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## **Design and Analysis of 2D Exoskeleton for Upper Limb Rehabilitation**

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**Abstract.** Stroke is one of the deadliest diseases in Thailand. Stroke patients lose control of their arms because of blood clots or bleeding in the brain, which can cause devastating damage to the brain. These patients need to be treated by a physiotherapist to rapidly recover to have a normal lifestyle. Thus, the device must be able to assist therapists while practicing rehabilitation for stroke patients. This research goal is to design and analyze a mechanical device called “Upper Limb Exoskeleton” for stroke patients. The kinematics of the upper limb exoskeleton are analyzed using renowned Denavit–Hartenberg parameters (also called D-H parameters). Hereby, the proposed upper limb exoskeleton provides 2 DOF motion in Planar. The simple trajectory for the upper limb exoskeleton is defined. The upper limb exoskeleton is actuated by two motors, one at the shoulder and another at the elbow. When receiving a command from the therapist, the upper limb exoskeleton moves the volunteer arm along the defined trajectory. Thus, the patients can exercise the desired postures, including raising arm and elbow in combination. The EMG signals in the biceps are measured and analyzed. The ease of availability to directly access the EMG data helps us evaluate muscle strength. The results show that the upper limb exoskeleton can operate well to a certain degree of expectation with good performance.

**Keywords:** exoskeleton, upper limb, stroke, rehabilitation.

### **1. Introduction**

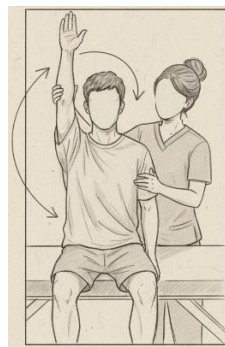
Nowadays, stroke is the number one disease in Thailand. The stroke patients severely suffer from motor disabilities of their body because of blood clot or bleed in the brain which can leave devastating damage [1-2]. These patients need to be treated by physiotherapist for rapidly recovering to have normal lifestyle. Many researches show that with functional therapy stroke patients will get higher opportunity of recovery [3-14].

While in Thailand, there is conventional rehabilitation therapy still in practice, robot-aided rehabilitation is increasing interests for physicists and therapists, since robots can provide certain tasks such as specific training therapy, high repetitive and long duration training. Yet it can be adapted to match the physical conditions of patients during therapy.



### 1.2. Rehabilitation for Upper Limb

Rehabilitation for stroke patients is very important. In order to regain and improve the quality of life after stroke, patients require practicing therapy. There are many methods such as one adopted from [1]. In this therapy, the therapist will assist the treatment by moving the arms and hands of the weak side of the patient. The training process consists of 8 positions. The practice of each motion, the patient will move at a low speed by performing 20 sessions/cycle, 2 Cycles/day (1 cycle takes about 30–60 min). This rehabilitation provides a basic posture for the research to develop an upper limb exoskeleton that is effective in aiding stroke recovery. For our research, we focus to posture 1 and 4 as shown in Figure 3. which emphasize on moving patient's shoulder and elbow respectively.



a) shoulder up and down



b) elbow in and out

**Figure 3.** Conventional physical therapy.

## 2. Research Methodology

This section details the design, development, and testing of the upper limb exoskeleton for stroke rehabilitation. The research methodology includes mechanical design, kinematics and dynamics analysis to ensure functionality and effectiveness.

