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Innovative 3D Printed Exoskeleton Robotic Arm for Stroke Recovery

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ABSTRACT

This paper presents a novel robotic arm designed for stroke recovery, focusing on addressing less targeted arm functions through a master-slave mechanism. The system utilizes ultra-high torque servo motor assistance and 3D-printed PLA material for cost-effectiveness and customizability. By mirroring the movements of the patient's left hand to assist in rehabilitating the right hand, the device offers personalized therapeutic exercises for conditions like stroke recovery. The precise synchronization of movements between the master and slave hands highlights the potential for tailored therapy sessions and improved arm mobility and control. This innovative approach showcases advancements in therapeutic interventions for stroke rehabilitation, emphasizing affordability, personalized treatment and enhanced rehabilitation progress.

1. Introduction

The development and validation of a method for designing arm exercises is a significant contribution to rehabilitation therapy. By examining the biomechanics of the human arm, researchers can create exercises tailored to individual needs, enhancing rehabilitation outcomes. Customized motion planning ensures exercises are both effective and safe. This innovative approach not only introduces a novel method for designing rehabilitation exercises but also provides a comprehensive analysis of its application and validation. By establishing this groundwork, researchers lay the foundation for future advancements in rehabilitation therapy technologies, potentially leading to more personalized and efficient treatment strategies and ultimately improving

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patient outcomes [1-3]. Some of rehab technique is focus on vision-based sensor technology. They argue for the potential of these systems in replacing traditional face-to-face therapy, pointing out their ability to support various rehabilitation settings [4]. The development of robotic systems for rehabilitation, especially for patients recovering from stroke, has seen significant advancements in recent years [5,6]. Stroke rehabilitation requires intensive, repetitive and task-specific exercises to regain lost motor functions, which is often labour-intensive when done manually by therapists. The introduction of robotic systems aims to address these challenges by providing a means to deliver high-intensity, repetitive, personalized and engaging rehabilitation exercises. Robotic rehabilitation systems can potentially offer consistent and precise therapy sessions, reduce the physical strain on therapists and enable the collection of quantitative data on patient progress [7].

They are many various exoskeleton-type robotic devices for rehab which have been previously developed with focuses ranging from single-joint assistance to whole-limb support. These tend to be either chair- or floor-mounted and often have limitations such as limited degrees of freedom, bulky designs and complex control requirements [8-10]. Besides, there are few robotic arms of the robotic device is of the development of a five-degree-of-freedom (5-DOF) haptic arm exoskeleton tailored for use in virtual environments for training and rehabilitation purposes. It emphasizes the engineering challenges and solutions in creating a high-quality haptic interface, including considerations for low apparent inertia and damping, high structural stiffness, minimal backlash, avoidance of mechanical singularities and alignment with the human arm's kinematic constraints [8]. Moreover, there are also development of 7 DOF model that corresponds to the major joints and segments of the upper limb. This comprehensive approach allows for a more accurate design of exoskeletons that can perform a wide range of daily activities by accurately calculating the joint torques required for movement, thus improving the device's efficiency and user experience and some robotic arm was develop five degrees of freedom to estimate the shoulder movement by using non-invasive wearable sensors [11,12]. In addition, the development of the ARMin III robot represents a significant leap in upper limb rehabilitation. Its design, featuring six motors enabling movements across multiple degrees of freedom, allows for comprehensive upper limb rehabilitation, including tasks mimicking activities of daily living (ADLs). Preliminary evaluations with healthy individuals and patients have demonstrated the device's safety, functionality and potential efficacy in improving motor performance in stroke patients [13-15].

The exoskeleton robotic not only focus movement assistance at critical joints, including the shoulder, elbow, forearm and wrist with the development and application ETS-MARSE an upper extremity wearable robot designed for rehabilitation exercises [16]. Thus, some of the exoskeleton robot for example which called the MEDARM's design focuses on mimicking natural upper-limb range of motion, avoiding singular configurations and maximizing manipulability across the workspace. By employing electric motors for actuation through cable and belt transmissions, the device ensures back driveability and minimizes inertia, catering to both therapy and assessment purposes [17]. Some of the robotic integrate with the integration of Virtual Reality (VR) and robotic technologies has shown significant promise in the field of rehabilitation, particularly for individuals recovering from stroke. The exoskeleton device, known as L-Exos, was designed to support the rehabilitation of the upper limb by providing force feedback and enabling the precise control of movement within VR scenarios [18-20]. Other than that, these robots employ various control mechanisms, including electromyography (EMG)-driven systems, to tailor the rehabilitation process to the individual needs of patients, potentially enhancing the efficiency of therapy sessions. Clinical studies have demonstrated the efficacy of these robotic systems in improving motor skills, although challenges remain in terms of cost, accessibility and proving their superiority over traditional therapy methods [21].

