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Cost-Effective Prosthetic Hand for Amputees: Challenges and Practical Implementation

Iylia Nabila Sujana[1], Jumadi Abdul Sukor[2*], Jamaludin Jalani[1], Frankie Ngerong Sali[1], Sujana Mohd Rejab[3]

[1]Department Department of Electronic Engineering, Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia Parit Raja, 86400 Batu Pahat, Johor, MALAYSIA

[2]Department of Electrical Engineering Technology, Faculty of Engineering Technology,
Universiti Tun Hussein Onn Malaysia Pagoh Campus, 84600 Panchor, Johor, MALAYSIA

[3]MyVista, Lot 396, Jalan Matang, 34700 Simpang, Ipoh, Perak, MALAYSIA

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Abstract: According to statistics, approximately 160,000 people in Malaysia, out of the current population of 32 million, need prosthetic or orthotic equipment. For individuals who have experienced upper extremity amputations, significant challenges are posed by the loss of functionality and the desire for a cosmetically appealing solution. To address this issue, a cost-effective prosthetic hand was proposed and developed. An overview of existing prosthetic hands is also offered, with an emphasis on cost-effectiveness, challenges, strengths, and weaknesses. The developed prosthetic hand incorporates a practical and underactuated finger mechanism. It is equipped with controllers based on EMG sensors to ensure that optimal responses are achieved during the grasping and releasing of objects. A suitable motor was carefully chosen to facilitate effective grasping and ungrasping activities. The proposed design was realized using SolidWorks and a 3D Printer. The capabilities of the prosthetic hand were demonstrated through a series of tests involving various objects, including pliers, a screwdriver, and a phone. The results indicate that objects of different sizes and shapes can be effectively grasped and ungrasped by the prosthetic hand. The unique bending angles in each finger result from the way tendons are connected via flexible cords and fishing lines to the servo motor. This design allows for a dynamic response based on the user's muscle flex and strength. The affordability of this cost-effective prosthetic hand demonstrates its potential as a practical and viable solution for amputees aiming to restore their grasping functionalities.

Keywords: Prosthetic hand, amputees, upper extremity, EMG, overview, cost effective

1. Introduction

Approximately 0.5 percent of the population in developing nations requires prosthetic or orthotic devices, accompanied by rehabilitation services, due to disabilities. This estimate suggests that around 160,000 people out of Malaysia's current population of 32 million could potentially need such assistance [1]. The loss of an upper extremity in amputees has two significant impacts. Firstly, there is a clear reduction in functional capability, impacting tasks like manipulation and grasping. Secondly, psychological hurdles arise due to changes in the visual aspect of the upper extremity. Many individuals experience the loss of one or both hands due to accidents, illnesses, disasters, and even conflicts. At present, hand prostheses stand as the most practical means for individuals with upper extremity amputations to regain hand functionality [2]. Prosthetics play a crucial role in emulating the intricate functions of the human body, aiming to restore essential functionalities for individuals who have experienced limb loss. Therefore,

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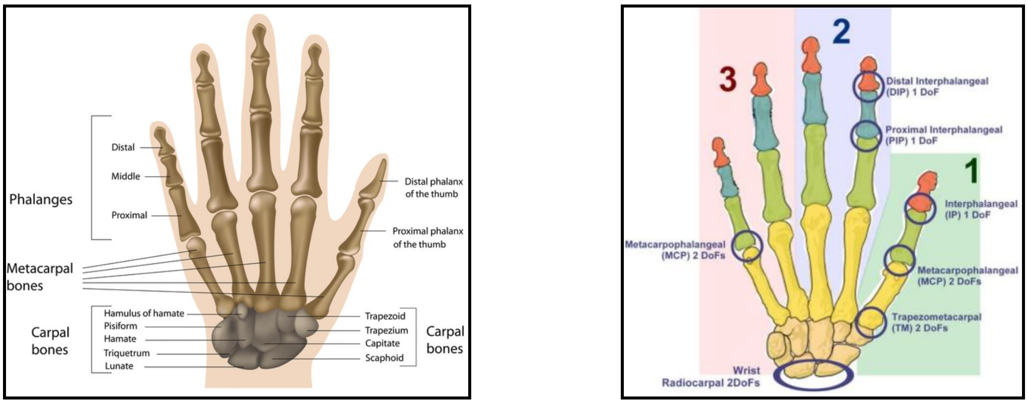
**Corresponding author: jumadi@uthm.edu.my* gaining an overview of the current status of prosthetic hands, highlighting its cost-effectiveness, challenges, strengths, and weaknesses is essential for designing new and improved prosthetic solutions.

2. Overview

The human hand is a sophisticated fusion of musculoskeletal, sensory, and control elements, playing a central role in daily activities. Moreover, the human hand is made up of many parts such as bones, muscles, strings (ligaments), wires (nerves), and tubes (arteries) [3]–[5]. People usually have around 27 bones in their hand, but it can be a little different for each person. There are also more than 30 different muscles and over 100 strings, wires, and tubes that all work together to make the hand able to move and perform different tasks. Figure 1(a) illustrates the intricate anatomy of the human hand, offering insights into the intricate interplay between its various components. This visual representation provides a valuable reference for researchers, designers, and engineers in their quest to develop prosthetic solutions that closely emulate the natural capabilities of the human hand.



(a) Anatomy of Human Hand [3].

(b) Degrees of freedom of the wrist and fingers joints [5]

Fig. 1 - Human hand

Replicating the natural movement capabilities of human limbs presents a significant challenge in the realization of prosthetic hands [6]. This challenge is closely tied to the concept of "degree of freedom," which refers to the smallest set of independent variables required to describe the position or motion of a system. For instance, a human finger possesses a total of four degrees of freedom. These degrees of freedom originate from the rotational movements occurring at various joints, specifically, the Distal Interphalangeal (DIP), Proximal Interphalangeal (PIP), and Metacarpophalangeal (MCP) joints, as illustrated in Fig. 1(b). These joints work together to make the finger bend and straighten smoothly. Furthermore, the knuckle, known as the MCP joint, permits additional movements such as abduction and adduction. This translates to the ability to wiggle the finger from side to side. The mechanics of the human hand reveal a remarkable interplay between biomechanics and neural control. The way our hand functions involves a complex neural network that orchestrates the activation of muscles and the coordination of joint movements.

