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DOI 10.3390/electronics10111279
ESSN 2079-9292

Publisher: MDPI

electronics

Article

Design of Portable Exoskeleton Forearm for Rehabilitation of Monoparesis Patients Using Tendon Flexion Sensing Mechanism for Health Care Applications

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Received: date; Accepted: date; Published: date

Abstract: Technology play a vital role in rehabilitation patient improves the quality of life of an individual. The increase of functional independence of disabled individuals requires an adaptive and commercially available solutions. The use of sensor-based technology helps patients and therapeutic practice beyond the traditional therapy day. Adapting skeletal tracking technology used could automate exercise tracking, record, and feedback for patient motivation and clinical treatment interventions and planning. In this paper, an exoskeleton was designed and subsequently developed for patients who are suffering from mono-paresis in the upper extremities. The exoskeleton was made according to the dimensions of a patient using a 3D scanner, and then fabricated with a 3D printer, the mechanism for the movement of the hand is via a tendon flexion mechanism with servo motor actuators controlled by an ATMega2560 microcontroller. The exoskeleton was used for force augmentation of the patient's hand by taking the input from the hand via flex sensors, and assisted the patient in closing, opening, grasping, picking objects and was also able to perform certain exercises for the rehabilitation of the patient. The exoskeleton is portable, reliable, durable, intuitive, easy to install and use at any time.

Keywords: Sensing mechanism; Exoskeleton Forearm; Flex sensors; Mono-paresis; Rehabilitation

1. Introduction

Degenerative muscle disorder is portrayed by weakness in the human hand that altogether influences the physical activities of affected people. A physiotherapy rehabilitation program, endorsed by the physiotherapist, is often an essential step for inactive people, better joint movement or muscular strength, joint pain or rehabilitation from dynamic disease [1]. Monoplegia is the weakness or incomplete paralysis of one limb, it can be one arm or one leg on any side of the body. Common symptoms of Monoplegia are lack of sensation and nerve damage in the affected limb of the body. Monoparesis is paresis affecting a single limb or part of a limb. It can be in the upper limb or lower limb; paresis is slight or incomplete paralysis [2]. The most common causes of monoparesis are cerebral artery infarction and stroke. Monoparesis is more common in the upper extremities than the lower extremities. Physical therapy is most beneficial for the treatment of monoplegia to help regain muscle tone and strength. Effective Monoparesis rehabilitation depends on repeated limb practice with voluntary efforts [3-5]. A person suffering from Monoparesis has to attend physiotherapy sessions . The treatment plan made by the therapist which includes exercises and movements should be carried out effectively and regularly for recovery [6,7]. However, patients having monoparesis usually cannot regain their full-potential and need an assistive device.

An exoskeleton, a type of assistive device, is designed and presented in this paper that will assist the patient in performing exercises and movements thus making more prompt and efficient recovery during rehabilitation process and later to wear for assistance in daily tasks.. The aiding-hand and forearm exoskeleton for the patients suffering from Monoparesis may also serve as a device to improve strength and support the elderly by pinching and gripping movements in their everyday activities. The exoskeleton is a type of external skeleton that supports and protects body. The exoskeleton will assist patients by extending requisite support using servo motors. Patients have the control of exoskeleton's actuation through the tendon flexion mechanism. This helps patients to undergo physical therapy without paying tedious visits to rehabilitation facilities. The subject system is handy in a way that patients can undertake afforested physical therapies at home or can take along with them as per their convenience. In a nut-shell, patients will be benefitted physically from its convenient use. In previous related works, robotics particularly exoskeletons in field of medical sciences, have proved to be a successful way of assisting patients during rehabilitation. In addition to that, it also shares and reduces the workload of the medical staff [8-12]. The use of exoskeleton robots has improved the rehabilitation efficacy in clinical practices due to active participation of patients [13-14].

The Hand of Hope, the first commercially available robotic hand for rehabilitation, is a mechanically sound device, but has a limited range of motion due to weight and metal construction. Moreover, non-customizable design leave no room for improvement [15]. The Festo Exohand, next commercially available robotic hand for rehabilitation, has 3D scanning capability for getting user specific dimensions that has improved the range in motion and degrees of freedom. However, this is an expensive solution as it employs eight proprietary pneumatic actuators. Additionally, user has to connect compressed air source, which is bulky and restricts overall mobility of the device [16].

Academic research group of Rudd and Grant et al [17], proposed a low-cost, customizable and 3D printed robotic hand exoskeleton for hand-motor function. Tendon flexion mechanism was used to achieve hand-motor function for actuation of the exoskeleton. Though the design is customizable as ring attachments were used, yet it lack support for the fingers. The wood group [18] developed a glove, which presented technology for embedding sensors in soft robotic gloves and laid foundation for incorporating flex sensors in the designs to achieve hand movement of the user. This work also introduced methods for assembling soft robotic glove from modular and individually fabricated pressure and strain sensors. Although, the inclusion of strain sensors on the upper side of each finger and pressure sensors on the lower side provided a massive data to the control system, but it requires cutting-edge fabrication technology.

Al Bakri, Anas, et al [19] proposed a training robot that is an electromyography (EMG) based exoskeleton primarily for the rehabilitation training of strokes. This robot enabled the use of EMG of the patient's body to control the opening and closing of the hand. The advantage of this device was that it could fit to any type of hand and fingers. Bian, Hui et al[20] developed a hybrid exoskeleton named EFW Exo II for rehabilitation of forearm. The device was based on a parallel 2-URR/RRS mechanism and a serial R mechanism which could fit on both left and right arm, with an adjustable design for different arm lengths. The main benefit of EFW Exo II was enabling rehabilitation exercises for joints. Sahadev, et al [21] reviewed the hand exoskeleton exercises and deduced that an exoskeleton hand can improve the therapy results and also to reduce the cost of rehabilitation.

Yahya, Y. Z., & Al-Sawaff, Z. H. [22-23] presented a design model of powered elbow exoskeleton that assisted the elbow joint movement for weak or disabled people by controlling the assistive torque, whose direction was being determined through EMG signals from biceps and triceps. However, the calibration of EMG Signals was required for every user. Dudley, Drew R., et al [24] performed a case study of testing a 3D printed hand exoskeleton with and without a 3D printed exoskeleton. The paper aimed to assess the functional and neuromuscular changes in a stroke patient using passive exoskeleton. The design of the passive exoskeleton employed elastic and tension control of the non-elastic components. In short, Multiple designs of exoskeletons are studied, reviewed and assessed in terms of functionalities, mobility and cost. However, an exoskeleton with combined forearm and hand motions is missing in literature. Also none of these studies address the needs of monoplegics.

This research proposes a design of exoskeleton that fulfills requirements of monoplegics. Motivated from the designs and technologies of exoskeletons, available in literature as discussed earlier, with different capabilities a unique design of exoskeleton for monopresis patients with both forearm and hand motion assistance is presented. This includes not only mechanical structure but complete electronics and control design too. This complete mechatronic design is completed with objectives of portable & easy to manufacture structure and controlled & automated motion generation for health care of monoparesis patients.

