Innovative design and fabrication of a 3d-Printed Prosthesis Arm for Automated Hand Rehabilitation

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Abstract − This study presents the innovative design and fabrication of a 3D-printed prosthesis arm aimed at enhancing automated hand rehabilitation for targeting hemiplegic patients who cannot open and close their hands. By leveraging surface electromyography (EMG) signals, the prosthesis arm translates muscle contractions in the forearm into precise hand movements, facilitating more effective rehabilitation. A comprehensive analysis of existing prosthesis designs guided the creation of a new, improved prototype. Using a concept scoring evaluation matrix, the best concept design was selected, designed, and fabricated through additive manufacturing. The finished prosthesis improves grip stability by imitating natural finger movements with flexible materials and a tendon system made of elastic ropes and fishing lines. Experimental comparisons between the designed prosthesis arm and a human hand showed significant similarities in flexion angles, though further refinement is needed for measurement accuracy and tactile feedback. The result present the designed prosthesis arm validity and can be used in automated control rehabilitation in the future. This research also highlights the potential of 3D printing and EMG technology in creating customizable, efficient prosthesis arms for automated rehabilitation, suggesting pathways for future improvements and broader applications.

Keywords: *Prosthesis Arm, 3D-Printing, Additive Manufacturing, Hand Rehabilitation, Hemiplegic, Electromyography (EMG)*

1. INTRODUCTION

Human hands are essential in our daily lives, performing a variety of tasks such as touching, gripping, feeling, holding, manipulating, and caring. They provide a substantial contribution to our identity and self-perception. Carrying out daily activities becomes difficult for people who do not have hands, resulting in slower and less efficient work performance and a limited ability to complete tasks [1-2]. In addition, individuals experience social shame and feelings of insecurity as a result of others' avoidance.

Prosthetic devices can significantly improve the quality of life for individuals with limb loss by providing independence and mobility. Prostheses are external devices that replace missing or defective limb segments (arms and legs), including all devices attached to a limb for structural or functional purposes, such as bone-anchored prostheses [3]. However, in this research, we focus on developing a prosthetic arm for rehabilitation purposes, targeting hemiplegic patients who are unable to open and close their hands due to a blockage of their nerve pathways caused by neurofunctional disorders such as apoplexy as shown in Figure1. These patients can use a rehabilitative automated prosthetic arm to help them open and close their hands. This automated prosthetic arm robot's movements, such as opening and closing fingers, are expected to be more effective in the rehabilitation process than passive movements with out the use of any equipment [4].

Integrating Electromyography (EMG) technologies into prosthetic arms is critical for improving functionality and usability [5-9]. EMG sensors monitor electrical signals produced by muscular contractions in the residual limb, providing useful feedback for intuitive control of the prosthetic arm's movements. By recording these signals, EMG allows users to start and control specific tasks with natural muscle movements, resulting in a more intuitive and responsive engagement with their prosthetic device. We will employ surface EMG signals to relay the patient's muscle signal, allowing them to open and close their hands. We will design and develop a rehabilitation prosthesis that suits this task as part of the total contribution of the automated control rehabilitation prosthesis arm [10-12].

The primary objective of this project is to design and fabricate an automated control prosthetic arm that can improve the quality of life for amputees in terms of functionality, ease of use, lightweight, portability, and cost-effectiveness, ensuring that all amputees can utilize it. The prosthetic arm will feature 3D-printed materials, strings that serve as tendons for the fingers, and algorithms for the mechanisms. The arm will be powered by a battery and can be controlled wirelessly via a smartphone app. The algorithms will be design ed to control the arm movements base don user feedback, with EMG sensors detecting the user's movements and providing feedback.