Note that researchers are working on ways to use robots for rehabilitation. They are making devices that help people move their arms after injuries or health problems like strokes. These robotic systems can help by giving repetitive, personalized and intensive exercises that would be hard for human therapists to provide consistently. There are many types of robotic aids being developed. Some are big and only help with one joint, while others support the whole arm. Some devices can be used in virtual reality, which might make rehab more interesting. There's also a robot called the ARMin III, which can move in many ways to help people get better at using their arms for daily tasks. Some robots use sensors to understand and assist with shoulder movement and others use electric motors to make movements smoother and more natural [22]. Virtual Reality (VR) is being combined with robots to make rehab more effective. VR can make exercises more engaging and realistic. Some robots can even change how they help patients by measuring muscle signals [23].

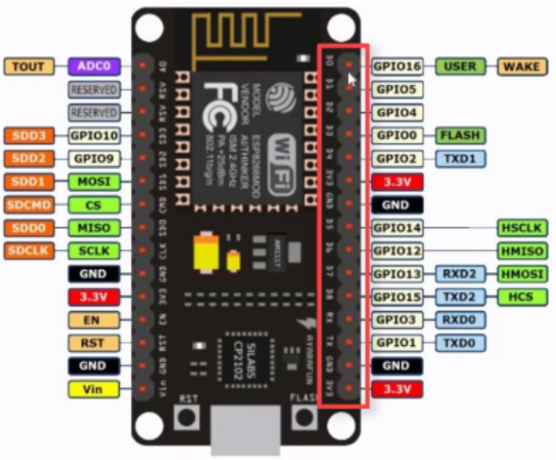
Although the above robots are promising, they are often expensive and not easy to get. Also, researchers are still trying to show that these robots are better than traditional therapy methods. There is a lot of potential for improvement in making these devices more customizable, less bulky, more integrated with virtual environments and more affordable [24]. Hence, the development of an innovative 3D printed exoskeleton robotic arm for stroke recovery in this study is vital due to its potential to customize rehabilitation interventions, improve patient comfort and outcomes, enhance cost-effectiveness and accessibility, integrate advanced features and stimulate further research and development in the field. In particular, the paper presents an innovative 3D printed exoskeleton robotic arm designed for stroke recovery, focusing on less targeted arm functions through a master-slave mechanism.

2. Methodology

In this section, the construction and operation of an advanced exoskeleton robotic arm is examined. The components used and their respective roles are identified and a detailed system block diagram elucidating signal flow and control mechanisms is presented. Subsequently, a comprehensive system flow chart detailing movement synchronization is provided.

2.1 Components

Figure 1 presents the integral electronic components that are employed in the construction of an advanced exoskeleton robotic arm. Included within these are a high-torque servo motor FT 5335M, which is vital for enacting precise angular movements and adjustments. There is also a microcontroller board which is Node MCU ESP 8266 replete with an array of inputs and outputs, which is used to process complex algorithms and control signals, directing the servo motor's actions. To power these components, there is a 9V AC to DC power adapter that ensures a consistent and safe electrical current is supplied. Lastly, a variable resistor or potentiometer, is included; this component can fine-tune control signals, allowing for subtle adjustments in the robotic arm's movement or position. Each of these components is critical for the overall operation of the system, leading to a well-integrated and functional exoskeleton robotic arm capable of performing tasks with a high degree of accuracy and control.



(a) NodeMCU ESP 8266

(b) Ultra-High torque servo motor (FT5335M)

(c) 3 D Printer PLA Filament

(d) Regulator

(e) 9V plug adapter

Fig. 1. Components used in this project

2.2 System Block Diagram

The block diagram in Figure 2 illustrates a holistic system for controlling a robotic arm in rehabilitation, beginning with the Master Control Unit for the Left Arm, where user movements are translated into signals. These signals are then processed by the Node MCU ESP8266, which serves as an intermediary device with Wi-Fi capabilities, before being transmitted to the Ultra High Torque Servo Motor. This motor, known for its precision and strength, executes the desired movements based on the processed signals received. Completing the system, the Slave Control Unit for the right arm mirrors the movements of the left arm, facilitating coordinated rehabilitation by replicating the actions of the healthy arm. This comprehensive setup offers an adaptable solution, allowing for interchangeability between the master and slave units to cater to the specific needs of patients, ultimately promoting efficient and effective arm rehabilitation.