The manuscript is organized as follows. Section 2 describes the client needs and overall exoskeletal system for monoplegics, human upper limb measurement method, and mechanism design for tendons along with their mathematical modeling. Section 3 discusses a detailed design of the exoskeleton structure, electrical circuits and control method. The control algorithm, sensors for feedback and their implementation in hardware is also presented in same section. Section 4 describes forearm arm and hand motion experiments in simulation as well as in real to evaluate both the exoskeleton & flex sensing design and the forearm and hand model. The experimental results are presented and discussed. Finally, Section 5 provides the conclusions and discusses future work.

2. Design Methodology

2.1. Exoskeleton system description

The exoskeleton is having one actuator for each of five fingers of the hand and one for the elbow joint. The actuators are servos that are driving the finger joint with tendon flexion mechanism. The servos are placed remotely away from the affected limb of the patient, to minimize the weight of the device from the affected limb. The mechanism used to drive the fingers from the servos is tendon flexion, which is a light and effective way. The input of the device is taken from the patient via flex sensors, when the patient tries to close or open the hand or move the elbow joint the Force Sensing Resister (FSR) registers that required little amount of force and send it to the micro-controller, then the microcontroller triggers the actuators (servos motors) to perform the movement in the specific finger, when the patient picks an object the FSR sensor placed at the tip of the fingers detects the object and hence the movement of the finger is stopped. Over all the exoskeleton has five servos for the hand and one servo for the actuating of the elbow joint. There are five flex sensors, one for each finger and five FSR sensors, each placed on each fingertip. Also, there are buttons for the selection of modes there are two modes of the exoskeleton which are as follows:

- Force Augmentation Mode: In force augmentation mode the force of the patient's hand is increased that helps patient to grasp and pick objects effectively.
- Rehabilitation Mode: In rehabilitation mode the pre-programed rehabilitation exercises are performed which will improve the muscle tone and function of the patient, therefore improving the patient's heath over time.

The overview of the input and the output is depicted in the block diagram in the figure 1.

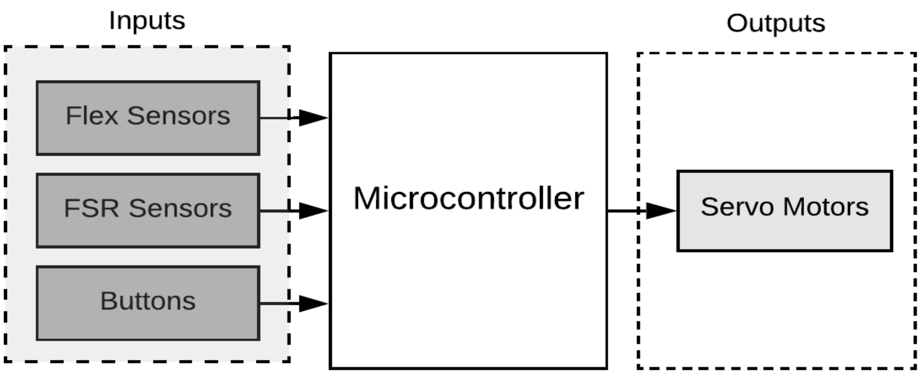

Figure 1: Block diagram of the system

2.2. Mechanical Design

2.2.1. Measurement

This section explains how the dimensions were taken for the design of the hand and forearm exoskeleton. A 3D scanner EinScan Pro 2X was used to scan the hand, the EinScan Pro 2X has an accuracy of 0.001mm which was sufficient enough for taking the measurements. The figure 1 shows the hand getting scanned from the EinScan Pro 2X. After the 3D scan, the scan is converted from surface model to a solid model for this purpose Computer Aided Design (CAD) software was used, CATIA V5 was used for converting the surface model to solid model using the generative surface model design tool in CATIA V5. CATIA V5 was used due to its advance capability of processing surface model to solid model. The surface model obtained from the 3D scanning converted into solid model is shown in the figure 2.

Figure 2: Hand getting 3D scanned.

Figure 3: Solid model of the 3D scanned hand

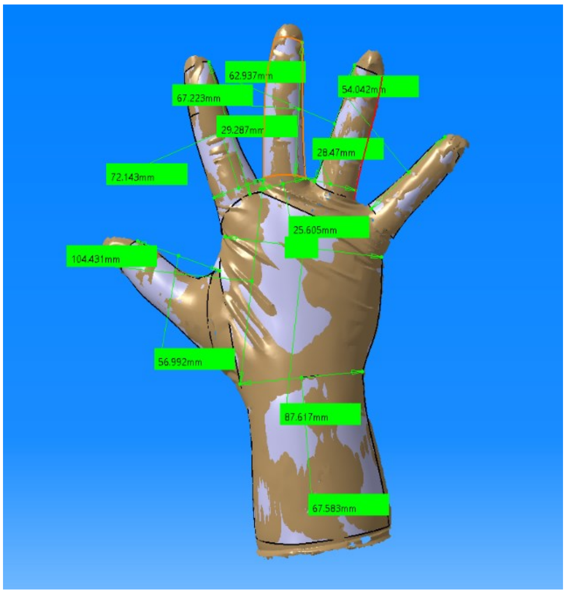

Figure 4: Dimension taken from the solid body model.

After converting into the solid model as shown in figure 3, dimensions were taken from the solid model to start the designing of the hand exoskeleton. The dimensions of the solid body model are shown in the figure 4. The dimensions for the forearm were taken with a measuring tape as it was a simpler way of easily measuring the dimension of the forearm.

2.2.2. Tendon Flexion - Design Mechanism

In this section, the design of the hand and elbow exoskeleton are is elucidated. The actuating mechanism selected was Tendon Flexion mechanism as it removes the weight from the limb of the patient providing comfort to the patient. Artificial tendons are elastic components which can store and transmit energy over the joints of humans. To minimize the mechanical work of human joints, the elastic characteristics of the tendons were optimized. Humans and animals have tendons that serve to improve mobility and provide contact between joints. This mechanism lowers the net joint work. The same tendon flexion mechanism is used to develop a link between finger joints. This tendon mechanism is restoring and increasing the joint force of the patient’s fingers. Furthermore, it is used in opening and closing of hand. The tendon flexion mechanism is implemented on the upper limb of the patient wearing the exoskeleton. Tendons are attached to the servo motors and then passing through the forearm, it is connected to the finger joints of the exoskeleton as shown in Figure 5. Servo motors are attached to wearer by backpack to lower the weight of exoskeleton. Its application provides mobility and creates a link between joints. When the initial force is applied by the patient, the servo starts to move. One side of the tendon is connected to a servo motor and the other end is connected to a finger’s joint. One tendon is labeled blue and the second one is labeled red as shown in figure 5. When servo applies force on the blue tendon it flexes and the hand gets opened. Similarly, when force is applied to red tendon the hand closes or grips the specified object. In this way, it helps in gripping and in rehabilitation exercises of the patient.

