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Enhancing Upper Limb Rehabilitation: Workspace, Singularity and Structural Analysis of an Adaptive Two-Link Planar Manipulator

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Abstract

The current shortage of therapists and caregivers who assist individuals with physical disabilities at home is anticipated to worsen in the future. Rehabilitation for upper limb exercises conducted by physical therapists is both time-consuming and expensive. This paper introduces a lightweight two-link planar device with revolute joints designed for upper limb rehabilitation. The primary focus is on the end-effector setup, evaluating its potential to enhance rehabilitation techniques. The manipulator's design aims to maximize end-effector coverage during training sessions, thereby improving the efficacy of rehabilitation. A mathematical model of the manipulator's kinematics is presented, detailing the relationships between joint angles and end-effector positions to understand its operational bounds. By analyzing singular configurations, the manipulator's limitations are determined, and control strategies are developed to prevent potential issues during rehabilitation. A device is constructed to simulate and visualize the manipulator's workspace within a computational environment, allowing for exploration of joint ranges and workspace boundaries. This computational framework facilitates a deeper understanding of the manipulator's capabilities, offering crucial insights for making informed decisions in rehabilitation training. Finally, the developed manipulator holds promise for enhancing the quality of upper limb rehabilitation, ensuring precise control over movement patterns, and enabling personalized training regimens. The insights gained from this study contribute to the ongoing development and refinement of robotic-assisted rehabilitation technologies, aiming to improve outcomes for individuals with upper limb impairments.

Keywords: Upper limb rehabilitation, planar manipulator, kinematic model, singularities, workspace analysis.

INTRODUCTION

Rehabilitation technologies have seen remarkable advancements in recent years, particularly in the healthcare and biomedical sectors. These innovations aim to improve the quality and efficacy of rehabilitation systems, especially for individuals with upper limb impairments. Among the various approaches to upper limb rehabilitation, robotic-assisted therapies have emerged as a promising solution. These therapies offer precise control over movement patterns, personalized training

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regimens, and effective progress monitoring [1]. Rehabilitation robots can be broadly categorized into end-effector-based robots and exoskeletons. End-effector-based systems have become a focal point of contemporary research due to their ability to facilitate targeted exercises that mimic real-life movements, resulting in a more immersive and effective rehabilitation experience. The design and kinematics of the planar manipulator play a crucial role in these systems, significantly impacting the robot's ability to guide patients through rehabilitation exercises [2, 3].

Recent research emphasizes the benefits of planar manipulators in upper limb rehabilitation. For example, Hogan et al [4]. developed a two-degree-of-freedom end-effector robot operating within a horizontal plane. Lum et al [5]. introduced MIME, a three-dimensional robot with six degrees of freedom suitable for unilateral and bilateral therapies. Hesse et al [6]. devised the Bi-Manu-Track system, adjustable for both limbs and capable of mirroring one limb's movements with the other. GAO Jianshe et al [7]. presented a five-bar mechanism characterized by high rigidity and a broad workspace. Qing Miao et al [8]. demonstrated a bilateral rehabilitation device with two degrees of freedom, validating its clinical utility. Chih-Kang Chang et al. [9] unveiled a semi-passive robot with adjustable resistances, offering cost-effectiveness and safety suitable for home use. Ceccarelli et al. [10] introduced a five-bar linkage robot for upper limb rehabilitation with a significant workspace. Cancrini et al [11]. employed the PlanArm2 prototype, capable of executing various upper limb movements with robotic assistance. NURSE-2, a 2-degree-of-freedom (DOF) device, was designed by Betsy D. M. Chaparro-Rico et al [12]. to assist individuals with neurological or orthopaedic injuries during repetitive movement therapies. Yali Liu et al [13]. introduced a new upper limb rehabilitation robot named EEULRebot, which consists of a two-link robotic arm with two active degrees of freedom. An assistive device called Nurse, tailored for upper limb rehabilitation, was introduced by Yavuz et al [14]. introduced a 2-degree-of-freedom (2-DOF) exoskeletal robot for upper limb applications, along with its control system design. The purpose of developing the robot was to facilitate load lifting operations, therapeutic exercise, as well as the evaluation of various biomechanical parameters.

In this study, the design of a 2R planar robot specifically tailored for upper limb rehabilitation is presented. The objective is to maximize the workspace area during exercises, utilizing mathematical models to comprehend joint movements and design optimal therapy exercises. Recognizing the robot's motion limits, controls are developed to enhance rehabilitation outcomes and prevent potential issues during therapy sessions.

Shoulder and Elbow Rehabilitation

To design a rehabilitation robot, it's essential to study the anatomy of the human upper limb. The motions of the upper limb are vital for everyday human activities, and the primary goal of rehabilitation is to restore these functions. The workspace defined for the development of this paper includes motions such as shoulder flexion/extension, shoulder adduction/abduction, and elbow flexion/extension, all of which are illustrated in Figure.1.

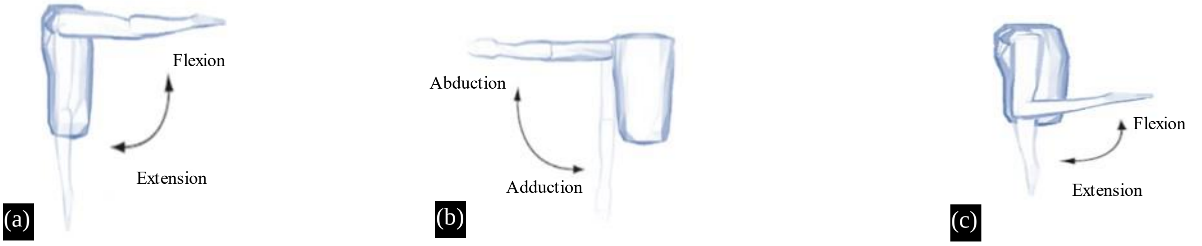

Figure 1. (a) Shoulder flexion/extension, (b) shoulder adduction/abduction and (c) elbow flexion/extension.

For upper limb rehabilitation, the functional range of motion (ROM) is a crucial parameter, often represented as the ROM needed to perform functional tasks, as detailed in Table 1 [15, 16]. Since the introduction of robotic rehabilitation, end-effector devices have gained attention because of their unique structural features.

