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DESIGN AND IMPLEMENTATION OF AN EXOSKELETON GLOVE FOR INFANT MEDICAL REHABILITATION

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ABSTRACT
This paper describes the design and implementation of an exoskeleton glove for infants of ages ranging from 12 months to 3 years. The glove is capable of assisting the patient in achieving a pincer grasp in active and passive modes of operation. It can record information about the hand movement, forces exerted by the fingers on the exoskeleton frame, and provide vibration stimuli to the finger tips. The data recorded by the glove can be used in early diagnosis of cerebral palsy among high risk infants. It can also be used as a standalone device for rehabilitation purposes. The hardware, software architecture and experimental validation of the system are outlined in this paper.

NOMENCLATURE

MCP	Meta-Carpophalangeal
PIP	Proximal Interphalangeal
DIP	Distal Interphalangeal
DP	Distal Phalanges
MP	Middle Phalanges
PP	Proximal Phalanges
IP	Interphalangeal

1 INTRODUCTION
Cerebral palsy (CP) is commonly described as the paralysis of voluntary movement in certain body parts as a result of abnormalities to the brain's cerebrum. CP is the most common motor disorder that affects children [1]. According to US population studies, an estimate of 0.3% children are diagnosed with CP [2]. Babies that are born prematurely or at a low birth weight have a greater risk of becoming diagnosed with CP [1]. As a result, many high risk infants are closely monitored in neonatal intensive care units. The average birth weight for babies' ranges from 2.5 – 4.5 Kg, with low birth weight considered as being below 2.5 Kg [3]. A report by the CDC found that among children who were born weighing less than 1.5 Kg, the prevalence of CP was 59.5 out of 1,000 live births as compared to 1.1 of 1,000 live births for children born weighing more than 2.5 Kg. For children born in the weight range of 1.5 – 2.5 Kg, the prevalence of CP was 6.2 out of every 1,000 live births [4].

The general procedures for CP diagnosis involve paternal observation and clinical assessments of motor skills and their developmental milestones. Many research groups have conducted studies [5], [6] that focus on the neurodevelopmental and motor control disabilities of high-risk infants, for earlier detection of CP. The medical research community has provided strong evidence that monitoring cerebral processing in response to somatosensory stimuli among at-risk patients is beneficial in the early diagnosis of CP [7]–[10]. Recent medical research [7] has also suggested that the "somatosensory deficits noted in children with CP may be somewhat reversible. [The

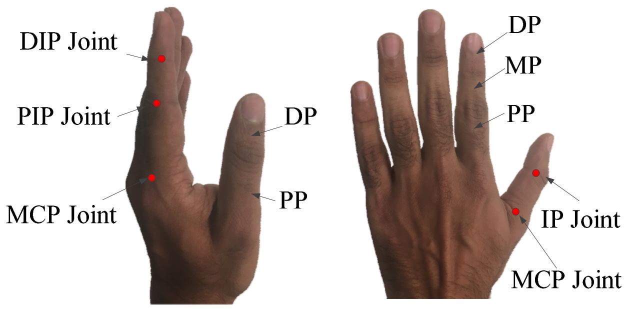

Figure 1. Anatomy of Human hand

researchers] suspect that employing an intensive sensory-training program (touch, proprioception, vibration, and stereognosis) with children with CP may help to restore the somatosensory cortical response to the afferent feedback, and promote beneficial structural improvements in the corticospinal and thalamocortical tracts".

This paper describes the design of an exoskeleton glove to aid with the rehabilitation of infants with CP. The proposed device can assist children of the ages 12 months to 3 years in achieving a pincer grasp using their index finger and thumb. The pincer grasp is known as an essential development milestone for children to accomplish during their infancy. This development typically occurs between the ages of 9 to 12 months of age. Learning the pincer grasp allows infants to pick up small objects on their own. More importantly, infants can start to gain the ability to feed themselves by picking up small bits of food using pincer grasp. Through further development of this grasp, children can begin to master certain tasks such as holding a pencil, or fastening a button. Thus, for children at a higher risk of experiencing some brain impairments and/or slow development of hand motor skills, having this rehabilitation device to teach infants on how to perform a pincer grasp can be of great benefits. Having explained the importance of achieving a pincer grasp, the rest of the paper will focus on the design of the exoskeleton glove to achieve the same in children of the above mentioned age group.