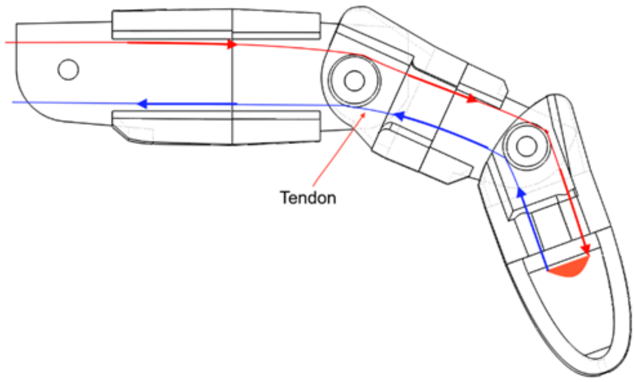

Figure 3: Tendon flexion mechanism

2.2.3 Mathematical Modelling

Mathematical model was made in MATLAB and forward kinematics of the model was done on Peter Croke robotics tool of middle figure as shown in figure 6. In this paper, we use the transfer equation of the middle finger because there is only change in link lengths of the other fingers. In table 1, DH parameters of the finger is shown and transformation matrix of the finger is given in equation (1), which is derived from the DH parameters of the middle finger.

Table 1: DH parameters of the finger

I	$\boldsymbol{\alpha_i}$	$\propto_i$	$\boldsymbol{d_i}$	$\boldsymbol{\theta_i}$
1	$-\frac{\pi}{2}$	0	0	θ_1
2	0	45	0	θ_2
3	0	28	0	θ_3
1	0	20	0	θ_4

$$\boldsymbol{T_4} = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & 20\cos\theta_4 \\ \sin\theta_4 & \cos\theta_4 & 0 & 20\sin\theta_4 \\ 0 & 0 & 1 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

After the transformation matrix was made, angles were given to the joint to check the end factor coordinates of the finger. Angles selected for the middle figure are given in table 2 and results achieved after multiplying all the transfer matrices are given in equation (2).

Table 2: Angles selected for middle finger

θ_i	$value$
θ_1	0
θ_2	$-\frac{\pi}{2}$
θ_3	$\frac{\pi}{3}$

θ_3	$\frac{\pi}{9}$

$$T_4 = \begin{bmatrix} \mathbf{0.9848} & \mathbf{0.1736} & \mathbf{0} & \mathbf{43.9449} \\ \mathbf{-0.1736} & \mathbf{0.9848} & \mathbf{1.0000} & \mathbf{-62.4730} \\ \mathbf{0.1736} & \mathbf{-0.9848} & \mathbf{0} & \mathbf{62.4730} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1.0000} \end{bmatrix} \quad (2)$$

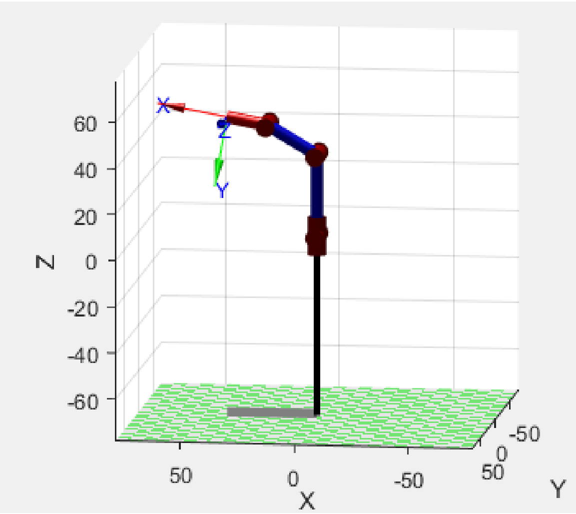

Figure 6: Peter Croke result for the middle finger

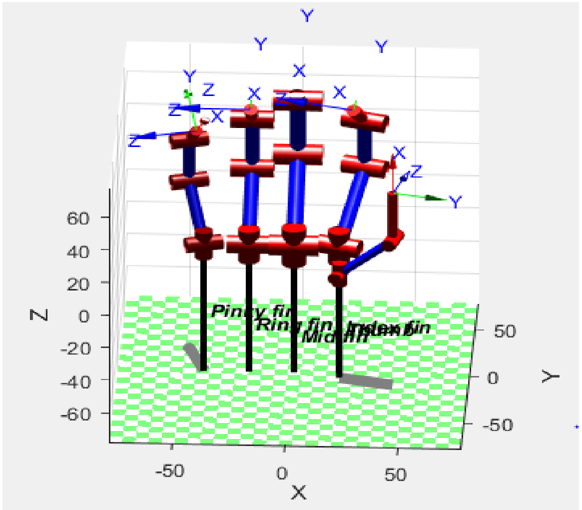

Figure 7: Forward kinematics of the entire hand

The forward kinematics of the entire hand exoskeleton was also performed. In the figure 7 the forward kinematics of the hand exoskeleton is shown.

2.2.4 Lagrangian Formulations

Dynamics deals with movement equations' mathematical formulations. Dynamic modeling uses two methods.

1. Lagrangian Euler Approach
2. Newton -Euler Approach

Newton Euler is a hierarchical approach to "power/momentum equilibrium," while Lagrangian is an "energy-based" approach to dynamics. This complex approach is called "Energy-based" The dynamic Lagrangian Formulation (named after Joseph-Louis Lagrange) provides the derivative tools of Movement equations of a scalar function called Lagrangian, known as the difference between mechanical system kinetic and potential energy. The finger in the hand consists of 3 links and their dynamics were identified with the aid of Lagrangian shown below, as the links are equal in number

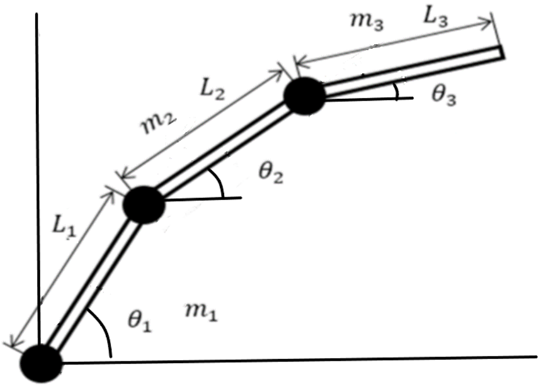

Figure 8: Finger links and labels

in each. The general equation for each finger is thus the same but its masses and lengths are different. In figure 8, this is shown. Consider a three degree of freedom system consisting of mass m1, m2, and m3.

The function Lagrangian (L) and motion equations are defined in (3).

$$\boldsymbol{\tau = \frac{d}{dt}\frac{\partial L}{\partial \dot{\theta}_i} - \frac{\partial L}{\partial \theta_i} \qquad where, \qquad L = sum_{i=0}^{n}(K_i - P_i)} \tag{3}$$

K = Kinetic Energy

P = Potential Energy

The position of mass of link 1 is (4).

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} L_1 & cos\theta_1 \\ L_2 & sin\theta_2 \end{bmatrix} \tag{4}$$

The position of mass of link 2 is (5).