Hence, to design a versatile prosthetic hand, there are at least seven (7) important factors must be considered. Firstly, an understanding of how the natural hand moves is essential, involving the study of biomechanics and natural movements. Replicating this flexibility in a prosthetic hand is crucial. Secondly, the focus should be on making the prosthetic hand adaptable for users. It should allow users to perform everyday tasks naturally and efficiently. This requires a design that is user-friendly and easy to learn. Thirdly, the incorporation of sensors and feedback mechanisms is important. These devices provide users with a sense of touch and orientation, making the movements of the prosthetic hand feel more realistic and intuitive. Fourthly, a solution needs to be found to connect the prosthetic hand to the user's nerves for control. This is a complex process that aims to mimic the brain's communication with the hand. Fifth, customization is key where everyone's needs and preferences are different. The prosthetic hand should be designed to be personalized while still functioning well. Sixth, the materials and engineering of the prosthetic hand are vital. It should be both sturdy and flexible, using durable materials that allow for smooth movement. Seventh, advanced technology is necessary to enable the prosthetic hand to move effectively. It should be lightweight, energy-efficient, and strong enough to perform tasks like a real hand. More discussion on the challenges in designing the prosthetic hand are have been discussed in [6]–[8].

Numerous design approaches exist for prosthetic hands. Table 1 outlines different design method with the principles, challenges, and innovations of each method. Every approach has its own benefits and trade-offs, and the chosen method relies on the user's needs, preferences, and technological limits, as well as the prosthetic design team's considerations. When opting for a design approach, factors including functionality, comfort, appearance, control methods, user input, and cost must be carefully weighed.

Table 1 - Different approaches to design the prosthetic hand design

Design Method	Strengths	Weaknesses
Bio-Inspired Design [9]–[11]	• Highly natural and human-like movement and appearance. • Mimics the biomechanics and functionality of real hands. • Can provide a sense of embodiment and familiarity to users.	• Complex design and engineering challenges to replicate biological systems. • Limited adaptability for unique user needs. • Potential difficulty in providing precise and fine motor control.
3D Printing and Open Source [12]–[14]	• Cost-effective and customizable designs. • Rapid prototyping and iteration. • Wide accessibility due to open-source nature.	• Lack of durability compared to traditional materials. • Limited availability of advanced features or high-tech components. • Customization may require technical skills.
Neural Interface and Brain-Controlled [15]	• Direct and intuitive control through neural signals. • Potential for seamless integration with user's intentions. • Can provide advanced degrees of freedom in movement.	• Complex signal processing and calibration. • Relies on accurate interpretation of brain signals. • Requires surgical implantation and ongoing maintenance.
Exoskeleton-Assisted Design [16], [17]	• Enhanced strength and dexterity. • Can assist with lifting and carrying heavy objects. • Potential for increased stability and balance.	• Bulkier and less discreet compared to standalone prosthetics. • Coordination between prosthetic hand and exoskeleton may be challenging. • May require additional training for users to master control.
Anthropomorphic Design [18]	• Emotional and social acceptance due to realistic appearance. • May facilitate a stronger sense of body image. • Potential for improved integration into daily life.	• Higher complexity in design and fabrication. • Realistic appearance may not necessarily translate to improved functionality. • May not address specific functional needs of all users.
Muscle-Driven Design [19]	• Utilizes natural muscle contractions for control. • Intuitive and proportional control based on user's intent. • Can provide multi-degree-of-freedom movement.	• Requires reliable and consistent muscle signals. • Limited range of motion and fine motor control. • Training and adaptation period needed for optimal control.
Modular and Customizable Design [20], [21]	• Adaptable to various user needs and preferences. • Components can be easily	• Modular components may introduce potential points of failure.

	replaced or upgraded. • Enables user-specific adjustments for comfort and fit.	• Additional complexity in assembly and maintenance. • Customization may lead to higher costs.
Haptic Feedback and Sensory Integration [22]	• Enhanced interaction with the environment and objects. • Improved grasping and manipulation through sensory feedback. • Greater awareness of hand position and force exertion.	• Technical challenges in creating realistic and reliable sensory feedback. • Integration of sensors and actuators can add complexity. • Potential for sensory overload or confusion.
Soft Robotics Design [23]–[25]	• Flexible and adaptive movement similar to biological tissue. • Improved safety and comfort during interactions. • Potential for natural grasping and object manipulation.	• Limited strength and durability compared to rigid designs. • Complexity in controlling soft materials. • May not provide sufficient support for heavy loads.
Hybrid Biomechanical Design [26]–[29]	• Combines benefits of mechanical engineering and biological insights. • Natural and functional movement while maintaining robustness. • Potential for realistic appearance and advanced control.	• Complex integration of biological and mechanical components. • Potential challenges in maintaining balance between form and function. • May require advanced manufacturing techniques.
Nanotechnology and Advanced Materials [30]	• Enhanced strength, durability, and responsiveness. • Potential for lightweight and compact designs. • Improved mechanical properties for better performance.	• Technologically advanced materials may be costly. • Requires expertise in materials science and fabrication. • Biocompatibility and long-term effects of nanomaterials may need consideration.

It is worth to highlight the cutting edge of the existing prosthetic hand in term of cost-effective. [31] presented and highlights the current prosthetic hand based on the region with the price as depicted in Table 2. The table provides an insightful overview of the diverse landscape of prosthetic models, reflecting varying price points, regional availability, and technological advancements. It demonstrates the commitment to providing accessible and innovative solutions for individuals seeking prosthetic hand options worldwide. The "TrueLimb" prosthetic hand stands out as one of the most affordable options, priced at less than $10,000. This lower cost makes it a potentially attractive choice for individuals seeking a functional prosthetic hand without an exorbitant price tag. Its affordability may be particularly beneficial for those with budget constraints or limited access to healthcare resources. While being cost-effective, the "TrueLimb" still offers the potential to significantly enhance the quality of life and functionality for users. On the other hand, several prosthetic hand models fall within the category of "More than $50,000," making them some of the most expensive options available. These models include the "Atom Touch," "i-Limb Ultra & Quantum," "LUKE Arm," "Michelangelo Hand," and "TASKA Hand."

Table 2 - Sophisticated prosthetic hand with the price

No	Prosthetic Hand	Price Category (USD)	Current Availability
1	TrueLimb [32]	Less than $10,000	USA, Canada
2	Grippy [33]	$10,000 to $20,000	India

3	KalArm [34]	$10,000 to $20,000	India
4	Hero Arm [35]	$10,000 to $20,000	USA, UK, Europe, Australia, New Zealand
5	OHand 2-Channel [36]	$10,000 to $20,000	China
6	Manifesto Hand [37]	$10,000 to $20,000	India, France, UAE, Malaysia, South Africa, African countries
7	OHand 8-Channel [36]	$20,000 to $30,000	China (launch date unknown)
8	Ability Hand [38]	$20,000 to $30,000	USA
9	BrainRobotics Hand [38]	$20,000 to $30,000	USA (launch date 2021/2022)
10	Nexus Hand [39]	$20,000 to $30,000	Global (now in 24 countries)
11	Zeus Hand [40]	$20,000 to $30,000	USA, Europe, Russia, India
12	MeHandB [41]	$20,000 to $30,000	Russia, Germany, CIS countries (launch date unknown)
13	Bebionic Hand [42]	$30,000 to $40,000	Global
14	Adam’s Hand [43]	$30,000 to $40,000	Italy Q1 2022, USA, Germany, France, Spain later in 2022
15	MeHandA [44]	$30,000 to $40,000	Russia, Germany, CIS countries
16	Vincent Evolution [45]	$30,000 to $40,000	USA, Europe, Russia
17	i-Limb Access [46]	$40,000 to $50,000	Global
18	Atom Touch [46]	More than $50,000	USA (launch date 2024)
19	i-Limb Ultra & Quantum [47]	More than $50,000	Global
20	LUKE Arm [48]	More than $50,000	USA
21	Michelangelo Hand [49]	More than $50,000	Global
22	TASKA Hand[50]	More than $50,000	USA, UK, Europe, Scandinavia, Canada, Australia, New Zealand

