Journal of Engineering Science and Technology Review 17 (2) (2024) 9 - 15

Research Article

JOURNAL OF
Engineering Science
and Technology Review

www.jestr.org

# Design and Modelling of a Human Upper Limb for Rehabilitation Exoskeleton

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Received 8 October 2022; Accepted 12 September 2023

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## *Abstract*

Electromechanical systems that interact with the user to offer power amplification, assistance, or replacement of motor function are known as exoskeletons for the upper limbs. The upper extremity rehabilitation exoskeletons have garnered increasing attention and impact in the healthcare sector over the past years due to the advancements in the field of robotic control devices and actuation elements. The necessity for assistive supporting and rehabilitation devices that either help improve human strengths or provide assistance in regaining lost motion of a specific limb joint arises as a result of changing trends and a growing population. Age-related bone loss often results in weaker, more fragile bones that make lifting and carrying huge loads more difficult. A stroke can impair mobility and is more likely occurs to the elderly people. Accidental paralysis as well as other health issues including spinal cord injuries, musculoskeletal disorders due to work environment are on the rise resulting in an increased urge for the assistive devices. The motive of this paper is to design a mathematical model of the human upper limb involving DH parameters and forward kinematics alongside with the human joint study to precisely design the model in order to design an upper extremity exo-skeleton for offering limb rehabilitation considering the human joint constraints with respect to the Sagittal, Coronal and Transverse planes. This study is aimed in providing a significant vision in developing the precise rehabilitation devices that can aim in offering the joint specific treatment to the user for human upper arm therapy.

*Keywords:* Upper Extremity Exo-Skeleton, Upper Limb Rehabilitation, Limb Biokinetics, Physical Disability, Limb Motion Study, Forward Kinematics

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## 1. Introduction

According to recent research trends, Exo-skeletons are currently widely used in a variety of applications, including the military, medical applications such as physiotherapy, rehabilitation etc, and industrial applications such as warehouse and construction. Bone strength generally decreases with age and as a result, bones weaken and become more brittle, making it challenging to lift and carry heavy loads. Elderly people are more likely to have a stroke, which may lead to mobility disorders. Accidental paralysis and other medical conditions are becoming more common. Many people who have spinal cord injuries in car accidents have mobility disabilities as a result. The first patent for a passive assistance device was granted in 1890 with the intention of minimising the human efforts [1]. Understanding the human biomechanics helps in developing such assistive exo-skeleton devices and makes it error-free for application specific usage.

Exo-skeletons [2] can be used for many different things, including weightlifting and enhancing user stability. Exo-skeleton use in the medical and defence sectors has skyrocketed in recent years as a result of the development of dependable and long-lasting control mechanisms and systems. Medical fields have started using exo-skeletons to deliver physiotherapy to their patients because the path of travel for the limbs is pre-programmed into the apparatus. The overview of the various exo-skeletons [3], [4], [5] based on their applications in terms of design, actuation technique [6], control methodology [4], and actuator type, as well as the various classifications [7], [8] of exo-skeleton systems that are available suggest the development of a full body exo-skeleton. Depending on the control method employed, exo-skeleton devices for industrial weight lifting [6] can be categorised as actuated or non-actuated. It is addressed how the exo-skeleton is currently used in medicine [9] and for strength improvement [10], [11] as well as how it has changed over the past few years.

Researchers in China have researched the issues with the muscle fibre [12] that arise with a growth in human age, resulting in low strength and an imbalance in muscle fibre with respect to ageing. In terms of fibre number %, area percentage, and mean fibre area, the paper illustrates the degeneration of Type IIA and IIB muscle fibres. It also shows how ageing adults' muscles lose strength and power [13]. The effects of movement on the human body dynamically [14] are measured by torque sensors attached to the body. Through the integration of engineering sciences and graphic modelling, the findings are rendered in both static and animated dynamic forms. By putting the proposal to the test on 10 healthy volunteers during body weight-supported gait training, the proposal is judged. Eight male volunteers' knee flexion and extension [15] at speeds between 50 and 250° s-1 were examined. In iso-velocity knee flexion, extension, and rotation, the peak values of Angle specific (P) and normalised torque (NP) were compared.

The advancement of the exo-skeleton system in terms of design [16], [17] and precise control has been able to create a fantastic foundation for the rise in medical rehabilitation [18], [19], [20] and assistive [21] devices, which surpass the

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doi:10.25103/jestr.172.02

limitations faced by the elderly and post-traumatic patients and assist them in nearly all aspects of their lives by providing neuro-motor training [22] and ultimately improving muscular strength [23]. Exo-skeleton systems can be classified as lower extremity, upper extremity, or complete body systems depending on the help they provide.

After a patient is admitted to the hospital, rehabilitation therapies [24] must be given to them, and they must be given treatment on a need basis. The benefits of robotic therapy were discussed along with a number of neuromuscular diseases. Exo-skeleton training and modification are discussed in the sections on feasibility [25] and the need for it [26], along with the advantages of doing so. Torque demand analysis [27], [28] for each joint is essential before developing any exoskeletal system. The exo-skeleton should offer rehabilitation in correlation with the dynamic physical support to the user"s limb. Dynamic modelling [29] and profile mapping has been carried out in a lower extremity exo-skeleton and torque estimation for actuator selection is made to acquire limb specific data for designing a real-time assistive device.