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} L_1 \; cos\theta_1 + \; L_2 \cos(\theta_1 + \theta_2) \\ L_1 \; sin\theta_1 + \; L_2 \; \sin(\theta_1 + \theta_2) \end{bmatrix} \tag{5}$$

The position of mass of link 3 is (6).

$$\begin{bmatrix} x_3 \\ y_3 \end{bmatrix} = \begin{bmatrix} L_1 \; cos\theta_1 + \; L_2 \cos(\theta_1 + \theta_2) + L_3 \cos(\theta_1 + \theta_2 + \theta_3) \\ L_1 \; sin\theta_1 + \; L_2 \; \sin(\theta_1 + \theta_2) \; + \; L_3 \sin(\theta_1 + \theta_2 + \theta_3) \end{bmatrix} \tag{6}$$

The equation of Kinetic energy used is mentioned in equation (7).

$$\boldsymbol{K = sum_{i=0}^{n}\left(\frac{1}{2}m_i v_i^{2} + \frac{1}{2}I_i \omega_i^{2}\right)} \quad (7)$$

The Kinetic energy terms K_1, K_2, K_3 are mentioned in equations (8, 9, 10).

$$\boldsymbol{K_1 = \frac{1}{2}m_1\left(x_1^{2} + y_1^{2}\right) + \frac{1}{2}I_1\left(\theta_1^{2}\right)} \quad (8)$$

$$\boldsymbol{K_2 = \frac{1}{2}m_2\left(x_2^{2} + y_2^{2}\right) + \frac{1}{2}I_2\left(\theta_1 + \theta_2\right)^2} \quad (9)$$

$$\boldsymbol{K_3 = \frac{1}{2}m_3\left(x_3^{2} + y_3^{2}\right) + \frac{1}{2}I_3\left(\theta_1 + \theta_2 + \theta_3\right)^2} \quad (10)$$

The equation of Potential Energy used is mentioned in equation (11).

$$\boldsymbol{P_i = m_i g y_i} \quad (11)$$

The Potential energy terms P_1, P_2, P_3 are mentioned in equations (12, 13, 14).

$$\boldsymbol{P_1 = m_1 g L_1 \ sin\theta_1} \quad (12)$$

$$\boldsymbol{P_2 = m_2 g(L_1 \ sin\theta_1 + L_2 \ sin(\theta_1 + \theta_2)} \quad (13)$$

$$\boldsymbol{P_3 = m_3 g(L_1 \ sin\theta_1 + L_2 \ sin(\theta_1 + \theta_2) + L_3 \ sin(\theta_1 + \theta_2 + \theta_3))} \quad (14)$$

3. Exoskeleton Structure Design

According to the research the design for exoskeleton should have the following features:

- Bidirectional: The exoskeleton should help both finger extension and bending, and each finger should also be able to be powered separately.
- High Weight-to-Power Ratio: The exoskeleton should be lightweight, while being able to produce sufficient output force to allow the user to move about freely while wearing the tool.
- Free palm and wrist: The exoskeleton should allow holding of objects and should not build obstacles when moving the other arm joints, such as the wrist and shoulder.
- Comfort and Safety: The device should be comfortable and safe for the wearer
- Durable: The device should be durable so it can be used without any worries of breaking easily.

It is a difficult task to fulfill all of the requirements in an exoskeleton system, with the major difficulties being limited space, the trade-off between compactness, positioning accuracy and weight, Also the requirement of efficient and easy to maintain actuators. Firstly, the degrees of freedom of the human hand is high and there is very limited space for hardware to be installed. Hence, the placement of the actuators of the exoskeleton were placed in a backpack (components box) away from the hand and forearm, so there is no extra weight of the patient's limb. After many revisions of the CAD model was made keeping in mind all the design constraints and improved the final design over

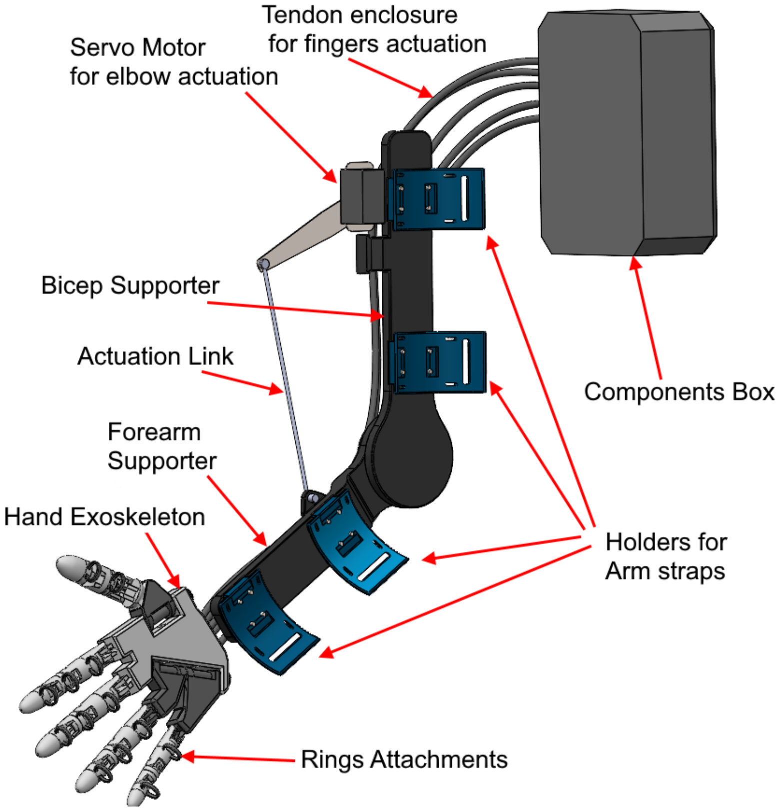

Figure 9: Design of the Exoskeleton

all. The design of the Exoskeleton is shown in the figure 9.

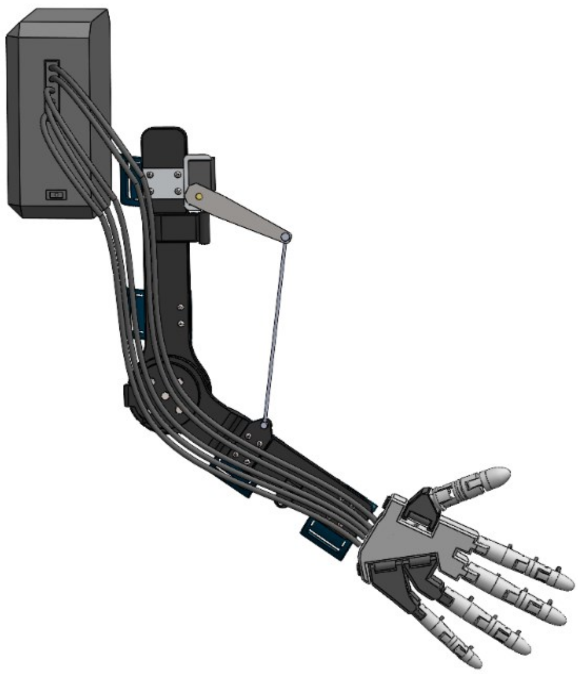

Figure 10: Side view of the Exoskeleton

The exoskeleton while designing was divided into two parts, hand exoskeleton and arm exoskeleton. The hand exoskeleton is designed for the actuation of fingers, each finger is controlled by a separate servo motor. Giving the advantage that each finger controlled individually by the user. Hence in total five Servo Motors were incorporated in the design to control the all five fingers of the hand exoskeleton. Ring like attachments were made so that the user can easily wear the hand exoskeleton. For the actuation of elbow joint arm exoskeleton was designed and only one Servo motor is used for the actuation of elbow joint. In this section the electrical design of the exoskeleton is explained. The electrical design was divided into three parts. First part is microcontroller portion where the circuits were made to integrate the sensors with the microcontroller. Second part is the battery and power connection, and lastly the connections for the buttons to operate the

Figure 11. CAD model of the PCB Designed.

