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THE EXOSKELETON HAND FOR PARALYSED FINGERS: AN OVERVIEW AND IOT BASED APPLICATION FOR PRACTICAL EXAMPLE

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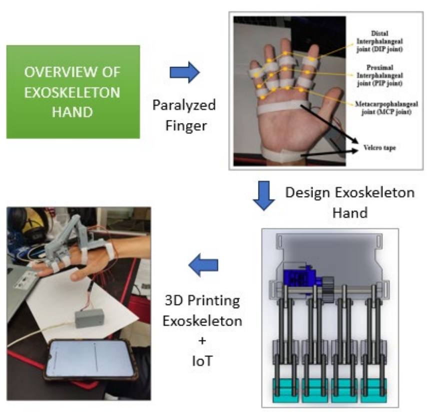

Abstract

Restoring finger mobility is crucial for overall movement recovery, particularly for individuals with paralyzed fingers, as fingers are instrumental in grasping and releasing actions. This study begins by providing an overview of the current state of exoskeleton hand technology, highlighting its strengths and weaknesses. Subsequently, it introduces a novel exoskeleton hand with integrated IoT capabilities, focusing on four fingers: the index, middle, ring, and small fingers to address paralysis. The IoT functionality is achieved using the Blynk application, allowing remote control of the exoskeleton hand via a mobile phone. Successful remote-control demonstrations showcase optimal responses during gripping and releasing motions. This study offers an efficient alternative for the rehabilitation process, empowering patients to regain control over their paralyzed fingers.

Keywords: Overview, Exoskeleton Hand, Paralysed Finger, Solidworks, 3D Printer.

1.0 INTRODUCTION

Stroke stands out as a significant global health issue, contributing significantly to disability on a worldwide scale [1]. Previous statistics [2] underscore that stroke's acute and annual mortality rates were recorded at 20%-25% and 30%-40% respectively. The data from [2] further reveals that around 20% of stroke survivors fail to regain upper limb function, while 65%-85% experience partial recovery. This underscores the importance of restoring upper-limb capabilities, prompting the need for rapid and intensive therapy. Given these concerning figures, addressing post-stroke upper limb challenges becomes imperative, necessitating innovative approaches and comprehensive rehabilitation efforts.

Moreover, post-stroke or paralyzed fingers necessitate neurorehabilitation to stimulate cortical reconfiguration, aiding motor control restoration in the affected area [3], [4]. Intensive training involving repetitive, task-specific motions has shown benefits for stroke patients, enhancing motor function recovery. Nervous system problems can lead to paralysis, as it's responsible for transmitting signals to muscles. Stroke and spinal cord injuries are the primary causes of paralysis. Stroke patients often experience flaccid paresis, evolving into hypertonia, spasticity, and finger flexor abnormalities, impairing voluntary movement control and finger extension. According to recent research [5], [6], grip force decreases by 82%, and finger extension decreases by 88% after a stroke.

This study introduces a new hand impairment solution with IoT features and provides an overview of related developments in exoskeleton hand technology. The human hand is truly remarkable, showcasing exceptional capabilities [7]. Its intricate structure and precise control enable us to seamlessly manage our daily activities [8]. However, the impact of a stroke, a widespread cause of disability, can significantly hinder the hand's functionality [9]. For individuals who have experienced a stroke, performing hand movements becomes a challenging endeavor [10]. Following a stroke, individuals often encounter difficulties in performing tasks that were once second nature. Basic activities such as gripping objects or holding a pencil can pose considerable challenges due to potential reductions in hand strength [11]. Moreover, simple actions that were previously taken for granted, like buttoning a shirt or holding a utensil, may become intricate feats.

Obviously, this loss of hand function after a stroke can have profound implications for a person's autonomy and quality of life. The frustration and sense of dependency that accompany this loss of hand dexterity can have emotional and psychological repercussions. As a result, there is a pressing need to develop effective strategies and interventions that can aid in restoring hand functionality and enhancing the overall well-being of stroke survivors. By addressing the intricate mechanics of the hand and designing targeted rehabilitation approaches, researchers and medical professionals aspire to empower stroke survivors to regain control over their essential everyday activities and regain a sense of mastery over their lives.

2.0 RELATED WORK

Various methods have been proposed by researchers [11] and [12] to address upper limb impairment caused by strokes, including Physical Therapy, Occupational Therapy, Virtual Reality and Gaming, and Robotic-Assisted Therapy or Exoskeleton Hand. This study specifically focuses on examining and presenting information about Exoskeleton Hand approaches. Within the realm of Exoskeleton Hand technology, at least seven distinct approaches have been identified. The first approach involves Robotic Exoskeletons, which are wearable devices designed to imitate the natural movements of the hand and fingers. These devices incorporate motors and sensors to aid users in performing tasks that involve gripping and fine motor control. They can offer both passive support and active training to help individuals regain hand function [13].

