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EMG-BASED BIOMECHANICAL AND MOLECULAR BIOMARKER ASSESSMENT OF ROBOT-ASSISTED UPPER LIMB REHABILITATION

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Abstract
The increasing scarcity of therapists and caregivers for individuals with physical disability underscores the need for readily available, home-based rehabilitation options. To address this aspect, this study introduces a compact and versatile two-degree-of-freedom planar manipulator specifically designed to aid in upper limb rehabilitation, with a focus on the shoulder and elbow joints. The manipulator can be used for both tabletop and vertical configuration with simplified set-up. Forward and inverse kinematics were mathematically derived to govern the movements of the manipulator to enable the execution of common physiotherapy exercises- characterized by straight lines, L-shapes, arcs, circles and loops. The motion of the simulated manipulator was validated using Robo Analyzer, where trajectory paths generated in Python were used to simulate typical exercise patterns. Experimental trials were conducted to replicate fundamental upper limb movements, including shoulder flexion/extension and abduction/adduction, as well as elbow flexion/extension. Furthermore, integrated electromyography (EMG) and force sensors facilitate the automated detection of patient interaction and movement. The tabletop configuration yielded experimental results showing shoulder flexion ranging from 0° to approximately 180°, shoulder extension to around 35°, and elbow flexion reaching approximately 150°. It should be noted that extension is limited to 0° due to the design focused on elbow rehabilitation. In the vertical configuration, the manipulator achieved shoulder extension of 60°, elbow hyperextension of approximately -5°, shoulder abduction from 0° to 180°, and shoulder adduction to 75°. These findings prove that the manipulator can assist a broad range of upper limb rehabilitation exercises, which is potentially an economical and feasible assistive device that can be used by the patient in both domestic and clinical locations.

Keywords: Planar Manipulator, Upper-Limb Rehabilitation, Kinematics, shoulder, and elbow therapy.

1. INTRODUCTION

Due to the ageing of the world population and the increase in chronic diseases, the demand to rehabilitate people has also increased significantly. Regrettably, the number of health professionals, such as therapists and care givers, who are trained is insufficient to match this growing demand, which poses an acute service gap. Home-Based Rehabilitation (HBR) is also used to help solve this problem by providing rehabilitation services to the individual in their home since it is an easy and preferred alternative to the conventional clinic or hospital care. It is effective since it addresses geographical barriers, transport challenges, and economic setback that many conventions rehabilitation is characterized by. HBR programs may be also accurately customized to personal needs and preferences so that recovery is more personal and effective. Rehabilitation is best done within a familiar environment, which will result in more participation and motivation of the patients and thus a better outcome. Moreover, the home-based programs tend to be more affordable especially to patients requiring long-term care than the traditional inpatient or outpatient solutions. In the future, it is necessary to integrate Telehealth and other technologies in the HBR in order to increase access and support. Rehabilitation community-based programs will also have a contribution to making headway to the underserved populations. Most importantly, effective care-giver support is critical to the effectiveness of any rehabilitation enterprise at home.

Considering upper-limb rehabilitation, physical therapists are known to be not as efficient in terms of time and cost in the classical form of upper limb rehabilitation. Robotic machines are also a promising option of upper limb training with benefits of self-regulated training intensity and frequency, and potential, independent practice [1]. Various robots in the field of rehabilitation of the upper extremities, such as exoskeletons and semi- exoskeletons, have been designed [2, 3]. Nevertheless, their large size and the necessity to set joint orientation precisely may

cause possible injuries. Moreover, the use might also require some adjustments to both arms, or individual exoskeletons would be required. Planar robots are also being used in rehabilitation particularly in cases of patients who have neurological or traumatic wound conditions [4]. Robotic rehabilitation systems could help decrease expenditures, increase the quality of treatment and to raise the efficiency of therapists, but they are not widely used in clinical practice. Portable 2R planar manipulator is lightweight with two rotational joints and a customizable end effector that translates planar motion accompanied by a vast workspace with easy kinematics. This machine is coded to move the patients in target paths along their rehabilitation.

Yavuz et al. [4] also presented a 2-DOF exoskeletal robot, together with its control structure, to be used in upper limbs. This robot had the purpose of load lifting, therapeutic exercise, and biomechanical parameter evaluation. Also, an electromyograph was developed as a measure of muscle activity. The paper suggested hardware enhances to ensure that the system becomes lighter, more modular, and wearable. Its architecture of force control was also mentioned when it comes to the use in the fields of rehabilitation and physical therapy. In the case of upper limb rehabilitation, Marco Ceccarelli et al. [5] introduced a helper device by the name "Nurse." This 2-degree-of-freedom planar goal appliance propels a 5-bar mechanism linkage system comprising of two built-in motors. It can be designed to utilize pantograph-scaled arm paths, and has large operational space to cover the natural spectrum of human arm movements, and is provided with sufficient force transmission. To test the working characteristics of the device and its applicability in rehabilitation or in the robots, the study was based on the finite element analysis and Transmission Index rating. Finally, conclusions of the research were that the design of Nurse proved to be a safe and effective way to guide and support rehabilitation exercises.

Yali Liu et al. [6] came up with the EEULRebot, an autonomous robot with an upper limb rehabilitation robot with two robotic links displaying two functional freedoms of movement. The core design features of the robot-kinematics, dynamics, control system, and the way the robot is used in rehabilitative therapies were the subject of their research. Comprehensively, the findings showed that the provision of mechanical constraints was of great beneficence to the hemiplegic patients because it allowed the robot to rectify the slouching behaviour and correct the muscle activity patterns to reestablish a normal muscle activity characteristic of a healthy human arm. This indicates that the EEULRebot presents significant benefits in terms of restoring motor activity in the patients and better enabling them to move in normal way during the rehabilitation period.

The EEULRebot study therefore highlights the use of the robot in rehabilitating the upper limbs especially the need to incorporate normal movement patterns in training. After this, Chih-Kang Chang et al. [7] have provided a theoretical account and prototyped a semi-passive rehabilitation robot SepaRRo which was used to perform authentic resistance training of the upper extremities in a functional manner. Their effort proved that semi-passive robots may provide an accurate and tuneable rehabilitation interface, in particular without active actuators. As a result, SepaRRo was discovered as one of the promising devices that could be used to conduct upper extremity rehabilitation. The NURSE-2 is a 2-degree-of-freed (DOF) device created by Betsy D. M. Chaparro-Rico et al. [8] and it is designed to aid persons with orthopaedic or neurological injuries in repetitive movement therapies. Its compact design and demonstrated repeatability of ±1.3 cm position it as a promising option for rehabilitation environments. The study concluded that NURSE-2 holds significant potential for physical therapy applications in patients with upper limb impairments.