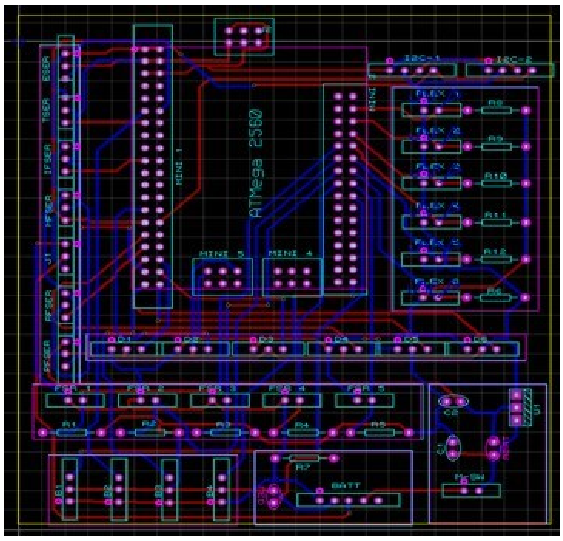

Figure 12. PCB layout of the PCB Designed.

exoskeleton. The Mega Pro Mini 2560 micro-controller is used for the coding and all the algorithm implementation. The micro-controller was mounted on top of the PCB, and all the sensors and the actuators are connected via the JST connectors. The PCB design is shown in the figure 11 and the 3D model of the PCB is depicted in figure 12. In the figure 11 the blue blocks are the connectors for the actuators, buttons and sensors.3.2 Control Mechanism

In the exoskeleton PI controller implemented on the AT Mega 2560 is used to obtaining accurate and desired force and angle for the exoskeleton. The aims were to control force generated for gripping and augmentation purposes. When initially force is applied, the FSR sensor sends a signal to the microcontroller which directs servos to move and achieve the desired value of force as shown in figure 13. The proportional control (Kp) and integral constant (Ki) which are most accurate for this case so that control runs wells between input and output. The control loop repeats itself till error becomes zero. Similarly, in the case of achieving the desired angle, the same control design is used for exoskeleton as shown in figure 14. The desired input angle is given as input and with flex sensor value that directs the microcontroller which in turn operates servos to obtain that input value. The error is subtracted and the setpoint value is achieved through the PI controller. In the case of a joint angle control algorithm, the Kalman filter is used as shown in figure 16. Kalman filter is an iterative mathematical process to quickly estimate the true value of an input. The data inputs we obtained consist of unpredictable random errors and uncertainty which created a lot of difficulty for the system to get the exact/true value. Another way to reduce the noise and get close to the actual value is to take the average of the input, but this is a very slow process and not very accurate which makes hard for the system to determine the actual value, so due to this reason process we used Kalman filter because it is faster and more accurate than other methods.