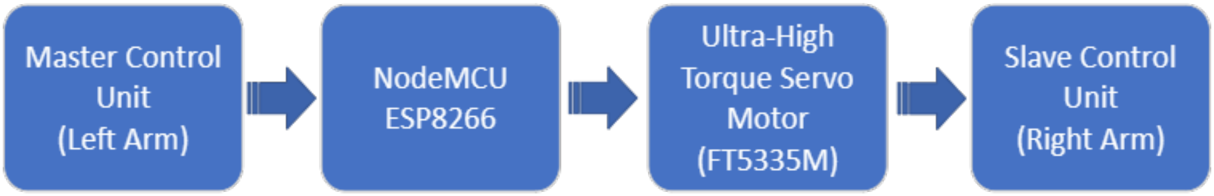


Fig. 2. Block diagram of exoskeleton robotic arm whole system

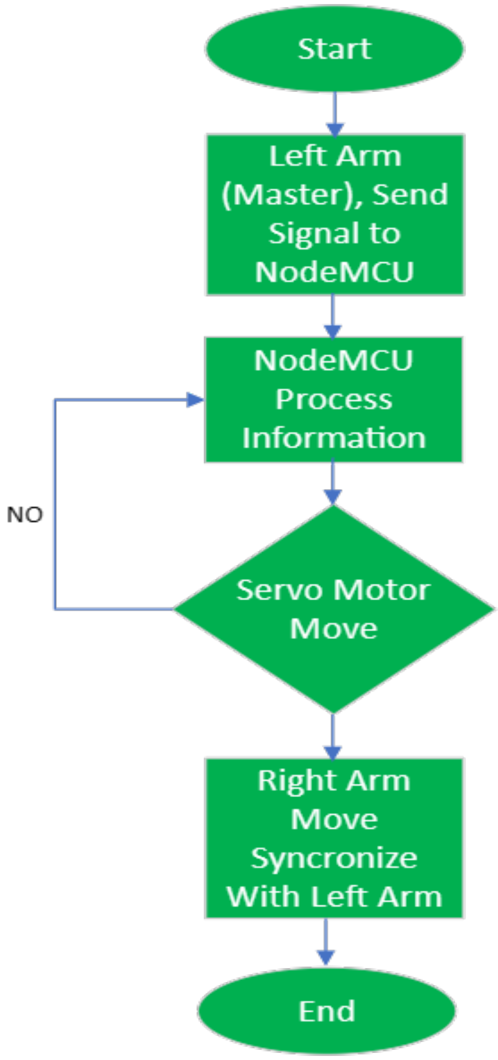
2.3 System Flow Chart and Coding

In this section, a flowchart depicting the steps involved in a robotic system designed to facilitate arm movement is presented. The system aims to replicate the movements of a human arm using servo motors controlled by an Arduino microcontroller. The flowchart outlines the sequential process from initiation to movement synchronization, while the accompanying code demonstrates the implementation of the initial step in this process.

Figure 3 illustrates the sequential steps involved in a robotic system designed to replicate the movements of a human arm. The system utilizes servo motors controlled by an Arduino microcontroller to mimic the actions of the left arm using the movements detected by a potentiometer. Specifically, Figure 3(a) begins with the initiation step, denoted by "Start," where the process commences. Initially, the left arm, acting as the master, performs a specific action, such as raising up. Subsequently, the Node MCU, functioning as a miniature computer with internet connectivity, receives a message regarding the left arm's movement. Upon receiving the message, the Node MCU processes the information regarding the left arm's movement. It then proceeds to determine whether it is time to initiate movement for the robotic arm. This decision point involves assessing various factors, such as predefined time intervals or specific conditions for arm movement.

If the Node MCU determines that it is not yet time to move the robotic arm, the process loops back to the Node MCU to potentially gather additional information or await further instructions. Conversely, if the Node MCU decides that it is time to move the robotic arm, the servo motor responsible for arm movement is activated. Once activated, the servo motor replicates the movement initiated by the left arm. This synchronization process ensures that the right arm, acting as the slave, mirrors the actions performed by the left arm. Finally, after the right arm completes its movement in sync with the left arm, the process concludes, as indicated by the "END" symbol at the bottom of the flowchart.

The accompanying code (see Figure 3(b)) corresponds to the initial step depicted in the flowchart. It demonstrates the control of a servo motor based on input from a potentiometer. While the code provides a foundational framework for arm movement, additional logic and hardware are necessary to implement the decision-making process and achieve synchronization between the left and right arms, as outlined in the flowchart.




```
#include <Servo.h>

Servo myServo;    // Servo motor object

const int potPin = A0; // Potentiometer pin
int potValue = 0;    // Potentiometer value
int angle = 0;     // Servo angle

void setup() {
myServo.attach(9);  // Attach servo to pin 9
pinMode(potPin, INPUT); // Set potentiometer pin as
input
Serial.begin(9600);  // Start serial communication
}

void loop() {
potValue = analogRead(potPin);// Read potentiometer
angle = map(potValue, 0, 1023, 0, 180);
// Map value to servo angle

myServo.write(angle); // Set servo angle
Serial.print("Pot: ");
Serial.print(potValue);
Serial.print(" - Angle: ");
Serial.println(angle);

delay(15); // Delay for stability
}}
```

(a) Flow chart (b) Coding

Fig. 3. Flowchart of the exoskeleton robotic arm system and coding

3. Results

In this section, the outcomes of designing and implementing an exoskeleton robotic arm for rehabilitation are presented. The design process involved creating a model using SketchUp software, showcasing the integration of components. The electrical circuit design detailed the functionality of various components such as the Node MCU board and servo motor. Fabrication utilized 3D printing technology and PLA material, ensuring precision. Integration into rehabilitation practices emphasized precise movement synchronization between the arms. These results deepen understanding of the arm's capabilities and its role in enhancing mobility for individuals with physical impairments.