Disabilities of the upper limbs can result from a number of disorders, such as degenerative diseases, spinal cord injuries, and stroke. The ability of a person to carry out necessary daily duties and fully engage in society can be severely restricted by these disorders. Although they can be effective in some cases, traditional rehabilitation techniques frequently lack the focus and accuracy needed for a full recovery. Exoskeletons used for upper limb rehabilitation are useful in this situation. While the traditional rehabilitation methods rely on the therapists, a continuous interaction between the patient and the therapist is mandatory in progressing the cure yet the procedure is cost intensive while the rehabilitation exo-skeleton system offers such interaction in a steady pace with a nominal cost. A deeper human anatomical and physiological study has been carried out in order to understand the human body dynamics and the advancements in technology in the field of sensors have paved a way for this to happen. The earlier studies used modelling tools to study and simulate the movements and understand the effects but in order to design a perfect assistive system for the human limb, it is essential to understand the joints as well its motion in detail.

With the intention of accurately design an upper extremity exo-skeleton for the specific joint of the human upper limb rehabilitation, taking into account the human joint constraints with respect to the Sagittal, Coronal, and Transverse planes, the purpose of this paper is to develop a mathematical model of the human upper limb involving the DH parameters, forward kinematics along with the upper limb joint study via simulation using the OpenSim [30], [31], [32] software to achieve a breakthrough in developing lightweight and straightforward designs that examines the use of wearable in providing all-around support and user-friendly rehabilitation methods by keeping in mind the motion limitations of the human upper limb joints along the Sagittal, Coronal and Transverse planes. The exo-skeleton enters the picture and plays a crucial part in the modern world as more accidents cause bone damage, locomotive disorders, and a natural decline in the strength of human joints. In recent years, numerous exo-skeleton systems have been developed and tested. Such exo-skeleton needs to be modelled keeping in mind the human body dynamics and its constraints in order to eliminate mishaps. This work aims to offer a significant vision for the development of precision rehabilitation tools that can target giving the user with joint-specific treatment for upper arm therapy.

## 2. Methodology

The main objective of using the rehabilitation exoskeleton in the healthcare sector is the precision and variability in the intensity of the therapy in a steady state to the user thus making the therapy more accessible and inclusive. In order to make the device more sophisticated and user-centric the exoskeleton must be possessing the clinical settings to accommodate different users with different degree of disability. In order to make such things possible there has to be some medium that offers mimicking and modelling of a human upper limb which will further be utilized to learn the human anatomical and structural joints which involves the use of biomodelling and analysis software for which OpenSim [30], [31], [32] has been utilized with which the human hand is made analysed for understanding its joint motion and its Degree of Freedom. With the aid of the biomodelling software OpenSim, the joint constraints are obtained, which further assists in developing a mathematical model involving the joint kinematics for the human upper limb by using the Forward Kinematics equation. In order to provide rehabilitation for the limb joints without endangering the user, the human limb joints have degree of freedom constraints along the specific directions that must be determined using the Denavit Hartenberg (DH) table, with which the angular movement of the limb with respect to the Sagittal, Coronal, and Transverse planes is defined. It also provides the safe travel of the limb comprising the minimum and maximum angles. The joint arrangement of a human upper limb is elaborated in the Figure 1 involving the OpenSim software.

The exact replica of the human biological right limb as an articulated joint is depicted in the Figure 2. For reducing the complexity, a single structure for the human upper limb with 3 joint frames is taken into account for performing the analysis and the model consists of link of length $L_1$ for shoulder to elbow, link $L_2$ between elbow and wrist and link $L_3$ for the fist and digits of hand with the joint angles $\theta_1$ for shoulder flexion and extension along the Sagittal plane, $\theta_2$ for shoulder abduction and adduction along the Coronal plane, $\alpha_2$for the Internal and External rotation twist between Shoulder and Elbow joints, $\theta_3$ for the elbow flexion and extension along the Sagittal plane, $\alpha_3$ for Pronation and Supination twist between Elbow and Wrist joints, $\theta_4$ for the wrist flexion and extension along the Sagittal plane and $\theta_5$ for the wrist ulnar flexion and radial flexion along the Transverse plane which is as depicted in the Figure 3.

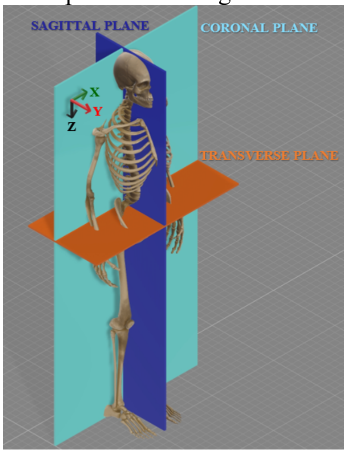

**Fig. 1.** Human upper limb arrangement

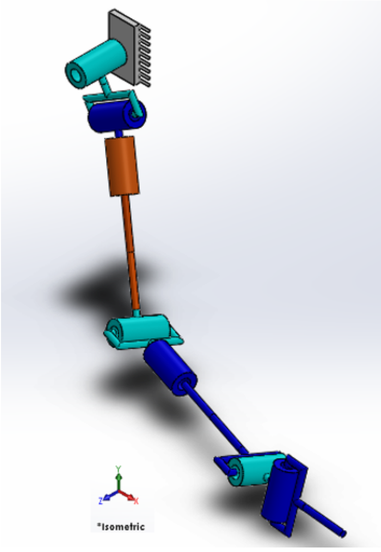

**Fig. 2.** Mechanical replica of the biological limb

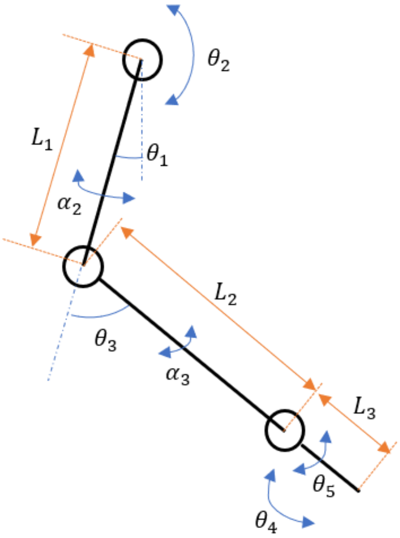

**Fig. 3.** Link segment model for the human upper limb

## 3. Results and Discussions

The human upper limb biokinetics were simulated using OpenSim software [30], [31], [32] and the graph plot is illustrated in the Figure 4 (A) and (B) elaborating on the muscle movements and its acquired data. The DH parameters were obtained for the human limb and are elaborated in the Table 1.