On the other hand, comparatively, Table 3 provide much lower prosthetic hand with more affordable price. It serves as a valuable resource for individuals seeking prosthetic hand options based on their budget and functional requirements, showcasing a wide spectrum of choices catering to different needs and preferences. Starting with affordability, we have the E-Nable Phoenix Hand and the Printable Prosthetics collection. The E-Nable Phoenix Hand, priced at an astonishingly low $20 - $100, is designed with children in mind, combining practicality and cost-effectiveness. On the other hand, the Printable Prosthetics series, ranging from $30 to $200, provides a variety of designs, catering to diverse preferences. At the other end of the spectrum, we encounter the epitome of prosthetic technology – the Ottobock Bebionic Hand and the Touch Bionics i-Limb Hand. These advanced marvels command a premium, with a price range of $15,000 - $20,000. These prosthetic hands epitomize the fusion of intricate myoelectric technology and precise control, offering unparalleled functionality and natural movement. In essence, the world of prosthetic hands spans from remarkable affordability, enabling access to functionality, to the pinnacle of sophistication, redefining the boundaries of what's possible. From the E-Nable Phoenix Hand to the Ottobock Bebionic Hand and Touch Bionics i-Limb Hand, these prosthetics cater to a wide range of individuals, each delivering a unique blend of restoration and empowerment. Note that the different costs between Table 2 and Table 3 associated with prosthetic hand designs reflect a combination of technology, features, materials, customization, research, regulatory compliance, and brand factors. Users should carefully consider their individual needs, priorities, and budget constraints when choosing a prosthetic hand that best meets their requirements.

Table 3 - Lower price prosthetic hand

No	Prosthetic Hand	Price Category (USD)	Current Availability
1	E-Nable Phoenix Hand [51]	$20 - $100	3D-printed hand design for children
2	Printable Prosthetics [52]	$30 - $200	Variety of 3D-printable prosthetic hand designs

3	Cyborg Beast [53]	\$50 - \$200	Open-source 3D-printed hand with functional design
4	Enabling The Future Raptor [54]	\$50 - \$200	Open-source 3D-printed prosthetic hand with various designs
5	3D Universe Hand [55]	\$100 - \$300	Customizable 3D-printed prosthetic hand
6	Flexy-Hand [55]	\$100 - \$300	3D-printed, economical, and functional prosthetic hand
7	Limbitless 3D-Printed Hand [56]	\$100 - \$500	Customizable 3D-printed prosthetic hand for children and adults
8	Raptor Hand [54]	\$150 - \$250	Open-source 3D-printed and assembled design
9	UnLimbited Arm [57]	\$150 - \$300	Affordable and customizable prosthetic arm
10	Bionico Hand [58]	\$150 - \$300	3D-printed prosthetic hand with multi-grip functionality
11	Exiii HACKberry Hand [59]	\$300 - \$400	Open-source 3D-printed hand with modern design
12	Dextrus Hand [60]	\$300 - \$600	Robotic hand with adaptable grip and control
13	OpenBionics Ada Hand [61]	\$500 - \$600	Open-source robotic hand DIY kit, affordable access
14	Handiii [62]	\$500 - \$1000	Smartphone-controlled hand prosthetic
15	Youbionic Hand [63]	\$900 - \$1000	Modular 3D-printed hand kit with customization
16	UNYQ Align [64]	\$1000 - \$1500	Customizable prosthetic covers for personalized aesthetics
17	Bionic Glove [65]	\$1000 - \$2000	Assistive glove with powered finger movement
18	ProDigits [66]	\$3000 - \$5000	Individual finger prosthetics with high dexterity
19	Naked Prosthetics MCPDriver [67]	\$4000 - \$6000	Finger prosthetics for partial hand amputations
20	Ottobock Bebionic Hand [68]	\$15,000 - \$20,000	Advanced myoelectric hand with lifelike movement
21	Touch Bionics i-Limb Hand [69]	\$15,000 - \$20,000	Multi-articulating myoelectric hand with precision control

As indicated in Table 3, the listed prosthetic hands have been produced using 3D printers such as the Creality Ender Series and Ultimaker. A notable and pivotal advantage of 3D printing in the domain of prosthetic hand design is its inherent capacity for customization. Unlike conventional manufacturing techniques, which frequently yield standardized prosthetics, 3D printing facilitates the precise tailoring of each prosthetic hand to conform to the distinctive anatomical structure and functional necessities of the individual user. 3D printing also offers other significant benefits, encompassing cost-effectiveness, lightweight construction, long-lasting attributes, and simplified replacement of hand prostheses [70]. However, it is important to acknowledge that certain drawbacks are associated with 3D printing, such as potential durability concerns and the intricacy of capturing fundamental underlying tissue characteristics while simultaneously capturing the surface topography of the limb [71]. A comparative study of 3D printing can be found in [72]. The InMoov project serves as an illustrative example when contemplating the use of 3D printing technology. This initiative, which is self-funded, harnesses 3D printing to fabricate lifelike humanoid robot components. Notably, the InMoov hand, a robotic prototype boasting 36 distinct components and 17 degrees of freedom (DOFs), closely mirrors the intricate structure of a human hand [73]. This project operates as an open-source endeavour, imparting comprehensive mechanical design insights for the 3D printing of robotic body components. It is worth noting that the InMoov hand's features can be enhanced by implementing an Internet of Thind (IoT) approach, as demonstrated in [74] and [75].

The paper has provided a concise overview of the methodology employed, detailing its challenges, advantages, and disadvantages in achieving the realization of a prosthetic hand. This critical essence serves as a foundation for contemplating the development of a cost-effective prosthetic hand. Accordingly, the primary objective of this research is the creation of a prosthetic hand tailored for amputees. The central focus is on the creation of a practical controller, utilizing EMG sensors, and the careful selection of appropriate underactuated finger mechanisms. This combined approach ensures optimal functionality during the gripping and releasing of objects. Moreover, the research endeavors to identify a motor that aligns well with the actuation requirements, thereby enabling precise and natural hand movements. Leveraging the merits of 3D printing technology, acknowledged as a highly efficient means of producing affordable prosthetics, constitutes an integral aspect of this endeavor. By synergizing practical controller design, suitable motor actuation, and the advantages of 3D printing, the research aspires to culminate in a prosthetic hand solution that is both cost-effective and fully functional. This research endeavors to enhance the independence and overall quality of life for individuals who have experienced limb loss.