Other developments in the field consist of N. Hogan et al. [9] who developed a two DOF (degree of freedom) end-effector robot operating in a horizontal plane; P. S. Lum et al. [10] developed MIME with 6-DOF three dimensional (3D) robotic system designed for therapies related to unilateral and also bilateral rehabilitations, Bi-Manu-Track developed by S. Hesse et al. [11] which consisted of a system that allowed for accommodating both limbs and demonstrated the ability to match the movement of either limbs, a five-bar linkage mechanism that with extreme rigidity was developed by GAO Jianshe et al. [12], with a relatively large workstation, Qing M. et al. [13] displayed two-DOF bilateral rehabilitation device which offered proof of concept of clinical effectiveness, and Adriana Cancrini et al. [14] used the PlanArm2 prototype which was capable of performing all types of upper-limb movements ranging through robotic assistance.

Besides, studies on combinations of shoulder and elbow rehabilitation several have been reported. When designing a rehabilitation robot, it is essential to have an insightful understanding of human upper limb anatomy, as the upper limb is crucial for performing daily activities. Rehabilitation is primarily focused on restoring these functional motor patterns. In terms of the range of motion that is explored in this study, we are targeting: shoulder with flexion & extension, adduction & abduction, and elbow with extension & flexion.

As shown in Table 1, the functional range of motion (ROM), which is frequently expressed as the ROM required to carry out functional tasks, is an essential measure for upper limb rehabilitation [15, 16]. According to the literature, end-effector devices have attracted considerable interest due to their distinctive structural characteristics.

Table 1. Movements and range of motion (ROM) for shoulder and elbow joints [15, 16]

Joint	Movement	Description	Range of Motion (ROM)
Shoulder	Flexion	Lifting the arm forward and overhead	0°– 180°
	Extension	Moving the arm straight backward	0°–60°
	Abduction	Lifting the arm sideways and upward	0° – 180°
	Adduction	Bringing the arm down and across the front of the body	0° – 75°
Elbow	Flexion	Bending the forearm toward the upper arm	0° – 150°
	Extension	Straightening the forearm away from the upper arm	–5° – 0°

Anthropometric measures can be used to estimate the average length or mass of specific body segments or parts (or segments of the body as a proportion of total body height or weight) [17]. Table 2 presents some approximate ranges for several common anthropometric measures for male and female humans. For instance, the weight of a single upper arm can vary from about 1.75 kg to 2 kg, which is roughly 5% of overall body weight. The idea behind the shoulder and elbow rehabilitation device is to mimic joint movements in a two-dimensional space. The device features a handle at one end that can only move back and forth along the horizontal and vertical directions. This robotic system aims to assist upper limb rehabilitation by providing endpoint traction during shoulder and elbow rehabilitation exercises.

Table 2. Average anthropometric measurements of the upper arm region

Measurement	Average dimensions (cm)	
	Men	Women
Height	165-172	152-159
Upper Arm Length	31-37	29-34
Hand Length	17-19	15-17

1.3 Planar Manipulator

An adaptable device that supports arm exercises in both horizontal and vertical planes is the 2R manipulator. As seen in Figure 1, its end-effector can support the patient's hand similarly to a therapist [18]. With its adaptive design, the manipulator can function on both tabletops and vertical pole supports. This flexibility allows for thorough shoulder and elbow therapy with minimal device adjustments, and schematic representation of a two-link planar manipulator as depicted in Figure 1

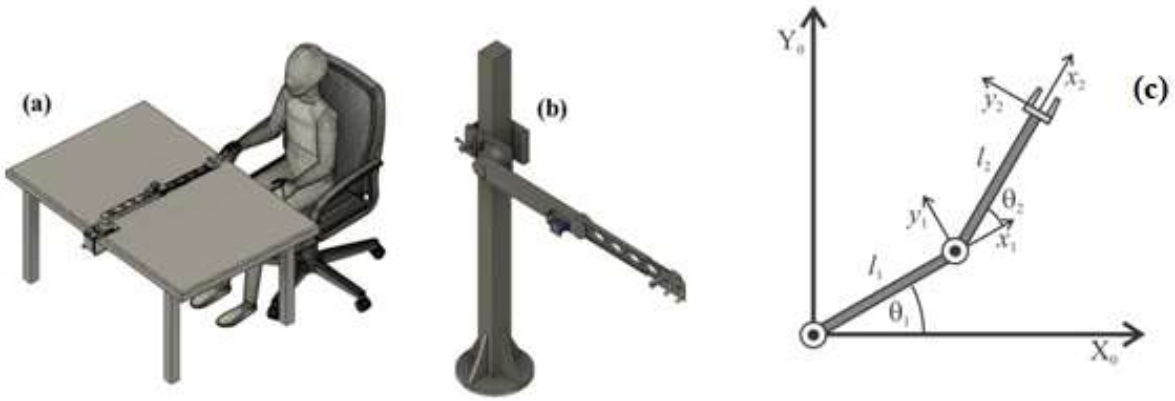


Fig. 1. Two-link manipulator for upper limb rehabilitation, showing (a) tabletop arrangement for horizontal plane, (b) vertical pole arrangement for vertical plane and (c) schematic representations of a two-link planar manipulator.

The physical activities encompass the movements of the shoulder and elbow as delineated within the range of motion articulated in Table 1. The 2R manipulator is designed to guide the human arm along a series of predetermined trajectories situated within both horizontal and vertical planes. The end-effector can navigate paths in both the X-Y and Y-Z planes, covering a significant area of the workspace for passive upper limb exercise in these planes. The training area is based on the average measurements for upper limb lengths. We will describe

this as the patient's hand being in line with the end of the planar end-effector. A major advantage of a planar system is its enhanced stiffness and reduced weight.

1.4 Research Gaps

Most existing rehabilitation systems lack adaptive control strategies that can dynamically tailor therapy to the individual needs and progress of patients. Additionally, many of these devices are stationary and non-portable, restricting their application to clinical environments and limiting the potential for home-based or community-based rehabilitation.

A significant limitation of 2R planar manipulators is their restricted workspace, which confines arm movements to the horizontal plane. This is particularly problematic since flexion/extension of the shoulder should appear in a number of activities of everyday living. Application of existing 2R systems that is not up to perform vertical motion would be a hindrance to training of these important patterns of movement which could adversely affect advances in functional recovery.