**Table 1.** DH parameters for the human upper limb

| | **Joint** | **Twist $(\alpha_{i-1})$** | **Link length $(a_{i-1})$** | **Joint distance $(d_i)$** | **Joint angle $(\theta_i)$** |
|---|---|---|---|---|---|
| Shoulder | 1 | 0 | 0 | 0 | $\theta_1$ |
| | 2 | $\alpha_2$ | 0 | 0 | $\theta_2$ |
| Elbow | 3 | $\alpha_3$ | $L_1$ | 0 | $\theta_3$ |
| Wrist | 4 | 0 | $L_2$ | 0 | $\theta_4$ |
| | 5 | 0 | 0 | 0 | $\theta_5$ |

Consider the shoulder frame and since the reference frame is set at shoulder ball and socket joint, we take the Z axis and make it inline to the axis of rotation of the joint 1 making rotation of $\theta_1$. In order achieve this, a translation of Y axis by -90° is made and is as elaborated in equation(1). The rotation matrix for the joint 1 making an angle of $\theta_1$is as shown in equation (2),

$$ {}^{0'}_{0}R\{Y_{-90}\} = \begin{bmatrix} \cos -90 & 0 & \sin -90 \\ 0 & 1 & 0 \\ -\sin -90 & 0 & \cos -90 \end{bmatrix} \tag{1} $$

$$ {}^{1}_{0}R\{\theta_1\} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2} $$

Similarly, the second motion in the shoulder along the sagittal plane makes an angle $\theta_2$ and for making the Z axis inline to the axis of rotation, X axis is made rotated by -90° as elaborated in equation (3). The rotation matrix for the joint 1 making an angle of $\theta_2$ is as shown in equation (4),

$$ {}^{1'}_{1}R\{X_{-90}\} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos -90 & -\sin -90 \\ 0 & \sin -90 & \cos -90 \end{bmatrix} \tag{3} $$

$$ {}^{2}_{1}R\{\theta_2\} = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 \\ \sin\theta_2 & \cos\theta_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4} $$

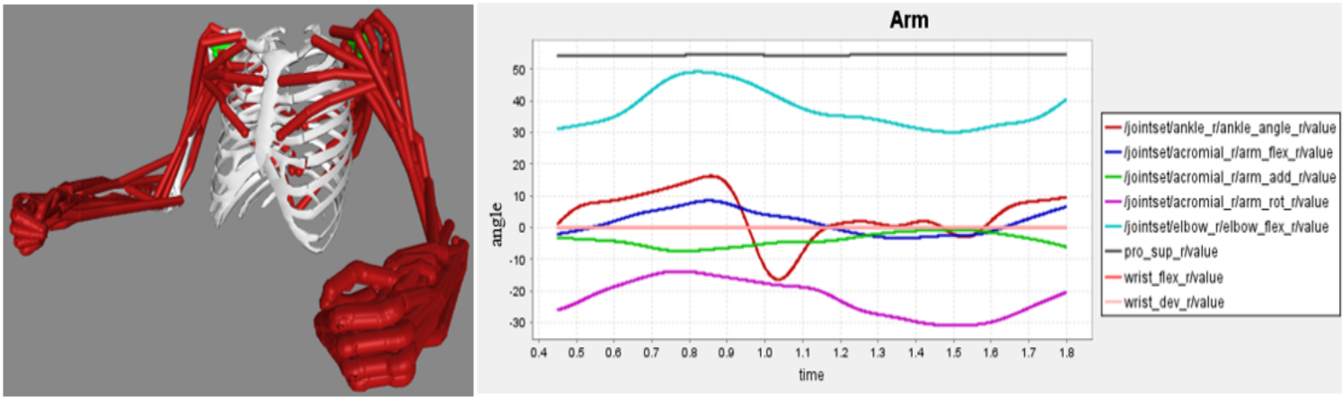

**Fig. 4.** Simulated human upper limb model data using OpenSim [30], [31], [32] software

The twist at shoulder for making the horizontal flexion and extension makes an angle $\alpha_2$ and for making the Z axis inline to the axis of rotation, Y axis is made rotated by +90° as elaborated in equation(5). The rotation matrix for the joint 1 making an angle of $\theta_1$is as shown in equation (6),

$$ {}^{2'}_{2}R\{Y_{+90}\} = \begin{bmatrix} \cos 90 & 0 & \sin 90 \\ 0 & 1 & 0 \\ -\sin 90 & 0 & \cos 90 \end{bmatrix} \tag{5} $$

$$ {}^{3}_{2}R\{\alpha_2\} = \begin{bmatrix} \cos\alpha_2 & -\sin\alpha_2 & 0 \\ \sin\alpha_2 & \cos\alpha_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{6} $$