3. Method

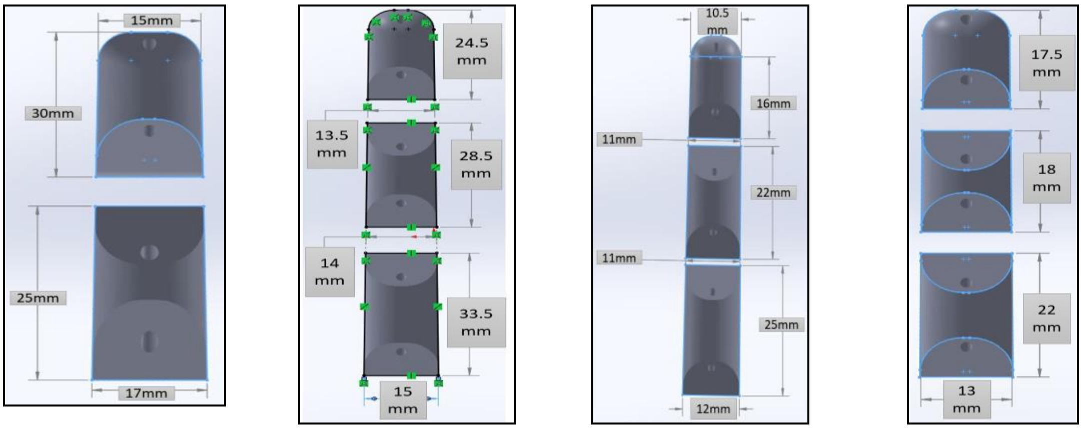
The convergence of mechanical, electrical, and software elements in prosthetic hand development is essential for crafting a device that closely resembles and replicates the capabilities of a human hand. The challenge lies in mimicking the complexity of human hand movements. The mechanical part needs to replicate the joints, tendons, and muscles of a hand to achieve lifelike motions. The electrical aspect powers the hand and connects it to sensors that interpret signals from the user's body. These signals then get translated by software algorithms into specific hand movements. Hence, making the prosthetic hand move realistically, like a genuine human hand, is a demanding yet fascinating endeavor that holds great potential.

3.1 Electrical Requirement

The development of prosthetic hands has seen a shift from basic mechanical forms to intricate devices replicating the actions of natural hands. Achieving this complexity necessitates seamless coordination, a role fulfilled by electrical design. The system employs MG995R servo motors for actuation, offering rotation of up to 180 degrees. These motors possess suitable size, weight, and torque to manipulate the prosthetic hand's fingers. Their accuracy impacts finger control due to minimal movement of artificial tendons. While pricier servos would enhance strength and precision, cost considerations led to the use of affordable options. The Arduino Nano, a compact, versatile microcontroller based on ATmega328p, serves as the system's central computer. With 16KB or 32KB flash memory, it supports program storage, complemented by 2KB SRAM and 1KB EEPROM. Electromyography (EMG) sensors measure muscle activity, with the Muscle Sensor v3 offering muscle-controlled interfaces by transforming electrical impulses into readable analog signals. For power, the system relies on its own source, utilizing 3 9V batteries for servo motors and EMG sensing boards. Circuit design employed Proteus software for simulation and PCB design, bridging theoretical and practical stages seamlessly.

3.2 Mechanical Requirement

The SolidWorks software is used in this project for modeling solid mechanical components and assemblies. Figure 2 to Fig. 5 depict the design measurements of the prosthetic hand based on SolidWorks. These measurements specifically include for the thumb, middle, index, ring, and small fingers. An underactuated mechanism is applied to the prosthetic hand. This allows objects to be grasped in a more natural and comparable manner to that of the human hand. The geometric configuration of the finger is defined automatically by external limitations relating to the object's form and does not necessitate coordinated actions of numerous phalanges.



(a) Thumb Finger (b) Middle Finger (c) Index Finger (d) Ring/Small Fingers

Fig. 2 - Fingers measurement of the prosthetic hand

The tendon locking point is necessary because when the tendon is tense, it pulls the tip of the finger and rotates all joints. If the tendon did not lock, when tensioned, it would simply slip, and the finger would not move. Tension is applied to the other end of the tendon to open the finger from its closed posture. Each finger is made up of three separate printed components connected by elastic cord (except the thumb is made up of two separate printed components). To produce a tendon locking point, the artificial tendon coils throughout the finger. This tendon forms an enclosed loop by running through channels within the finger. Rotational forces are delivered to all joints when the tendon is pulled, and the finger curls up. Figure 3(a) shows the example curl of the finger. The torque required on the finger to initiate grip greatly outweighs the gripping force produced, a technical difficulty in the design of the prosthetic hand. These complete fingers are then attached to the palm as seen in Figure 3(b).

(a) Example of curl of the index finger

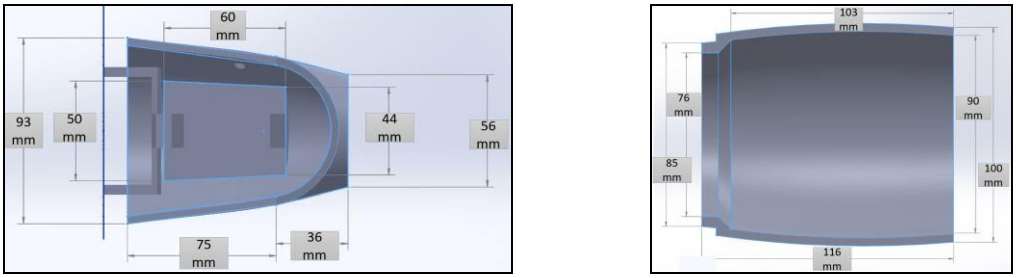
(b) Design of the Palm

Fig. 3 - Finger and palm are attached together

For the proposed prosthetic hand design to be fully realized, it is crucial to establish a secure attachment to the user's arm, which consists of two distinct areas: the lower armpiece and the upper armpiece. The seamless integration of these segments, along with the fingers and palm, forms a complete prosthetic hand assembly. Precise measurements for both the lower and upper armpiece are depicted in Fig. 4, ensuring an accurate fit for the prosthetic attachment. Additionally, detailed measurements for the cover armpiece, including length and circumference, are provided in Fig. 5, essential for crafting a personalized prosthetic hand that perfectly aligns with the individual user's arm dimensions.

The successful integration of the prosthetic hand with the user's arm is a critical aspect of the design process. A proper fit and secure attachment are essential to ensure that the prosthetic hand remains comfortable and stable during use, allowing the user to effortlessly control and operate the device. By meticulously considering individual arm measurements, the prosthetic hand can be fully realized, offering a functional and empowering solution for individuals with limb loss. The cohesive integration of the lower and upper arms, fingers, and palm results in an effective prosthetic hand system, significantly enhancing the user's overall quality of life and enabling them to perform daily activities with confidence and independence.