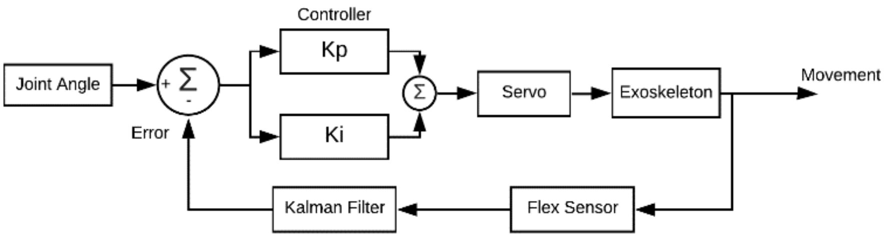

Figure 13: Feedback control diagram for the opening and closing of fingers

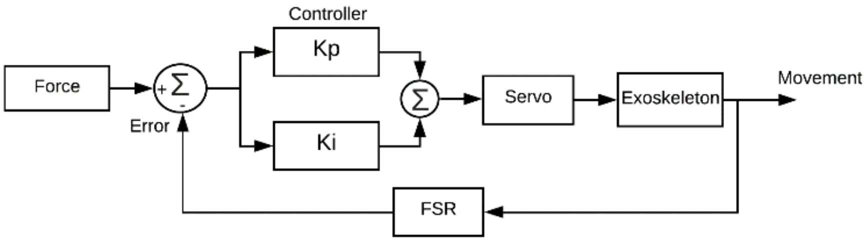

Figure 14: Feedback Control diagram for the opening and closing of fingers

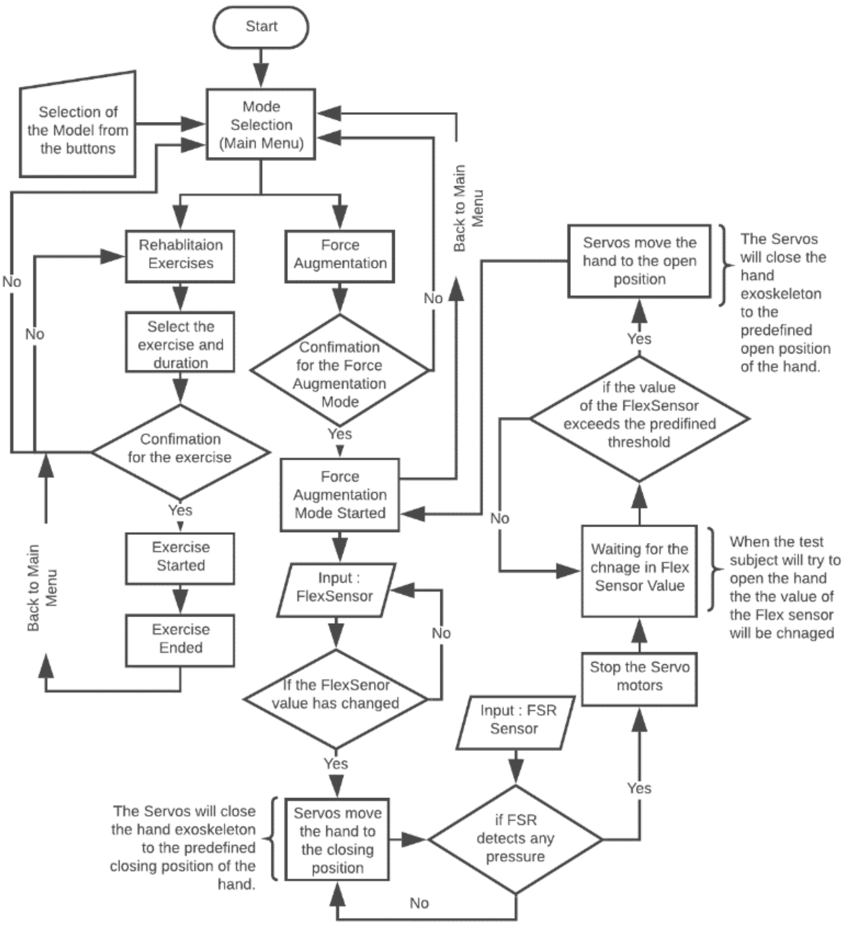

Chart 1: Flow Chart for Control algorithm

The programming was done on AT Mega 2560. The flow chart for control algorithm is given in chart The program starts with the waiting for the user input for the selection of the mode, there are two modes programmed, force augmentation and rehabilitation. When the user selects a mode, confirmation is needed to start that mode. For example, when the force augmentation mode is selected the program will wait for any increase in value of the flex sensor, if the value has increased the servo motors will start to close the hand exoskeleton and move till the closing position preprogramed, meanwhile the hand is closing the FSR sensor placed at the tip of each finger detects if there is any object which is grasped by the user, if FSR detects any force feedback due to picking an object the servo motors will stop and wait for the user to open their hand, this mode stay in the loop until the user selects to end the mode or turn off the exoskeleton.

3.3 Sensors

FSR (Force Sensing Resistor) was used to find out when the patient has firmly grasped the object. For example, when the test subject was trying to close its hand the flex sensor will take the input and send the value to the microcontroller, then as an output, the servos will start to close the hand till there is reading from the FSR, when we will get the reading from the FSR it means that now the object is firmly grasped and then the servos will stop. Later on, when the test subject will try to open the hand, the servos will move in the opening direction, and hence now the hand is open.

3.3.1. Flex Sensor

Flex sensor is used measure the amount of deflection or bending. The sensor is placed usually on the surface, when deflection occurs it changes its resistance. Sensor resistance is proportional to the amount of bending so it is also called a flexible potentiometer. Whenever the patient tries to move the hand to perform any task the flex sensor will change its resistance and it will change its value up to the specified limit. After reaching that value flex sensor triggers a microcontroller that will then direct servos accordingly. Spectra symbol makes the flex sensors to bend. They are coated on one side with a polymer with little conductive bits inside. When the sensor is flat (unbent), we measured 27.3KOhms, and the 30 K Ohms with 30 percent tolerance in this flex sensor's datasheet is in a flat place, so it's just below the limits. FSR was used to find out when the patient has firmly grasped the object. For example, when the test subject will try to close its hand the flex sensor will take the input and send the value to the microcontroller, then as an output, the servos will start to close the hand till there is reading from the FSR, when we will get the reading from the FSR it means that now the object is firmly grasped and then the servos will stop. later on, when the test subject will try to open the hand, the servos will move in the opening direction, and hence now the hand is open at the angle of 0 degrees.

3.3.2. Force Sensing Resistor (FSR)

FSR sensor detects the force or pressure. Depending upon how much force is applied it changes its resistance. They are accurate and low cost. The FSR is made of 2 layers separated by a spacer. The more one applies force, the more of those active element dots make contact with the semiconductor and decreases the resistance. The FSR sensors are made by Winsen Electronics Technology Co., Ltd based on new-type nanometer-sensitive, pressure sensitive materials, supplemented by Young's modulus and disposable pater ultrathin film substrate. It has functions that are both waterproof and pressure-sensitive. The sensor's resistance value changes as the sensor detect external pressures. The sensor we use is DF9-40 @1Kg, this sensor is chosen because it fits our specifications because we don't need to use more force to pick up an item of 1 kg weight. The FSR is calibrated to remove errors. These errors come due to some structural errors in the sensor outputs. To achieve the best possible accuracy, a sensor should be calibrated in the system where it will be used. So, the FSR was calibrated to achieve best possible results. Because FSR is not giving accurate result before calibration.

3.3 Control Algorithm

The data is acquired as input from the flex sensor which is an analog signal. This signal then goes to digital converter (ADC) analog which transforms this analog signal into a digital signal. Arduino has an 8-bit ADC which means 1024 discrete analog levels are detected. In this way, the analog signal coming from 0 to 5 volts is converted into 1024 discrete levels through ADC. This signal goes through the Kalman filter which removes the noise and filter signal. The sample rate of the Kalman filter is set to 1 second Kalman filter is an iterative mathematical method for the rapid calculation of an input's true value. The data inputs that we received consist of unpredicted random errors and uncertainty that generated a lot of difficulty in getting the exact/true value for the method. Kalman Filter helps us to predict and determine values that are really close to the actual value. The control parameters P and I determines the desired output. By setting gain we get the desired angle of the exoskeleton. The control algorithm of Flex sensors implemented on Mega Pro is shown in figure 15.

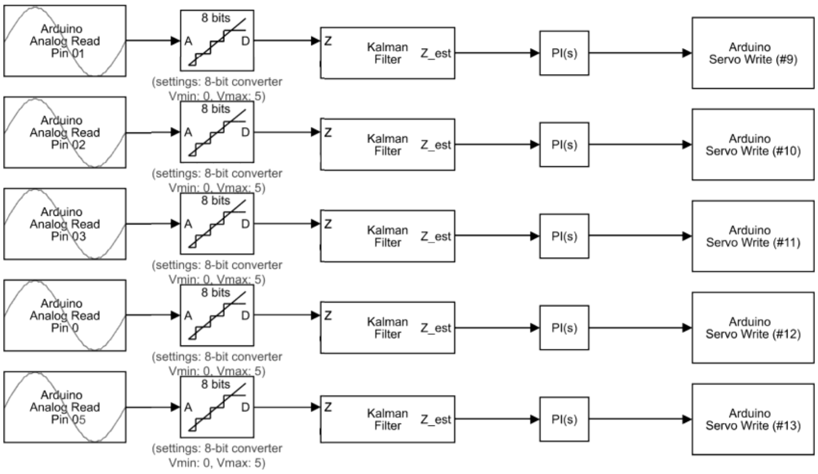

Figure 15: Control algorithm of Flex sensors implemented on Mega Pro

The control algorithm implementation of FSR sensor is shown in Figure 16. The FSR sensor is sending analog signal to micro controller. The analog to digital converter on micro controller converts this analog signal to digital one. It has 8-bit ADC which converts 0 to 5 volts of analog signal of FSR to 1024 discrete analog levels. In this process we don't need any filter and works fine without it. The PI controller then sets the desired output for plant. By changing the values of gains P and I exoskeleton gets the desired value of force. Then it directs actuator to move with desired output values.