The first objective of this research is to study and analyze current prosthetic arms and components available on the market, identifying their limitations and potential improvements. Second, we aim to determine the appropriate product design specifications (PDS) for conceptual design development. Third, we will apply the concept scoring evaluation matrix to select the optimal prosthesis design concept. Finally, we will design and fabricate the prosthetic arm and test its proto type. Additive manufacturing techniques like 3D printing are used for fabricating this prosthesis [13-14]. 3D printing offers design freedom, reduces manufacturing time, minimizes material waste, and facilitates the creation of customized prostheses. Designing and manufacturing a functional prosthetic arm involves

overcoming challenges in both design and manufacturing processes. The primary goal is to create a prosthetic arm robot that will improve the quality of opening and closing the hands of the patient during rehabilitation.
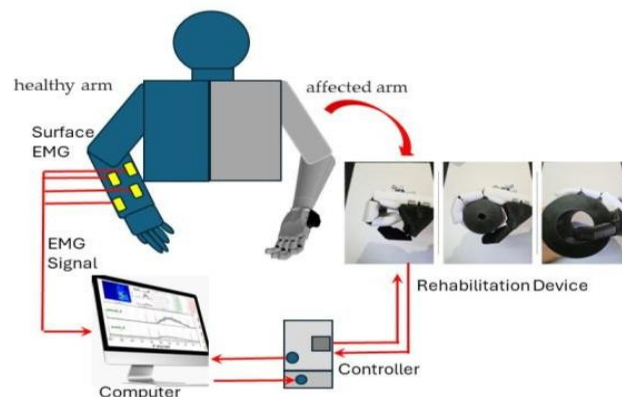

Figure 1. The Concept of EMG-Controlled Master-Slave Manipulatorfor Upper Limb Rehabilitation

2. METHODOLOGY

This section examines various aspects of existing designs, including their design features, materials, mechanisms, and overalleffectiveness. By analyzing previous works, the report aims toidentify strengths, weaknesses, and areas for improvement in current prosthetic arm designs. Previous research has focused more on the development of prosthetic arms as replacements for amputee arms [15-24]. This study focuses on designing a prosthetic arm that supports rehabilitation tools for opening and closing fingers. Table 1 Show sprevious researchers' contribution s to prosthetic arm research

Table 1: Summary of the contributions of the existing designs

Author(s)	Contributions
Sheikh Metal.[15]	• 3D printed orearm prosthesis with 6 servos for fingers and elbow. • Developed a versatile prosthesis arm voice and manual control, featur featuring accessible commands. Lightweight, affordable, and easy to use
Fulzele etal.[16]	• A 3D-printed forearm prosthesismade with PLA filament, with 2 Servosat the forearm, using fishing lines and nylon paracords for tendons. • Lightweight,250g pros thesis with astrong grip for ce of 55N. • Cost-effective and customizable fo rindividual hands and needs.
Selvan Metal.[17	• Anopen-source designfora3D-printed for earm prosthesis wasused. • Itconsistsof5servosforthefingers,with fishing line sastendon joints.
Tenore Fetal.[18]	• The purpose of the report is to enhance the accuracy of EMG signals inupper-limbprostheses. • 32 bipolar electrodes attached to the forearm to perform both
Venkate sh Bet al [19]	• 3D-printed forearm prosthesis made of PLA filament with 6 servoslocated in the forearm, providing 16-DOF. It uses nylon string tendons. • The prosthesis has a gripping and cable system for adapting to irregularobjects. Lightweight, with weight of less than 750 grams.
Gretsch Ketal.[20]	• Forearm prosthesis made with 3D printing,using ABS filament as the material. Use 5 servos located in the forearm, providing 10-DOF. • Joint mechanis mismade with elastic cordand beadweaving thread. • Alightweight,240ghand prosthesis,controlled by shoulder movements,with the ability to open and close the thumb independently.
Bahari Metal.[21]	• Acrylic plastichandprosthesisismadefromanSLA3Dmachine.5servosin the palm, with 14 DOF controlled via belts and pulleys. • Use LDR sensors, and force sensors, and is manually and autonomously controlled. Calculate mechanical and perform kinematic analysis.
Sivaraman Pet al. [22]	• Performbasicgraspingmovementsoneverydayobjectsbutlackssufficientforce transmission for precision grip simulations. • Forearmprosthesisismadeusing3DprintingwithPLAfilament.Use6servos located in the palm and uses nylon paracord for the tendons.