3.1 Exoskeleton Robotic Arm Design

The design an exoskeleton robotic arm using SketchUp software can effectively illustrate the prototype from various angles, showcasing the integration of components such as the DAQ (Data Acquisition) box, which is central to capturing and analysing sensor data and the arm's structural casing that houses all mechanical and electrical elements essential for its operation.

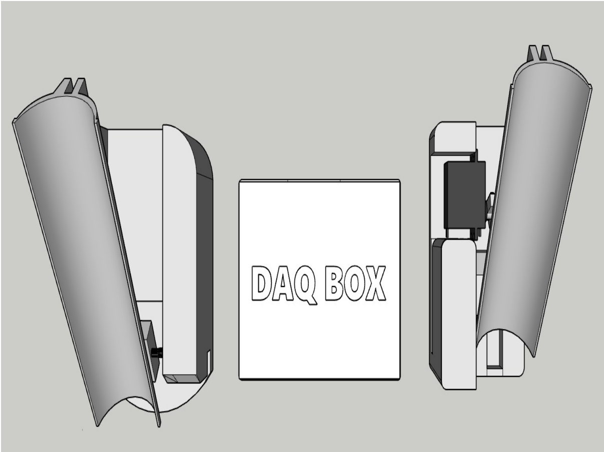


Fig. 4. Top view of the whole design

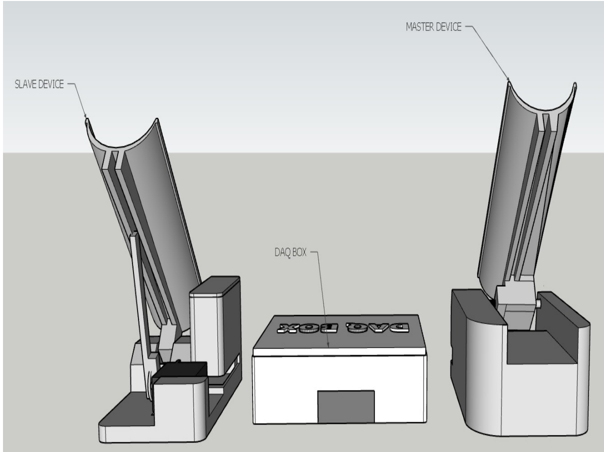


Fig. 5. Front view of the whole design

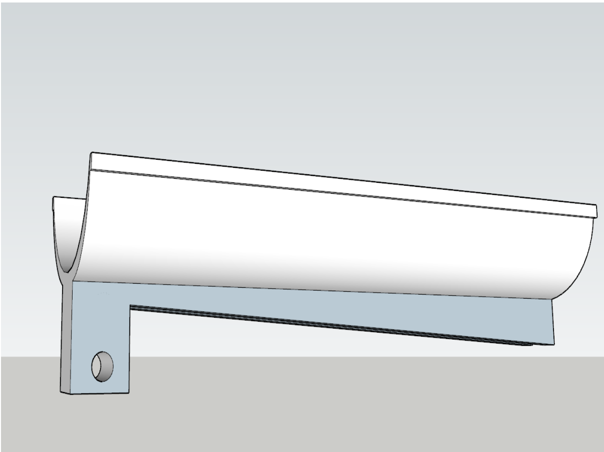


Fig. 6. Arm holder

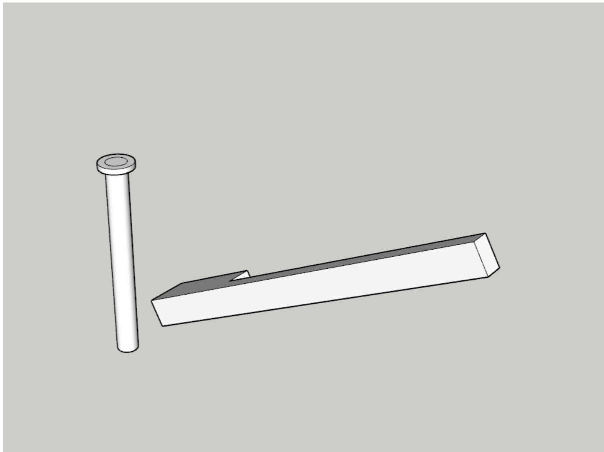


Fig. 7. Shaft design for arm holder

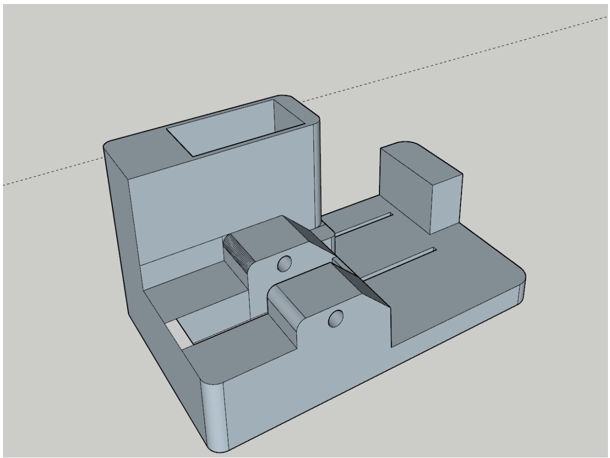


Fig. 8. Base for arm holder

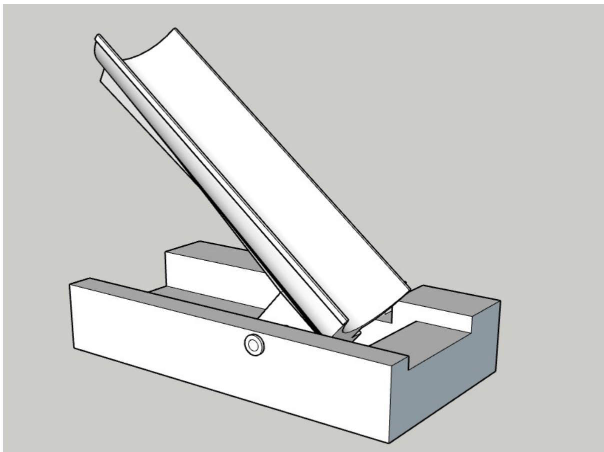


Fig. 9. Master design (left arm)

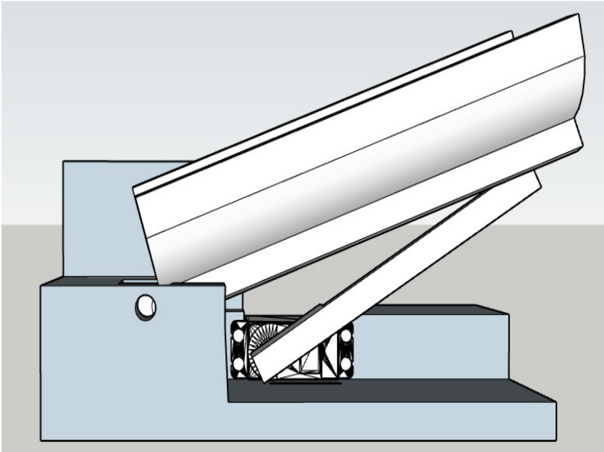


Fig. 10. Slave design (right arm)

3.2 Electrical Circuit Design

First, the Node MCU board is utilized, serving as the central processing unit of the system. It can establish internet connectivity and exchange messages to regulate other components. The motor driver is then connected to the Node MCU, governing the power supplied to the motor based on instructions received from the Node MCU. Following this, the servo motor, known for its high torque capabilities, is employed to execute precise movements as directed by the motor driver. A power supply is incorporated to provide electrical energy to all components, resembling a standard wall plug. Lastly, a variable resistor, commonly referred to as a potentiometer, enables adjustment of current flow by rotation, with feedback relayed to the Node MCU for precise motor control. Collectively, these components collaborate to regulate functions related to an exoskeleton robotic arm. The Node MCU processes input from the potentiometer, instructs the motor driver on power allocation and subsequently, the motor moves to the specified position. Such a setup holds potential applications in robotic movement or machinery control systems.