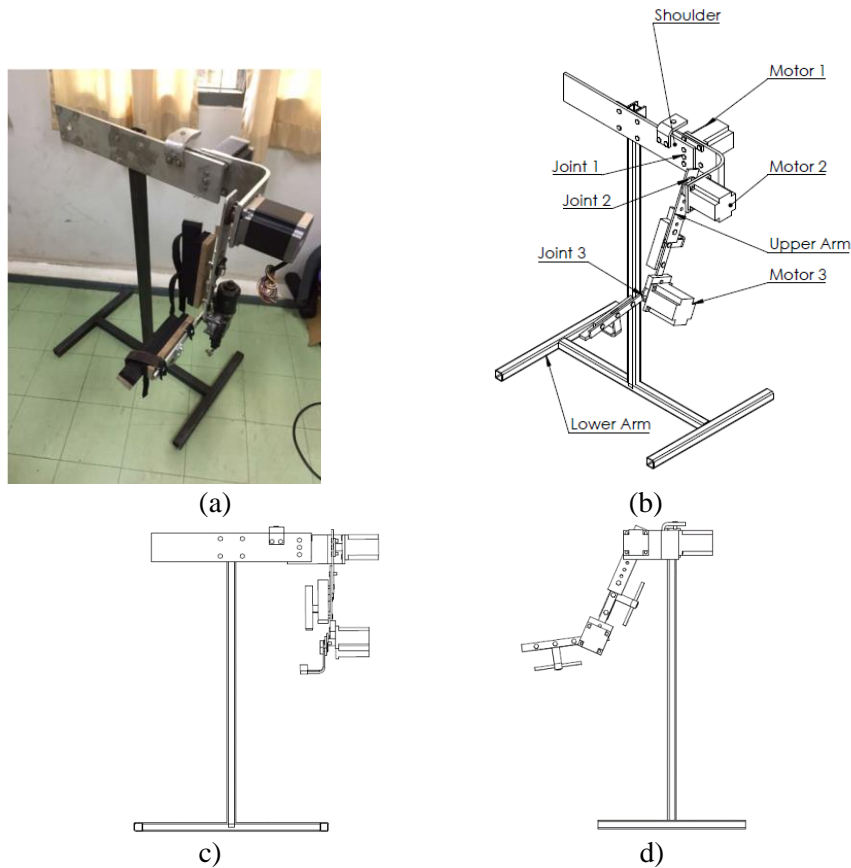
### 2.1. Design of the Arm Exoskeleton

Several studies have explored powered exoskeletons designed to assist individuals with limited mobility due to stroke or neurological disorders. Key findings include:

- Exoskeletons must be lightweight yet strong to avoid excessive strain on the user.
- Motion control should be smooth to prevent rapid or forceful movements that might harm patients.
- Some models use cable-driven systems to create flexible and natural motion.
- Systems often integrate intelligent feedback mechanisms to adjust assistance levels based on user needs.

In this study, the upper limb exoskeleton is built by using aluminium which is lightweight yet strong materials to ensure durability and ease of movement. 3D model is designed using CAD software. The final model includes linkages and joints that mimic human arm articulation as shown in Figure 4. Also, there are arm adjustable supporter for comfortable and user-friendly operation.

In this study, we examine exoskeleton design, which establishes the kinematic chain by aligning the exoskeleton's joints with those of the patient. To facilitate the movement of the patient's joints, additional passive connectors are employed to link the patient's limbs to the exoskeleton components. These connectors ensure the effective transmission of force to move the patient's joints, irrespective of the structural characteristics or the alignment of the exoskeleton joints relative to the patient's joints.

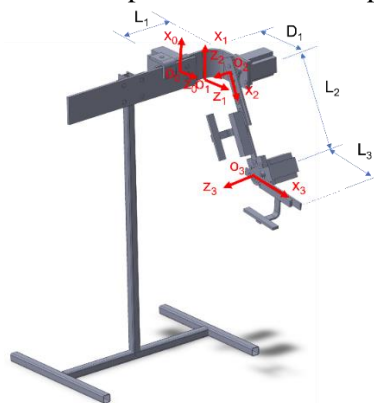


**Figure 4.** a) Designed Prototype of Upper Limb Exoskeleton b) 3D Model of Upper Limb Exoskeleton c) Front View of Upper Limb Exoskeleton d) Left View of Upper Limb Exoskeleton

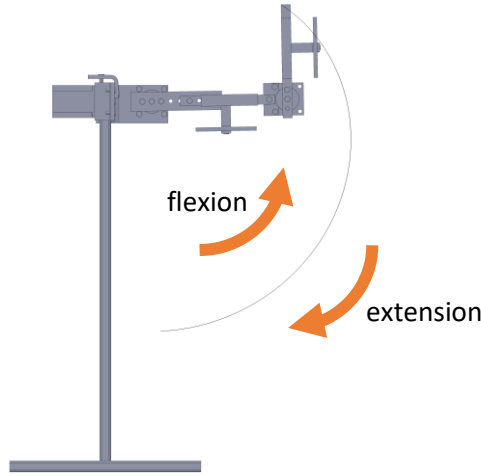
## 2.2. Kinematics and Dynamics Analysis

A mathematical model of arm exoskeleton was developed to study the motion analysis enhance motion control and efficiency. This involved:

- **D-H (Denavit-Hartenberg) parameters** are defined to use in kinematics analysis which later will be used to find joint angles and design path and trajectory for our upper limb exoskeleton. In Figure 5, upper arm exoskeleton kinematics can be analysis using D-H notation. In order to analyze our Upper Limb Exoskeleton, we use D-H notations. The coordinates are attached to our upper limb exoskeleton at 4 locations including shoulder (frame 0), glenohumeral joint and elbow (frame 3). Table 1 shows D-H parameters for our upper limb exoskeleton.