Using anthropometric measurements, the average length or mass of a body segment can be estimated as a fraction of the total standing height or total mass, respectively [17]. Table 2 displays an approximate range of some common anthropometric measurements for both men and women. The weight of one upper arm is approximately 1.75 kg to 2 kg, which represents about 5% of a human's total weight.

The core idea behind the shoulder and elbow rehabilitation device is to translate the natural movements of these joints into a two-dimensional plane. One end of the device features a handle that moves strictly within the horizontal and vertical axes. The main goal of this robot's design is to support upper limb rehabilitation training by applying end traction during shoulder and elbow joint exercises. This paper introduces a configuration for a 2-DOF end-effector-based upper limb rehabilitation robot, designed to assist the shoulder and elbow in performing rehabilitation exercises.

Table 1. Shoulder and Elbow Joint Movements and Range of Motion

Joint	Joint movement	Range of motion (ROM)
Shoulder	*Flexion:* Lifting the arm straight in front and overhead.	0° to 180°
	Extension: Moving the arm straight behind you.	0° to 40°-60°
	Abduction: Lifting the arm out to the side and upward.	0° to 180°
	Adduction: Moving the arm down from the side and across the body.	0° to 75°
Elbow	*Flexion*: The motion of the forearm toward the upper arm.	0° to 150°
	Extension: The motion of the forearm away from the upper arm.	-5° to 0°

Table 2. Anthropometric measurement of Upper Arm

Measurement	Average for men	Average for women
Height	165-172 cm	152-159 cm
Upper Arm Length	31-37 cm	29-34 cm
Hand Length	17-19 cm	15-17 cm

MATERIALS AND METHODS

The 2R manipulator is an apt mechanism for supporting arm exercises on a horizontal/vertical plane. Its end-effector can assist the patient's hand in a manner akin to a therapist, as illustrated in Figure.2 [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, as depicted in Figure. 2.

The exercises involve shoulder and elbow movements as detailed in the range of motion in Table.1. The 2R manipulator aims to guide the human arm along set trajectories in horizontal/vertical planes. Its end-effector is planned to move along both the X-Y and Y-Z coordinates, encompassing a substantial part of the workspace needed for upper limb exercises in these planes. The necessary space for training is determined using average anthropometric measurements of upper limb lengths. In this configuration, the patient's hand aligns with the endpoint of the robot's planar end-effector. Employing a planar system brings advantages like enhanced stiffness and reduced weight.

KINEMATIC MODELLING

Forward Kinematics

Consider a two-link planar manipulator with link lengths l_1 and l_2 and joint angles θ_1 and θ_2, aiming to reach position (P_x, P_y), as illustrated in Fig.3. In this setup, joint axes z_0 and z_1 are perpendicular to the plane of motion. A base frame $o_0x_0y_0z_0$ sets the manipulator position and orientation, with its origin where z_0 meets the plane. After this base, $o_1x_1y_1z_1$ frame is set according to the D-H convention [19], with its origin at of z_1. To complete the two-link planar manipulator setup, the final frame $o_2x_2y_2z_2$ is fixed by selecting the origin O_2 to be located at the end of link-2.

Figure 2. 2R Manipulator for upper limb rehabilitation (a) Tabletop arrangement for Horizontal Plane (b) Vertical pole arrangement for Vertical Plane.

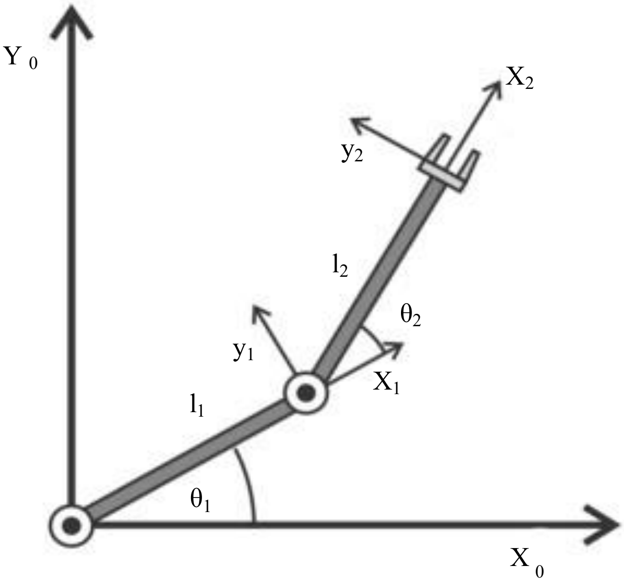

Figure 3. Schematic diagram of 2 link planar manipulator.

The position of the end effector (located at the tip of the second link) in the plane is defined as per reference [20]. These equations represent the forward kinematics of the manipulator, determining the end effector's position based on the joint angles.

$$X = \quad l_1 cos\theta_1 + \ l_2 \cos{(\theta_1 + \theta_2)}$$

$$Y = \quad l_1 sin\theta_1 + \ l_2 \sin{(\theta_1 + \theta_2)}$$

Jacobian of the 2-Link Manipulator

The Jacobian matrix can be expressed as [14], it relates rate of change of joint variables to rate of change of Cartesian variables.

$$J = \begin{bmatrix} -l_1 sin\theta_1 - l_2 \sin{(\theta_1 + \theta_2)} & - l_2 \sin{(\theta_1 + \theta_2)} \\ l_1 cos\theta_1 + \ l_2 \cos{(\theta_1 + \theta_2)} & l_2 \cos{(\theta_1 + \theta_2} \end{bmatrix}$$

The inverse of the Jacobian matrix is:

$$J^{-1} = \begin{bmatrix} -\frac{\cos(\theta_1+\theta_2)}{l_1 sin\theta_1 \cos(\theta_1+\theta_2) - l_1 \sin(\theta_1+\theta_2) cos\theta_1} & -\frac{\sin(\theta_1+\theta_2)}{l_1 sin\theta_1 \cos(\theta_1+\theta_2) - l_1 \sin(\theta_1+\theta_2) cos\theta_1} \\ -\frac{l_1 cos\theta_1 + l_2 \cos(\theta_1+\theta_2)}{-l_1 l_2 sin\theta_1 \cos(\theta_1+\theta_2) + l_1 l_2 \sin(\theta_1+\theta_2) cos\theta_1} & -\frac{l_1 sin\theta_1 + l_2 \sin(\theta_1+\theta_2)}{-l_1 l_2 sin\theta_1 \cos(\theta_1+\theta_2) + l_1 l_2 \sin(\theta_1+\theta_2) cos\theta_1} \end{bmatrix}$$

This matrix provides the relationship between the rate of change of Cartesian variables (end-effector position and orientation) and the rate of change of joint variables (joint angles).