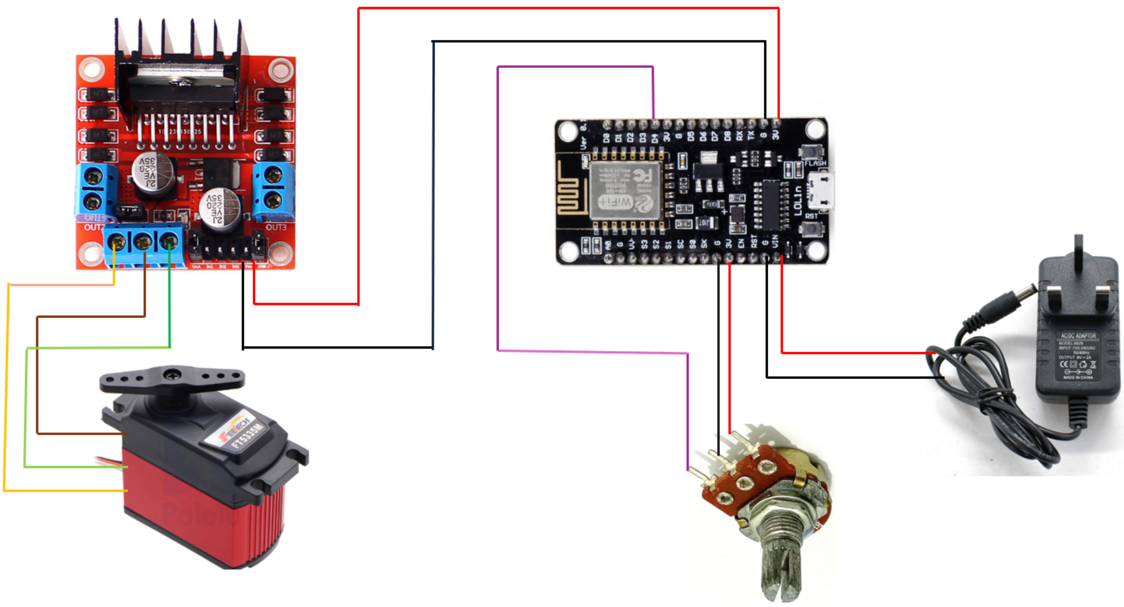
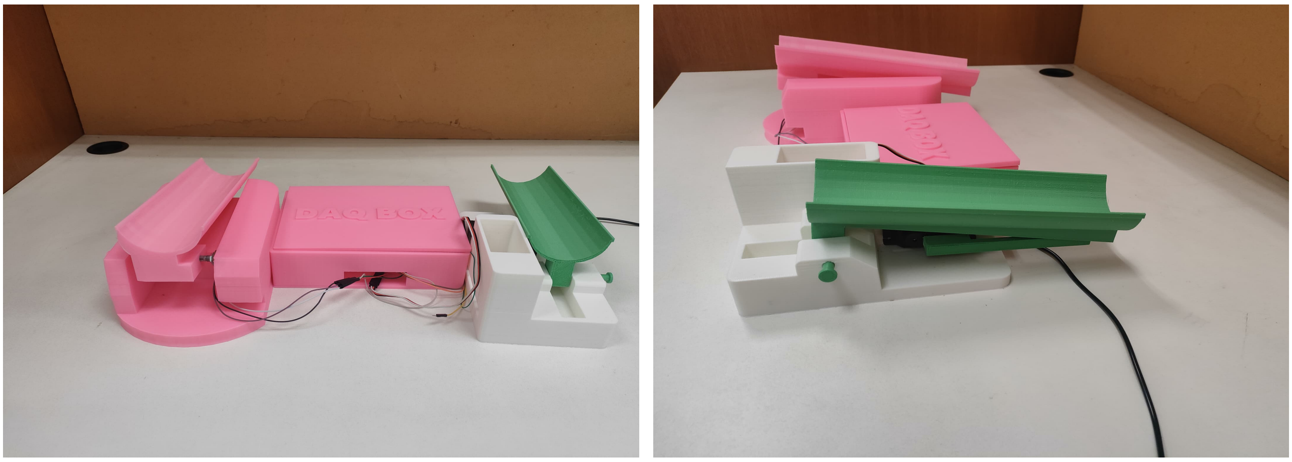


Fig. 11. Electrical wiring diagram

3.3 Prototype Fabrication

The prototype creation process involves utilizing a 3D printer and crafting it with PLA (Polylactic Acid) material, a biodegradable plastic known for its eco-friendly nature and suitability for 3D printing. The use of distinct colours (pink and green) for different parts suggests the employment of varied PLA filaments, selected either to assist in assembly or to provide visual guidance for component identification. Furthermore, the meticulous attention to detail indicates careful and precise execution of the printing process. Achieving such exceptional quality often entails adjusting printer settings, a task simplified with slicing software like Ultimaker Cura. This software is important in translating 3D designs into printable instructions, allowing for customization of parameters such as layer height, print speed and infill density to ensure optimal results. Moreover, in this context, the pink prototype is specifically designed for lifting the left hand (i.e., the Master), while the green prototype arm serves as the Slave control for the right hand (i.e. paralysed hand). This design is tailored for individuals with paralysis in one hand, allowing them to utilize their healthy hand for control purposes. Such a design not only highlights the adaptability of 3D printing technology but also reveals its potential in addressing specific needs and enhancing accessibility in healthcare applications.



(a) (b)

Fig. 12. Figure description (a) Top view of the 3D printed design (b) Side view of 3D printed design

3.4 Master and Slave Analysis

Integrating the system into rehabilitation practices highlights the precise synchronization of movements between the Master (Left hand) and Slave (Right hand) under varying loads, emphasizing its potential for personalized therapeutic exercises. This precision plays a crucial role in restoring full mobility and strength in the affected arm, thereby positioning it as a valuable tool for conditions such as stroke recovery and other physical rehabilitation needs. To further comprehend the movement of the proposed exoskeleton arm, the correlation between PWM, Angle and Voltage with and without load, a comprehensive analysis is conducted. This analysis aids in elucidating the intricacies of their relationship and enhances our understanding of the system's behaviour. The developed exoskeleton arm undergoes testing to evaluate its range of motion, strength and overall functionality. Figure 13 depicts the arm's initial state at a 0° angle, while Figure 14 illustrates the post-rehabilitation condition after targeted exercises. Equipped with adjustable resistance settings and customizable limb positioning of up to a 60° angle, the device enables tailored therapy sessions. Through data analysis, enhancements in arm mobility and control are assessed, offering a quantitative measure of rehabilitation progress. This data-driven approach empowers therapists to optimize strategies and set achievable goals for patient improvement, ensuring a personalized and effective rehabilitation process.