**Figure 5.** Affixed Coordinate on Upper Limb Exoskeleton Model



**Figure 6.** Planar View for Upper Limb Exoskeleton Applied on Left Arm with the Defined Trajectory at the tip of Lower Arm

**Table 1.** D-H parameters for Upper Limb Exoskeleton

Joint	$a_{i-1}$	$\alpha_{i-1}$	$d_i$	$\theta_i$
1	0	0	$D_1$	$\theta_1$
2	0	$-90^\circ$	$-L_1$	$180^\circ + \theta_2$
3	$L_2$	0	0	$\theta_3$

**Table 2.** Specification for Upper Limb Exoskeleton

Shoulder (L1)	160 mm.
Shoulder-Elbow (L2)	355 mm.
Shoulder-Wrist (L3)	258 mm.
Weight (Link L1, Link L2 and Motors)	12 kg.
Payload	5 kg.
Joint Range of Shoulder (Flexion-Extension)	$10^\circ - 90^\circ$
Joint Range of Elbow (Flexion-Extension)	$10^\circ - 90^\circ$
Max. Speed Joint 2 (shoulder)	$45^\circ/s$
Max. Speed Joint 3 (elbow)	$45^\circ/s$
Motor at Joint 2 (shoulder)	Stepper Motor Nema 34 with Planetary Gear 60 N-m
Motor at Joint 3 (elbow)	12 Vdc Wiper Motor

### • Forward Kinematics

Once the link frames have been defined and the corresponding link parameters found. Developing the kinematic equations is straightforward. From the values of the link parameters, the individual link-transformation matrices can be computed. Then, the link transformation can be multiplied together to find the single transformation that relates from frame {3} to frame {0}. The transformation matrix is obtained in form of  ${}^{i-1}T_i$

$${}^{i-1}T_i = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Using link parameters from Table 1, compute the individual link transformation for each link by substituting the parameters into Equation (1), we obtain Equations (2-6).

$${}^0_1T = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 0 & D_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$${}^1_2T = \begin{bmatrix} -c\theta_2 & s\theta_2 & 0 & 0 \\ 0 & 0 & 1 & -L_1 \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$${}^2_3T = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & L_2 \\ s\theta_3 & c\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Transformation matrix,  ${}^0_3T$

$${}^0_3T = {}^0_1T * {}^1_2T * {}^2_3T \quad (5)$$

$${}^0_3T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & P_x \\ r_{21} & r_{22} & r_{23} & P_y \\ r_{31} & r_{32} & r_{33} & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

where

$$\begin{aligned} r_{11} &= c\theta_1 s\theta_2 s\theta_3 - c\theta_1 c\theta_2 c\theta_3 \\ r_{12} &= c\theta_1 c\theta_2 s\theta_3 + c\theta_1 c\theta_3 s\theta_2 \\ r_{13} &= -s\theta_1 \\ r_{21} &= s\theta_1 s\theta_2 s\theta_3 - c\theta_2 c\theta_3 s\theta_1 \\ r_{22} &= c\theta_2 s\theta_1 s\theta_3 + c\theta_3 s\theta_1 s\theta_2 \\ r_{23} &= c\theta_1 \\ r_{31} &= c\theta_2 s\theta_3 + c\theta_3 s\theta_2 \\ r_{32} &= c\theta_2 c\theta_3 - s\theta_2 s\theta_3 \\ r_{33} &= 0 \\ P_x &= L_1 s\theta_1 - L_2 c\theta_1 c\theta_2 \\ P_y &= -L_1 c\theta_1 - L_2 c\theta_2 s\theta_1 \\ P_z &= D_1 + L_2 s\theta_2 \end{aligned}$$

Due to our first attempt to develop the first prototype, we only focus on the movement of the patient's left hand. In this particular special case, the upper limb of the patients would be rehabilitated with posture 1 and 4 in Figure 3. In Figure 6, the arm lays on the planar plane parallel to sagittal plane. Therefore, the analysis is simplified by reducing the order degree of freedom to 2 degree of freedom ( $\theta_2$ ,  $\theta_3$ ). This case is 2D planar which we consider only left hand due to first approach in order to develop the first prototype. The transformation matrix is reduced to Equation (7)