Singularities of the 2-Link Manipulator

The singular positions of the 2R manipulator, as determined by setting the determinant of the Jacobian matrix to zero, are:

$$\det(J) = l_1 l_2 sin\theta_2$$

Form the above equation, it's evident that the determinant is zero when $\theta_2 = 0$ or $\theta_2 = \pi$. For the 2R manipulator, singularities occur in the following scenarios:

Elbow singularity: When the two links are fully extended in a straight line or fully folded onto each other, the manipulator is in an elbow singularity. In this configuration, it's impossible to change the orientation of the end-effector by moving just one joint; both joints must move.

Shoulder singularity: This is less common in simple 2R planar manipulators. A typical scenario for a shoulder singularity in more complex robots is when the end-effector moves in a circle around the base, and at some point, the orientation cannot be maintained without moving the end-effector itself. However, for a 2R planar robot, this isn't a typical concern.

The elbow singularity is the primary singularity of concern for a 2R manipulator. When the robot is in this configuration, it's essential to avoid high-speed movements, as the manipulator can become unstable or place undue stress on its joints.

WORKSPACE CONSIDERATIONS

For a 2R planar manipulator designed for upper limb rehabilitation, the workspace is the set of all points that the end-effector (usually where the patient's hand would be) can reach. The workspace bounds can be derived from the geometry of the manipulator and the range of motion of its joints.

Minimum Reach

The minimum distance the end-effector can be from the base (or shoulder joint) is $l_1 - l_2$ when $\theta_2 = \pi$. But if $l_1$is smaller than l_2, the arm cannot fold back on itself, the minimum reach is zero.

Maximum Reach

When $\theta_2 = 0$ or $\theta_2 = \pi$ (i.e., both links are fully extended or fully folded onto each other), the maximum reach is $l_1 + l_2$.

Range of Motion Constraints

In upper limb rehabilitation, the range of motion based on the patient's therapeutic needs and safety. If θ_1 (shoulder joint) doesn't have a full 360° rotation, this will limit certain parts of the workspace. The elbow doesn't fold back onto itself (an unphysiological 0°) and typically doesn't fully extend to 180°; such limitations on θ_2 impact the inner boundary of the workspace. For a 2R manipulator, if the first link l_1 is longer than the second link l_2, the robot can reach any position within the annular region defined by the radii $l_1 - l_2$ and $l_1 + l_2$. If l_1 is shorter than l_2, the robot can still reach any position within the circle defined by $l_1 + l_2$, but the shape of the inner boundary becomes more complex due to joint limitations. If $l_1 = l_2$, the robot can reach any point in a circle with a radius of $2 \times l_1$ (or) $2 \times l_2$. At the terminal end of the manipulator is the end-effector. This component is ergonomically designed for the patient to grip. In the described scene, a patient is actively engaged with the manipulator by holding this end-effector. As the manipulator goes through its pre-programmed set of motions, it assists, guides, or resists the patient's own movements, thereby facilitating targeted muscle training and joint mobilization.

ANALYSIS OF 2R MANIPULATOR

Consider the following when analysing the workspace of a 2R planar manipulator for upper limb rehabilitation.

θ_1: This is likely the angle between the base or the table plane and the first link of the manipulator. The workspace bounds for θ_1 would be from 0° (when the first link is completely aligned with the base/table) to 180° (when the first link points in the opposite direction, assuming it can rotate a full half-circle).

θ_2: This is probably the angle between the first link and the second link. Depending on the construction of the joint, the bounds for θ_2 could range from -180° to 180°. If the joint allows full rotation, then it has a 360° range. If not, the bounds might be more restricted.

Consider the 2R Planar Manipulator designed for upper limb rehabilitation. This manipulator consists of two primary links, each measuring 20 cm in length. These links are interconnected, allowing them to move in a coordinated fashion and emulate the range and precision of upper limb movements. The manipulator is mounted on a table, as depicted in Figure.2(a). This table offers a stable platform for the manipulator's operations and ensures the patient's safety and comfort throughout the rehabilitation process. The base of the manipulator is centrally positioned at the top of the table and aligns with the horizontal axis. This positioning optimizes the range of motion and accessibility for the patient. The workspace result of the tabletop setup is illustrated in Figure.4. The singularities result of the tabletop setup is illustrated in Figure.5. In a different configuration shown in Figure.2(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.6. The singularities result of the vertical setup is illustrated in Figure.7.

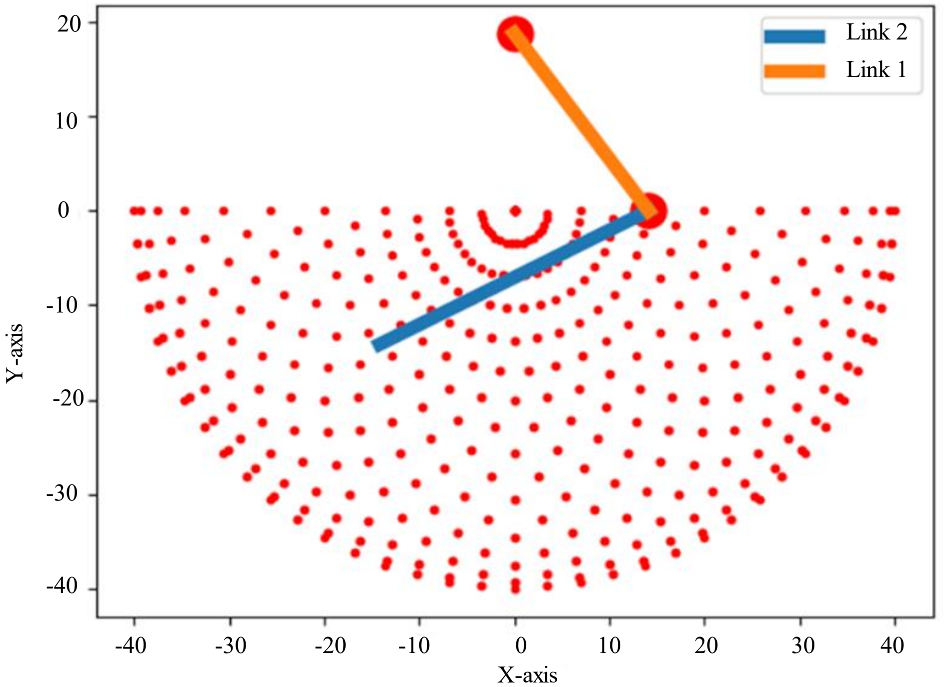

Figure 4. Workspace of 2R manipulator in table-top setup.