Additionally, 2DOF manipulators lack workspace coverage which is insufficient to accommodate the natural and complex joint motion repertoire of the shoulder and elbow. This limits their effectuality in the provision of functional and task-specific rehabilitation activities that reflect real-life movement's needs.

1.5 Objectives

The main aim of this study is to build a generalized robotic manipulator customized to upper limb rehabilitation with specific focus on major limitations in the current 2DOF systems. The designed device is so designed to be more versatile and portable with customable height features; together with an integrated mobile base, which includes support wheels, so that it can be used in both seated and standing modes. The design allows convenient repositioning either in front of, to the right level in front of or at right side in front of the patient to allow flexibility in rehabilitation sessions in a wide range of physical locations including home-based and clinical settings.

The device is designed to offer structural flexibility by presenting a new design principle enabling the manipulator to be placed on top of tabletops and on vertical pole supports. This allows a thorough shoulder and elbow therapy with only minor physical conversion, which is capable of supporting exercises in the three planes of motion, including vertical components that are important in actions requiring shoulder flexion and extension.

The suggested device is designed to overcome the limited workspace of the traditional 2R planar manipulators by allowing the extension of the reach and widening the scope of rehabilitation. The proposed system supports natural and functional movement patterns, better aligning with the complex kinematics of the human upper limb. Accommodate diverse patient needs and therapy scenarios, laying the foundation for future integration of adaptive control strategies, such as real-time feedback-based exercise progression and task-level customization, thereby personalizing rehabilitation to individual patient profiles.

1.6 Outline of this research

Based on the literature survey proper research gaps were identified and objectives of the study are outlined. The goals of this research include creating and building a flexible, lightweight 2-DOF planar manipulator aimed at helping with shoulder and elbow rehabilitation in the upper limb. It is ensured that the manipulator is suitable for both tabletop and vertical pole settings with minimal adjustment.

This research focuses on the design and development of an adaptive two DOF planar manipulator intended for upper limb rehabilitation. The system is designed to provide context-specific therapeutic assistance, potentially enabling patients to regain greater range of motion and leading to improved functional abilities. Precise motion control is achieved through the derivation and application of both forward and inverse kinematics equations, enhancing the device's value for rehabilitation purposes. Furthermore, the device integrates EMG and force sensors to capture patient movement and performance data, while incorporating straightforward physiotherapy modes to support rehabilitation progress.

The upper limb rehabilitation trajectory planning for shoulder and elbow therapy is programmed and simulated using various physiotherapy motion patterns, including linear, arc, L-shaped, circular, and loop trajectories, to achieve the desired movements of a planar manipulator.

Experiments were carried out on the adaptive planar manipulator to validate the simulation results. The Tested movements were shoulder flexion/extension, shoulder adduction/abduction, and elbow flexion/extension. This paper outlines a design for a 2-DOF robot equipped with an end-effector aimed at helping upper limb rehabilitation, specifically to support shoulder and elbow joint movements in rehabilitation exercises.

2. KINEMATIC MODELLING OF 2R MANIPULATOR

The kinematic modelling of the 2R manipulator involves the following procedures:

2.1 Forward Kinematics:

Consider a two-link planar manipulator characterized by link lengths l_1 and l_2, as well as joint angles θ_1 and θ_2, with the objective of achieving a specified position (P_x, P_y), as depicted in Figure 1(c). The axes of the joints, denoted as z_0 and z_1, are aligned perpendicularly to the plane of motion.The foundational coordinate frame$o_0x_0y_0z_0$delineates the spatial position and angular orientation of the manipulator, with its point of origin situated at the intersection of z_0 and the designated plane.Following this, the frame $o_1x_1y_1z_1$is assigned according to the D-H convention [19], with its origin at the axis z1. Finally, the frame $o_2x_2y_2z_2$ is fixed at the end of the second link by placing the origin O2 at the tip of link-2, completing the setup for the two-link planar manipulator. The location of the end effector, found at the end of the second link, in the plane is calculated using the forward kinematics formulas mentioned in reference [14]. These formulas connect the end effector's position to the specified joint angles.

$$X = l_1 cos\theta_1 + l_2 cos\,(\theta_1 + \theta_2) \quad (1)$$

$$Y = l_1 sin\theta_1 + l_2 sin\,(\theta_1 + \theta_2) \quad (2)$$

2.2 Inverse Kinematics

In contrast, inverse kinematics focuses on computing the joint angles θ_1 and θ_2 required to achieve a specified end effector position (X, Y) in the plane.

(i) Calculating θ_2:

$$cos\theta_2 = \frac{X^2+Y^2-l_1^2-l_2^2}{2l_1l_2} \quad (3)$$

$$\theta_2 = arccos\left(\frac{X^2+Y^2-l_1^2-l_2^2}{2l_1l_2}\right) \quad (4)$$

(ii) Calculating θ_1:

$$\theta_1 = arctan2(Y,X) - arctan2\,[l_2\,sin(\theta_2),\ \ l_1 + l_2\,cos(\theta_2)] \quad (5)$$

2.3 Trajectory Planning

The trajectory path between the initial and goal positions can be connected by multiple segments with smooth acceleration at the connection points. If the position, velocity, and acceleration at the beginning and end of trajectory segments are specified, a cubic polynomial can be utilized. Mathematically, a cubic polynomial curve is represented between an initial point and an intermediate point in time (t) as follows [20, 21]:

$$\theta(t) = a_0 + a_1t + a_2t^2 + a_3t^3 \quad (6)$$

In the cubic polynomial equation (6), the function of time (t) is denoted by θ and the arbitrary constants are represented by a_0, a_1, a_2, a_3.

To generate the trajectory using a cubic polynomial, four boundary conditions are needed since there are four arbitrary constants in the polynomial Equation (6) represents the position function, then taking one derivative with respect to time gives the velocity as

$$v(t) = a_1 + 2a_2t + 3a_3t^2 \quad (7)$$

Again, differentiation will give acceleration, as

$$a(t) = 2a_2 + 6a_3t \quad (8)$$

To generate a trajectory for a robot manipulator that takes t_f time from the initial point to the goal point, four conditions can be specified, such as:

At $t = 0, \theta(t) = \theta_0\ (initial\ position)$ 9 (a)

At $t = t_f, \theta(t_f) = \theta_f\ (goal\ position)$ 9 (b)

At $t = 0, v(t) = 0$ 9 (c)

At $t = t_f, v(t_f) = 0$ 9 (d)

By applying the four boundary conditions i.e from 9(a) to 9(d) to Equation (6) and (7) for a robot manipulator that moves from the initial point to the goal point in a time interval of t_f, the values of the arbitrary constants can be obtained as follows:

$a_0 = \theta_0$ 10 (a)

$a_1 = 0$ 10 (b)

$a_2 = \frac{3}{t_f^2}(\theta_f - \theta_0)$ 10 (c)

$a_3 = \frac{-2}{t_f^3}(\theta_f - \theta_0)$ 10 (d)

The cubic polynomial equation can be utilized to establish a connection between an initial joint-angle position and any desired final position. However, this approach is only applicable when the joint's initial and final velocities are both zero.