K.Wanetal.[23	• Cost-effective,highlyefficientroboticsystemwithseparateactuationcapable of performing 120 distinct movements for a wide range of tasks.
Swetha Retal.[24]	• Gestureandmovementdetection. • The arm was construc tedusing low-costandeasilyaccessiblematerials. • Software design and CT images of amputated and non-amputated armswere used to create a CAD model of the socket, forearm, and hand. • This CAD model was design edtoperfectlyfitaspecificamputee,withthepotential to improve their quality of life.

Table 2: The prosthesis arm design concepts

	Conceptual Design1	Conceptual Design2	Conceptual Design3
Knuckle joint to finger	1:1ratio(male-to-female connection)	1:1ratio(male-to-female connection)	2:2ratio(male-to-female connection)
Finger	Split2parts	Split3parts	Split3parts
Forearm	Separate with wrist	Combine with wrist	Combine with Wrist
Thumb	2parts	2parts	3parts
Finger Positioning	Litle,ringfingers atpalm35°	Allfingers≈90° fromthepalm	Allfingers≈90° fromthepalm
ThumbAngle	90° from the indexfinger	90° from the indexfinger	35° from the indexfinger
PartSections	Palm+Wrist+ Forearm	Palm+Wrist& Forearm	Palm+Wrist& Forearm
Servo Motor Location	5servosatthe forearm	5servosatpalm	5servosatthe forearm
Controlmec hanism	ArduinoUnoSMD+FishingLineandElasticRope		
SensorControl	EMGMuscleSignalSensor		
Material	PLA+plastic		
Servotype	6xSG90ServoMotor+PCA968516Channel		

Product Design Specification And Concept Analysis

Product Design Specification (PDS) criteria were established to guide the design and fabrication process through several design concepts as shown in Table 2. The first step in developing a concept design for a prosthetic arm is identifying the common components likely to be employed, as show nin the exampleof Conceptual Design 3 in Figure 2. We developed three base design concepts. From the three concepts developed, we evaluated them by using the concept scoring evaluation matrix to identify the best design.

3. DESIGN SELECTION

Several factors can be used to select the best concept design for a prosthetic arm, and a concept scoring evaluation matrix shown in Table 3, can play acrucialrolein thi sprocess.In an evaluation matrix, criteria and specific requirements for a prosthetic arm are broken down into categories such as user-friendliness, durability, stability, ease of control, light weight, easy to assemble, and aesthetic value.The selected criteria ensured that the prosthetic arm would be affordable, easy to use, energy-efficient, customizable, comfortable, low- maintenance, and visually appealing

Each concept is rated and scored according to how well it meets each criterion, enabling a clear and objective comparison between options. From this evaluation approach, the best concept design offers the optimal combination of features and functionalities for the prosthetic arm. Based on the total value from the scoring evaluation matrix in

Table 3, Conceptual Design 3 had the highes to verallrating with a total of 4.22 weight score and was thus selected as the base concept design for the prosthetic arm in this study. Conceptual Design 2 came in second with a total of 3.85 scores, while Conceptual Design 1 was last with a total of 2.80 scores. These rankings were based on a personal evaluation and analysis survey

Figure 2: The example of prosthesis arm Conceptual Design 3

Table 3: The concept scoring matrix

EvaluationCriteria	Weight(%)	Conceptual Design1		Conceptual Design2		Conceptual Design3	
		Ranking(1-5)	WeightedScore	Ranking(1-5)	WeightedScore	Ranking(1-5)	WeightedScore
UserFriendly	8	4	0.32	3	0.24	2	0.16
Cost	10	3	0.30	4	0.40	3	0.30
Durability	10	3	0.30	4	0.40	5	0.50
Stability	10	3	0.30	4	0.40	4	0.40
Efficiency	10	3	0.30	4	0.40	5	0.50
Easyto Control	10	2	0.20	4	0.40	5	0.50
Weight	7	4	0.28	3	0.21	3	0.21
EasytoAssemble	25	2	0.50	4	1.00	5	1.25
Aesthetics	10	3	0.30	4	0.40	4	0.40