The second method involves Soft Robotic Exoskeletons, which differ from traditional rigid exoskeletons by employing flexible materials and air chambers for motion. This results in a more natural and lightweight solution, providing comfortable and adaptable support during rehabilitation [14], [15]. The third strategy revolves around Electromyography (EMG)-Controlled Exoskeletons, where EMG sensors pick up signals from the user's remaining hand muscles. These signals are then utilized to operate the exoskeleton, allowing users to initiate movements in their paralyzed hand based on their existing muscle activity [16]. The fourth approach delves into Brain-Computer Interface (BCI) Exoskeletons. BCI technology translates the user's intentions directly from their brain signals to control the exoskeleton. While this approach is still being developed, it shows potential for potentially restoring hand function in individuals with paralysis [17].

The fifth tactic involves Constraint-Induced Movement Therapy (CIMT) Exoskeletons. These exoskeletons limit the movement of the unaffected hand, encouraging greater utilization of the paralyzed hand. The objective is to stimulate neural pathways, enhance motor control, and improve coordination [18]. The sixth strategy integrates Virtual Reality-Assisted Exoskeletons, which combine virtual reality environments with exoskeletons to generate interactive training scenarios. Within the virtual world, users partake in tasks that promote motor recovery and bolster motivation [19]. The final approach encompasses hybrid methods, wherein multiple technologies merge within a single exoskeleton system. This could entail elements of robotic assistance and neuromuscular stimulation, resulting in a comprehensive and potentially more efficacious rehabilitation approach [20], [21].

The above-mentioned methodologies exemplify how diverse mechanisms employed in exoskeleton hand systems embody an inventive and creative approach to replicating the intricate movements of human hands. These mechanisms encompass a range of technologies, spanning from cables and linkages to flexible materials, enabling exoskeletons to mimic the inherent motions of hands in various ways. Furthermore, the capability of certain exoskeletons to execute multidirectional movements, including bending and twisting, underscores the intention to encompass the full array of hand gestures. Ultimately, the selection of a method depends on factors like an individual's specific condition, rehabilitation objectives, and the available technology. This research seeks to offer a comprehensive view of these Exoskeleton Hand approaches, contributing to the comprehension of upper limb rehabilitation for stroke survivors.

Current exoskeleton hand technologies have made significant advancements, but they still have some weaknesses and limitations. For instance, the complexity and size when designing a robotic hand exoskeleton proves challenging due to the intricacy and compact size of the human hand. The size of current actuators renders active control for each degree of freedom unfeasible. As a result, researchers focusing on building such exoskeletons must prioritize under-actuated devices. Underactuated exoskeleton fingers for example are popular due to their ability to replicate natural and energy-efficient hand movements while simplifying the design and control of the exoskeleton [22]. The concept of underactuation refers to having fewer actuators than degrees of freedom (DOFs), allowing the system to exploit passive mechanisms, such as springs or tendons, for motion. In principle, underactuated exoskeleton fingers offer advantages such as emulating natural hand movements for familiar interactions, simplifying creation and control for cost reduction, conserving energy through passive components for prolonged use, enabling smoother and more natural transitions between motions, adapting to diverse objects held for flexibility, facilitating easy control due to their innate movement patterns requiring fewer commands, enhancing safety with their gentle and secure nature to prevent harm, expediting development and testing processes for rapid building, and proving beneficial for therapeutic purposes by aiding improved movement during rehabilitation [22]–[25].

In addition to the intricacy and compact size of the human hand, the design of the exoskeleton hand needs to be compact and lightweight, fitting seamlessly into the palm while enabling natural finger movements. The ReHand portable hand exoskeleton for example [26] offers users the ability to engage in physiotherapeutic training during daily activities, aiding with ADL. It features multiple control modes, is lightweight, affordable, user-friendly, and adaptable across various rehabilitation stages. Stroke patients with impaired upper-limb motor function responded positively to the exoskeleton intervention, significantly improving hand function after 20 training sessions.