By substituting the values of a_0, a_1, a_2, a_3. using the equations from 10 (a) to 10 (d) in the Equation no (6), the required single cubic polynomial equation that meets the given conditions is:

$$\theta(t) = \theta_0 + \frac{3}{t_f^2}(\theta_f - \theta_0)t^2 - \frac{2}{t_f^3}(\theta_f - \theta_0)t^3 \quad (11)$$

The tracing point of the end-effector sets the path of the manipulator, which can mimic different paths for upper limb rehabilitation on a flat surface, including arm therapy.

Several major research gaps have been introduced in the literature review. One of the main limitations in current rehabilitation robots is their size; for many existing rehabilitation robots, it is impossible to deploy these assistive devices in the home environment as they take too much space. This is an area in need of improvement, as increasing portability may, in turn, improve user access/use, which can increase rehabilitation outcomes. In addition to the current models of rehabilitation robots already available, improving simplicity by looking at manipulated systems like end-effectors and planar devices opens opportunities in the creation of lightweight, durable, and user-friendly therapy devices at home.

3. EXPERIMENTAL SETUP OF 2R MANIPULATOR

The control architecture of the robotic system in Figure 2 is designed specifically to allow upper limb rehabilitation of patients in a seated position at a table. During the rehabilitation session, the patient holds a handle attached to the end effector plate of the robot and moves along the path provided by the robot. The end effector has force and position sensors, allowing for the patient's applied force and the position of the end effector to be tracked throughout the rehabilitation session.

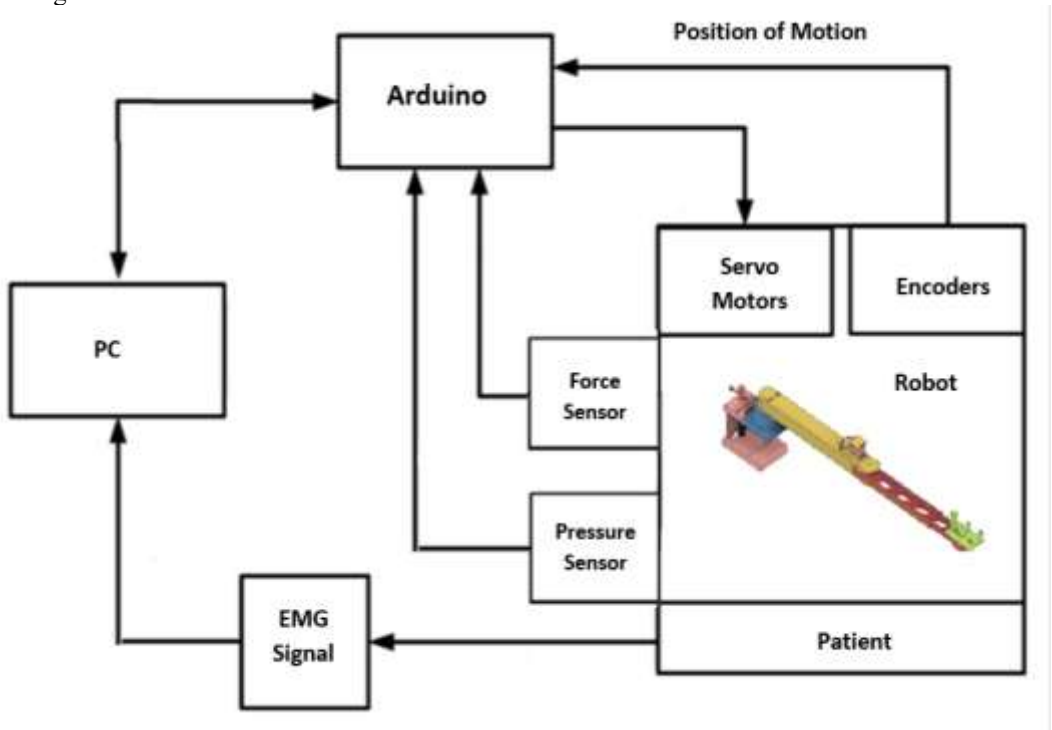


Fig. 2. The electronics hardware block diagram

Two servomotors power the end effector located at the position revolute joints. Each joint has an encoder to track positional movement. The robot uses an Arduino microcontroller to operate the servomotors, collect data from the sensors. A separate computer collects the reference biomechanical parameters from EMG signals, ultimately indicating the rehabilitation mode for the patient (if the mode is appropriate given the patient's condition). The computer is responsible for the communication and sending control commands to the Arduino board. The manipulator's base is clamped onto a stable surface at the edge of the table. Figures 3 depict the robotic manipulator fabricated from separate aluminium square beam sections, and both links are the same length (L1 = 20 cm: L2 = 20 cm).