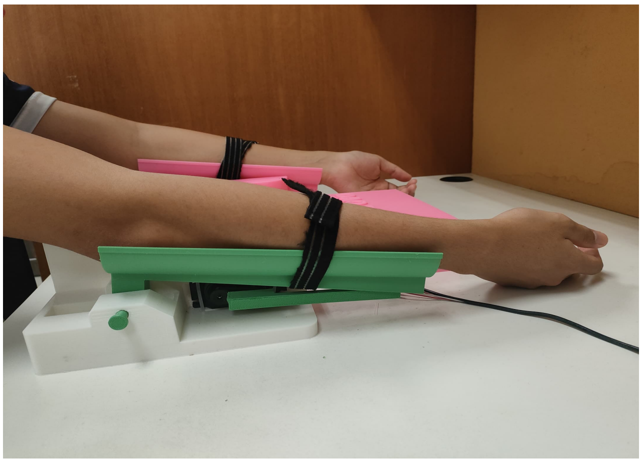


Fig. 13. Before rehab of the arm (0°)

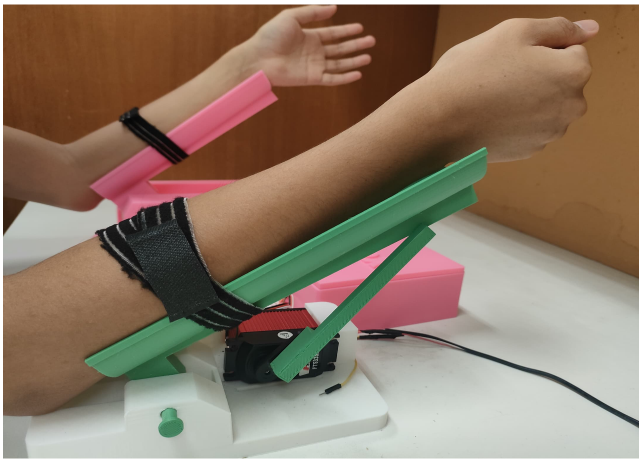


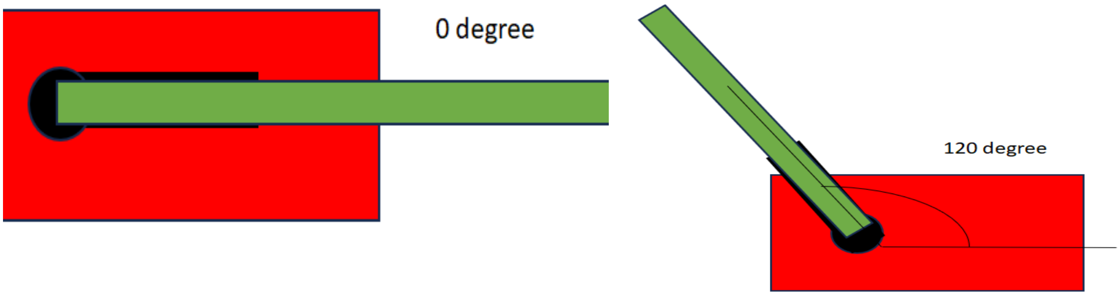
Fig. 14. After rehab of the arm (60°)

Table 1 provides data from an experiment where PWM (Pulse Width Modulation) signals are used to control an angle position. PWM is given in microseconds (us), the desired angle in degrees, the actual angle achieved and the voltage feedback in volts (V), with some values in millivolts (mV) for clarity. There is a clear linear relationship between the PWM signal and both the desired and actual angles. As the PWM value increases, so does the angle, although there is a noticeable deviation between the desired and actual angles. The actual angle consistently overshoots the desired angle, indicating either a systematic calibration error in the control system or a mechanical lag/overshoot in the servo response. The voltage feedback decreases as the PWM increases, which suggests that the voltage feedback could be inversely proportional to the PWM signal or directly related to the position of the servo motor arm. Typically, a lower voltage might indicate a higher position (or load) on the servo motor as it tries to maintain or reach a desired angle. Thus, after 1800 us of PWM, the voltage feedback dropping below 1 volt. This could be due to the design of the voltage measurement system or an indication of the limitations of the servo motor as it approaches its maximum range.

Table 1
Relationship between PWM, angle and voltage without load

PWM, *μs*	Angle (desired), *deg*	Angle (actual), *deg*	Voltage feedback, *volt*
900	0	0	1.72
1000	10	14	1.64
1100	20	25	1.55
1200	30	36	1.46
1300	40	46	1.37
1400	50	55	1.28
1500	60	62	1.21
1600	70	71	1.12
1700	80	81	1.02
1800	90	91	0.931
1900	100	100	0.840
2000	110	109	0.775
2100	120	119	0.693

Figure 15 illustrates a robust ultra-high torque servo motor system featuring a shaft initially positioned at a specific angle which is 0° angle. With a torque of 30 kg/cm, this motor can exert considerable force. An ultra-high torque servo motor designed to achieve a maximum rotation of 120° is specialized for applications requiring significant force with a limited range of motion.