$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} l_2 \cos \theta_2 + l_3 \cos(\theta_2 + \theta_3) \\ l_2 \sin \theta_2 + l_3 \sin(\theta_2 + \theta_3) \end{bmatrix} \quad (7)$$

#### • Inverse Kinematics

To find joint angles, we use inverse kinematics of Eq.(5). Since we use the specific rehabilitation positions as mention in the previous section, we consider our upper limb exoskeleton as a simple planar two link manipulator which has two different possible solutions. From Figure 5 and 6, we consider the end of the link 3 of the upper limb exoskeleton, which is the length of  $l_3$ . Its position ( $x_2, y_2, z_2$ ) is specified relative to base frame {2}. They limit the subspace of workspace where there end of the exoskeleton can reach. By considering 2D planar, the solution of the joint angles in 2D plane ( $\theta_2, \theta_3$ ) is obtained by inverting Eq. (7).

$$\theta_2 = \tan^{-1} \frac{y_2}{x_2} - \tan^{-1} \frac{l_3 \sin \theta_3}{l_2 + l_3 \cos \theta_3} \quad (8)$$

$$\theta_3 = \cos^{-1} \frac{x_2^2 + y_2^2 - l_2^2 - l_3^2}{2l_2 l_3} \quad (9)$$

- **Velocity and Acceleration** to ensure smooth movement. The Jacobian can be obtained. By differentiate Eq. (7), it yields

$$\begin{bmatrix} \dot{x}_2 \\ \dot{y}_2 \end{bmatrix} = \begin{bmatrix} -l_2 \sin \theta_2 - l_3 \sin(\theta_2 + \theta_3) & -l_2 \sin(\theta_2 + \theta_3) \\ l_2 \cos \theta_2 + l_3 \cos(\theta_2 + \theta_3) & l_2 \cos(\theta_2 + \theta_3) \end{bmatrix} \begin{bmatrix} \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} \quad (10)$$

- **Equation of Motion** to be able to analyze the dynamics of the upper limb exoskeleton

### 3. Defined Trajectory

To implement the upper arm exoskeleton, the trajectory must be defined properly for patients to follow. The trajectory is created to maintain steady position and velocity. Basically, we use a linear function to create the trajectory which is resemble to the posture in Figure 3, posture 1 and 4. Equation (7) shows the linear equation for the  $i$  th joint of the human arm.

$$\theta_i(t) = c_0 t \quad (7)$$

By differentiating Equation (7), one obtains corresponding velocity and acceleration Equation (8) and Equation (9).

$$\dot{\theta}_i(t) = c_0 \quad (8)$$

And

$$\ddot{\theta}_i(t) = 0 \quad (9)$$

Joint space is more appropriate for our application because we can easily define velocities for the motors, at the shoulder and the elbow without the singularity problem. Joint 2 has range of motion from  $0^\circ - 90^\circ$ . Also, Joint 3 has range of motion form  $0^\circ - 90^\circ$ .

We define a linear function for a path with via points. The trajectory is defined in particular as following. For simplicity, we select path points are  $0^\circ, 90^\circ, 0^\circ$  for both joints including Joint 2 and 3. This is particular true, because the aim is to move the patient's shoulder and elbow in flexion and extension. The duration of two segments should be 2 seconds. The velocity can be obtained as following

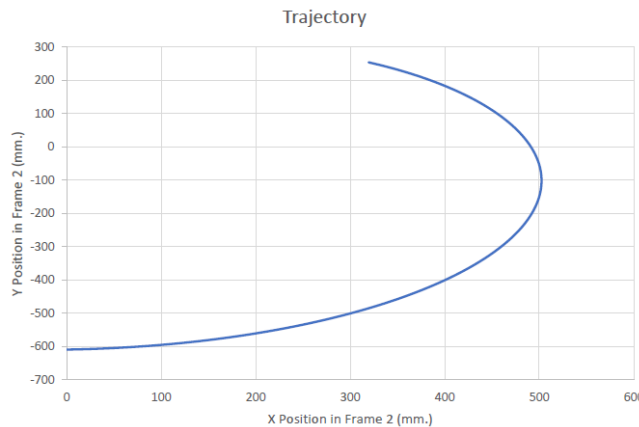
For 1st segment (flexion), the angular velocity, is calculated as

$$\omega_{12} = d\theta_{12}/dt = (90-0)/2 = 45 \text{ degree/s.}$$

Next, at 2nd segment (extension), the angular velocity is calculated as

$$\omega_{23} = d\theta_{23}/dt = (0-90)/2 = -45 \text{ degree/s.}$$

Thus, the absolute angular velocity ( $\omega$ ) at all segments is 45 degrees/second (0.785 rad/s). Due to motor specification stepper motor, we simply assign both joint speeds at about 7.5 rpm. Figure 7 shows the trajectory used in the rehabilitation which is resemble to the combination of the posture in Figure 3, posture 1 and 4.