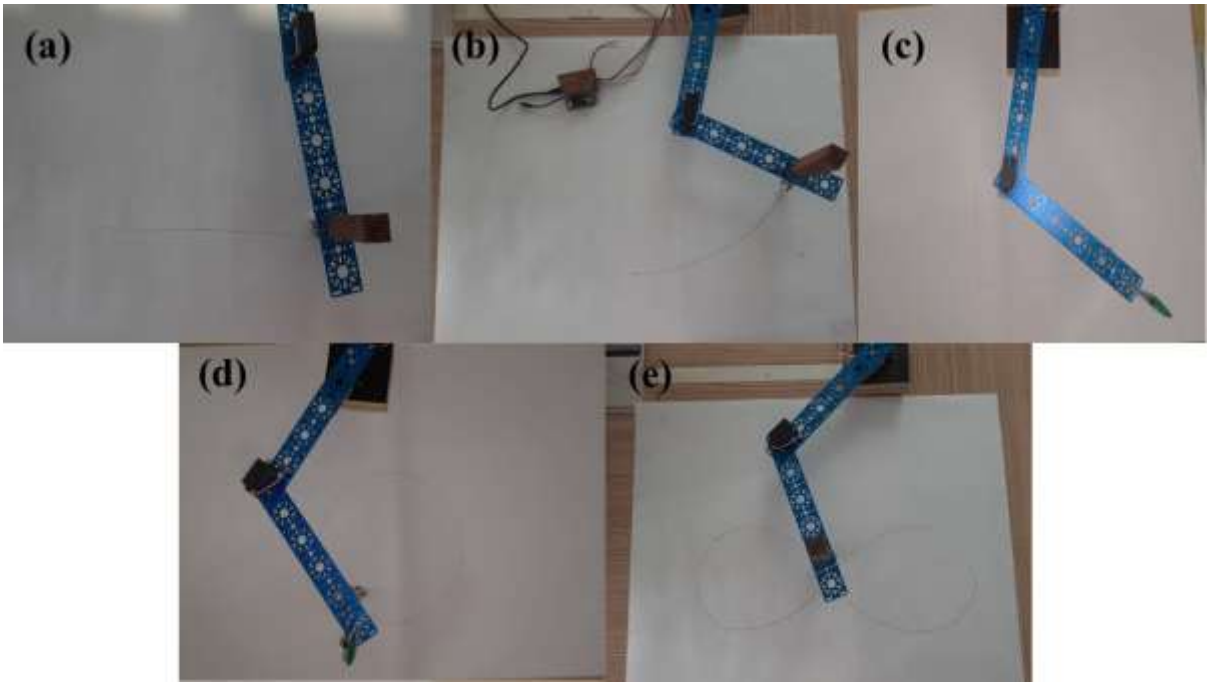


Fig. 3. Manipulator end-effector trajectory plots in Experimentation: (a) Line (b) Arc (c) L-shape, (d) Circle, (e) Loop

To perform the trajectory task, the manipulator needs to be set up as depicted in Figure6 prior to execution. The manipulator is positioned in its initial state, with its joints set to their starting positions and the lengths adjusted as needed. The participant positions their forearm on the support base and holds the handle with their hand. The surface EMG electrodes are affixed to the subject's skin surface to measure the EMG noise level, which serves as the threshold value during the resting state. After positioning the 2R manipulator, trajectory tasks were performed in all rehabilitation modes, as shown in Figure 3 and as measured by the robot's end-effector with the support system to measure interaction forces. The intention of the trials was to test the performance of the controller, not any biological or clinical outcomes, thus only one healthy volunteer (22 years old - male, 65 kg) was included in the evaluation.

Based on the experimental results, it is observed that the trajectory tracking performance is like that of the simulations carried out using Robo-Analyzer. Hence, the findings indicate that the proposed algorithms are accurate and effective. Additionally, the results obtained from the prototype test align with the simulation results, indicating that the upper limb rehabilitation robot satisfies the desired design specifications and can successfully accomplish the required motion functions necessary for upper limb rehabilitation training.

The upper limb rehabilitation trajectories used for the experimental characterization of the 2R planar manipulator are depicted in Figure 3. Specifically, Trajectory (a), (b) & (c) is designed for the Shoulder flexion and extension exercise and Trajectory (d) & (e) are designed for the simultaneous exercise of both the Shoulder Flexion & Extension and Elbow Flexion & Extension.

The 2R planar manipulator, used in upper limb rehabilitation, has two links that are 20 cm long each. The linkage system allows coordinated motion to simulate natural upper limb motion regarding precision and range of motion. The manipulator is bolted to a table in Figure 1(a), supporting the manipulator during therapy to guarantee patient safety during those movements. The base of the manipulator frame is cantered to the horizontal axis at the of the tabletop, which maximizes range and access for the patient while exceeding the range of up to 120 degrees (depending on the situation) dynamic motion. The workspace resulting from the tabletop manipulator's position is shown in Figure. 4 after simulating the proposed device using a Python program.

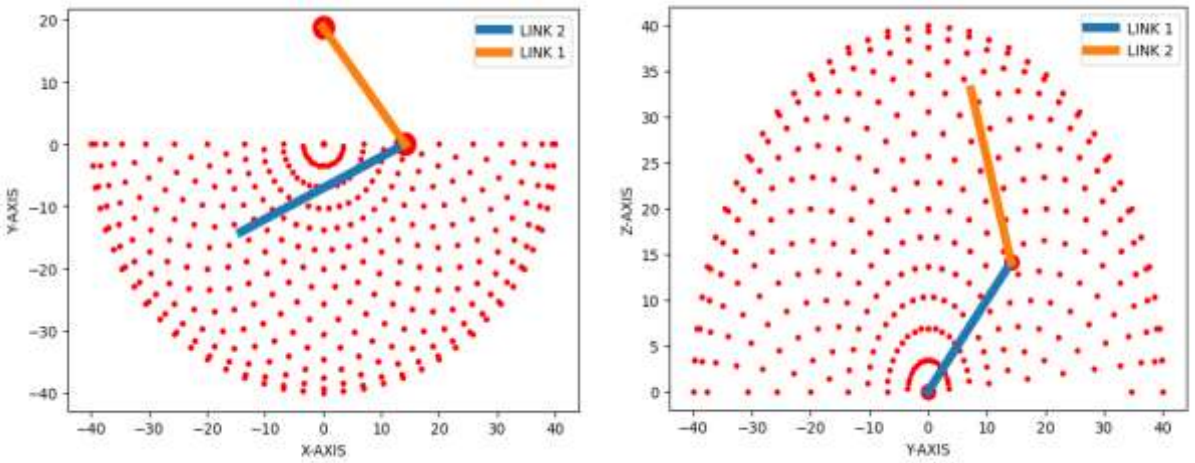


Fig. 4(a) 2-R manipulator workspace in tabletop arrangement and (b) workspace of 2-R manipulator in vertical pole setup.

In a different configuration shown in Figure 1(b), the manipulator is attached to vertical pole supports. Here, the manipulator's base is deliberately positioned to align with the patient's shoulder and elbow on the vertical axis, ensuring optimal range of motion and accessibility. The workspace result of the vertical pole setup is presented in Figure. 4(b), after simulating the proposed device using a Python program.

Given the manipulator positions in Figure 1(a) and the motion of the end-effector in Figure.4 (a), a user holding the end-effector would perform shoulder and elbow flexion and extension in the defined workspace. This configuration allowed for both forward and lateral reaching, but severely restricted backward targeting: the forearm could be positioned from 0° shoulder flexion to approximately 180° shoulder flexion; shoulder extension ranged from 0° to just past 30°. Again, depending on physical constraints on the manipulator setup in Figure 1(a), it should be noted that not all desired range of shoulder extension, as in the corresponding motion end-effector displayed in Figure., was possible due to physical obstructions from the tabletop manipulator layout. Elbow flexion was from 0° to approximately 150° elbow flexion, while elbow extension was restricted to 0° elbow extension, constrained by the tabletop manipulator layout.