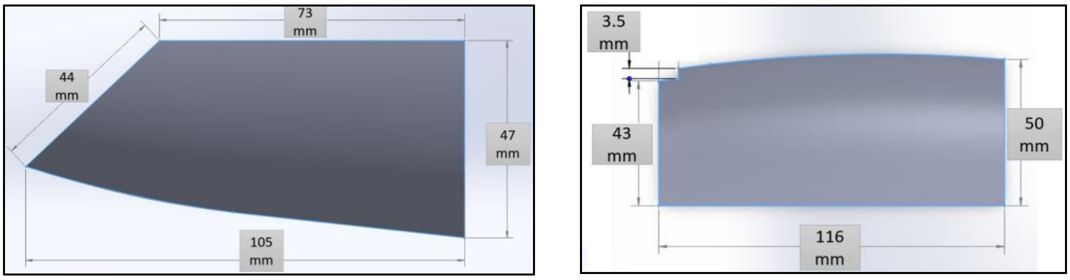
Once the designs for the fingers and palm are finalized, the next step involves assembling the different components, such as electrical components, fishing lines, and elastic cords. Each finger consists of three independent parts (except the thumb, which has only 2 segments) connected by tendons, utilizing fishing lines and elastic cords. These tendons will then be linked to the palm. The fishing line will be tied to the servo motors located at the armpiece, where the circuit is situated. On the other hand, the elastic cord will be secured to the palm after passing through the finger phalanges. The input for this project relies on EMG (Electromyography) muscle sensors, which detect muscle signals from the user. An Arduino nano serves as the control device, interpreting the EMG signals and sending corresponding commands to the servo motors. The servo motors, in turn, move the prosthetic hand, enabling the hand to mimic the user's intended movements based on their muscle activity. This integrated system allows for an interactive and functional prosthetic hand controlled by the user's muscle signals.



(a) Lower Armpiece

(b) Upper Armpiece

Fig. 4 - Measurement of lower and upper arm



(a) Cover for Lower Armpiece (b) Cover for Upper Armpiece

Fig. 5 - Measurement of lower and upper arm cover

3.3 Software/Coding

Using the Arduino IDE program, uploading the Arduino code to the board becomes a seamless process. The availability of the user-friendly and open-source Arduino software greatly simplifies the task of writing code and uploading it to the board, making it accessible to developers and enthusiasts alike. This versatility allows for smooth integration between the Proteus simulation and the Arduino nano, both of which played a vital role in the successful development of the prosthetic hand. In Fig. 6, a visual representation of the code used in this research is showcased, offering insights into the intricacies of the programming that drive the prosthetic hand's functionality. This code is the backbone of the device, coordinating the interaction between the electrical components and ensuring the precise movements and responses of the prosthetic hand.

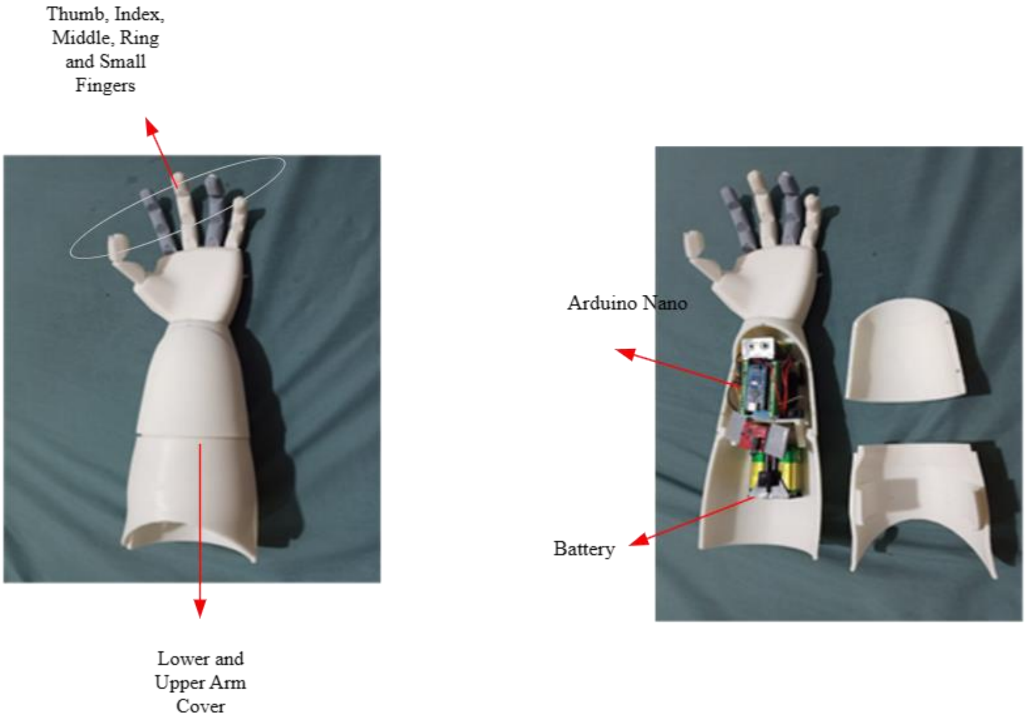
```
#include <Servo.h>
//The threshold can be set according to the maximum and
minimum values
of the muscle sensor.
#define THRESHOLD 160
//Pin number where the sensor is connected. (Analog 0)
#define EMG_PIN 0
#define SERVO_one 8
#define SERVO_two 9
//Define Servo motor
Servo SERVO_1,SERVO_2;
void setup(){
Serial.begin(9600);
SERVO_1.attach(SERVO_one);
SERVO_2.attach(SERVO_two);
}
void loop(){
//The "Value" variable reads the value from the analog
pin to which the sensor is connected.
int value = analogRead(EMG_PIN);
//If the sensor value is GREATER than the
THRESHOLD, the servo motor
will turn to 180 degrees.
if(value > THRESHOLD){
SERVO_1.write(180);
SERVO_2.write(180);
}
//If the sensor is LESS than the
THRESHOLD, the servo motor will turn
to 0 degrees.
else{
SERVO_1.write(0);
SERVO_2.write(0);
}
//Use serial monitor to set THRESHOLD
properly, comparing the values
shown when open and close the hand.
Serial.println(value);
                                }
```

Fig. 6 - Arduino coding

4. Results Analysis

4.1 The 3D Printed of the Prosthetic Hand

A HALOT-ONE Resin 3D Printer was utilized to create all mechanical parts. The final product of the 3D printed prosthetic hand is visually presented in Fig. 7, showcasing both the outside and inside views of the hand's design. Figure 7(a) provides an external view of the complete set of the proposed prosthetic hand. This view highlights the hand's appearance, displaying its intricate design and attention to detail, giving the prosthetic hand a realistic and natural look. On the other hand, Fig. 7(b) offers an inside view, revealing the internal components and mechanisms that enable the hand's functionality. This view provides a glimpse of the underactuated mechanism, the elastic tendons, and the servo motors that work in harmony to produce the hand's lifelike finger movements.