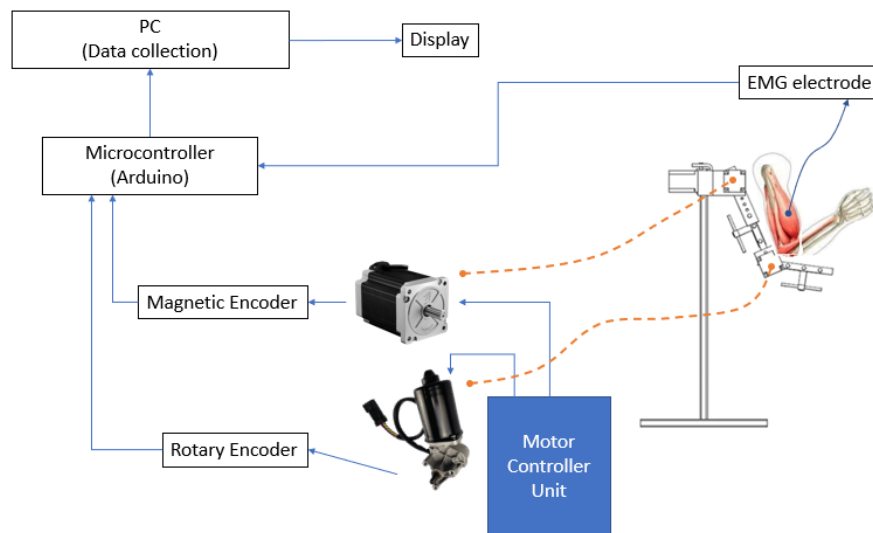
**Figure 7.** Trajectory Planning for Upper Limb Exoskeleton

### 4. Control System

The control system is the essential of the exoskeleton, allowing users to interact with the device through muscle signals and programmed commands. In Figure 8, main processing utilised Arduino

microcontrollers as the controller and data acquisition unit. It enables real-time adjustment for smooth operation. Stepper motor and dc motor manipulate the upper limb exoskeleton which supports arm movement based on user inputs. EMG sensors detect muscle signals, allowing the exoskeleton to respond to the user's intended movements. Studies show that EMG-based control is highly effective in rehabilitation because it directly reflects muscle activity, allowing for personalized assistance.

The system ensures that the exoskeleton provides real-time assistance based on user input, allowing for a personalized rehabilitation experience.



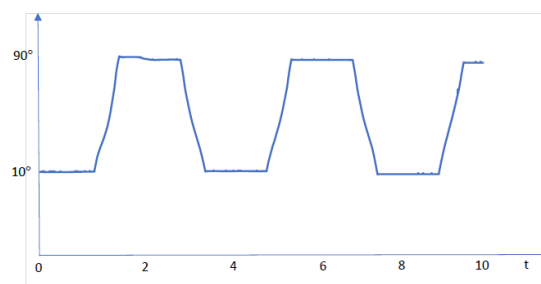
**Figure 8.** Assembly of Upper Limb Exoskeleton on Human Arm with Motor Control

## 5. Research Results

The results of designing, developing, and testing the arm exoskeleton for stroke rehabilitation are presented in following. The findings are categorized into control system design, movement testing, and EMG signal measurement and analysis.

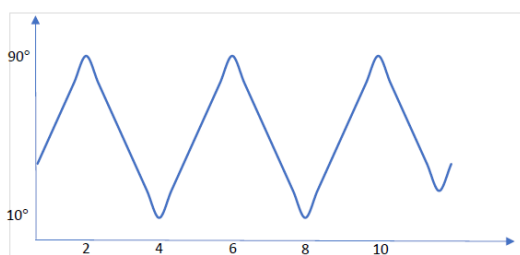
### 5.1. Actuation and Movement Test

The exoskeleton supports arm movement by lifting the arm up. The motor 2 locates at shoulder joint of the upper limb exoskeleton supports the demonstrator's upper arm. The motor 3 locates at elbow joint of the upper limb exoskeleton supports the demonstrator's forearm. The motors rotate to support the demonstrator's arm following the design trajectory in Figure 7. Due to safety precaution, the initial angle starts at 10 degrees to prevent it from moving backward to negative direction. When the exoskeleton operated, the measurement of the angle at the shoulder and elbow were measured and recorded. In Figure 9, angular displacement of shoulder joint (Joint 2) is initially at 10°. It gradually increases to 90°. After it has reached 90°, it holds for a moment, Later it decreases back to 10 degree.