From Figure 1(b), which showcases a manipulator mounted on a vertical stand, achieving a shoulder extension of 60° appears more feasible when the device is parallel to the vertical plane of the human hand. The manipulator's design seems to permit extensive movement without interference from the mounting stand. If the user aligns their hand with the manipulator and no other external constraints are present, reaching 60° of shoulder extension achievable. Furthermore, achieving an elbow extension of -5 degrees would imply that the forearm slightly hyperextends beyond a straight position. In the context of the manipulator setup in Figure 1(b) and the outcomes in Figure 4 (b), the shoulder abduction range seems to be between 0° to 180°. The shoulder adduction range might be from 0° to somewhere between 60° and 75°.

3.1 Ethical Approval and Consent

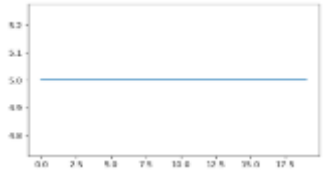
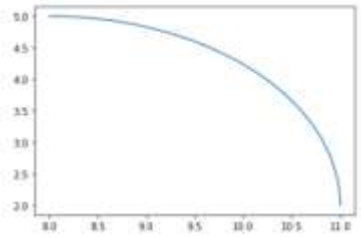
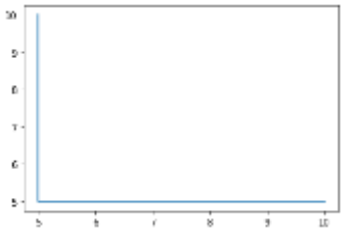
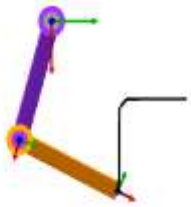
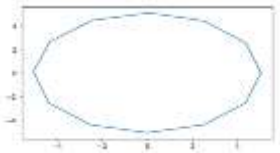
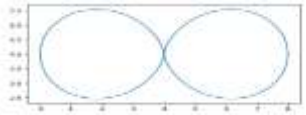
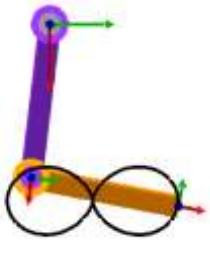
All methods were carried out in accordance with relevant institutional and national guidelines and regulations. The experimental protocol involving a human participant was reviewed and approved by the Institutional Ethics Committee of Koneru Lakshmaiah Education Foundation, Vaddeswaram, India (Approval No: KL04/2025). The study involved a single healthy adult volunteer for engineering system validation using non-invasive robotic interaction and surface EMG acquisition. Written informed consent was obtained from the participant prior to participation in the study.

4. RESULTS AND DISCUSSION

The 2-DOF manipulator was analysed using kinematic modelling and a cubic polynomial trajectory planning algorithm in a PYTHON program. This method produces the input commands for the manipulator's control system, enabling it to carry out the desired motion. The program output data in terms of joint variables can be exported as a CSV (comma separated values. Robo-Analyzer is used to simulate the manipulator obtained from the PYTHON program out as a CSV input. The plots of the end-effector coordinate simulated with help of python and Robo Analyzer as shown in Table 3. During the process of determining the trajectory of the rehabilitation

robot, the joint parameters are calculated. This allows for the derivation of the motion trajectory curve for each joint through simulation.
Figures 5 to 7 shows the same behaviour through time of the corresponding joint variables for both joints. The time is along the horizontal axis, while the joint variables are adjacent to the vertical axis. It can be observed that the curves are smooth and continuous which indicates a successful control performance and that the forward kinematics and inverse kinematics models were adequate for the rehabilitation robot. Figure 5 shows the joint angle deviations (in degrees on the y-axis) Joints 1 and 2 in a 5-second interval (x-axis) as the end effector moved along a prescribed path.
Figures 6 and 7 depict the variation of angular velocity and angular acceleration over time as the end moves. The plots for joint velocity (in degrees/sec) and joint acceleration (in degrees/sec^2) are illustrated in Figure 6 and Figure 7respectively.

Table 3 Manipulator end-effector trajectory plot: (a) line, (b) arc, (c) L-shape, (d) circle and (e) loop paths.

Path of End-effector	**Desired output simulation in PYTHON Software**	**Acquired output simulation in RoboAnalyzer**	**Obtained Rehabilitation of Shoulder**
Line Path			Flexion and extension
Arc Path			Flexion and Extension
L-Shape Path			Flexion and Extension
Circle Path			Flexion and Extension of Elbow and Shoulder
Loop Path			Flexion and Extension of Elbow and Shoulder