Over the years there has been much research and development on exoskeleton gloves [11]–[15] for both rehabilitation and the assistance in performing daily life activities. Unfortunately, none of these gloves can be used for children due to their heavy and bulky design. In addition, most of the gloves are designed for general grasp-like functionalities instead of a specific rehabilitation exercise like the pincer grasp. In this paper we present the design and implementation of an exoskeleton glove for high risk infants (ages 12 – 36 months) that can be used to help with CP diagnosis. The glove will have a vibration feature that will serve as a stimulus to prompt the infant to achieve a pincer grasp. It can also record hand movement data while the patient is performing pincer grasps. As mentioned in [7], [10], EEG sensors can be used to monitor the reaction time between triggering the vibration stimulus from brain and the infant's initiation for the pinch as recorded by the glove. This data can be used to detect the presence or chances for developing motor control impairments in the hand. For infants already impacted by motor impairments, the glove can be used as a rehabilitation device to assist them with achieving the pincer grasp.

The remainder of the paper has been organized as follows: Section 2 presents the mechanical design of the exoskeleton glove. Section 3 explains the electrical design aspects of the exoskeleton, detailing the sensors and actuators that were chosen. Section 4 describes the prototype implementation, including the overall architecture of the system and its software user interface. The experimental validation is addressed in Section 5. Finally, Section 6 concludes the paper and discusses future work.

2 BACKGROUND

The various joints and segments of the index finger and thumb are described in Fig. 1. In order to achieve the pincer grasp, all three joints (MCP, PIP and DIP) on the index finger and the IP joint of the thumb (keeping the MCP joint restrained) are moved. This can be considered as a single degree of freedom coupled motion on part of each finger.

The overall design requirements can be summarized as follows:

- Achieve proper joint angles for the index finger and the thumb by using only one actuator for each
- Overall size of the system must be small enough to fit a child aged 12 months to 3 years
- Finger trajectory tracked by the mechanism should be repeatable and robust, but should not cause any fatigue to the person wearing it

Based on the above requirements, an initial mechanical design was prepared as shown in Fig. 2. The concept was primarily inspired by the design of the R^3 Robotic tail, a parallel project being conducted in the Robotics and Mechatronics Lab at Virginia Tech. The mechanism for the index finger consists of three planar links that are connected by means of revolute joints. Electric motors are fixed rigidly on the base segments, actuating the first segment through the driving gear. The rest of the segments are coupled by gears, as discussed below:

- The first segment is coupled with the motor shaft (gear ratio G1)
- The second segment is coupled with the stationary base segment (gear ratio G2)
- The third segment is coupled with the first segment (gear ration G3)

The gear ratios were decided based on the relative amount each of the three joints bends on a normal human hand. In [16], experiments were performed to measure the joint angles for the index and thumb during a tip-pinching motion. The data shows that with a tip-pinch force of ~0.98 N and pulp distance of 3 cm, the index finger DIP, PIP, and MCP joints yield average joint angles of 37.1° (SD 9.1°), 35.4° (SD 16.6°), and

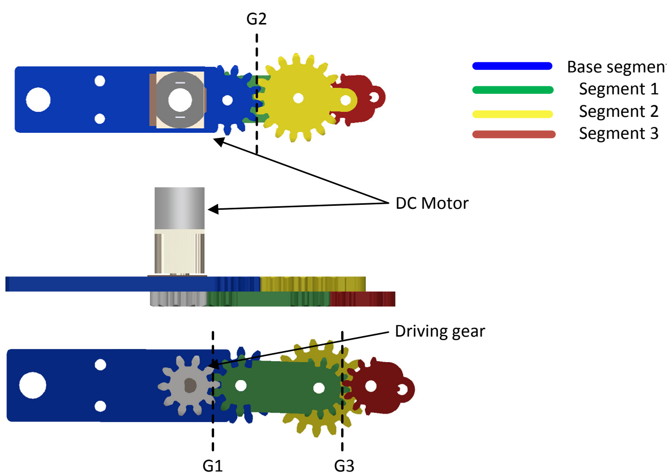

Figure 2. Bending Mechanism for Index finger

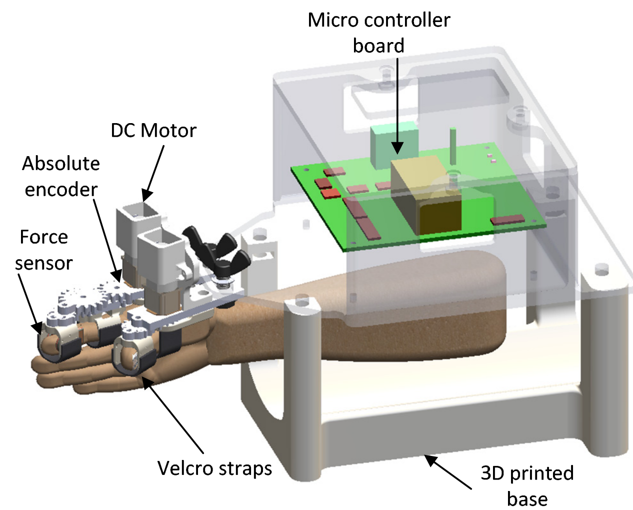

Figure 3. Detailed CAD design of the proposed system

36.3° (SD 9.5°), respectively. Based on the above the gear ratios were selected to be:

- G1 = DC Motor : DIP = 1:1
- G2 = DIP : PIP = 1:1.037
- G3 = PIP : MCP = 1:1.215

In the case of the thumb, a similar but much simpler mechanism was used. Since only one joint (IP) needs to be moved, it was driven directly by the DC motor at 1:1 gear ratio. The prototype was designed specifically for children in the age group of 12 months to 3 years. Based on the data we obtained from [17], the average hand measurements for this age group is as follows:

- Thumb: Interphalangeal – 17.5mm, distal phalange – 17.5mm
- Index finger: proximal phalanx - 15mm, middle phalange - 10mm, distal phalange – 10mm

The overall dimensions of the mechanism including the gear modules were decided based on the above measures.

3 ELECTRICAL DESIGN

The following section details the electrical design of the glove.

Actuation: Pololu micro DC gear motors, rated at 6V, 1.6A were used for both the index finger and thumb segments of the exoskeleton device. Based on the coupling mechanism for the joints of the exoskeleton, the DC motors were able to provide sufficient actuation to achieve the desired flexion and extension trajectories.

Sensors: To achieve absolute position sensing, Bourns rotary encoders were inserted at the base segment above the driving gears for each of the two base segments. These rotary position sensors have a range of $0 - 330$ degrees which is more than the desired range of motion for the MCP joints on the finger and thumb . When the finger and thumb are inserted in the exoskeleton, the encoders in the base segments will therefore be parallel to the MCP joints. The encoder values are converted into angle measurements after proper calibration using digital protractor. The remaining PIP and DIP joints of the index and the IP joint of the thumb are estimated using the mathematical (kinematic) model of the exoskeleton

Force Sensitive Resistor (FSR) sensors by Interlink Electronics were used to measure the amount of force the index finger and thumb are inserting on the respective exoskeleton frames. These FSR sensors have a continuous analog resolution and a force sensitivity range of 0.2N – 20N. The sensors are placed on 3D printed fingertip pieces attached to Segment 3 of both the index and thumb mechanisms. Two force sensors are used for each of the fingertip pieces, one touching the top of finger nail and the other touching the bottom of fingertip. Since the force sensors output resistance values, the sensors had to be connected to a simple voltage divider circuit in order to convert the resistance values into output voltages. This conversion is needed in order to feed the outputs from the force sensors to the analog voltage I/O pins of a microcontroller. The final conversion step was to relate the output voltage values to meaningful force measurements, which was done by performing a calibration process with known weights.

As mentioned earlier, vibration motors are used to provide a stimulus to prompt the user to perform a pincer grasp during the CP rehabilitation process. The Adafruit mini vibration motors are rated for 5V max with a current draw of 100mA. These motors, which have a weight of 0.9 grams each, can provide a vibration output similar to a standard mobile phone vibration.

4 PROTOTYPE INTEGERATION

The detailed design of the system was done in SolidWorks, as shown in Fig. 3. The base segments of each of the bending mechanism were connected to a flat plate by means of thumb screws. This facilitates adjusting the position and orientation of the mechanism to suit for different hands. The flat plate is fixed