The entire rotation at the shoulder joint can be arrived from (7) and with which the translation matrix as shown in equation (8) about the joint with link $L_1$ can be obtained as follows,

$$ {}^{3}_{0}R = {}^{0'}_{0}R\{Y_{-90}\} * {}^{1}_{0}R\{\theta_1\} * {}^{1'}_{1}R\{X_{-90}\} * {}^{2}_{1}R\{\theta_2\} * {}^{2'}_{2}R\{Y_{-90}\} * {}^{3}_{2}R\{\alpha_2\} \tag{7} $$

$$ {}^{3}_{0}R = \begin{bmatrix} C\theta_2 * S\alpha_2 & C\theta_2 * C\alpha_2 & -S\theta_2 \\ (-S\theta_1 * S\theta_2 * S\alpha_2) + (C\theta_1 * C\alpha_2) & (-S\theta_1 * S\theta_2 * C\alpha_2) - (C\theta_1 * S\alpha_2) & -S\theta_1 * C\theta_2 \\ (-C\theta_1 * S\theta_2 * S\alpha_2) - (S\theta_1 * C\alpha_2) & (-C\theta_1 * S\theta_2 * C\alpha_2) + (S\theta_1 * C\alpha_2) & -C\theta_1 * C\theta_2 \end{bmatrix} $$

$$ {}^{3}_{0}T = \begin{bmatrix} C\theta_2 * S\alpha_2 & C\theta_2 * C\alpha_2 & -S\theta_2 & 0 \\ (-S\theta_1 * S\theta_2 * S\alpha_2) + (C\theta_1 * C\alpha_2) & (-S\theta_1 * S\theta_2 * C\alpha_2) - (C\theta_1 * S\alpha_2) & -S\theta_1 * C\theta_2 & L_1 * C\theta_1 \\ (-C\theta_1 * S\theta_2 * S\alpha_2) - (S\theta_1 * C\alpha_2) & (-C\theta_1 * S\theta_2 * C\alpha_2) + (S\theta_1 * C\alpha_2) & -C\theta_1 * C\theta_2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8} $$

At the elbow joint for making the Z axis inline to the axis of rotation, Y axis is made rotated by -90° as elaborated in equation(9). The rotation matrix for the joint 1 making an angle of $\theta_3$ is as shown in equation (10),

$$ {}^{3'}_{3}R\{Y_{-90}\} = \begin{bmatrix} \cos -90 & 0 & \sin -90 \\ 0 & 1 & 0 \\ -\sin -90 & 0 & \cos -90 \end{bmatrix} \tag{9} $$

$$ {}^{4}_{3}R\{\theta_3\} = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 \\ \sin\theta_3 & \cos\theta_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{10} $$

Similarly, the second motion twist in the elbow along the sagittal plane makes an angle $\alpha_3$ and for making the Z axis inline to the axis of rotation, Y axis is made rotated by +90° as elaborated in equation(11). The rotation matrix for the joint 1 making an angle of $\alpha_3$ is as shown in equation (12),

$$ {}^{4'}_{4}R\{Y_{+90}\} = \begin{bmatrix} \cos 90 & 0 & \sin 90 \\ 0 & 1 & 0 \\ -\sin 90 & 0 & \cos 90 \end{bmatrix} \tag{11} $$

$$ {}^{5}_{4}R\{\alpha_3\} = \begin{bmatrix} \cos\alpha_3 & -\sin\alpha_3 & 0 \\ \sin\alpha_3 & \cos\alpha_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{12} $$

The entire rotation at the elbow joint can be arrived from (13) and with which the translation matrix as shown in equation (14) about the joint with link $L_2$ can be obtained as follows,

$$ {}^{5}_{3}R = {}^{3'}_{3}R\{Y_{-90}\} * {}^{4}_{3}R\{\theta_3\} * {}^{4'}_{4}R\{Y_{90}\} * {}^{5}_{4}R\{\alpha_3\} \tag{13} $$

$$ {}^{5}_{3}R = \begin{bmatrix} C\alpha_3 & -S\alpha_3 & 0 \\ C\theta_3 * S\alpha_3 & C\theta_3 * C\alpha_3 & S\theta_3 \\ -S\theta_3 * S\alpha_3 & -S\theta_3 * C\alpha_3 & C\theta_3 \end{bmatrix} $$

$$ {}^{5}_{3}T = \begin{bmatrix} \cos\alpha_3 & -\sin\alpha_3 & 0 & 0 \\ \cos\theta_3 * \sin\alpha_3 & \cos\theta_3 * \cos\alpha_3 & \sin\theta_3 & 0 \\ -\sin\theta_3 * \sin\alpha_3 & -\sin\theta_3 * \cos\alpha_3 & \cos\theta_3 & L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{14} $$

At the wrist joint for making the Z axis inline to the axis of rotation, Y axis is made rotated by -90° as elaborated in equation(15). The rotation matrix for the joint 1 making an angle of $\theta_4$ is as shown in equation (16),

$$ {}^{5'}_{5}R\{Y_{-90}\} = \begin{bmatrix} \cos -90 & 0 & \sin -90 \\ 0 & 1 & 0 \\ -\sin -90 & 0 & \cos -90 \end{bmatrix} \tag{15} $$

$$ {}^{6}_{5}R\{\theta_4\} = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 \\ \sin\theta_4 & \cos\theta_4 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{16} $$

Similarly, the second motion in the wrist along the sagittal plane makes an angle $\theta_5$ and for making the Z axis inline to the axis of rotation, Y axis is made rotated by +90° as elaborated in equation(17). The rotation matrix for the joint 1 making an angle of $\theta_5$ is as shown in equation (18),

$$ {}^{6'}_{6}R\{Y_{+90}\} = \begin{bmatrix} \cos 90 & 0 & \sin 90 \\ 0 & 1 & 0 \\ -\sin 90 & 0 & \cos 90 \end{bmatrix} \tag{17} $$

$$ {}^{7}_{6}R\{\theta_5\} = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 \\ \sin\theta_5 & \cos\theta_5 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{18} $$