(a) Outside View (b) Inside View

Fig. 7 - Prototype of the prosthetic hand

The assembly process of this prosthetic hand was a challenging task, involving the use of various tools and techniques. To ensure a flawless final product, sandpaper was employed to meticulously remove any imperfections that might have been exposed during the finishing stage, resulting in a polished and refined appearance. The successful assembly of this prosthetic hand required a combination of precision and perseverance. Tensioning the tendons demanded precise adjustments to achieve the optimal balance between flexibility and control. Threading the tendon lines through their guide holes was a meticulous process, requiring careful attention to ensure smooth and unobstructed movements. Fine-tuning the servo/finger movements was another critical step, ensuring that the hand responded accurately to the user's commands.

4.2 Prosthetic Hand Grasping Analysis

The hardware circuit was tested with servo motor MG996R, EMG muscle sensor and an Arduino nano. This shows that the simulation and coding were efficient and that they can be combined for the next step. The sensor's detection value was proven to be suitable for EMG sensors to record the movement of muscles or muscle activity through measurements. However, the sensor's threshold will be modified accordingly for testing on people with disabilities. Figure 8 shows the hardware test on grasping objects. The Arduino nano is fitted onto the servo motors together with the sensor board and other circuitry. The component is then merged and soldered by wires and zip ties to keep the wires tidy and components in place. To allow stability, strong glue, double side tape and shrinking tube are also used to solidify the component from moving around and prevent the wires from being loose. The fingers move rather naturally and without any effort. Servo control, friction between moving plastic parts, the tension of the tendon fibers, and other factors all affect how smoothly fingers move. It is important to note that the grasping analysis in this study does not take into account the pressure applied to the objects during grasping as the force sensor was not installed on the prosthetic hand. Therefore, to ensure a safe grasp without damaging the objects, it is essential to carefully select the desired angle for the object to be grasped.

The grasping analysis showed that the ring and small finger are good at opening and closing. The middle finger does not close entirely or as smoothly as they should. This is because the tendons of the are longer than the other finger when connected to the servo, forcing it to work hard to move both fingers at once. The tiny finger's tendons do not need to move as far to open and close the finger because it is scales smaller than the index finger. The small and thumb fingers are fluid in motion because the tendon is activated in an ideal way.

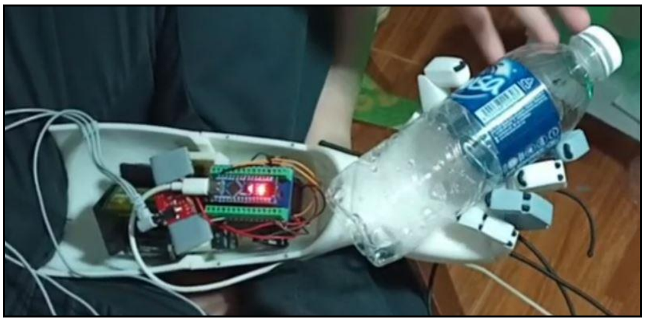


Fig. 8 - Prosthetic hand test

The result of the hand design was as expected. There is still some improvement needed for the design such as the hole for lines to be inserted through the fingers and through the palm. The size of fingers also can be adjusted for better movement and gripping of object. Because the thumb and index finger do not touch appropriately, the precision grip cannot be used for tiny objects. The phalanges of the individual fingers clash before the finger are fully bent, and complete flexion of the fingers is not feasible. Hence, addressing the issue of phalanges clashing and improving finger flexion requires a combination of design iteration, mechanical adjustments, and innovative solutions.

4.3 Improvement of Prosthetic Hand

To resolve the clashing phalanges issue, there are several potential approaches to enhance hand flexibility and achieve more natural finger movements. First, refining the lengths of individual finger components can prevent premature collisions between phalanges, ensuring smoother bending motions. Second, redesigning finger joints to allow a broader range of motion while avoiding early clashes can result in improved flexibility. Proper clearances and angles in joints can facilitate a more natural bending sequence. Third, the choice of flexible materials can enhance the hand's ability to bend further. Using suitably elastic materials can enable smoother and gradual bending. Fourth, optimizing the routing of artificial tendons can influence finger motion and prevent collisions. Adjusting tendon paths can create controlled and fluid finger movements. Fifth, evaluating and refining the underactuated mechanism responsible for finger movements can enhance overall hand performance. This might involve modifying tendon tensioning or reconfiguring mechanics for better finger bending. Lastly, incorporating sensor feedback to detect hand position and adjust finger movements accordingly can optimize performance and avert clashes between phalanges.

4.4 Control Method

Electromyography (EMG) is used in controlling the developed prosthetic hand. EMG is a technique that involves measuring the electrical activity generated by muscles. When we move our muscles, they produce small electrical signals. EMG sensors are devices that can detect these signals from the surface of the skin. More specifically, the fundamental Boolean EMG control allowed for cycling and actuation in different states. In one stage, the finger could be open, while in another, the fingers could be close to grip object. The servo may be told to close, rotate to a specific position, rotate back, and then open again. Several small objects might be grabbed using a similar motion. However, because transitioning between the two states was necessary, using this straightforward EMG control rendered the procedure time-consuming and exhausting. Figure 9 shows the user controls the prosthetic hand's opening and closing state.

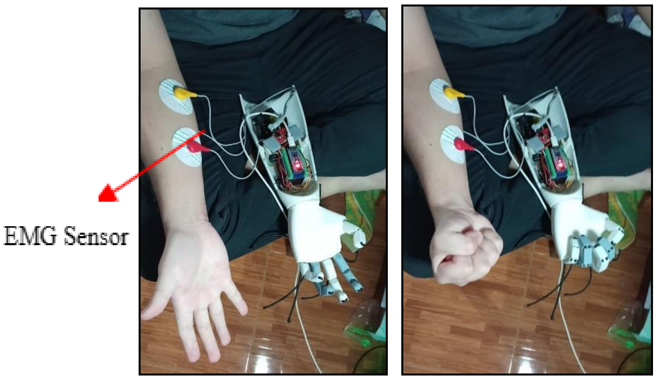


Fig. 9 - Muscle flexing by the user controls the hand's opening and closing

The fingers could be controlled proportionally; the user might increase finger closure by flexing their fingers more forcefully according to the threshold set. However, this proportional control caused the fingers to begin trembling when trying to close since the servo locations were being controlled by noise signals. The Arduino Nano includes a useful feature called an Analog to Digital Converter (ADC), which converts an analog voltage on a pin into a digital number. The Arduino's ADC is 10-bit, which means it can distinguish 1,024 (2 to the power of 10) distinct levels of analog input. The ADC reports a ratio of metric value. This means that the ADC assumes 5V is 1023 and anything less than 5V will be a ratio between 5V and 1023. Table 4 shows the analog sensor value of muscle sensor according to muscle flex intensity. Based on the provided data, we can draw the following conclusions that the average ADC value for the light muscle flex is approximately 119.150 and the corresponding average converted voltage is approximately 0.583 V. Moreover, the average ADC value for strong muscle flex is approximately 236.400 and the corresponding average converted voltage is approximately 1.155 V.