Incorporating advantages from each conceptual design will helprefine our final design. For instance, the placement of the thumb is important and considered within a range of 35° to 90° from the index finger, as observed in initial drawings where extremes in size hindered object manipulation. Additionally, the optimal positioningof motors is prioritized to avoid component overcrowding and make efficient use of available space as we decided in Conceptual Design 3 for 5 servo motors located at the forearm. The number of parts is also crucial, with a higher quantity facilitating easier repairs or replacements when parts become worn or damaged. While a higher joint ratio enhances stability, the design must balance this with space constraints to ensure practical functionality. The final design will usea 2:2 joint ratio for better stability compared to the 1:1 ratio, taking both stability and space efficiency into account as summarized in Table 2.

4. FLEXION ANGLEFOR FINGER DESIGN

Flexion angles of the hand's joints were measured using a standardized procedure involving cylinders of varying sizes. The procedure ensured accurate measurement of flexion angles at the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joints. By meticulously measuring these angles, crucial data were obtained to inform the design and development of the prosthetic arm, optimizing functionality and natural movement. The measured angles provided essential data for designing a prosthetic arm that replicates natural hand movements and flexibility.

The flexion angle procedures involved utilizing both of the author's own hands, left and right, as the subjects for measurement (Figure 3). This approach ensured consistency and reliability in the data collection process, as the measurements were taken from the same individual under controlled conditions.

Accurate measurements of hand and arm dimensions were crucial for designing a customized prosthetic arm. A method involving tracing, marking, and measuring was employed to obtain precise dimensions. These measurements servedas the basis for designing aprosthetic arm that prioritized comfort, functionality, and alignment with individual anatomical and bio mechanical needs. The procedure is as follows:

i. Ensure the cameraissetupataconsistentangledirectlyabove the subject's hand.

ii. Provide the subject with cylinders of three different sizes: 10mm, 60mm, and 120mm, as shown in Figures 3and 4. These cylinders are used to assess flexion angles at the DIP, PIP, and MCP joints.

iii. Capture images of the subject holding the cylinders, maintaining consistent hand positions across differentcylinder sizes.

iv. On the digital or physical copies, draw lines parallel to the top of the fingers, connecting MCP to PIP, PIP to DIP, and DIP to the fingertips. This visual aid assists in accurately visualizing the flexion angles.

Measure the angles between each drawn line by placing a protractor on top of the copies. Record the measured angle values in a tabulated form. This dataserves as the basis forthe final design implementation in subsequent steps.
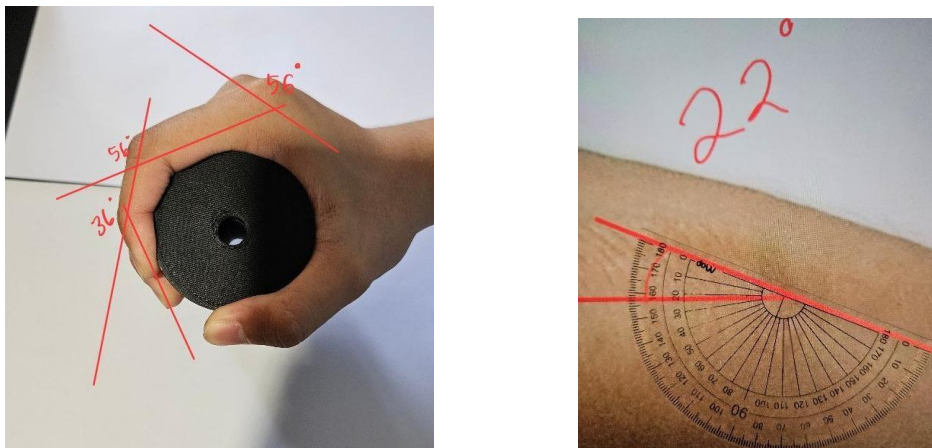