**Figure 9.** Angular Displacement of Shoulder Joint (Joint 2).

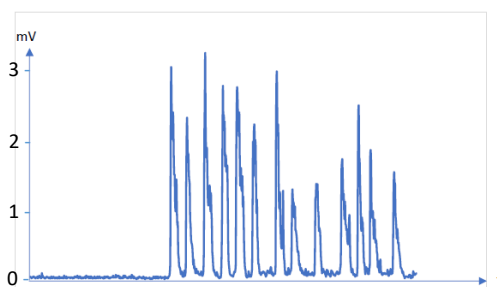
In Figure 10, angular displacement of elbow joint (Joint 3) is initially at  $10^\circ$ . It also gradually increases to  $90^\circ$ . When it reaches  $90^\circ$ , it decreases back to  $10^\circ$ . Both angular displacements create the trajectory resemble to the trajectory shown in Figure 7. During flexion, the angular displacements ramp up as shown in Figure 9 and 10. In contrary, during extension, the angular displacements ramp down as shown in Figure 9 and 10. During operating, the EMG signal at bicep is measured. As shown in Figure 11, there is higher EMG signals during the bicep flexion while the angular displacements are increasing in Figure 9 and 10. In other hand, there is lower EMG signals during the bicep extension while the angular displacements are decreasing in Figure 9 and 10.



**Figure 10.** Angular Displacement of Elbow Joint (Joint 3).

### 5.2. Experiment Test with EMG signal

To evaluate the effectiveness of the exoskeleton, the study measured and analysed electromyography (EMG) signals of the Bicep muscle which is the main muscle using during flexion and extension in sagittal plane during movement exercises. The EMG electrodes were placed on top of the left-hand bicep muscle of the demonstrator. The result is shown in Figure 11. During the bicep flexion, the result shows higher EMG signals where the exoskeleton is operated. During the bicep extension, the EMG has lower signals. There are different EMG signals between flexion and extension bicep muscle.



**Figure 11.** EMG Signal for Biceps.

The EMG signal is rectified and filtered with a second-order low pass. Figure 11 shows the EMG activities during the arm motion. It is evident that the exoskeleton supports were higher during flexion but lower during extension. As a consequence, the muscle would interact compulsively with the brain. Thus, there is a chance for patients to be able to progressively recovery after practicing repeatedly.

The experiment assures that the exoskeleton functions as intended, with potential for further improvement in movement precision and usability. The exoskeleton successfully supports the demonstrator's arm movement. EMG data confirms that muscle activity increases when using the device. The control system responds accurately to movement commands.

## 6. Conclusion

We proposed a design prototype for the upper limb exoskeleton that modulates the human arm in rehabilitation. By augmenting the motion of the human based on the rehabilitation training, the proposed design effectively maintains the defined trajectory in the entire workspace of the human arm.

We validated our approach by an experimental study where a human subject wearing the upper limb exoskeleton perform two motions including flexion and extension of the arm. The results show that indeed, the exoskeleton supports the arm while it successfully operates along the defined trajectory. In effect, the muscular effort of the subject wearing the exoskeleton is measured and recorded during for both motions. Experimental results showed increased EMG signals, confirming muscle engagement and effective assistance. This indicates that the patient is affected from rehabilitation which are being performed. The purpose of this study is to be able to design the upper limb exoskeleton and analyze how manipulation of human's manipulability by upper limb exoskeleton influence human motor control and improve human's performance. In the future, we plan to improve our design. Since there is movement limitation, the exoskeleton could not fully support all natural arm movements.

Future designs should incorporate additional joints and actuators for improved flexibility. Our control system caused slight inaccuracies in motor movement. Future versions should use advanced filtering techniques to stabilize sensor readings. We plan to explore thoroughly in an extensive experimental study where a group of subjects wearing the exoskeleton will perform rehab exercise training according to therapist to analyze the level of recovery.

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