The entire rotation at the wrist joint can be arrived from the equation (19) and with which the translation matrix as shown in equation Equation (20) about the joint with link $L_2$ can be obtained as follows,

$$ {}^{7}_{5}R = {}^{5'}_{5}R\{Y_{-90}\} * {}^{6}_{5}R\{\theta_4\} * {}^{6'}_{6}R\{Y_{90}\} * {}^{7}_{6}R\{\theta_5\} \tag{19} $$

$$ {}^{7}_{5}R = \begin{bmatrix} C\theta_5 & -S\theta_5 & 0 \\ C\theta_4 * S\theta_5 & C\theta_4 * C\theta_5 & S\theta_4 \\ S\theta_4 * S\theta_5 & -S\theta_4 * C\theta_5 & C\theta_4 \end{bmatrix} $$

$$ {}^{7}_{5}T = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & 0 \\ \cos\theta_4 * \sin\theta_5 & \cos\theta_4 * \cos\theta_5 & \sin\theta_4 & 0 \\ \sin\theta_4 * \sin\theta_5 & -\sin\theta_4 * \cos\theta_5 & \cos\theta_4 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{20} $$

The overall translational motion along the planes can be obtained by combining (8), (14) and (20) and is as elaborated in equation(21) below,

$$ {}^{7}_{0}T = {}^{3}_{0}T * {}^{5}_{3}T * {}^{7}_{5}T \tag{21} $$

After feeding in the angle and limb length values into the (8), (14) and (20) and obtaining the (21) can be used to arrive the forward kinematics of the robotic assistive device or prosthesis. The given equations are valid for exoskeleton devices, prosthesis and humanoids resembling the human biological upper limb.

**Table 2.** Initial and final angles of each joint axis

| | $\theta_1$. | $\theta_2$. | $\alpha_2$. | $\theta_3$. | $\alpha_3$. | $\theta_4$. | $\theta_5$. |
|---|---|---|---|---|---|---|---|
| Initial | $-50^\circ$ | $0^\circ$ | $-45^\circ$ | $0^\circ$ | $-80^\circ$ | $-40^\circ$ | $-30^\circ$ |
| Final | $130^\circ$ | $150^\circ$ | $45^\circ$ | $140^\circ$ | $80^\circ$ | $40^\circ$ | $30^\circ$ |

The position, velocity and acceleration profiles for each joint of the upper limb are plotted by arriving the third order polynomial equation with respect to time and is explained for the shoulder joint 1 making an angle of $\theta_1$. Let $\theta_i$ and $\theta_f$ be the initial and final angles of the link with respect to time $t$. The initial and final angles with respect to each joint axes are plotted in the Table 2 with $\pm 10^\circ$ deviation. The polynomial equation may be written as shown in equation (22) and similarly the velocity profile be as shown in equation (23) and acceleration profile as in (24).

$$\theta_t = C_0 + C_1 t + C_2 t^2 + C_3 t^3 \tag{22}$$

$$\dot{\theta}_t = C_1 + 2C_2 t + 3C_3 t^2 \tag{23}$$

$$\ddot{\theta}_t = 2C_2 + 6C_3 t \tag{24}$$

Let the initial position of shoulder joint making an angle $\theta_1$ along the coronal plane be $C_0 = -50^\circ$ and the final position at time $t_f = 10Sec$ be $\theta(t_f) = 130^\circ$ and substituting the above values in (22) gives,

$$-50 + 10C_1 + 100C_2 + 1000C_3 = 130 \tag{25}$$

Since the initial and final velocity is 0, $C_1 = 0$ and (25) and (23) may be rewritten with substituting the time $t_f = 10Sec$ as,

$$100C_2 + 1000C_3 = 180 \tag{26}$$

$$20C_2 + 300C_3 = 0 \tag{27}$$

Upon equating and evaluating (26) and (27), we get the values $C_2 = 5.4$ and $C_3 = -0.36$ from which the position, velocity and acceleration profiles can be plotted by substituting the aforementioned values in (22), (23) and (24) and is plotted in the Figure 5 for Shoulder Forward Flexion-Hyper Extension.

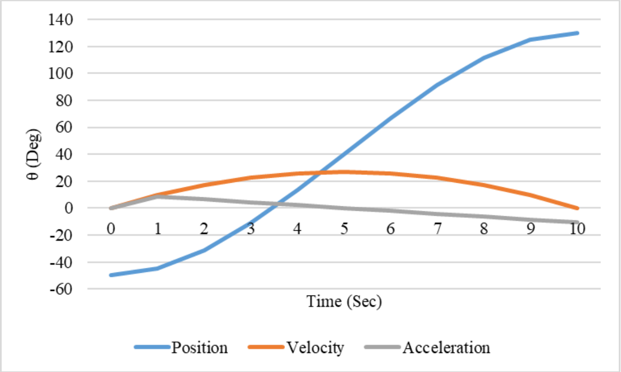

**Fig. 5.** Position, Velocity and Acceleration profile for shoulder Forward Flexion-Hyper Extension

Similarly, the equations may be arrived for the other upper limb joints for Shoulder Abduction-Adduction, Elbow Internal Rotation-External Rotation, Elbow Flexion-Extension, Elbow Pronation-Supination, Wrist Radial Deviation-Ulnar Deviation and Wrist Flexion-Extension and are plotted from Figure 6 to Figure 11.