Figure 3:Measurement procedure-Lines drawn parallel to the fingers. (Measurement of the flexion angle using a protector)
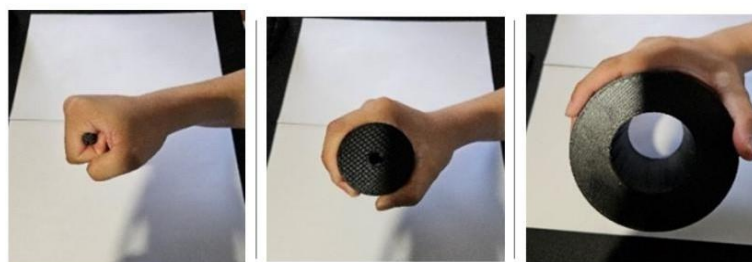

Figure 4: The subject is holding 10 mm, 60 mm, and 120mm cylinder

Finger Mechanism

The finger mechanism of the prosthetic arm incorporates an innovative design utilizing fishing lines and elastic rope as tendons, mimicking the natural movement of human fingers, as shown in Figure 5. The mechanism consists of a series of interconnected joints and segments, each controlled by a combination of fishing line and elastic rope using a servo motor. As the user initiates movement commands through sensors or manual controls, tension is applied to the fishing line and the elasticrope, causing the jointst of lex or extend
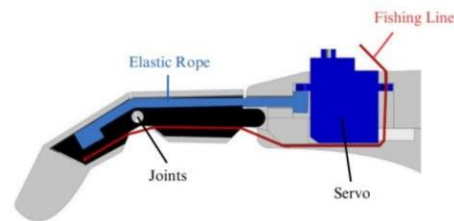
Figure 5: Finger mechanism-Fishing line and elasticrope

The fishing line serves as the primary actuator, transmitting mechanical force from the user's input to the individual finger segments. Its high tensile strength and low stretch properties ensure precise and responsive movement, enabling the prosthetic fingers to perform a wide range of gripping and grasping motions withaccuracy and dexterity. Additionally, the fishing line's durability and resistance to wear make it well-suited for long-term use in prosthetic applications, providing reliable performance and longevity.

Complementing the fishing line, elastic rope acts as a passive element within the finger mechanism, providing flexibility and resilience tothe system. By incorporating elastic elements into the tendon system, the prosthetic fingers can exert variable levels of force and adapt to different gripping tasks, enhancing versatility and grip stability. Furthermore, the elastic properties of the rope contribute to the natural feel and compliance of the prosthetic fingers, mimicking the spring-like behavior of biological tendons and enhancing usercomfort and control.

Final Design

The final design of the prosthetic arm is done using 3D Computer- Aided Design (CAD) software, SolidWorks. Each component's design and assembly are also done in SolidWorks, as shown in Figure 6. This includes all the fingers, palms, wrists, forearms, and even the joints within those fingers. The Hand of the Final Design is intelligently divided into two parts to facilitate the easy placement of the Metacarpophalangeal (MCP) joints for each finger. This division ensures precise alignment and attachment of the MCP joints to theend of the palm, optimizing finger movement and functionality.
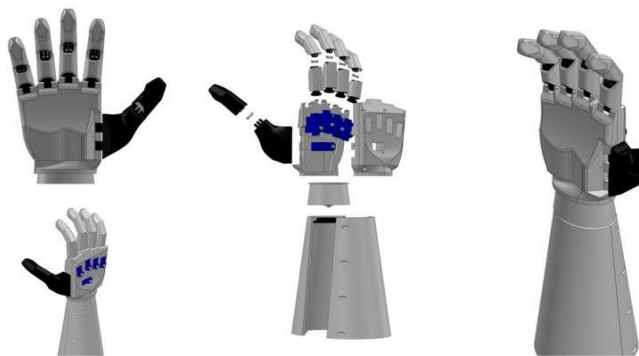