The data indicates that the ADC values and corresponding converted voltages are higher for strong muscle flex compared to light muscle flex. This suggests that the stronger the muscle flex, the higher the ADC value and voltage recorded. It is important to note that the given data consists of multiple measurements for each muscle flex scenario, and the average values have been calculated. These conclusions are based on the average values, and individual measurements may vary. Additionally, without further context, we cannot make any specific inferences about the measurement system or the significance of the recorded values.

Table 4 - Analog sensor value of muscle sensor according to muscle flex intensity

No. of output	Light muscle flex (ADC value)	Converted into voltage	Strong muscle flex (ADC value)	Converted into voltage
1.	119	0.582	251	1.227
2.	119	0.582	253	1.237
3.	119	0.582	255	1.246
4.	120	0.587	248	1.212
5.	119	0.582	237	1.158
6.	121	0.591	225	1.100
7.	121	0.591	231	1.129
8.	120	0.587	228	1.114
9.	119	0.582	243	1.188
10.	119	0.582	243	1.188
11.	119	0.582	236	1.153
12.	118	0.577	239	1.168
13.	119	0.582	237	1.158
14.	118	0.577	232	1.134
15.	119	0.582	231	1.129
16.	118	0.577	228	1.114
17.	119	0.582	232	1.134
18.	120	0.587	236	1.153
19.	119	0.582	224	1.095
20.	118	0.577	219	1.070
Average	**119.150**	**0.583**	**236.400**	**1.155**

For proportional control to function effectively, it is essential to have an EMG signal that demonstrates a linear relationship with flex intensity. The user can establish a threshold using the average data from an analog sensor value. This approach enables the user to control the servo more seamlessly based on their muscle flexing intensity. As the flex strength increases, the signal magnitude demonstrates a linear growth. Table 5 demonstrates the initial condition for each finger before grasping. The Thumb starts with 0° at Joint 1, then bends at an angle of 49° at Joint 2, and Joint 3's angle is undefined since the thumb has two degree of freedom movement. The Index finger is bending at an angle of 0° in Joint 1 for a start, followed by a bend of 21° at Joint 2, and it can bend up to 37° at Joint 3. Moving on to the Middle finger, there is no initial bend at Joint 1, but it can be bent at an angle of 33° at Joint 2, and up to 31° at Joint 3. As for the Ring finger, it exhibits no bend at Joint 1, then bends at an angle of 46° at Joint 2 and can bend up to 39° at Joint 3. Lastly, the small finger can be bent at an angle of 0° at Joint 1, 30° at Joint 2, and up to 20° at Joint 3. The Thumb has two joints that can bend (Joint 1 and Joint 2), while the Index, Middle, Ring and Small fingers have three bending joints each. Additionally, the angles of bending vary between the fingers, with the Middle finger having the lowest maximum bending angle at Joint 3 (31°) and the Thumb having the highest maximum bending angle at Joint 2 (49°).

Meanwhile, for grasping angle as shown in Table 6, each finger has its unique range of motion and bending angles at its respective joints. The Thumb can be bent at an angle of 33° at Joint 1, 101° at Joint 2. The Index finger exhibits bending angles of 75° at Joint 1, 96° at Joint 2, and 74° at Joint 3. The Middle finger can be bent at 76° at Joint 1, 87° at Joint 2, and 62° at Joint 3. The Ring finger displays bending angles of 75° at Joint 1, 88° at Joint 2, and 84° at Joint 3. The Small finger can bend at 78° at Joint 1, 60° at Joint 2, and 81° at Joint 3. Obviously, each finger has its unique range of motion and bending angles at its respective joints.

Table 5 - Initial condition (opening state)

Finger Type	Joint 1	Joint 2	Joint 3
Thumb	0°	49°	-
Index	0°	21°	37°
Middle	0°	33°	31°
Ring	0°	46°	39°
Small	0°	30°	20°

Table 6 - Grasping (closing state)

Finger Type	Joint 1	Joint 2	Joint 3
Thumb	33°	101°	-
Index	75°	96°	74°
Middle	76°	87°	62°
Ring	75°	88°	84°
Small	78°	60°	81°

4.5 Grasping Analysis for Different Objects

Figure 10 shows different objects used to test the prosthetic hand's ability to grasp. The hand is capable of successfully grabbing objects of various sizes, including a plier, screwdriver, and a phone. This test demonstrates the versatility and functionality of the prosthetic hand, as it can handle objects with different shapes and dimensions effectively.

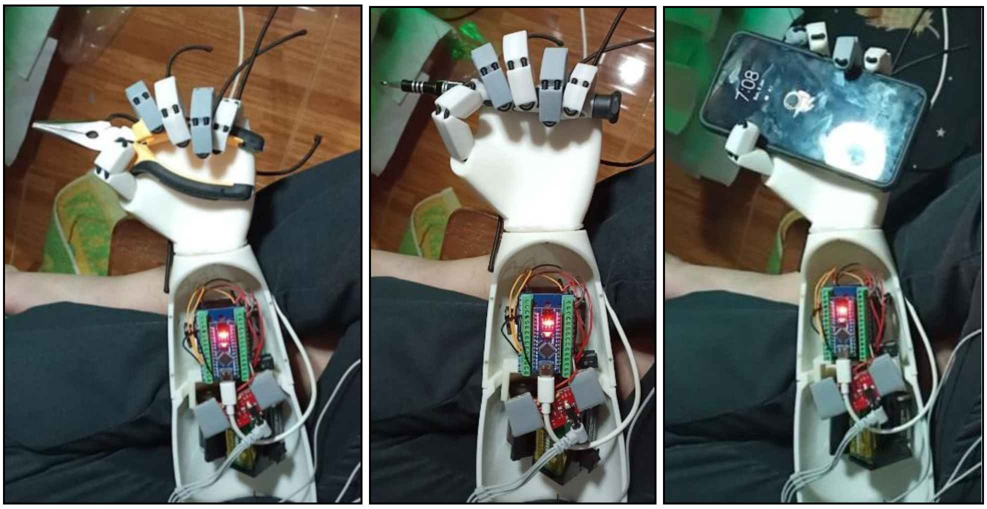


Fig. 10 - Prosthetic hand grip on different objects

Moreover, Tables 7 to 9 present the bending angles of each finger based on different grasped objects. More specifically, Table 7 demonstrates grasping angles for a screwdriver. The Thumb can be bent at an angle of 33° at Joint

1, 101° at Joint 2. The Index finger exhibits bending angles of 75° at Joint 1, 96° at Joint 2, and 74° at Joint 3. The Middle finger can be bent at 76° at Joint 1, 85° at Joint 2, and 67° at Joint 3. The Ring finger displays bending angles of 75° at Joint 1, 86° at Joint 2, and 80° at Joint 3. The Small finger can bend at 78° at Joint 1, 57° at Joint 2, and 78° at Joint 3. The fingers exhibit various degrees of flexibility at their respective joints, with the Thumb having the highest bending angle at Joint 2 (101°), and the Middle finger having the lowest bending angle at Joint 3 (67°).

