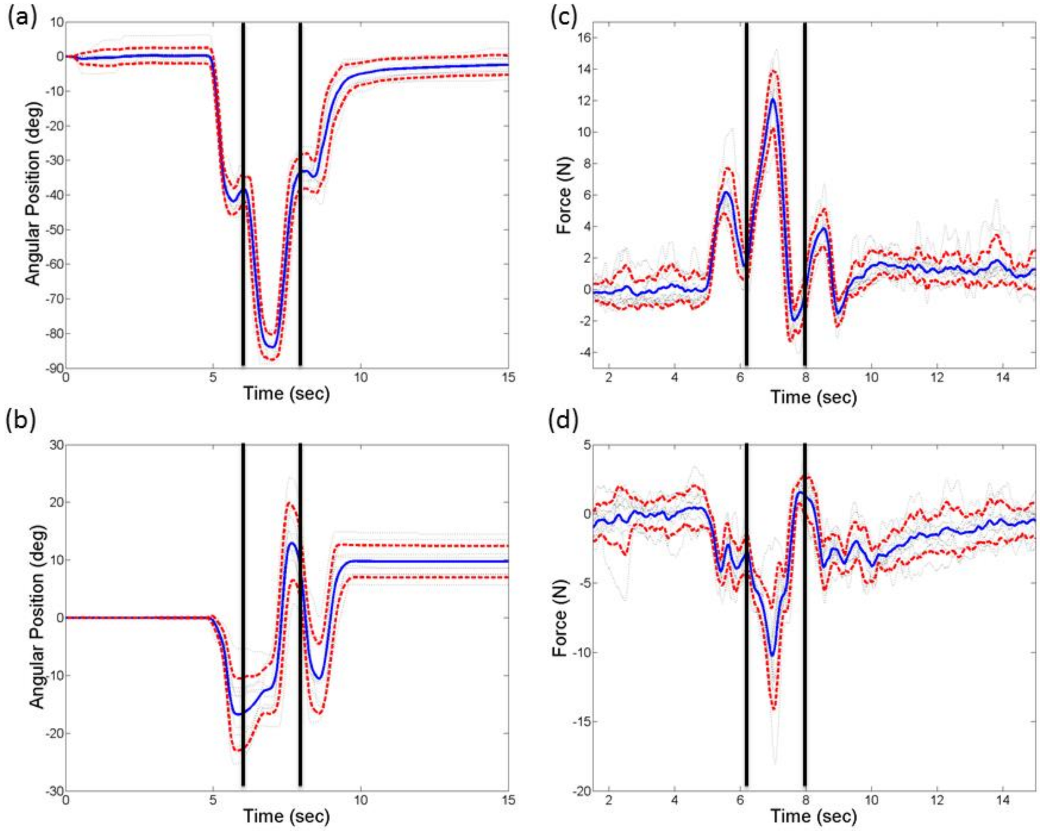

Figure 5. Normative position and force profiles for cup to mouth task. The blue lines represent the mean trajectory, the red dashed lines represent one standard deviation, and the black dotted lines are the raw data. (a) Position profile for pronation (-) and supination (+). (b) Position profile for flexion (-) and extension (+). (c) Force profile for tension (+) and compression (-) of top load cell. (d) Force profile for tension (+) and compression (-) of bottom load cell. The black vertical lines denote the three major events within the task; moving from home position to the cup, bringing the cup to mouth and back down, and moving from the cup back to home position.

cell and compression at the bottom cell indicates pronation, and is verified by the position change in fig. 5a.

Moving forward, the formulation of normative task-specific trajectories shown here will be used to evaluate active compensation of the orthosis during task-based therapies in which normal functioning subjects purposely deviate from the nominal trajectory while performing the task-based therapy. To accomplish this, the subject will make predetermined deviations from the desired path while performing the task. Subjects will then be asked to keep their limb relaxed throughout the task as a means of testing how well the device works in a situation where the user is unable to make the movement themselves. This condition will test the ability of the device to overcome the total inertia of the limb to complete the motion, and simulates an instance where the user has limited use of the extremity due to spasticity or physical deformity. Quantitative analyses of task response time, trajectory and endpoint accuracy at predefined task events, and qualitative assessments of the quality and "feel" of the assistance by users will be used to further optimize the control system and refine the device design.

V. Conclusion

The lightweight and modular design of the wrist orthosis makes it ideal for use in task-based therapy. By using light metals and plastics in its structure, the device is easily maneuvered and manipulated by the user. With its modular structure, the device can easily be detached from the current setup and implemented into a different therapy environment. With positive verification that the device is able to assist the maintenance of normative task-specific trajectories in healthy subjects, the device will be incorporated into task-based therapies conducted on a CP population. Robotics has shown to have a positive effect in upper extremity rehabilitation and to have a tool like this in task-based therapy would be invaluable.

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