Figure 6: Final design of prosthesis arm-Isometric view with servo motor and explode view

3D-Printing and Fabrication Process

The 3D Printing stage involves the digital model being sliced into layers and transferred to the 3D printer, which builds up the physical object layer by layer. Then, the post-processing stage involves printed components that may under go sanding, smoothing,orpainting to improve surface finish and functionality. Finally, the testing and adjustment stages involve the prosthetic arm being tested for functionality, fit, range of motion, durability, and comfort. For assembly stages, the components are assembled according to design specifications, including attaching joints, hinges, and electronic components. Once assembled, the prosthetic arm is finalized and prepared for comparison with the human hand in the subsequent experimental procedure. Any necessary adjustments or modifications are made to optimize performance and user experience. This may involve attaching joints, hinges, or other moving parts, as well as integrating any electronic components such as EMG sensors and actuators. The completed final 3D printing prosthesis arm and its assembly of the system as shown in Figure 7.

The EMG sensors detect the electrical activity in the arm muscles, allowing the servo motors to move the prosthetic arm according tothe user's muscle movements. An Arduino is used to control these servo motors and process the data from the EMG sensors. EMG control algorithms measure myoelectric signals from specific forearm muscles. The device's actuators and servo motors are controlled using these EMG signals. When the EMG signals exceed set thresholds, specific commands are executed. This system captured signals from the forearm muscles to perform actions likeclosing fingers or rotating joints. It enables users to control grip patterns and wrist or elbow movements, but only one action can be performed at a time.
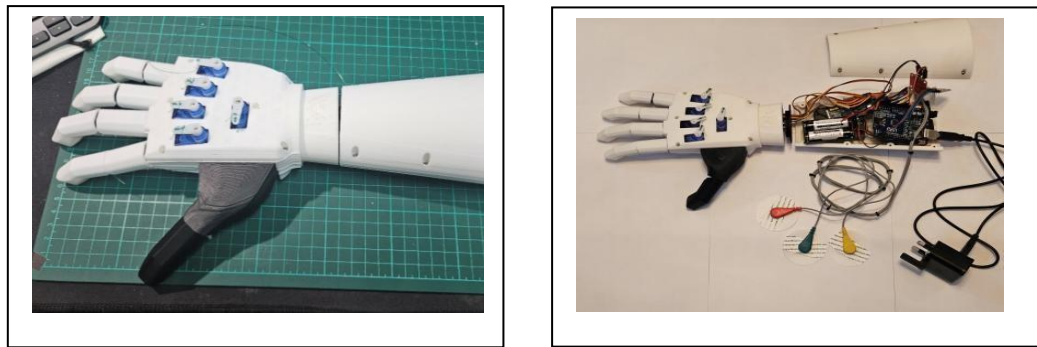
Figure 7: 3D-Printing prosthesis arm and final assembly system

Experiment Procedure

In this experiment, the procedure for measuring flexion angles mirrors the methodology outlined in section 2.3, where flexionangles of the human hand were assessed. The experiment focuses on manually controlling the flexion of the prosthetic finger, with the pros the tic arm servingas the subject and under going necessary modifications to accommodate the artificial limb. Flexion is induced by manually manipulating the control unit. This setup enables a direct comparison of flexion capabilities between the human hand and the prosthetic arm under different control mechanisms, offering valuable insights into the performance and usability of the prosthetic arm.