Table 1 An overview of each exoskeleton hand product/system's

No	Product/ Developer	Important Features	Design Limitations
1	WaveFlex Petre et al. [27]	• Focus on continuous passive motion (CPM) rehabilitation. • Utilizes a linkage mechanism with 1 active degree of freedom (DOF). • Driven by a DC motor.	• Limited to CPM rehabilitation. • Only 1 active DOF, which restricts functionality.
2	Gloreha Hand Borboni et al. [28]	• Serves both CPM and assistive purposes. • Cable-based force transmission system with 5 active DOFs. • Powered by an electric actuator.	• Cable-based force transmission may have limitations in force precision and durability. • Limited to 5 active DOFs.
3	Exohand Festo [29]	• Supports CPM, assistive, and replacement scenarios. • Linkage mechanism with 6 active DOFs. • Actuated using pneumatic actuators. • Incorporates torque, position, and EEG sensing methods.	• Pneumatic actuators can be bulky and noisy. • May have limitations in replicating the full dexterity of the human hand.
4	PolyU Exo. Tong et al. [30]	• Focus on CPM and active motion. • Linkage mechanism with 5 active DOFs. • Driven by linear actuators. • Utilizes EMG sensing.	• Limited to CPM and active motion, limiting versatility. • Linear actuators may have limitations in speed and agility.
5	HEXORR Schabowsky et al. [31]	• Active motion and CPM applications. • Linkage mechanism with 2 active DOFs. • Powered by brushless DC actuators. • Sensing torque and position.	• 2 active DOFs may not provide the full range of hand movements. • Brushless DC actuators can be power-hungry.
6	HANDEXOS Chiri et al. [32]	• Underactuated system with a cable and crank-slider mechanism. • Focuses on force application. • 5 active DOFs driven by a DC motor.	• Underactuated system may have limitations in fine motor control. • Focusing on force application limits versatility.
7	HIT Exo. Fu et al. [33]	• Underactuated system with a cable and crank-slider mechanism. • Focuses on force application. • 5 active DOFs driven by a DC motor.	• Similar to HANDEXOS, underactuated system limitations. • Focusing on force application might limit versatility.
8	HandSOME Brokaw et al. [34]	• Passive system without active DOFs. • Focuses on continuous passive motion (CPM). • Designed for rehabilitation purposes.	• Lack of active DOFs means it cannot provide active assistance or support.
9	TUB Exo. Wege and Hommel [35]	• Focus on active motion. • Cable and linkage system with 20 active DOFs. • Driven by DC motors. • Utilizes EMG and force sensing methods.	• 20 active DOFs may be complex to control effectively. • The device may be bulky and heavy due to the large number of DOFs.
10	IIT Exo. Iqbal et al. [36]	• Designed as an underactuated system. • Linkage mechanism with 2 active DOFs. • Driven by DC motors. • Incorporates force and position sensing methods	• 2 active DOFs may have limitations in replicating complex hand movements. • DC motors may limit speed and responsiveness.
11	iHANDRehab Li et al. [37]	• Focus on CPM and active motion. • Cable and linkage mechanisms with 8 active DOFs. • Driven by DC motors. • Utilizes angle and force sensing methods.	• Despite having 8 active DOFs, there may still be limitations in replicating the full range of hand movements. • DC motors may have limitations in speed and precision.
12	NIT Exo. Arata et al. [38]	• Focus on active motion. • Compliant mechanism with 4 active DOFs. • Actuated using linear actuators. • Incorporates EMG and force sensing methods.	• The compliant mechanism may have limitations in force and precision compared to rigid mechanisms. • Limited to 4 active DOFs.
13	HX Cempini et al. [39]	• Operates within CPM and assistive contexts. • Cable and linkage mechanisms with 7 active DOFs.	• Limited to CPM and assistive contexts, which may not cover all potential use cases.

		• Driven by DC motors. • Designed for assistive purposes.	
14	SSUP Exo Sarac et al. [40]	• Designed for assistive purposes. • Linkage mechanism with 5 active DOFs. • Actuated using linear actuators. • Incorporates force sensing.	• Primarily designed for assistive purposes, limiting its application to rehabilitation.
15	BRAVO Lambercy et al. [41]	• Focus on active motion. • Linkage mechanism with 2 active DOFs. • Driven by DC motors. • Utilizes EMG and force sensing methods.	• With only 2 active DOFs, it may have limitations in replicating complex hand movements. • DC motors may have limitations in speed and responsiveness.
16	Soft Robotic Globe Polygerinos et al. [14]	• Focus on assistive applications. • Compliant mechanism with 5 active DOFs. • Actuated using soft fiber-reinforced actuators. • Utilizes force and position sensing methods.	• The compliant mechanism may have limitations in terms of force and precision compared to rigid mechanisms.