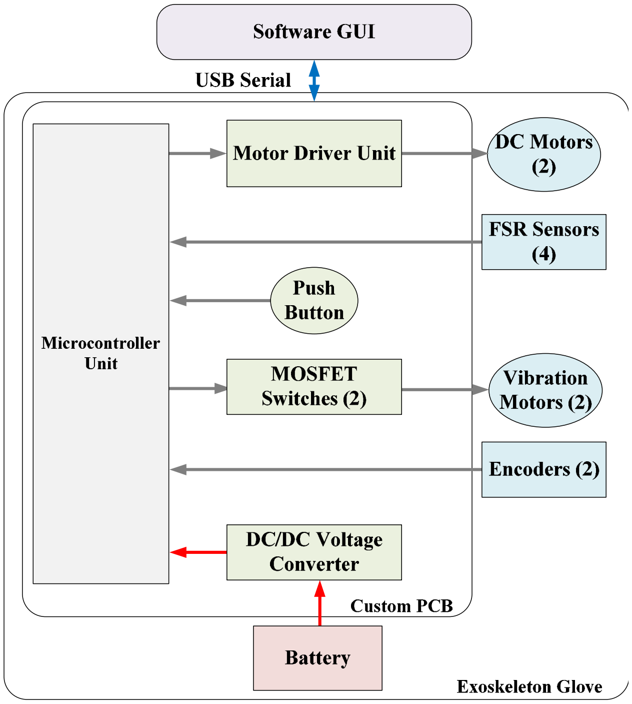

Figure 4. Electronic architecture of the Exoskeleton glove

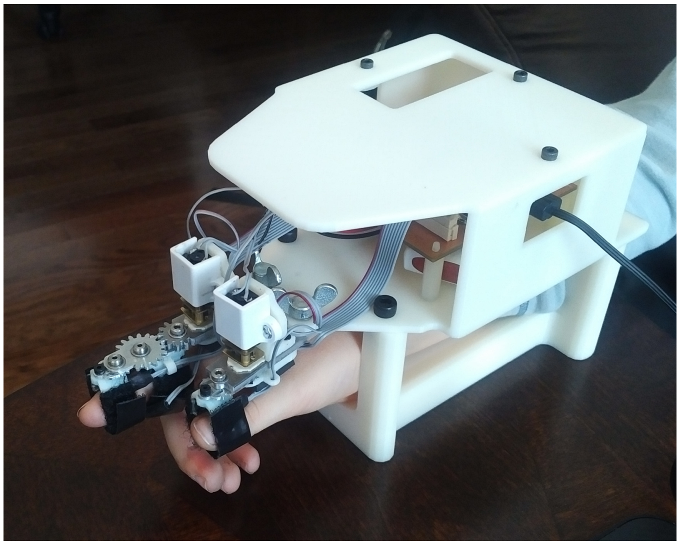

Figure 5. Integrated prototype design shown with a three year old child's hand

onto a 3D printed base, which supports the weight of the entire system. As a result, the child will not experience any fatigue while operating the system. The microcontroller board, associated electronics and onboard power supply are housed in an enclosure on the top allowing the system to be operated as a standalone rehabilitation mechanism.

The bottom of the mechanism that makes contact with the hand is covered with 3D printed plastic pieces attached to each segment. These are then covered with a soft cushion to minimize discomfort for the child wearing the system. The index finger is attached to the mechanism by means of two adjustable Velcro straps that restrain the proximal and distal phalanges to move through the desired trajectory so as to achieve pincer grasp. The thumb is retrained by two straps; one connecting the distal phalanx with moving link and the other connecting the interphalangeal with the base to restrain the MP joint from moving.

Electrical Circuit: A printed circuit board (PCB) was developed to integrate the sensors and actuators with the microcontroller unit and other electrical components. The force sensors and encoders are connected to the microcontroller unit as inputs while the DC motors and vibration motors are output connections. To control the vibration motors, the microcontroller powers them on/off via N-MOSFET switches. The DC motors are directly connected to a motor driver as the current ratings of the motors exceed the tolerance of the Teensy input/output (I/O) pins. The microcontroller connects to the motor driver with three pins: two direction pins and one PWM pin. To actuate the motors, a max PWM is given and the corresponding direction pins are set LOW/HIGH to achieve the flexion and extension motions. To power down the DC motors, both direction pins are set LOW and the PWM pin is given a 0V input.

A Teensy 3.1 rated at a clock frequency of 72 MHz, serves as the microcontroller unit for the system. This provides sufficient speed to acquire sensor data from the encoders and force sensors while performing commands to control the vibration motors and the actuation for flexion or extension of the index and thumb. In addition to the sensors and motors, the PCB contains a DB-9 connector and a tactile pushbutton. The DB-9 connector can be used for sending signals that represents a timestamp of the triggered vibration stimulus to a computer. The pushbutton can be used to send a time automated flexion and extension command. This allows the exoskeleton device to serve as a standalone device for rehabilitation purposes. For full feature controls, the PCB can be interfaced with the Graphical User Interface (GUI) for the Exoskeleton Glove System that provides additional commands and functionalities.