The experiment is to demonstrate the difference between the finger flexion angle of the fingers of the hand and prosthetic with theuse of 3 graphs to illustrate this difference, the 10mm, 60mm, and 120mm diameters as shown in Figure 8. The use of different diameters allowsforacomprehensive analys is of the fingerflexion angleacross a range of sizes. This helps to evaluate the performance and adaptability of the prosthetic arm in various situations, such as grasping objects of various sizes. Comparing the flexion angles at different diameters, it provides valuable insights into the prosthetic arm's versatility and potential areas for improvement.
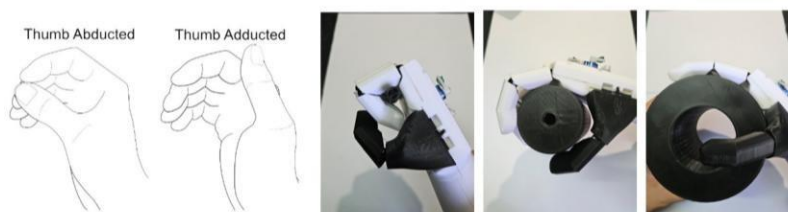

Figure 8: The prosthesis arm is holding a 10 mm, 60 mm, and 120 mm cylinder estimated dimensions of a human hand

5. RESULTAND DISCUSSION

The experimental results show impressive parallels between the prosthesis arm and a real hand in terms of finger flexion angles, as shown in Figures 9, 10, and 11. These studies demonstrate how well the prosthesis design replicates natural hand movements and capabilities. However, some substantial variations in particular joints were discovered. These inconsistencies could be attributable tohuman error during the photo-taking process or incorrect placement during the marking process. Refining measurement techniques to enhance accuracy and consistency in future investigations is an area for improvement. Several issues were encountered during the project, complicating the development process. Onenotablechallenge

occurred from 3D printing, where prints occasionally halted midway due to power outages, necessitating a restart of the printing process. This interruption resulted in wasted material and time. These lines could be sanded down to improve the aesthetics of the final product.

Another significant challenge was the malfunction of the prosthesis arm's control system, impacting its functionality and leading to disruptions in the testing and evaluation processes. Despite prior successfultesting,themal function emergedun expectedly towardsthe end of the project timeline, causing the prosthesis arm to cease functioningasintended.Initialassessmentspointedtowardspotential issues with the motor components or an insufficient power supply, causing the servo motor to operate below full capacity. This setback prompted a thorough investigation, necessitating additional troubleshooting and diagnostic procedures to identify and rectify the underlying issue.
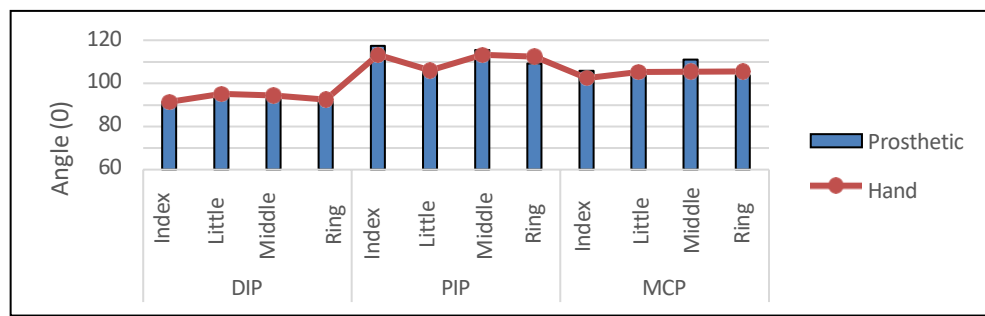
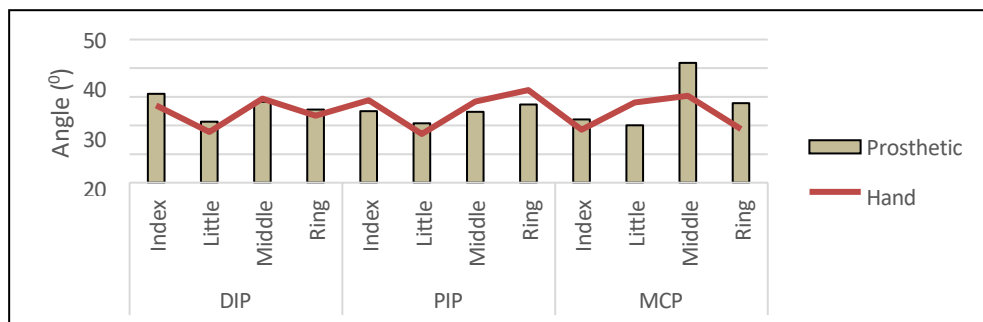Figure 10: Flexion angle comparison: Hand vs. Prosthesis (60 mm cylinder)