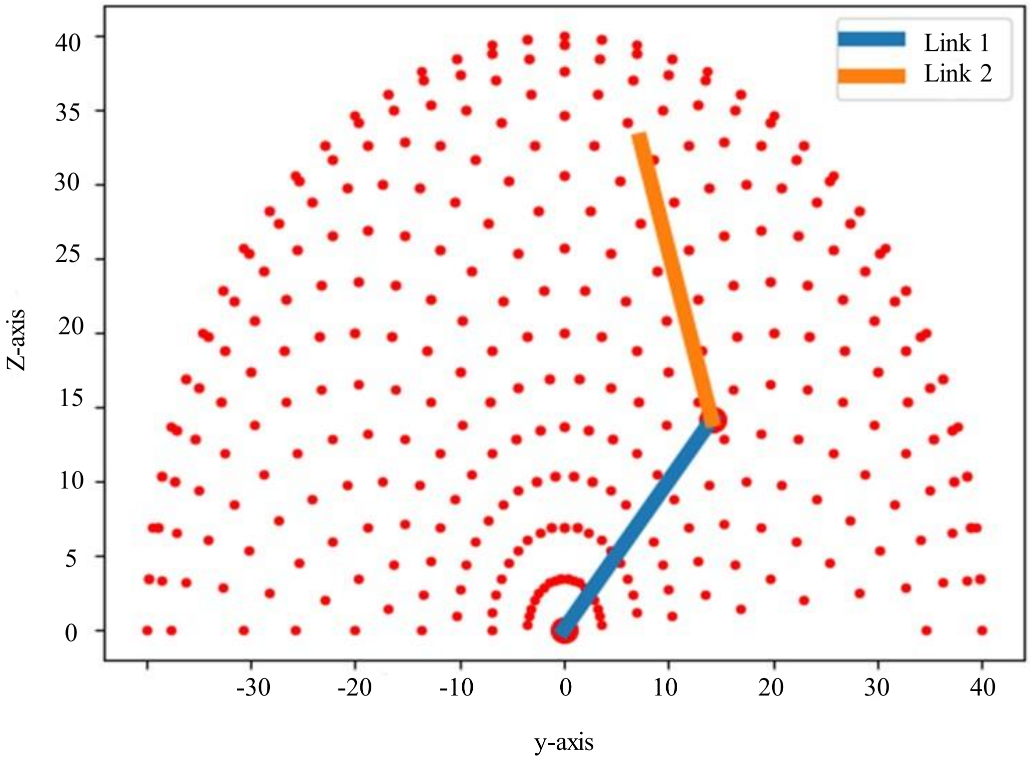

Figure 5. Workspace of 2R manipulator in vertical pole setup.

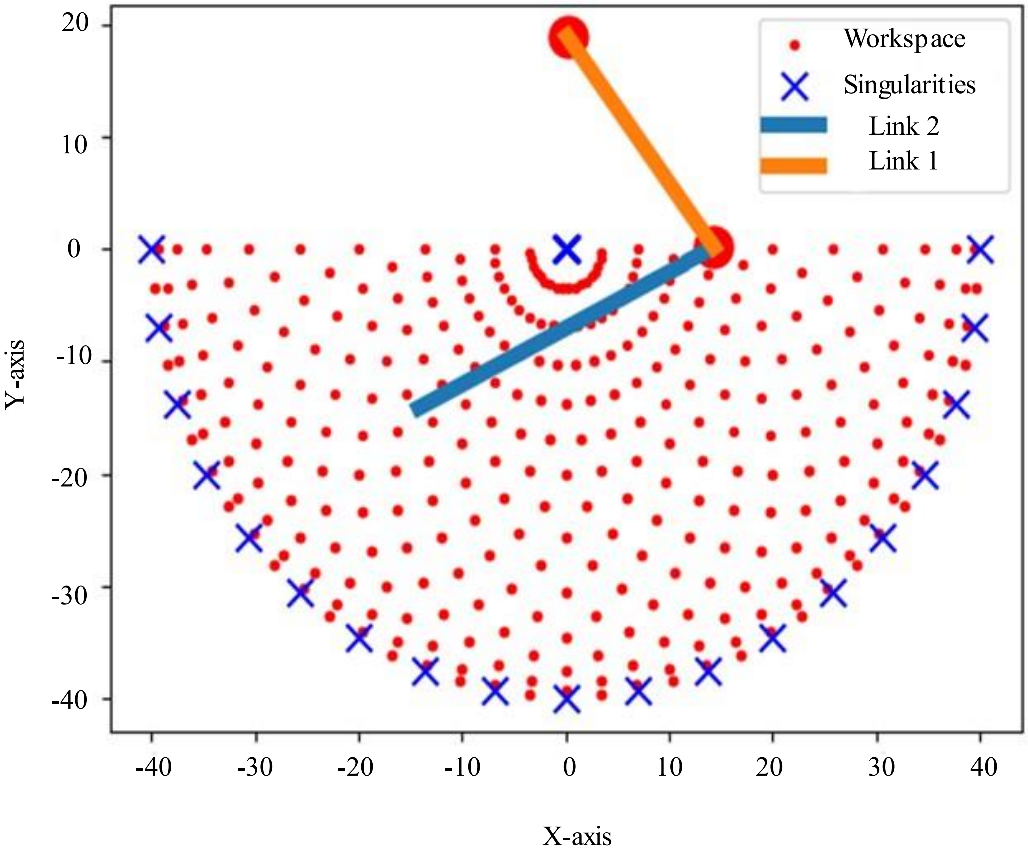

Figure 6. Singularities of 2R manipulator in table-top setup.