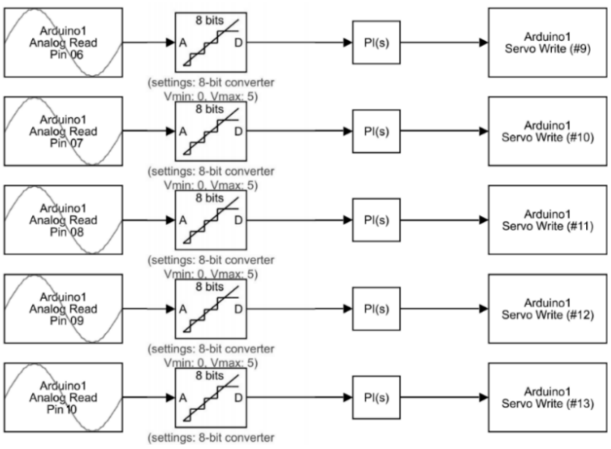

Figure. 16: Control Algorithm of FSR Sensor implemented on Mega Pro

4. Results and Discussion

Prior to the development of the presented exoskeleton, the model was tested in simulation. Motion analysis was performed on SOLIDWORKS for both hand and arm exoskeleton in order to test the design for its functionality and range of motion. Selected experiments of motion study for grip (hand closed) and victory gestures were performed. In figure 17 the closed position of hand exoskeleton is shown and in figure 18 the victory gesture is made from the hand exoskeleton to demonstrate the ability to have individual finger control. In figure 19 the motion analysis of arm exoskeleton is shown.

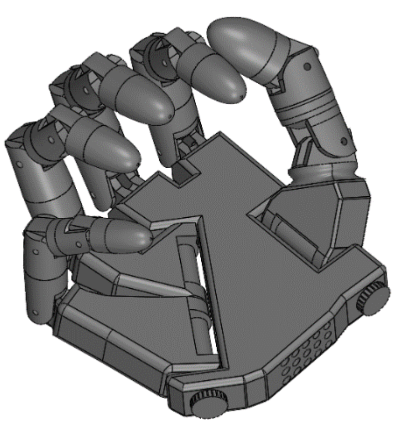

Figure 17: (Hand Closed Position) Motion Analysis of the Hand Exoskeleton

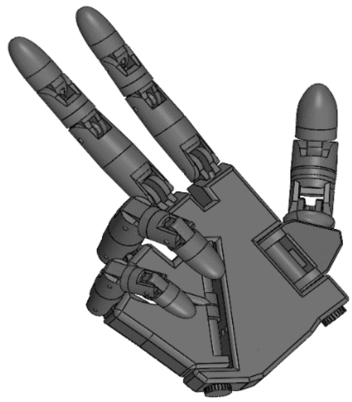

Figure 18: Motion Analysis of the Hand Exoskeleton (Semi Hand-Open Position)

In order to get portability advantage of the proposed model of the exoskeleton, it was manufactured using 3D printing. The 3D printing made the exoskeleton cost effective and easy to

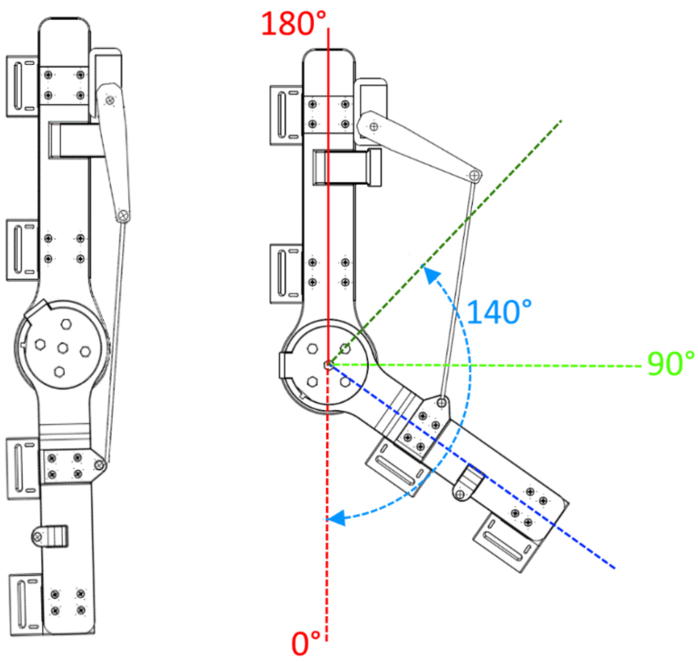

Figure 19: Motion Analysis of the Arm Exoskeleton

manufacture. Prior to experiments for motion study on the hardware, The hardware and the algorithm were tested. The input from the flex sensor was non uniform and quite noisy so to overcome that problem Kalman filter was used. In figure 20 the raw signal from the flex senor is shown. The raw signal shows relationship between the change in resistance and the change in

position (bent angle) with time. The raw signal is communicated to the microcontroller. A continuous signal variation due to noise is not acceptable for the control algorithm as it will demand high input energy. Hence, Kalman filter is used. In figure 21 Kalman filter is applied on the raw input from the flex senor making it smooth output for actuation loop for the servo motors. Experiments for the hand and elbow joint motion were performed to evaluate the effectiveness of the purposed exoskeleton. In the experiments the participant was healthy and the participant was advised to apply little to no movement and force respectively, in order to test the capabilities of the exoskeleton for a monoparesis patient.

The first experiment was to record the motion of the hand fingers in pick and place task. The

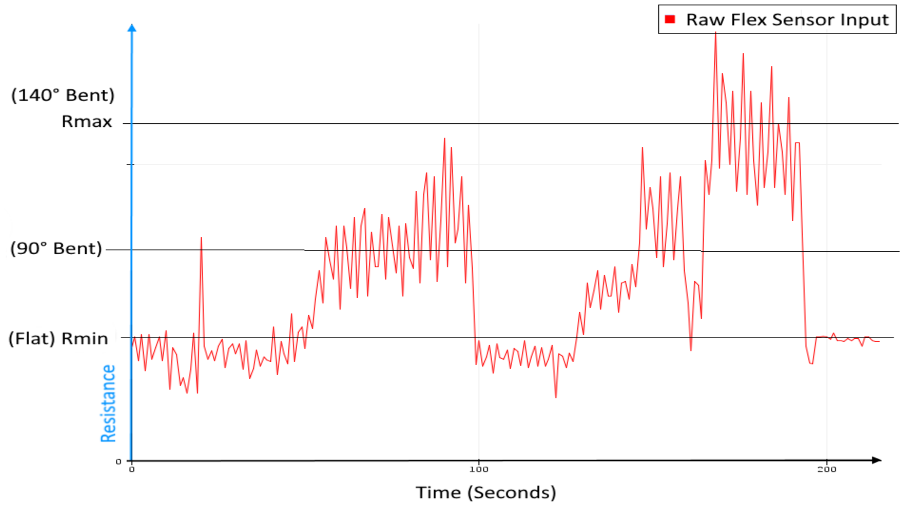

Figure 20. Raw Input Graph of Flex Sensor.