Table 8 demonstrates grasping angles for a plier. The Thumb can be bent at an angle of 29° at Joint 1, 93° at Joint 2. The Index finger exhibits bending angles of 73° at Joint 1, 77° at Joint 2, and 65° at Joint 3. The Middle finger can be bent at 74° at Joint 1, 81° at Joint 2, and 70° at Joint 3. The Ring finger displays bending angles of 73° at Joint 1, 80° at Joint 2, and 70° at Joint 3. The Small finger can bend at 77° at Joint 1, 45° at Joint 2, and 73° at Joint 3. The Thumb has the highest bending angle at Joint 2 (93°), and the Small finger has the lowest bending angle at Joint 2 (45°).

Table 9 demonstrates grasping angles for a phone. The thumb demonstrates bending angles of 0° at Joint 1 and 93° at Joint 2. On the other hand, the index finger exhibits bending angles of 13° at Joint 1, 21° at Joint 2, and 87° at Joint 3. Similarly, the middle finger can be bent at 11° at Joint 1, 74° at Joint 2, and 84° at Joint 3. The ring finger displays bending angles of 13° at Joint 1, 84° at Joint 2, and 76° at Joint 3, while the small finger can bend at 9° at Joint 1, 61° at Joint 2, and 69° at Joint 3.

In conclusion, each finger exhibits a unique range of motion with different bending angles at their respective joints. The thumb possesses two bending joints, while the index, middle, ring, and small fingers have three bending joints each. These varying bending angles between the fingers and at different joints allow for a wide range of motion in the hand and fingers, enabling the hand to perform a diverse array of functions and activities.

Table 7 - Grasping screwdriver

Finger Type	Joint 1	Joint 2	Joint 3
Thumb	33°	101°	-
Index	75°	96°	74°
Middle	76°	85°	67°
Ring	75°	86°	80°
Small	78°	57°	78°

Table 8 - Grasping plier

Finger Type	Joint 1	Joint 2	Joint 3
Thumb	29°	93°	-
Index	73°	77°	65°
Middle	74°	81°	70°
Ring	73°	80°	70°
Small	77°	45°	73°

Table 9 - Grasping phone

Finger Type	Joint 1	Joint 2	Joint 3
Thumb	0°	93°	-
Index	13°	21°	87°
Middle	11°	74°	84°
Ring	13°	84°	76°
Small	9°	61°	69°

The unique bending angles in each finger are a result of the way tendons are connected via flexible cords and fishing lines to the servo motor. This design allows for a dynamic response based on the user's muscle flex and strength. When strong muscle flexion occurs, the fingers will curl according to the set threshold, and the actual bending angle will vary depending on the size and weight of the items being grasped. This adaptive mechanism ensures that the prosthetic hand can effectively grasp objects of different sizes and adapt to the user's muscle strength, providing a more natural and intuitive user experience.

4.6 Overall Cost

The complete cost of developing the prosthetic hand is detailed in Table 10. The prices of the components differ greatly; some are quite economical, like jumper wires and cable ties, while others are pricier yet still affordable, such as the electromyography sensor and 3D printer UV curable resin. The total expenditure for all listed items in the table comes to RM307.99/$66.20, a cost that is both competitive and reasonable. This amount represents the overall investment for creating the suggested prosthetic hand. Some items are available in multiple quantities, such as the 9V battery holders and MG996R servo motors, which can be beneficial for individuals or projects requiring multiple units. The affordability of this cost-effective prosthetic hand demonstrates its potential as a practical and viable solution for amputees aiming to restore their grasping functionalities. This alternative approach holds promise as an immediate intervention, offering individuals an accessible means to regain crucial hand functions and engage in a range of activities.

Table 10 - List of estimated cost exoskeleton hand project

No.	Component/Product	Qty	Unit Cost (RM)	Total Cost (RM)
1.	3D printer UV Curable Resin (1liter)	1	RM120	RM120
2.	Jumper Wire Male to Female 30cm (40 pieces)	1	RM3.20	RM3.20
3.	Elastic cord Black 3mm diameter (1 meter)	3	RM1.30	RM3.90
4.	Fishing line	1	RM4.00	RM4.00
5.	Arduino Nano V3.0 ATMEGA328P (Type-C)	1	RM25.50	RM25.50
6.	Arduino Nano I/O Pin Expansion Terminal Adapter Block Screw Shield	1	RM7.50	RM7.50
7.	9V Battery Holder with Cable	3	RM1.30	RM3.90
8.	9V Battery	3	RM2.90	RM8.70
9.	Electromyography Sensor (EMG) v3.0 Muscle Activity Monitor Kit Muscle Sensor	1	RM92.99	RM92.99
10.	MG996R Servo Motor	2	RM16.90	RM33.80
11.	Cable tie (bundle)	1	RM3.50	RM3.50
12.	Switch	2	RM0.50	RM1.00
	Total Cost		**RM307.99 / $66.20**	

5. Conclusion

The overview of the prosthetic hand development, including its costs, is essential. It sheds light on challenges and opportunities in helping amputees. By showing the development process and costs, the overview highlights both the obstacles and achievements of current prosthetic hand solutions. It also emphasizes the positive impact of innovative efforts in this field. The developed prosthetic hand incorporates an underactuated mechanism and has been successfully built and sufficiently tested. One of its most notable features is its affordability, making it an accessible solution for many individuals. The hand gripping capabilities closely resemble that of a human hand, allowing it to grasp various objects with ease. The successful integration of the underactuated mechanism, affordable materials, and common servo motors results in a prosthetic hand that exhibits a natural and functional range of movements. The device grants users the ability to accomplish daily tasks effectively, leading to increased independence and an enhanced quality of life.

Further improvements are suggested and recommended in the future such as power and voltage regulators are recommended to regulate the voltage and power provided to the servos and the microprocessor. These regulators prevent the likelihood that a servo would stall and significantly drain the battery's current. Servo motors consume a lot of current when in use. Using rechargeable lithium polymer (LiPo) batteries is better because of the high-density energy. The servo motors can rotate the tendons more by using longer servo horns, which would further increase the tension on the tendons. The theoretical finger power to grasp an object will be increased by using numerous servos to operate each finger, as well as the fingers' ability to move more smoothly and naturally. Create a separate space with a socket connection to connect to the amputee as well as a compartment for the circuit.

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