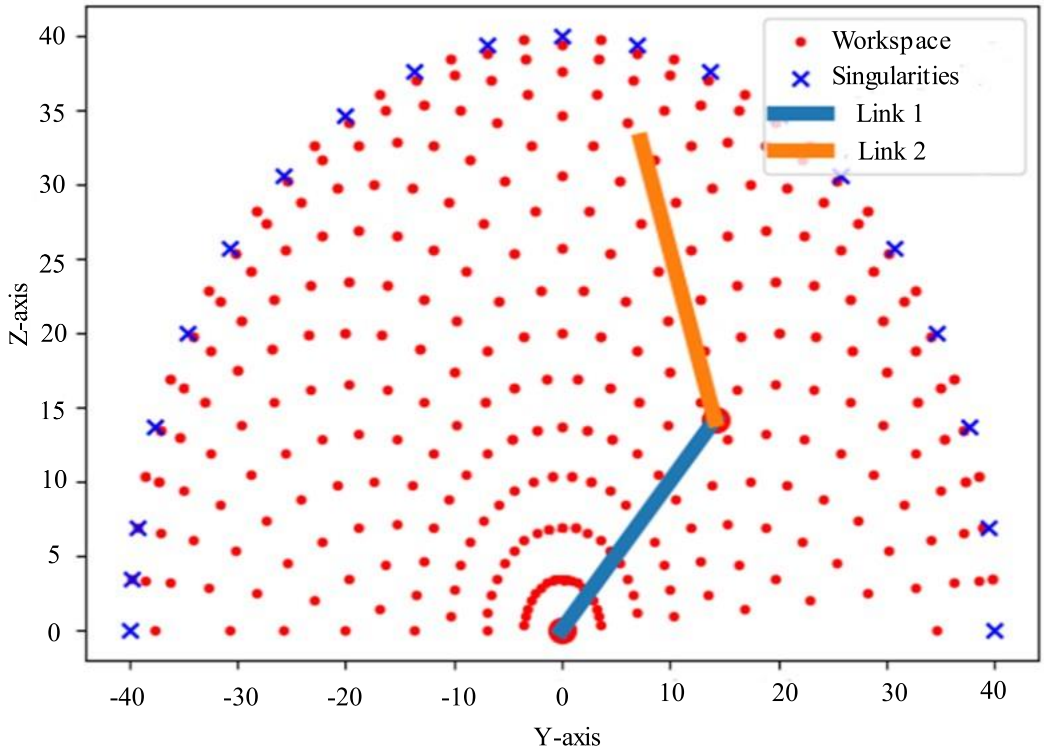

Figure 7. Singularities of 2R manipulator in vertical pole setup.

EXPERIMENTAL SETUP

Figure.8 depicts the robot's control architecture, designed for upper limb rehabilitation. The setup positions the patient seated on a chair in front of a Table. The patient grips the handle on the robot's end-effector plate and follows the trajectory set by the end-effector during the rehabilitation process. The robot's end-effector is equipped with force and position sensors, capturing the force applied by the patient and the end-effector's position during therapy. Two servomotors, situated at the revolute joints, drive the end-effector. Encoders at these joints determine the motion's position. The device is operated by an Arduino, which also receives sensor signals. A PC references biomechanical parameters based on the EMG signal and allows the selection of the rehabilitation mode tailored to the patient's condition. The PC also controls the Arduino for the rehabilitation process. The manipulator's base is clamped to the table's end, and as illustrated in Figure.9, the manipulator is constructed from an aluminum square beam section.

Before operation, the manipulator should be set up as shown in Figure.9. Initially, the manipulator is positioned in its starting state. The participant then places their forearm on the support base and grips the handle. Surface EMG electrodes are attached to the subject's skin to gauge the EMG noise level. This measurement establishes the threshold value during rest. Once the 2R manipulator is configured, the rehabilitation process is carried out, as illustrated in Figure.10(a). Similarly, when the robot is set up on a vertical pole, the rehabilitation process is conducted as shown in Figure.10(b).

STRUCTURAL ANALYSIS

A linear static analysis is performed to determine the stress exerted on the manipulator attains its operational range. During the simulation, a 1060 aluminum alloy has been used for Manipulator and Wheel. Table.3 shows the main material characteristics of the 1060 aluminum alloy. It is important to note that the materials used during simulations correspond to the materials used in practice for the lab prototype of manipulator in Figure.9. The weight of the human upper arm part has been assumed as 2Kg according to the average weight of a human arm [17].

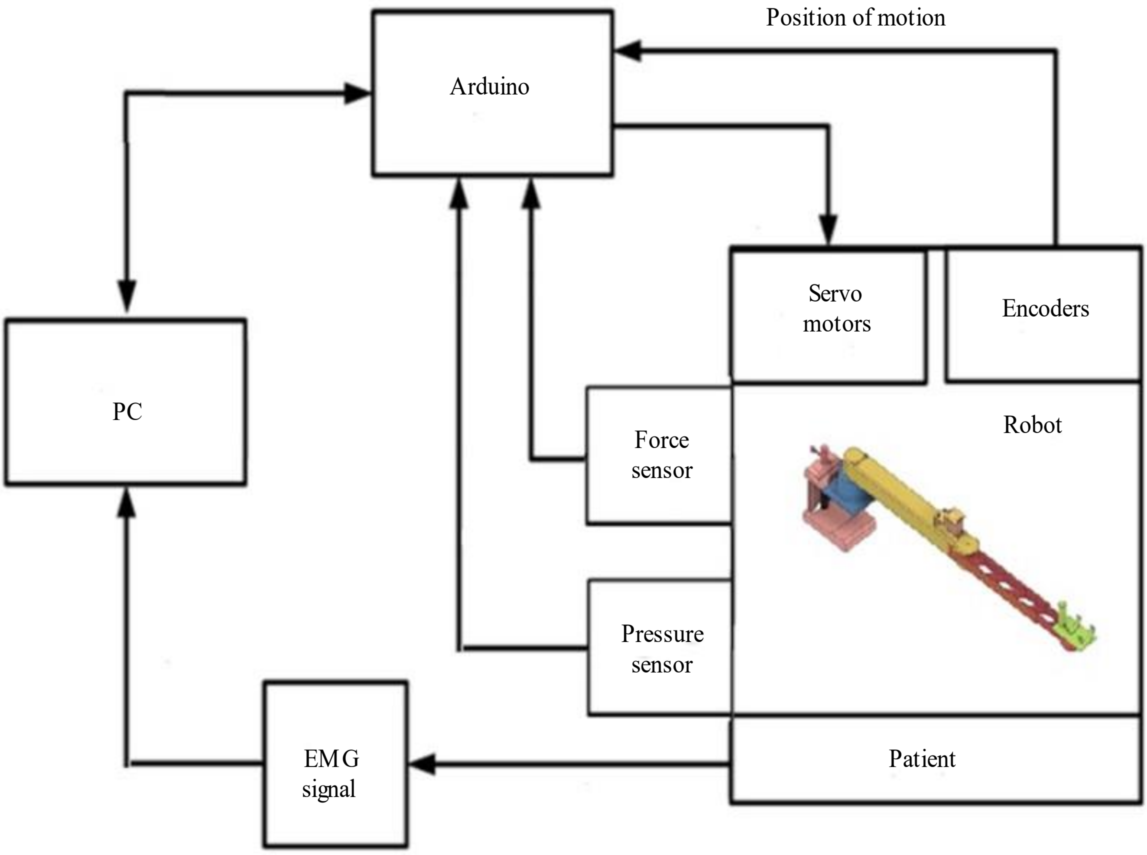

Figure 8. The hardware block diagram.