Software GUI: The GUI software for the exoskeleton glove is an executable application that was developed in MATLAB. It allows the user to control the glove and record data from the sensors. The commands to control the glove are divided into groups to reflect controlling the index finger and thumb individually, as well as both of them together. Each group consists of Trigger Motion, Release, and Vibrate Pulse commands that will control only that specific finger/thumb. For the Index and Thumb combined group these commands will control both the index and thumb simultaneously. In addition, the combined Index and Thumb group contains an Auto Trigger and Release Pinch command that will actuate the index and thumb into a pincer grasp and then release the pinch after a 1.5s time period. The vibration pulse commands for the index finger

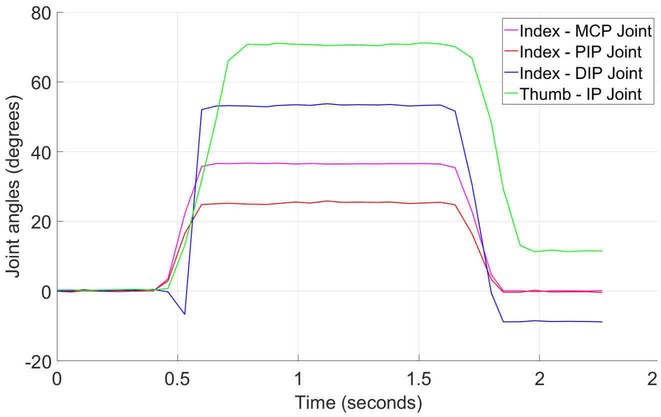

Figure 6. Results of the experimental validation

and thumb are programmed to turn on the corresponding vibration motors for 500 ms.

For reading sensor data, the GUI displays the FSR data in Newtons and encoder sensors data in degrees. A SolidWorks-developed CAD model of a human hand is used as an animation to show an approximate real-time motion of the user's hand. The GUI provides a feature to operate the exoskeleton in a passive operating mode that can help with CP rehabilitation process. It uses the force sensors to detect forces over a specific threshold ~0.88 N, which indicates the user is trying to initiate a flexion/extension movement. When the force is detected, the DC motors are powered until the force sensor readings fall below the threshold. This feature allows the user to perform desired motions on their own initiative. To record and collect sensor data, a record feature is provided that will store encoder angles and force data into a Microsoft Excel file at a rate of 20 Hz.

5 EXPERIMENTAL VALIDATION

An experiment for verifying the actual mechanism of the device was conducted for the validation process of the exoskeleton device. The purpose of the experiment was to check that the joint angles enforced by the mechanism resemble the natural joint angles of a human hand while performing a pincer grasp. This was accomplished by fixing the prototype onto a table and tracking the motion of the mechanism links as the device was commanded to perform pinch and release pinch motions. For the duration of the experiment, no human hand was strapped into the system so that it can be actuated freely. The decision to do this was based on the assumption that when the system is being used for rehabilitation purposes, the child's hand would provide minimal resistance to the actuation of the system. Therefore, the system would execute the same motion of joint angles regardless of having a child hand strapped in or not.

The tracking aspect was done using a Point Grey Chameleon 1.3MP camera. The camera was setup to capture images at 15 frames per second (FPS), allowing for pictures at various stages of the pincer grasp to be taken. To analyze the captured images of the mechanism experiment, a MATLAB script using computer vision techniques was used. The concept of the computer vision code was to identify blue markers that were placed on each of mechanism links, specifically at the index finger joints (MCP, PIP, and DIP) and the thumb joints (MCP and IP).

After identifying these blue markers, their centroids were computed to reflect the center of each joint angle. From using the joint angle centers, the corresponding angles between the joints were calculated accordingly. Thus from identifying these blue markers from image to image, the positions of the index finger and thumb joints were tracked over time while recording their joint angles. The collected data is plotted in Fig. 6 to show the variation of each of the joint angles with respect to time. The MIP, PIP and DIP joints of the index finger each bends through angles of 37°, 36° and 20° respectively. The IP joint of thumb bends through an angle of 70°.

As seen from Fig. 6, the thumb IP joint does not return back to its starting angle. This is due to backlash present in the system between the motor and the driving gear of the thumb link. The larger bending angle of the thumb was expected due to the design of the system suppressing the thumb MCP joint rotation. This was done by fixing the proximal phalanges of the thumb to the device using Velcro straps. The pincer grasp was achieved in 1.60 seconds; with 0.40 seconds for the pinch, 0.80 seconds to hold the pinch, and another 0.40 seconds for releasing. From Fig. 6, the results show that the joint angles produced by the system matches with the normal joint angles of a human hand during pincer grasp as mentioned in [13].

6 CONCLUSION

This paper presented the design and integration of an exoskeleton glove aimed at helping with rehabilitation in medical conditions such as cerebral palsy in children. The mechanism was designed to assist the child in achieving natural joint angles that were needed to perform a pincer grasp on both the index finger and the thumb. The actual joint angles dictated by the system were compared with natural human hand motion and was found to be within acceptable limits. The developed system can be used with EEG sensors or other associated software for detecting the early onset of cerebral palsy or other similar medical conditions in children. This can be done as part of future work.

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