Figure 11:Flexionanglecomparison:Handvs.Prosthesis(120mmcylinder)

Table 4 shows the mean flexion angle of both the left and right hand. By averaging the left and right-hand values, the mean flexion angle of each finger joint between the index and little finger when gripping cylinders of different diameters can be obtained.

Additionally, the absence of a rubbery grip in the prosthesis arm highlights a potential avenue for enhancing tactile feedback and grip stability, warranting further investigation in future design iterations. Table 5 indicates a significant increase in the flexion angles of all joints across the four fingers as the cylinder diameter decreases.

Table 4:Mean flexion angle of both the left-and right-hand (Hand)

Diameter	Index			Middle		
	DIP	PIP	MCP	DIP	PIP	MCP
10	62.8	106.5	84.7	68.8	106.5	90.8
60	37	56	57.2	41	53.2	65
120	27	28.8	18.5	28.2	24.7	41.8
Diameter	**Ring**			**Little**		
	DIP	PIP	MCP	DIP	PIP	MCP
10	64.8	104.8	91	70.2	91.8	90.3
60	34.5	48.7	45.3	27.8	41.7	42.2
120	25.5	27.3	27.7	21.3	20.7	20

Diameter	Index			Middle		
	DIP	PIP	MCP	DIP	PIP	MCP
10	62.7	114.7	91.7	70.0	111.0	102.0
60	38.0	49.0	17.0	41.3	55.3	55.7
120	31.0	25.0	22.0	29.3	28.3	30.3
Diameter	**Ring**			**Little**		
	DIP	PIP	MCP	DIP	PIP	MCP
10	63.3	98.3	87.3	70.3	91.3	89.3
60	34.7	31.7	67.7	32.3	28.3	74.3
120	23.3	32.3	18.7	17.7	17.0	28.0

6. CONCLUSION

The design and fabrication of the prosthesis arm represent significant achievements. Despite unforeseen malfunctions, diligent troubleshooting allowed the arm to function successfully, achieving the objectives of designing a prosthesis for use in arm finger open and close rehabilitation. Several objectives were accomplished, including creating the prosthesisarm using 3D CAD software and additive manufacturing technology. This project provides valuable insights for future endeavors, highlighting the importance of robust testing procedures, contingency planning, and resource management in the development of assistive technologies.The results demonstrate that the prosthesis can be use dinautomated control rehabilitation in future projects.

To enhance future designs, it is recommended toutilize rubber- type or flexible filaments to boostst rength, durability, andcomfort.Investigating methods to integrate EMG sensory feedback systems into 3D-printed prosthesis arms for automated rehabilitation purposes will enable users to receive tactile feedback and better interact with their environment. Additionally, continuously refining prosthesis arm designs for improved grip strength, articulation, and range of motion in arm rehabilitation will further enhance their effectiveness and use rexperience.

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AUTHOR CONTRIBUTIONS

Individual contributions of authors are as follows: I. Zunaidi: Conceptualization, Methodology, Design, Analysis, Validation, Writing- Final Draft Preparation, Review and Editing, and Supervision; Y. Rahayu: Evaluation, Review, Examiner; A. Elaklouk: Software and Programming; P. Hamizan: Concept, Design, Draft Preparation, Fabrication, and Data Curation.

CONFLICTS OF INTEREST

This research paper has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission, and declare no conflict of interest.

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