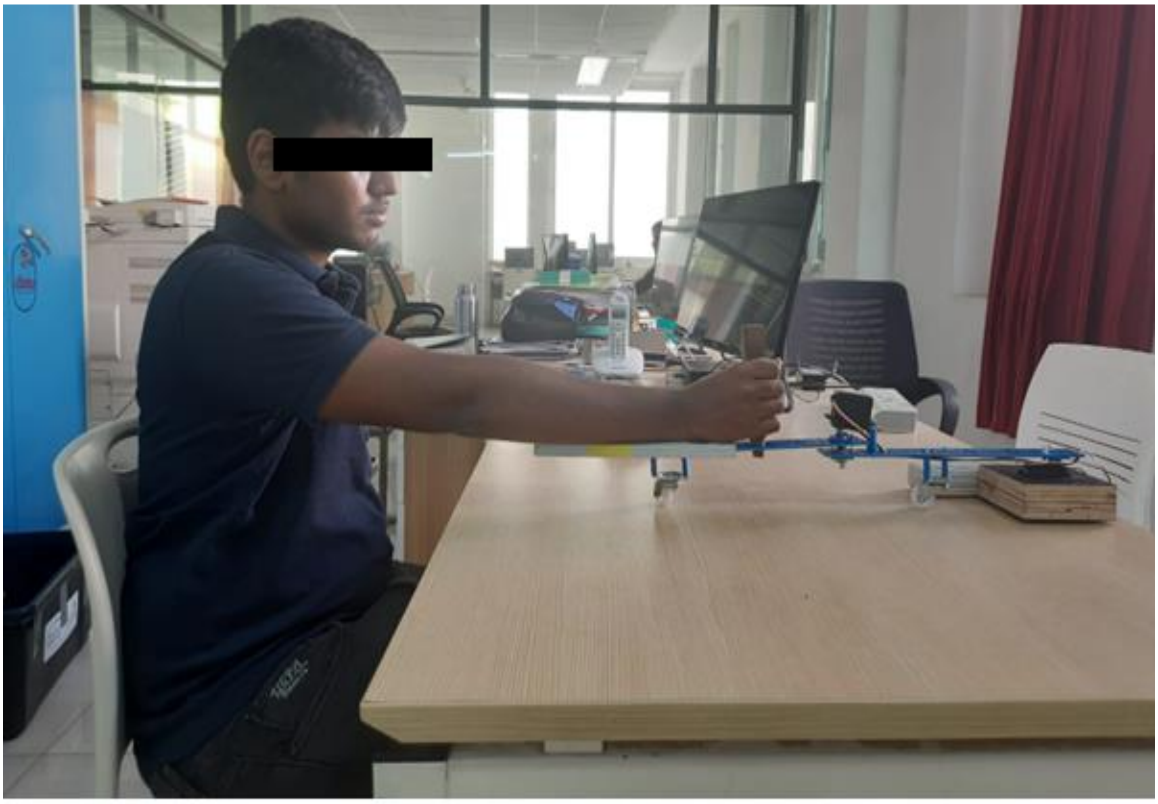
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Figure 9. Experimental setup of 2r manipulator.