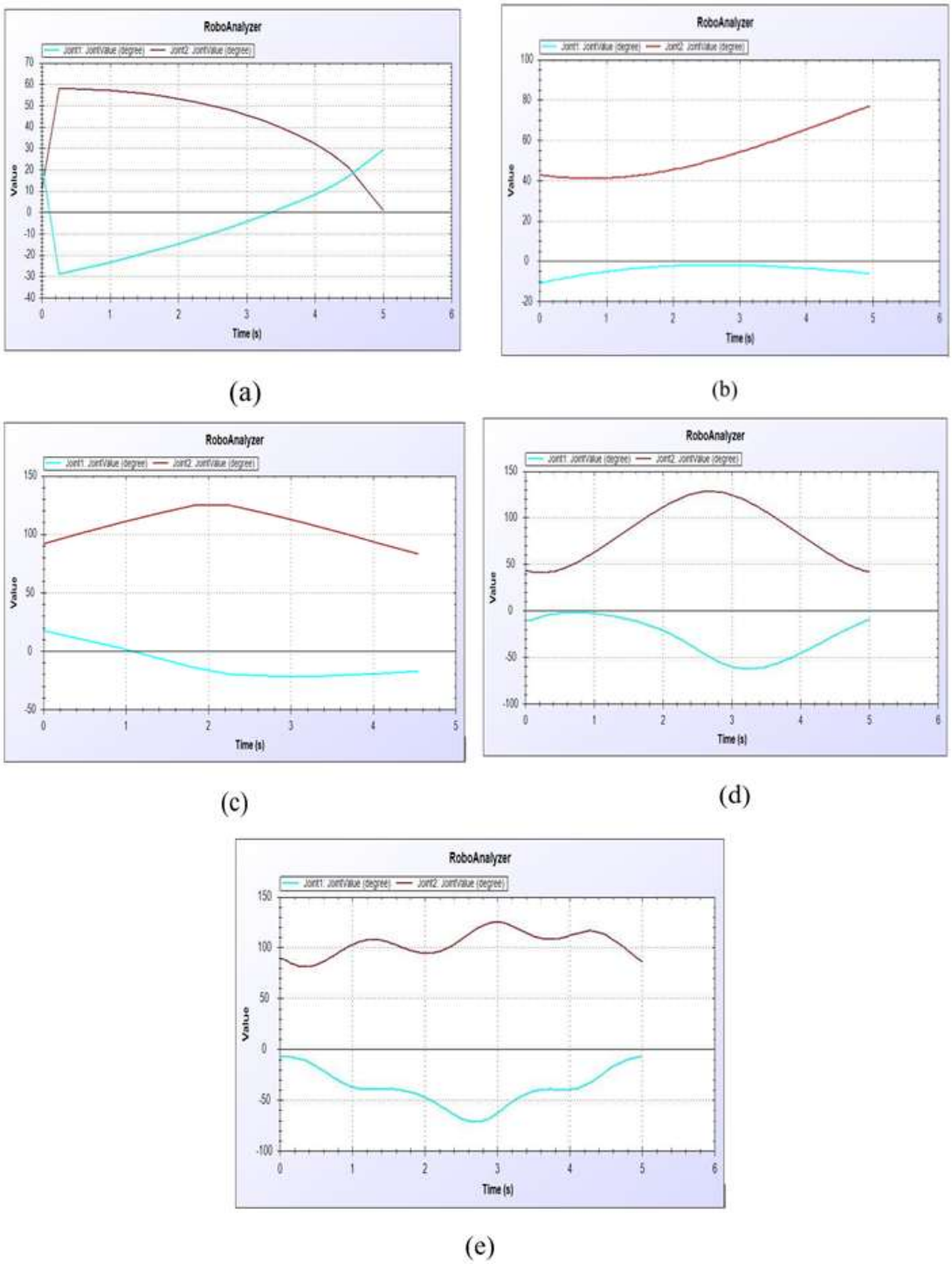


Fig. 5. Joint angle parameters for Joint-1 and Joint-2: (a) Line Path, (b) Arc Path, (c) L-shape Path, (d) Circular Path, (e) Loop Path

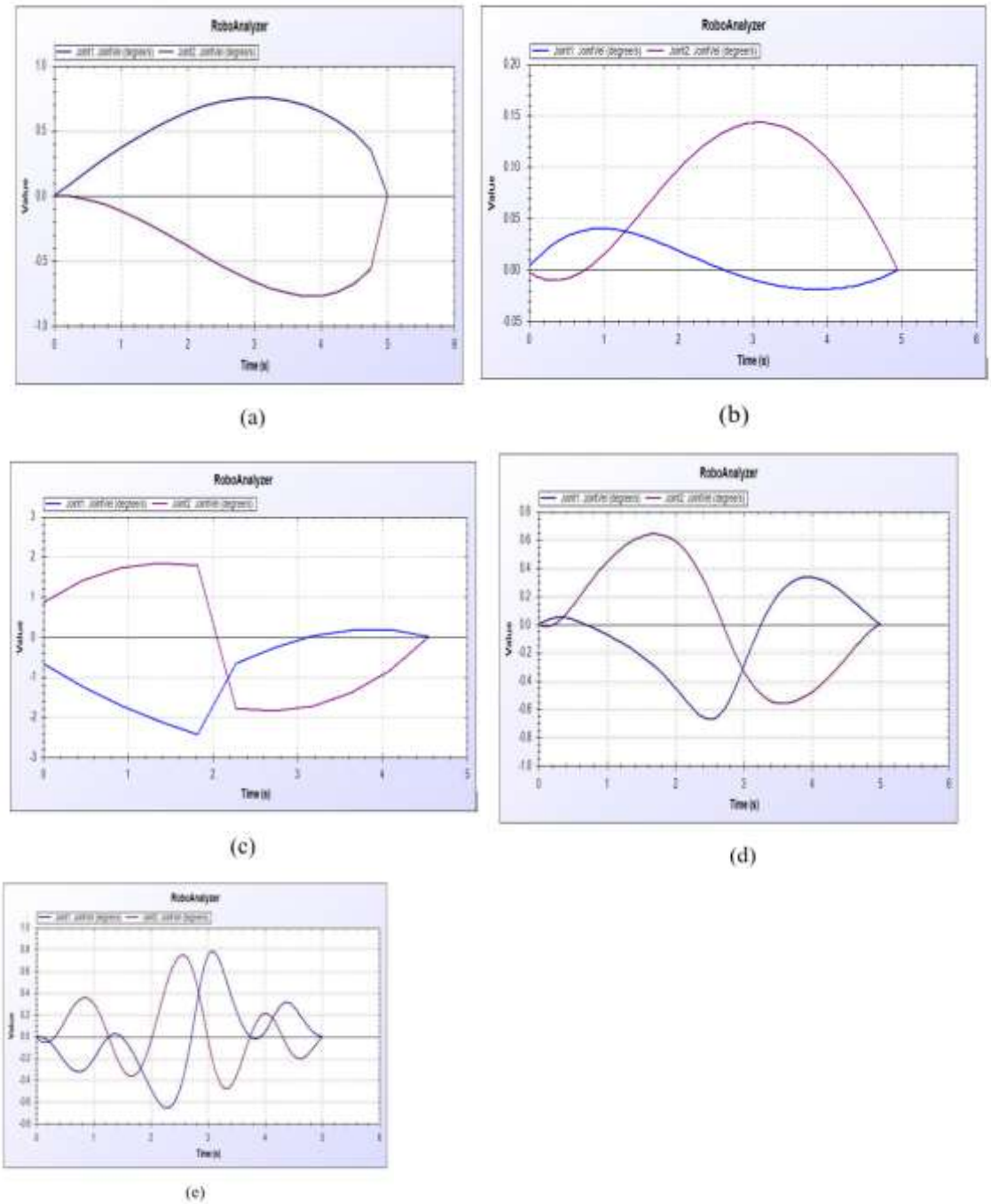


Fig. 6. Joint velocity parameters for Joint-1 and Joint-2: (a) Line Path, (b) Arc Path, (c) L-shape Path, (d) Circular Path, (e) Loop Path