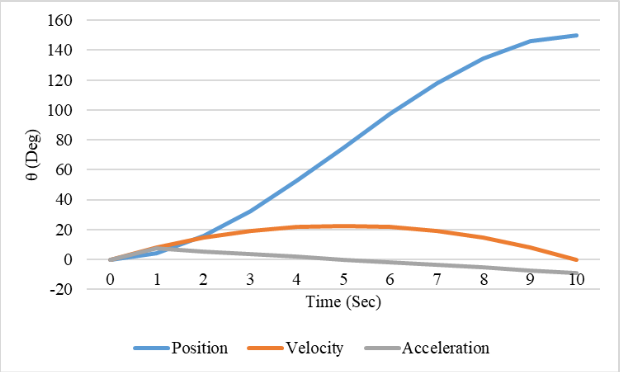

**Fig. 6.** Position, Velocity and Acceleration profile for Shoulder Abduction-Adduction

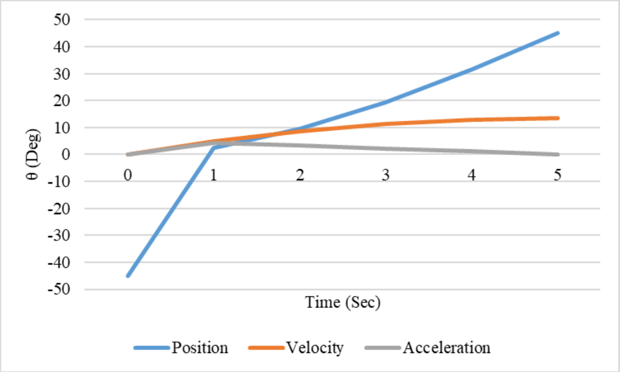

**Fig. 7.** Position, Velocity and Acceleration profile for Elbow Internal Rotation-External Rotation

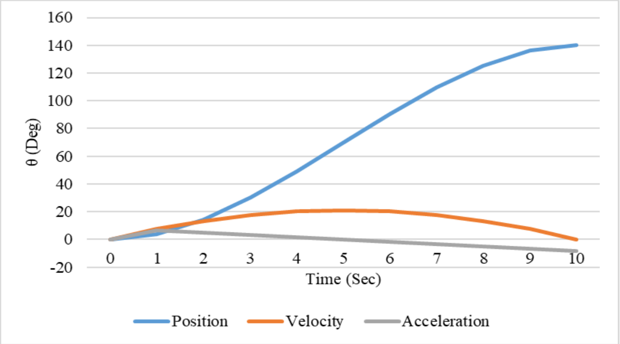

**Fig. 8.** Position, Velocity and Acceleration profile for Elbow Flexion Extension

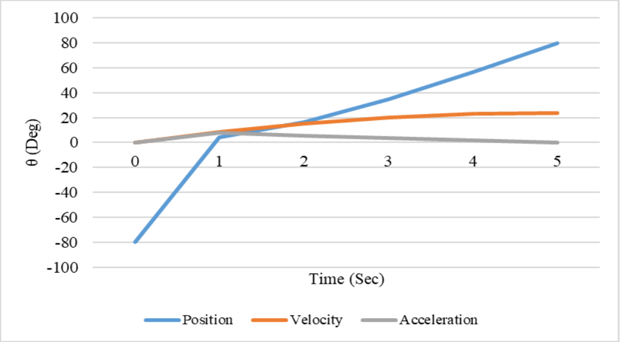

**Fig. 9.** Position, Velocity and Acceleration profile for Elbow Pronation-Supination

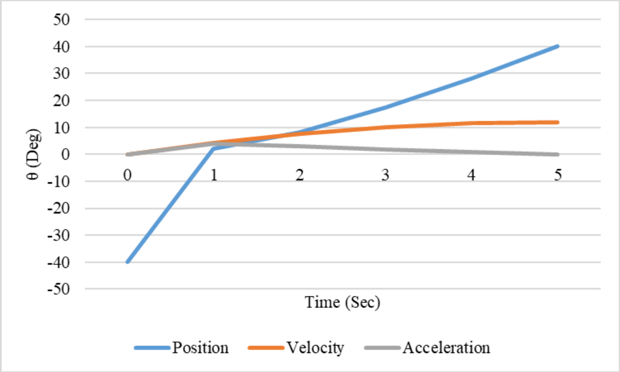

**Fig. 10.** Position, Velocity and Acceleration profile for Wrist Radial Deviation-Ulnar Deviation

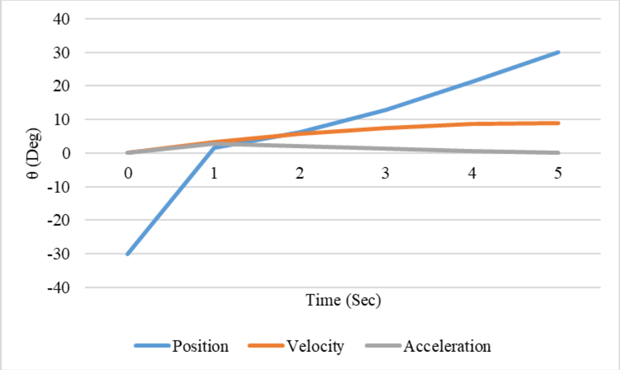

**Fig. 11.** Position, Velocity and Acceleration profile for Wrist Flexion-Extension

For upper limb treatment training / rehabilitation, a set therapy sequence is specified. Based on the application and needs, it has a lot of practicality at the moment. An adaptive structure that suits with the user requirement is the need of the hour. Some have been made of rigid materials like metal or carbon fibre, while others are made of flexible and soft materials like rexon belt, fibre. The exo-skeleton was formerly constructed using a variety of materials, including aluminium, PVC, and premium metals.

## 4. Conclusion

Exoskeletons for upper limb rehabilitation are clearly needed in the modern environment. Exoskeletons have the potential to revolutionize rehabilitation and enhance quality of life for many people as technology develops. The paper gave a broader and deeper insights of the human upper limb arrangement and made an attempt to convert the bio model into a biokinetic equation and mapping the movements by drawing a velocity and acceleration profiles thereby to enhance the understanding and accelerate the research in the fields of assistive devices and humanoids to mimic and replicate the human limb action. The arrived equations can be applied directly to obtain the forward kinematics end position which is the essential parameter in designing the medical rehabilitation devices. The ultimate aim of a rehabilitation exo-skeleton is primarily meant to repair or enhance people's ability to walk or carry everyday objects, it should be lighter, stronger, and smarter. These state-of-the-art instruments solve the challenges faced by people with upper limb issues when it comes to the rehabilitation process by ensuring precision, intensity, and accessibility. Modern exo-skeleton devices utilize a variety of sensor as feedback to offer precise treatment just to the degree needed by the user to enhance the therapy to the needy thus throws light on the rehabilitation sector thanks to the advancements in the monitoring and data collection algorithms which acquires the data collected from the user in real-time that enables the exo-skeleton to vary the intensity accordingly.