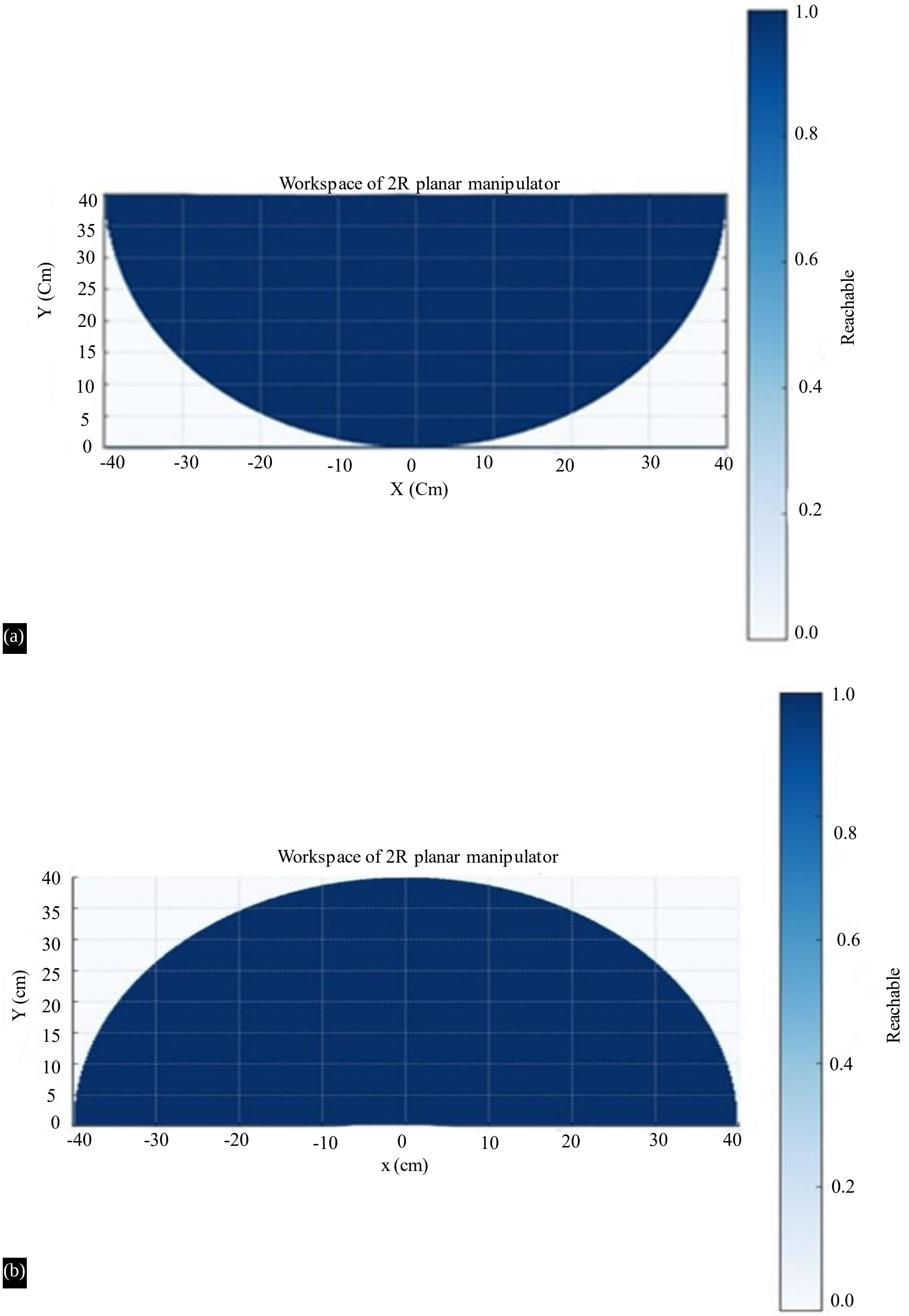

Figure 10. Workspace of 2R Planar Manipulator for upper limb rehabilitation: (a) Tabletop setup (b) Vertical Pole Setup.

Table 3. 1060 Aluminum Alloy Material Characteristics.

Material properties	**Values in units**	
Elastic Modulus	6.90×10^{10}	$N/_{m^2}$
Poisson’s Ratio	0.33	
Shear Modulus	2.70×10^{10}	$N/_{m^2}$
Mass Density	2700	$kg/_{m^2}$
Tensile Strength	6.89×10^{7}	$N/_{m^2}$
Yield Strength	2.76×10^{7}	$N/_{m^2}$

Manipulator stresses have been obtained from the FEM analysis. Figure 11 show that the manipulator achieves a maximum stress value on the manipulator when its links are fully extended, i.e., reaching critical positions with a maximum stress of $1.19\times 10^{6}\ N/_{m^2}$. Figure 12 shows that the manipulator deformation with 0.0006 cm.

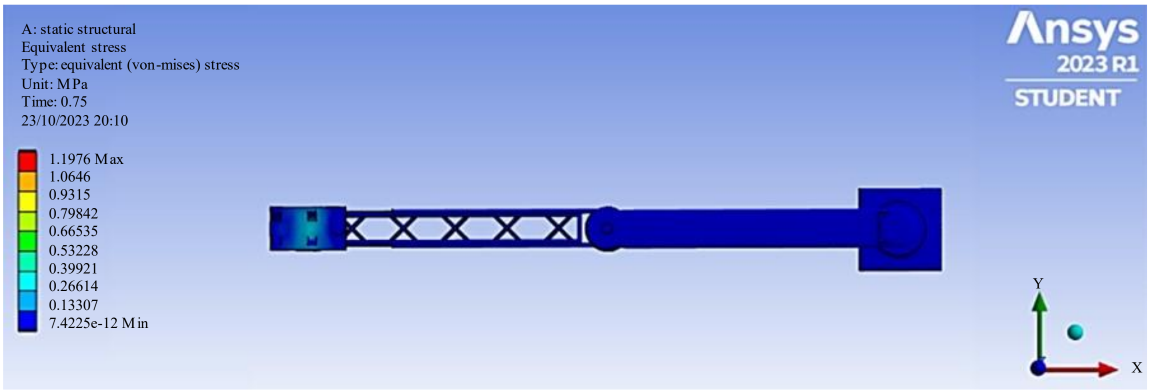

Figure 11. Von-mises stress of 2r manipulator.

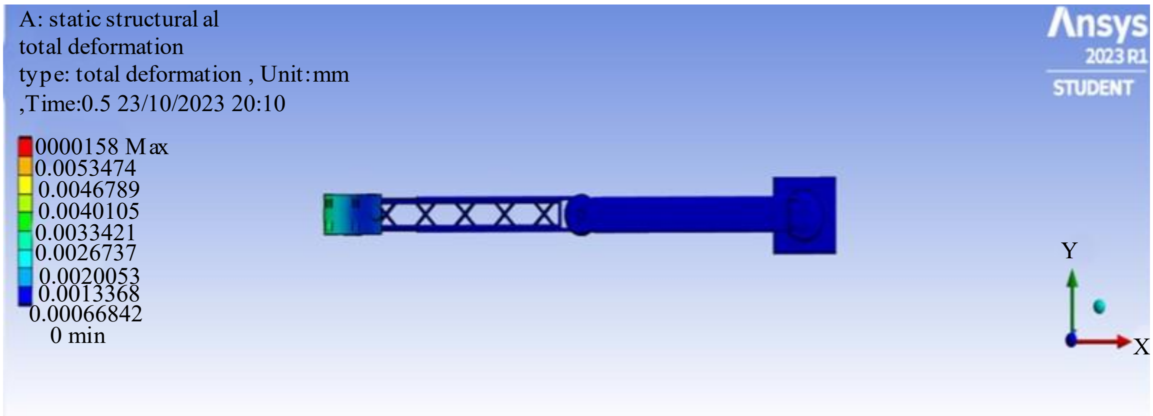

Figure 12. Deformation of 2R manipulator

RESULTS AND DISCUSSIONS

The 2R planar manipulator, illustrated in Figure. 2(a) and Figure. 2(b), is a versatile device for upper limb rehabilitation. Its design supports both tabletop and vertical pole exercises, offering a broad range of therapy options. The manipulator seems to be an ergonomic representation, possibly designed based on the average anthropometric measurements from Table. 1 and 2. Its adaptability distinguishes it from many existing devices. Furthermore, its simple and robust structure, combined with cost-effectiveness, makes it ideal for both clinical and home use.