The significance of exoskeleton hand systems as aids for individuals with hand disabilities or weaknesses remains paramount. Table 1 presents a diverse array of potential exoskeleton hand designs, focusing on essential elements such as key features, actuation methods, sensing technologies, intended applications, and notable attributes. This comprehensive reference offers valuable insights into the landscape of exoskeleton hand technology. In the selection of an exoskeleton hand, careful consideration of users' specific needs, rehabilitation objectives, and the compatibility of system attributes is vital. Utilizing advanced technology, these systems emulate human hand movements with distinct designs tailored to various functions. Despite their contributions, challenges inherent to these systems warrant thoughtful attention. Notably, Table 1 identifies existing exoskeleton hands that hold potential for enhancing design to address disabilities.

More reviews on the development of the exoskeleton hand can be found in [4], [42]–[45]. More specifically, in the review by Tran et al. [42], the authors delve into the realm of hand exoskeleton systems, clinical rehabilitation practices, and the promising avenues that lie ahead. They explore the latest developments in the field and discuss how these systems are being integrated into rehabilitation processes. This comprehensive review sheds light on the current state of hand exoskeleton technology and its potential impact on medical robotics and patient recovery. Oujamaa et al. [43] present an extensive literature review focusing on the rehabilitation of arm function after stroke. They investigate different methodologies and approaches utilized to restore arm mobility and function after a stroke. This examination provides insights into the challenges encountered in the realm of rehabilitation and gives a broad view of strategies implemented to enhance the recovery of arm motor skills.

Takeuchi and Izumi [4] provide an insightful review centered on motor recovery and rehabilitation following a stroke. They underscore the importance of neural plasticity in the recovery process and discuss the role of various interventions in facilitating the optimal restoration of motor function. The review showcases the latest discoveries in neural plasticity research and how they impact stroke rehabilitation. Chu and Patterson [44] present a narrative review that delves into soft robotic devices designed for hand rehabilitation and support. The authors explore the application of soft robotics in creating wearable devices that aid in the recovery of hand movement. This review explores the advantages of incorporating soft materials into exoskeleton designs and examines their potential to improve patient outcomes. Du Plessis et al. [45] contribute a review focused on active hand exoskeletons for rehabilitation and support. They analyze the landscape of active exoskeleton technology and its applications in assisting individuals with hand impairments. This comprehensive review offers an overview of various active exoskeleton designs, their control mechanisms, and their potential impact on rehabilitation outcomes. Taken together, these reviews offer a wealth of information about the development, applications, and implications of hand exoskeleton systems in rehabilitation and support. They cover a wide range of topics in the field, spanning from technological advancements to clinical practices, making them valuable resources for researchers, clinicians, and anyone interested in the intersection of robotics and healthcare.

Currently, the integration of Internet of Things (IoT) technology with exoskeleton hand technology provides exciting possibilities for personalized and interconnected assistive solutions [46]. Further references on IoT-based applications can be found in [47]–[49]. By incorporating IoT, remote monitoring and tele-rehabilitation become feasible, enabling healthcare professionals to access data, monitor progress, and adjust therapy in real time. This could improve therapy accessibility, particularly for those with limited physical access to specialized facilities. Moreover, exoskeleton hands are becoming more advanced with IoT. Equipped with specialized sensors, they wirelessly transmit hand movement data to computers, allowing users to control and receive feedback via devices like phones. The exoskeleton adapts its assistance based on sensor input, benefiting individuals with restricted hand movement, and enhancing remote patient therapy. However, challenges like data security, battery life, and device integration need to be addressed. In this study, we introduce an exoskeleton hand that incorporates IoT technology. Due to the intricate nature of thumb finger design, we focused on testing four fingers—index, middle, ring, and small. Importantly, our research highlights the transformative potential of IoT in revolutionizing exoskeleton hand technology, enhancing accessibility and efficiency in therapy and support applications.

Hence, the primary contributions of this research include offering an overview of the current state of exoskeleton hand technology, identifying its strengths and weaknesses, and proposing a cost-effective exoskeleton finger with integrated IoT features.

3.0 METHODOLOGY

The design of the exoskeleton phalanges draws inspiration from both the anatomy and functionality of human phalanges. The goal is to recreate and enhance the hand's capabilities for diverse practical applications [50]. Essentially, a human finger comprises three categories of phalanges: the distal phalanx, middle phalanx, and proximal phalanx. These phalanges collectively contribute to the finger's intricate mobility and agility. These attributes serve as the basis for designing the exoskeleton hand in this study.