Thus, it is encouraged to use lightweight materials like aluminium, PVC, and soft fabrics. Nowadays, a lot of people have back pain, muscle aches, and other physical discomfort as a result of their jobs and workplaces. Flexible and adjustable designs that can accommodate various arm lengths are appreciated because they are attached to the human arm at various points and are made to function in combination with the human upper limb. As the research and commercially accessible prototypes are compared and evaluated, the mechanical concerns are also emphasized. The time when the exo-skeleton will improve human life and make it better by lessening or eliminating the limitations and flaws that humans currently encounter had already started.

To guarantee that these devices continue to develop and satisfy the ever-increasing need for improved upper limb rehabilitation treatments, it is crucial to support research and development in this area. For making the exo-skeleton systems that are accessible and cheap to the general population, cost-effective and adaptable designs are solely recommended. In order to do this, design perspectives must be considered in order to create fewer complex designs and alleviate manufacturing restrictions. The user may utilize the battery-operated exo-skeleton gadget on the injured limb as necessary. The links must be constructed from lightweight, bolted, modular frames made of aluminium that can be disassembled when not in use. Compact harmonic gear-based drives paired with DC motors or servos must be employed to actuate the limb joints.

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## References

[1] N. Yagn, “Apparatus for Facilitating Walking, Running, and Jumping,” 440,684 [Online]. Available: https://patentimages.storage.googleapis.com/94/70/4e/f46773a82b1caa/US440684.pdf

[2] P. Rangan R and R. Babu S, “Exo skeleton pertinence and control techniques: A state-of-the-art review,”, in *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.*, Feb. 2024, doi: 10.1177/09544062241226842.

[3] A. Agrawal, A. N. Dube, D. Kansara, S. Shah, and S. Sheth, “Exoskeleton: The Friend of Mankind in context of Rehabilitation and Enhancement”, *Indian J. Sci. Technol.*, vol. 9, no. S1, pp. 1–8, Dec. 2016, doi: 10.17485/ijst/2016/v9is1/100889.

[4] H. Lee, W. Kim, J. Han, and C. Han, “The technical trend of the exoskeleton robot system for human power assistance”, *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 8, pp. 1491–1497, 2012, doi: 10.1007/s12541-012-0197-x.

[5] G. Bao *et al.*, “Academic Review and Perspectives on Robotic Exoskeletons”, *IEEE Trans. Neural Sys. Rehab. Eng.*, vol. 27, no. 11, pp. 2294–2304, Nov. 2019, doi: 10.1109/TNSRE.2019.2944655.

[6] M. P. de Looze, T. Bosch, F. Krause, K. S. Stadler, and L. W. O”Sullivan, “Exoskeletons for industrial application and their

potential effects on physical work load", *Ergonomics*, vol. 59, no. 5, pp. 671–681, May 2016, doi: 10.1080/00140139.2015.1081988.

[7] C. J. Yang, J. F. Zhang, Y. Chen, Y. M. Dong, and Y. Zhang, "A review of exoskeleton-type systems and their key technologies", in *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.*, vol. 222, no. 8. pp. 1599–1612, Aug. 2008. doi: 10.1243/09544062JMES936.

[8] K. H. Low, "Robot-Assisted Gait Rehabilitation: From Exoskeletons to Gait Systems", in *2011 Defen. Sci. Res. Conf. Expo (DSR)*, 2011, pp. 1–10. doi: 10.1109/DSR.2011.6026886.

[9] C. A. A. Sharma, A. S. K. Sai Vishnu Kumar, A. Prasad, R. Begum, G. S. Sharvani, and A. E. Manjunath, "Multifaceted bio-medical applications of exoskeleton: A review," in *2018 2nd Int. Conf. Invent. Sys. Cont. (ICISC)*, Coimbatore: IEEE, Jan. 2018, pp. 11–15. doi: 10.1109/ICISC.2018.8399053.

[10] S. Yeem, J. Heo, H. Kim, and Y. Kwon, "Technical Analysis of Exoskeleton Robot", *World J. Eng. Tech.*, vol. 07, no. 01, pp. 68–79, 2019, doi: 10.4236/wjet.2019.71004.

[11] M. E. Rosheim, "Man-Amplifying Exoskeleton," in *1989 Symp. Vis. Communic., Im. Process., Intellig. Robot. Sys.*, Philadelphia, PA, United States, Mar. 1990, pp. 402 - 411. doi: 10.1117/12.969901.

[12] W. S. Lee, W. H. Cheung, L. Qin, N. Tang, and K. S. Leung, "Age-associated decrease of Type IIA/B human skeletal muscle fibers", *Clin. Orthop. Relat. Res.*, vol. 450, pp. 231–237, 2006, doi: 10.1097/01.blo.0000218757.97063.21.

[13] M. Grimmer, R. Riener, C. J. Walsh, and A. Seyfarth, "Mobility related physical and functional losses due to aging and disease - A motivation for lower limb exoskeletons", *J. Neuroeng. Rehabil.*, vol. 16, no. 2, pp. 1–21, Jan. 2019, doi: 10.1186/s12984-018-0458-8.

[14] E. Y. S. Chao and J. Lim, "Virtual Interactive Musculoskeletal System (VIMS) in orthopaedic translational research", *J. Ortho. Trans.*, vol. 1, no. 1. Elsevier (Singapore) Pte Ltd, pp. 25–40, 2013. doi: 10.1016/j.jot.2013.07.006.