(a) Initial Angle (0°) (b) Final Angle (120°)

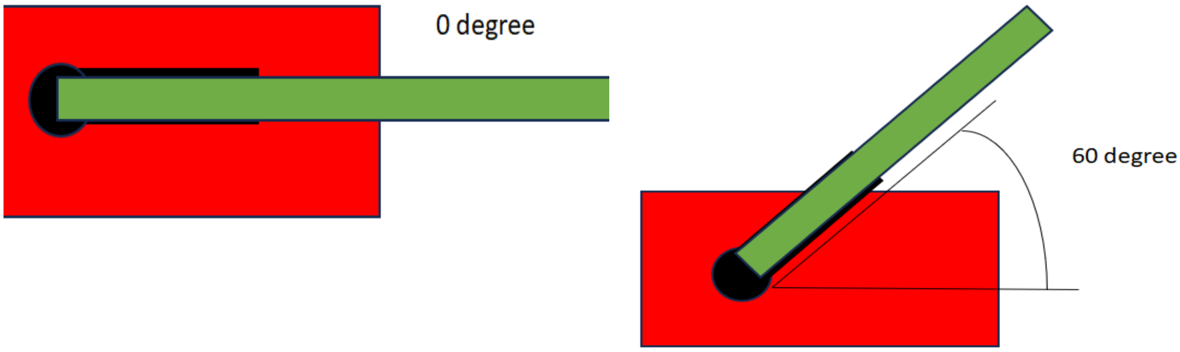
Fig. 15. Figure description (a) Before testing (0°) (b) After testing (120°)

Table 2 illustrates the relationship between Pulse Width Modulation (PWM) values, desired and actual angles and voltage feedback for a robotic arm mechanism under load, simulating an arm's resistance. This setup is integral to a rehabilitation device employing a master-slave concept, where the left hand (master) controls the robotic arm (slave) to support and mimic movements for the right hand (slave arm). As the PWM values increase from 900 to 1500 µs, corresponding to desired angles from 0 to 60 degrees, the actual angles achieved by the robotic arm show a consistent pattern of exceeding the desired angles slightly, suggesting a precise control mechanism capable of fine adjustments even under the varying resistance of a load. This accuracy is crucial for rehabilitation, where the goal is to replicate natural movements as closely as possible to retrain muscle memory and enhance recovery.

Table 2
Relationship between PWM, angle and voltage with load (arm)

PWM, *µs*	Angle (desired), *deg*	Angle (actual), *deg*	Voltage feedback, *volt*
900	0	0	0.73
1000	10	14	0.69
1100	20	25	0.66
1200	30	36	0.62
1300	40	46	0.58
1400	50	55	0.54
1500	60	62	0.51

Figure 16 represent the motor's angle directly affects the support arm's ability to bear weight effectively, making precise control crucial for optimal performance. Through this testing and adjustment, operators ensure the motor operates reliably and accurately in various applications. Final angle of the servo motor can achieve 60 degrees on the right hand which defined as the slave.



(a) Initial Angle (0°) (b) Final Angle (60°)

Fig. 16. Figure description (a) Before testing (zero degree) (b) After testing (60 degree)

In brief, Table 1 and Table 2 in general highlighting the relationship between PWM, Angle and Voltage with and without load. The table provides insights into how the system behaves under different conditions. Table 1, representing data without load, shows a consistent increase in the actual angle compared to the desired angle as the PWM values increase. The voltage feedback decreases as the PWM values increase, indicating an inverse relationship between PWM and voltage feedback. This behaviour suggests a systematic calibration error or mechanical lag/overshoot in the servo response. In contrast, Table 2, which includes data with a load (arm), exhibits a similar trend of the actual angle slightly exceeding the desired angle as the PWM values rise. However, the voltage feedback values are lower compared to Table 1, indicating that the system may be under higher load conditions. This could result in a more pronounced decrease in voltage feedback for a given PWM value. Overall, comparing these tables highlights how the presence of a load can impact the system's performance, influencing factors such as angle accuracy and voltage feedback. Understanding these variations is crucial for optimizing control strategies and ensuring reliable operation of systems utilizing PWM for motor control or similar applications.

4. Conclusions

In conclusion, the development of a 3D printed exoskeleton robotic arm for stroke recovery and rehabilitation presents a promising avenue for personalized therapy sessions. The integration of high-torque servo motors and microcontrollers allows for precise control and mimicking of natural movements crucial for optimizing recovery. The customizability of the system, along with its ability to provide tailored therapy sessions, highlight its potential in enhancing rehabilitation outcomes for stroke patients. Additionally, the utilization of a master-slave mechanism in the exoskeleton robotic arm design highlights a unique approach to mirror movements and provide engaging rehabilitation exercises, further emphasizing the importance of personalized and effective interventions in stroke recovery. The positive outcomes observed in various studies on robotic exoskeletons and virtual reality in rehabilitation post-stroke underscore the potential impact of integrating technology into rehabilitation practices for improved motor activity and gait in individuals after stroke. Future research focusing on enhancing IoT capabilities for remote monitoring and personalized treatment optimization could further advance the field.

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