Regarding the setup of the manipulator in Figure. 2(a) and the results in Figure. 4, a person holding the end-effector would undergo shoulder flexion and extension, as well as elbow flexion and extension, within the illustrated workspace. This motion enables forward and side-reaching but appears limited in the backward direction. The shoulder flexion has a range of motion between 0° and close to 180°. The shoulder extension range of motion is between 0° and slightly beyond halfway to 60°. Due to potential obstructions in Figure. 2(a), the device cannot achieve the desired shoulder extension range of motion. The elbow flexion range of motion spans from 0° to nearly the specified 150°, while the elbow extension is limited to 0° due to the device's tabletop arrangement.

From Figure. 2(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 is 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. 2(b) and the outcomes in Figure. 5, 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°.

The 2R manipulator's experimental setup has been meticulously designed and tested to meet the specific needs of upper limb rehabilitation. The range of motion facilitated by the manipulator, as evidenced by the setup in Figure. 2(a) and 2(b) and outcomes in Figure. 10, indicates a comprehensive range of exercises, including shoulder flexion/extension, shoulder adduction/abduction, and elbow flexion/extension. Preliminary observations indicate that the manipulator can be smoothly integrated into rehabilitation routines, offering support that is both comfortable and effective for the participant. The ease of transition between exercises and the adaptability of the device to both horizontal and vertical orientations underscore its potential as a versatile tool in upper limb rehabilitation. These promising results lay the groundwork for extensive clinical trials to further evaluate the efficacy and safety of the 2R manipulator in therapeutic applications.

The linear static analysis, conducted as part of the experimental evaluation, sheds light on the performance and resilience of the manipulator when constructed with 1060 aluminum alloy. The analysis confirms the manipulator's robustness and validates its design for efficient operation within its designated range of motion. It assures that the manipulator can withstand the physical demands of rehabilitation exercises without undergoing significant stress or deformation.

CONCLUSION

The 2R manipulator has been designed and controlled with the specific aim of optimizing upper limb rehabilitation, with careful attention to the required workspace and the avoidance of singularities during the rehabilitation process. The findings from simulations suggest that the manipulator is robust, efficient, and reliable. It supports a range of exercises, including shoulder flexion/extension, shoulder adduction/abduction, and elbow flexion/extension. The materials and design considerations have been meticulously chosen to ensure durability and efficient operation within the manipulator's range of motion, without experiencing significant stress or deformation.

The research contributes to the field of rehabilitation technology by presenting a solution that is not only technically feasible but also practical for clinical applications. The adaptability of the manipulator and its ability to provide consistent and repeatable movements make it a valuable tool for patient rehabilitation.

REFERENCES

1. Mehrholz J, Pohl M, Platz T, Kugler J, Elsner B. Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke. Cochrane Database Syst Rev. 2018:9(9):1-137.

2. Maciejasz P, Eschweiler J, Gerlach-Hahn K, Jansen-Troy A, Leonhardt S. A survey on robotic devices for upper limb rehabilitation. Journal of Neuro Engineering and Rehabilitation. 2014;11(3):1-29.
3. Qassim HM, Wan Hasan WZ. A review on upper limb rehabilitation robots. Appl Sci. 2020;10(19):6976.
4. Hogan N, Krebs HI, Charnnarong J, Srikrishna P, Sharon A. MIT-MANUS: a workstation for manual therapy and training. IEEE International Workshop on Robot and Human Communication, Proceedings. 1992:161-165.
5. Lum PS, Van der Loos H, Shor P, Burgar CG. A robotic system for upper-limb exercises to promote recovery of motor function following stroke. International Conference on Rehabilitation Robotics Stanford, CA, USA. 1999:235-239.
6. Hesse S, Schulte-Tigges G, Konrad M, Bardeleben A, Werner C. Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects Archives of Physical Medicine and Rehabilitation. 2003;84(6):915-920.
7. Jianshe G, Mingxiang L, Allison G, Lei C. Optimal Dimensional Synthesis of a Symmetrical Five-Bar Planar Upper-Extremity Neuromotor Device. Chinese Journal of Mechanical Engineering. 2015;28(4):684-690.
8. Miao Q, Zhang M, Wang Y, Xie SQ. Design and Interaction Control of a New Bilateral Upper-Limb Rehabilitation Device. Journal of Healthcare Engineering. 2017:2017:1-9.
9. Chang CK, Washabaugh EP, Gwozdziowski A, Remy CD, Krishnan C. A Semi-passive Planar Manipulandum for Upper-extremity Rehabilitation. Annals of Biomedical Engineering. 2018;46(7):1-33.
10. Ceccarelli M, Russo M, Cafolla D, Chaparro-Rico BDM. Operation Safety of a 2-DoF Planar Mechanism for Arm Rehabilitation. Inventions. 2021;6(4):85.
11. Cancrini A, Baitelli P, Lavit Nicora M, Malosio M, Pedrocchi A, Scano A. The effects of robotic assistance on upper limb spatial muscle synergies in healthy people during planar upper-limb training. PLoS One. 2022;17(8).
12. Chaparro-Rico BDM, Cafolla D, Ceccarelli M, Castillo-Castaneda E. NURSE-2 DoF device for arm motion guidance: kinematic, dynamic, and FEM analysis. Appl Sci. 2020;10:2139.
13. Liu Y, Li C, Ji L, Bi S, Zhang X, Huo J, Ji R. Development and implementation of an end-effector upper limb rehabilitation robot for hemiplegic patients with line and circle tracking training. J Healthc Eng. 2017:2017:4931217.
14. Yavuz A, Akdogan E, Aktan ME, Koru AT. Design, produce and control of a 2-dof upper limb exoskeletal robot. J Therm Eng. 2019;5(2):119-130.
15. Perry JC, Rosen J, Burns S. Upper-limb powered exoskeleton design. IEEE/ASME Trans Mechatron. 2007:12(4):408-417.
16. Namdari S, Yagnik G, Ebaugh DD, Nagda S, Ramsey ML, Williams GR Jr, Mehta S. Defining functional shoulder range of motion for activities of daily living. J Shoulder Elbow Surg. 2012:21(9):1177-1183.
17. Winter DA. Biomechanics and Motor Control of Human Movement. 4th ed. John Wiley & Sons.
18. Yedukondalu G, Syed K. A Portable Planar Robot Device for Upper Limb Rehabilitation. India Patent. Published on 16/12/2022.
19. Siciliano B, Sciavicco L, Villani L, Oriolo G. Robotics: Modelling, Planning and Control. Springer.
20. Craig JJ. Introduction to robotics: mechanics and control. Pearson Education.