[15] S. Spada, L. Ghibaudo, S. Gilotta, L. Gastaldi, and M. P. Cavatorta, "Investigation into the Applicability of a Passive Upper-limb Exoskeleton in Automotive Industry", *Procedia Manuf.*, vol. 11, pp. 1255–1262, 2017, doi: 10.1016/j.promfg.2017.07.252.

[16] S. Panich, "Design and Simulation of Leg-Exoskeleton Suit for Rehabilitation", *Global J. Med. Res.*, vol. 12, no. 3, pp. 1–8, 2012.

[17] R. A. R. C. Gopura and K. Kiguchi, "Mechanical Designs of Active Upper-Limb Exoskeleton Robots", in *IEEE 11th Int. Conf. Rehabil. Robot.*, 2009, pp. 178–187. doi: 10.1109/ICORR.2009.5209630.

[18] D. Shi, W. Zhang, W. Zhang, and X. Ding, "A Review on Lower Limb Rehabilitation Exoskeleton Robots", *Chinese J. Mech. Eng. (English Edition)*, vol. 32, no. 74, pp. 1–11, Dec. 2019, doi: 10.1186/s10033-019-0389-8.

[19] P. Maciejasz, J. Eschweiler, K. Gerlach-Hahn, A. Jansen-Troy, and S. Leonhardt, "A survey on robotic devices for upper limb rehabilitation", *J. Neuroeng. Rehabil.*, vol. 11, no. 3, pp. 1–29, 2014, doi: https://doi.org/10.1186/1743-0003-11-3.

[20] S. Dalla Gasperina, L. Roveda, A. Pedrocchi, F. Braghin, and M. Gandolla, "Review on Patient-Cooperative Control Strategies for Upper-Limb Rehabilitation Exoskeletons", *Front. Robot. AI*, vol. 8, pp. 1–24, Dec. 2021, doi: 10.3389/frobt.2021.745018.

[21] I. Indrawibawa and G. S. Virk, "Exoskeleton for assisting human walking", in *Nature-Inspired Mobile Robotics: Proceed. 16th Intern. Conf. Climb. Walk/ Rob. Supp. Techn. Mob. Mach., CLAWAR 2013*, World Scientific Publishing Co. Pte Ltd, 2013, pp. 117–124. doi: 10.1142/9789814525534_0018.

[22] S. K. Banala, S. K. Agrawal, S. H. Kim, and J. P. Scholz, "Novel gait adaptation and neuromotor training results using an active leg exoskeleton", *IEEE/ASME Trans. Mechatron.*, vol. 15, no. 2, pp. 216–225, Apr. 2010, doi: 10.1109/TMECH.2010.2041245.

[23] J. Son, J. Ryu, S. Ahn, E. J. Kim, J. A. Lee, and Y. Kim, "Effects of 4-Week Intensive Active-Resistive Training with an EMG-Based Exoskeleton Robot on Muscle Strength in Older People: A Pilot Study", *Biomed. Res. Int.*, vol. 2016, pp. 1–5, 2016, doi: 10.1155/2016/1256958.

[24] L. M. Vaca Benitez, M. Tabie, N. Will, S. Schmidt, M. Jordan, and E. A. Kirchner, "Exoskeleton technology in rehabilitation: Towards an EMG-based orthosis system for upper limb neuromotor rehabilitation", *J. Robotics*, vol. 2013, pp. 1–13, 2013, doi: 10.1155/2013/610589.

[25] R. M. Lester and A. S. Gorgey, "Feasibility of robotic exoskeleton ambulation in a C4 person with incomplete spinal cord injury: a case report", *Spin. Cord Ser. Cases*, vol. 4, no. 36, pp. 1–7, Dec. 2018, doi: 10.1038/s41394-018-0053-z.

[26] K. L. Poggensee and S. H. Collins, "How adaptation, training, and customization contribute to benefits from exoskeleton assistance", *Sci. Robot*, vol. 6, no. 58, pp. 1–16, Sep. 2021, doi: 10.1126/scirobotics.abf1078.

[27] B. Hwang and D. Jeon, "A method to accurately estimate the muscular torques of human wearing exoskeletons by Torque sensors", *Sensors (Switzerland)*, vol. 15, no. 4, pp. 8337–8357, Apr. 2015, doi: 10.3390/s150408337.

[28] S. Han, H. Wang, and Y. Tian, "Adaptive computed torque control based on RBF network for a lower limb exoskeleton", in *2018 IEEE 15th Int. Works. Adv. Mot. Cont. (AMC)*, 2018, pp. 35–40. doi: 10.1109/AMC.2019.8371059.

[29] R. Prashanna Rangan *et al.*, "Design, development and model analysis of lower extremity Exo-skeleton", *Med. Eng. Phys.*, vol. 106, p. 103830, Aug. 2022, doi: 10.1016/j.medengphy.2022.103830.

[30] A. Seth *et al.*, "OpenSim: Simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement", *PLoS Comput. Biol.*, vol. 14, no. 7, Jul. 2018, doi: 10.1371/journal.pcbi.1006223.

[31] C. L. Dembia, N. A. Bianco, A. Falisse, J. L. Hicks, and S. L. Delp, "OpenSim Moco: Musculoskeletal optimal control", *PLoS Comput. Biol.*, vol. 16, no. 12 December, Dec. 2020, doi: 10.1371/journal.pcbi.1008493.

[32] S. L. Delp *et al.*, "OpenSim: Open-source software to create and analyze dynamic simulations of movement", *IEEE Trans. Biomed. Eng.*, vol. 54, no. 11, pp. 1940–1950, Nov. 2007, doi: 10.1109/TBME.2007.901024.