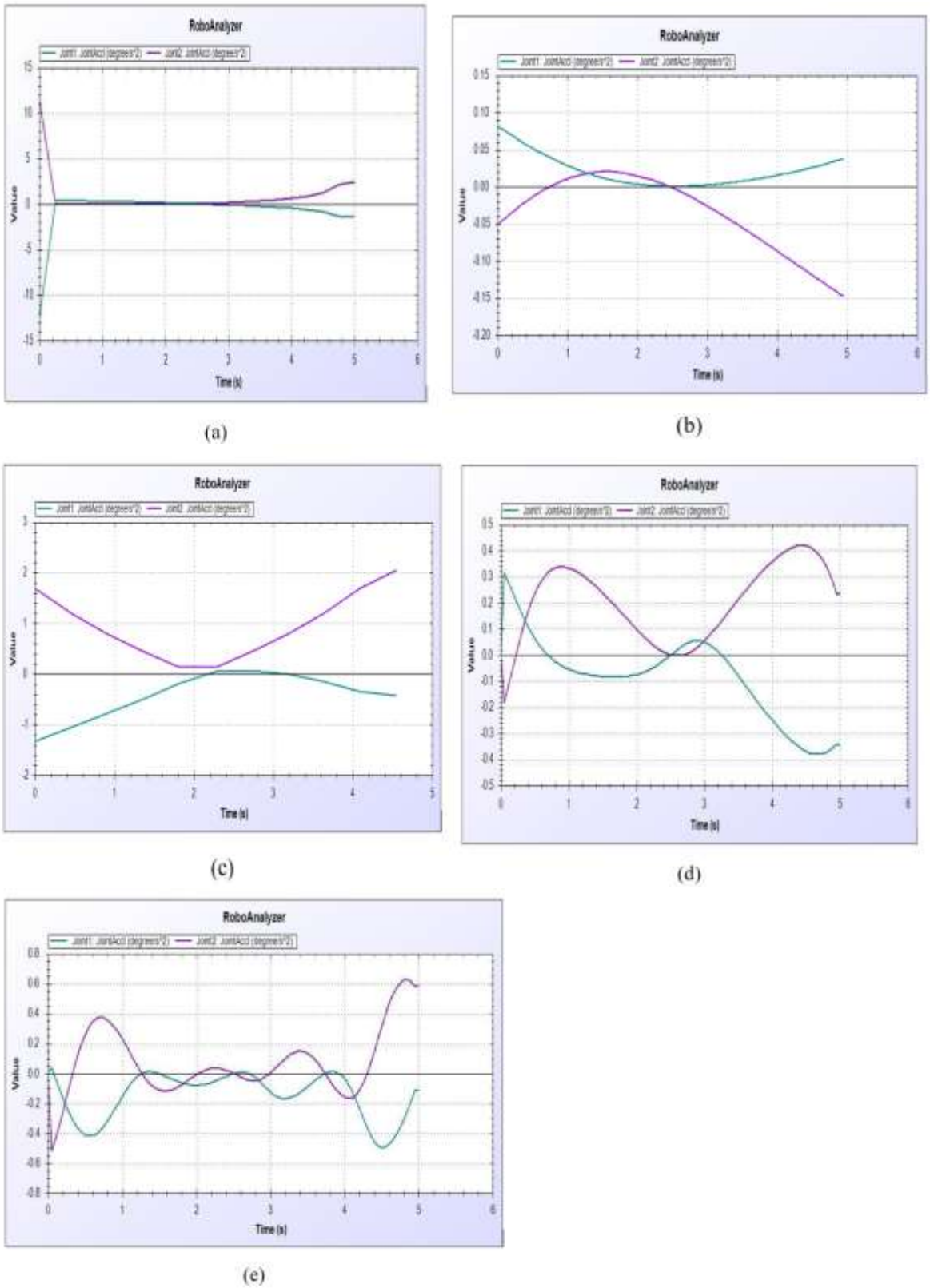


Fig. 7. Joint acceleration parameters for Joint-1 and Joint-2: (a) Line Path (b) Arc Path (c) L-shape Path (d) Circular Path (e)Loop Path

5. CONCLUSIONS

This research established a 2-DOF planar manipulator and then was controlled to perform physiotherapy motions— line, arc, L-shape, circle, and loop. The motions were based on the upper limb rehabilitation motions

of the manipulator. Inverse kinematics were developed along with a cubic polynomial trajectory planning to generate the correct motion paths. The study provides a simulation of the manipulator in a rehabilitation setting that can be easily used where the user can feel comfortable and have success. The ability of the manipulator to transition smoothly between exercises and in horizontal and vertical directions provides an unconventional aspect for rehabilitation. Several experimental results supported that the manipulator demonstrates feasibility for assisting upper limb rehabilitation movements. However, clinical effectiveness and therapeutic benefits must be validated through controlled trials involving patients. The results provided encouragement for future clinical studies in order to assess the safety and therapeutic effects of using the 2R manipulator for rehabilitation.
The tabletop testing determined the following ranges of motion: shoulder flexion from 0° - approx. 180°, shoulder extension from 0° - approx. 35°, elbow flexion from 0° - approx. 150°, elbow extension 0° with the setup limiting the range of motion. In the vertical stand position shoulder extension was achieved with 60° and elbow extension to -5° (slight hyperextension). The range of shoulder abduction was from 0° - approx. 180° and adduction was from 0° - approx. 75°.

5.1 Novelty
The suggested 2R manipulator is a flexible tool designed to help with arm workouts on both horizontal and vertical surfaces. Its end-effector can provide support to the patient's hand similar to that of a therapist. With its adaptive design, the manipulator can function on both tabletops and vertical pole supports. This flexibility allows for thorough shoulder and elbow therapy with minimal device adjustments.

5.2 Limitations
The proposed 2R manipulator can be configured for use in either a table-top or vertical stand setup to facilitate complete shoulder and elbow therapy. The therapist must adjust the manipulator arrangement between the table-top and vertical configurations as needed.
The experimental validation was conducted on a single healthy adult participant and was limited to mechanical trajectory tracking performance. No clinical population was evaluated, and no quantitative functional recovery metrics were assessed. Therefore, therapeutic effectiveness cannot be inferred from the present study. Future work should involve multi-subject clinical trials with standardized rehabilitation outcome measures.

5.3 Future directions
To create lighter structures, selecting the right actuators is essential. Pneumatic, shape memory alloy, and electroactive polymer actuators are attractive because they are lightweight and quick to respond. Soft robotics methods can also boost adaptability and comfort. Moreover, merging robotic therapy with other treatment methods, like neuromuscular electrical stimulation, may enhance the overall effectiveness of robotic rehabilitation systems, especially for patients with hemiplegia.

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