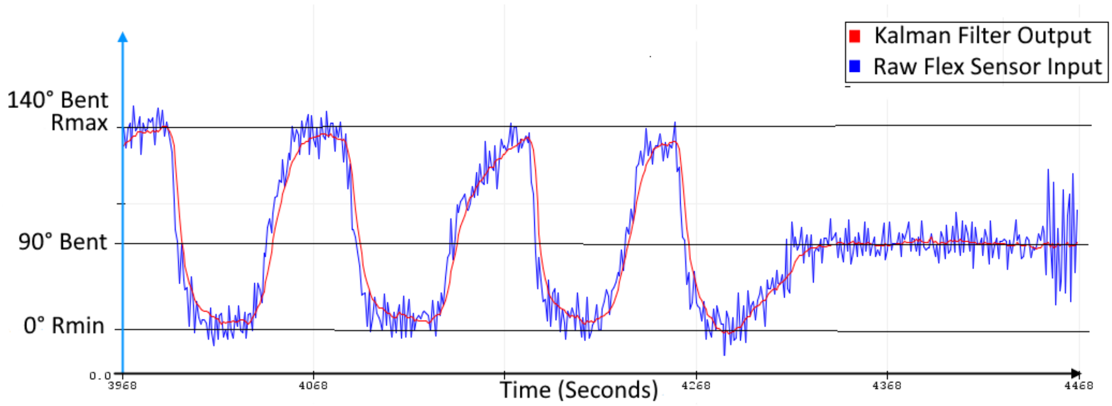

Figure 21. Kalman Filter Output.

task includes the procedure of picking, lifting, holding and releasing. A bottle of water was used in this experiment. In the experiment the hand exoskeleton was controlled to follow the movement of the user's hand with the help of flex sensors providing support and grip to the user's hand. After getting used to wearing the exoskeleton the participant was asked to perform the task five times for about 15 seconds, for a demonstrative example of the test results. The output motion of the index finger is shown along with the flex sensor input in figure 22. MCP (Meta Carpo Phalangeal), DIP (Distal Inter Phalangeal) and PIP (Proximal Inter Phalangeal) are the three joints of the index finger.

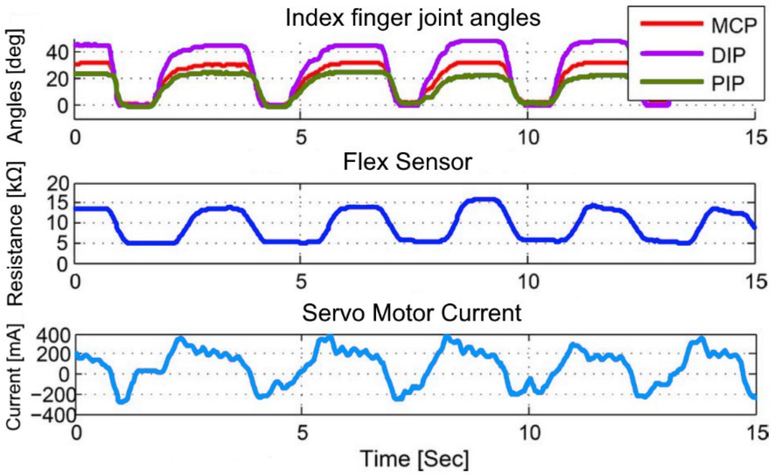

Figure 22. Index finger motion, filtered flex sensor output and current drawn by servo motor during the pick and place task.

The second experiment was to record the motion of the elbow joint in a flexion and extension task. The task includes the flexion and extension of the elbow joint while wearing the exoskeleton. In the experiment the forearm exoskeleton was controlled to follow the movement of the user's elbow joint to provide support and strength. In this experiment the participant was asked to perform the flexion and extension task 5 times in 15 seconds for the demonstration of test results. The output motion of the elbow joint and the flex sensor input is shown in figure 23.

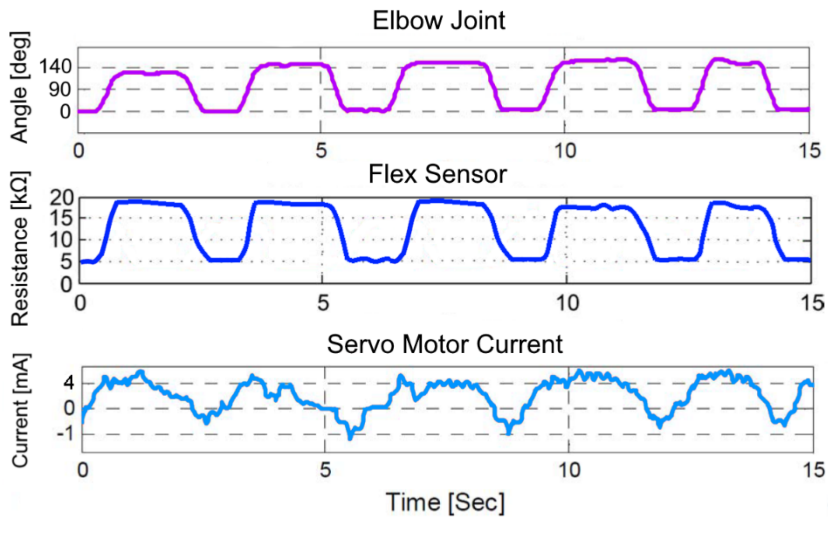

Figure 23. Elbow joint motion, filtered flex sensor output and current drawn by servo motor during the extension and flexion task.

The experiments showed that the motion of the finger joints of the hand exoskeleton was proved to be satisfactory in the test experiments with a minor room of improvement in the control algorithm. However, the motion of the forearm exoskeleton is accurate. While designing the arm exoskeleton it was kept in mind that it should have a range of motion of 140°, which is the range of motion of the elbow joint of an adult [25]. The 140° range of motion of the arm exoskeleton is also validated in the experiment. The structure of the hand exoskeleton can be designed more ergonomic to further enhance the comfort for the user.

5. Conclusion

In this paper, a low-cost exoskeleton hand and forearm for patients with monoparesis was designed and developed. The exoskeleton provided force augmentation and support for the user and it can enhance the muscle tone function and provide rehabilitation for patients with muscle weakness. The exoskeleton was able to perform the grasping and picking motions in motion study in SolidWorks and in test experiments as well. Control algorithm enabling the use of Kalman filter was developed to effectively control the movement of the servos and subsequently the exoskeleton. In addition, the complete flowchart was chalked out to implement the said control algorithm. Moreover, it was inferred that 3D scanning of an irregular part of the body i.e. hand, is an efficient way of taking measurements, and can be easier to design the exoskeleton for it. Also, SolidWorks motion was studied, which proved to be an effective tool to analyze and test the motion limitations of the designed CAD model. A limitation of the system designed in this research is the range of motion considered with force augmentation for monoparesis patients with rigid structure of exoskeleton. However, the motion range may be extended with flexible structure. Realization of the presented model and clinical measures of hand grip are future extensions of this work.

Author Contributions: Conceptualization, Muhammad Saad bin Imtiaz and Zareena Kausar; Formal analysis, Jawad Ahmad and Muhammad Imran; Funding acquisition, Syed Aziz Shah; Investigation, Qammer Abbasi; Methodology, Channa Babar Ali; Project administration, Muhammad Saad bin Imtiaz and Syed Yaseen Shah; Supervision, Zareena Kausar; Validation, Zareena Kausar; Writing – original draft, Muhammad Saad bin Imtiaz, Channa Babar Ali; Revision. Muhammad Saad bin Imtiaz and Zareena Kausar.

Funding:

Conflicts of Interest: The authors declare no conflict of interest

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