3.1 Exoskeleton Hand Design

The practical exoskeleton hand has been meticulously crafted using the sophisticated 3D modeling software, SolidWorks. This design incorporates a series of intricate components, each skillfully created to ensure optimal functionality and performance. Figure 1 presents an in-depth view of the SolidWorks design of the Proximal Phalanx, an essential element responsible for facilitating natural hand movements. The Proximal Phalanx's intricate details have been meticulously modeled, ensuring a seamless fit within the overall exoskeleton hand structure. Meanwhile, Figure 2, realizes the Proximal Phalanx through 3D printing.

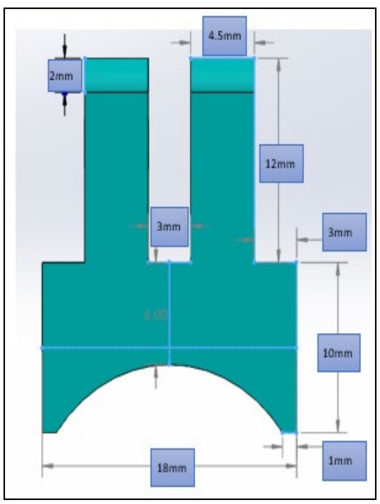

Figure 1 SolidWorks of Proximal Phalanx

Figure 2 3D Printing of Proximal Phalanx

A significant part of the exoskeleton hand, the Middle Phalanx, is unveiled in Figure 3, portrayed in all its intricate through SolidWorks. This intermediate component plays a vital role in enabling multi-joint movements and enhancing the exoskeleton's dexterity. Meanwhile, Figure 4 displays the 3D-printed version of the Middle Phalanx.

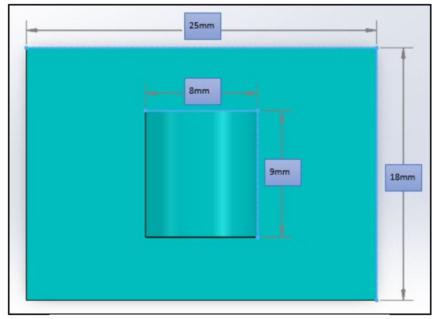

Figure 3 SolidWorks of Middle Phalanx.

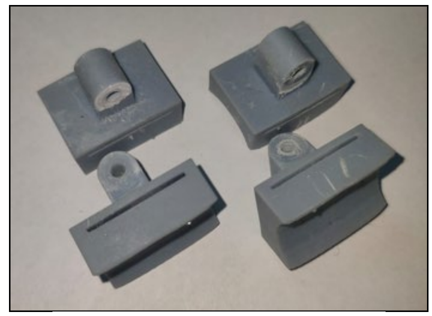

Figure 4 3D Printing of Middle Phalanx

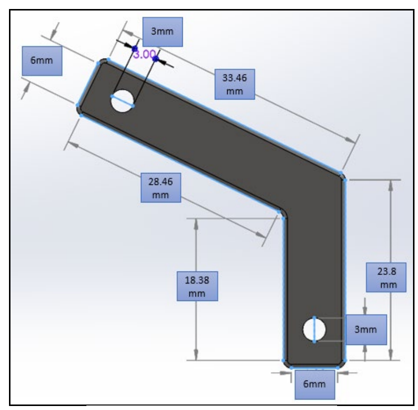

Figure 5 SolidWorks of Link 1

Figure 6 3D Printing of Link 1.

Link 1, a pivotal element in the exoskeleton hand's articulated structure, is meticulously designed in SolidWorks, as depicted in Figure 5. This component's precise dimensions and strategic placement are critical for achieving optimal hand functionality.

Meanwhile, Figure 6 allows us to witness the transformation of Link 1 from a digital model to a tangible object through 3D printing.

The next crucial component, Link 2, is presented in Figure 7. Its intricate design and careful consideration of mechanical properties ensure smooth joint movement within the exoskeleton hand. Meanwhile, Figure 8 brings Link 2 to life with its 3D-printed counterpart, offering a tangible demonstration of the component's robustness and compatibility within the larger exoskeleton hand framework.

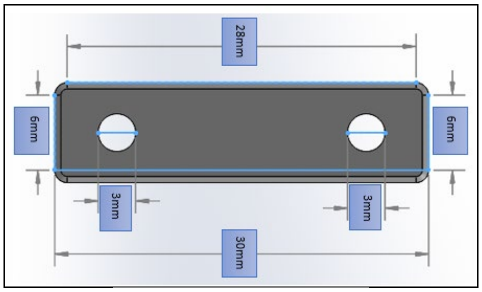

Figure 7 SolidWorks of Link 2.

Figure 8 3D Printing of Link 2.

Figure 9 and Figure 10 take center stage to exhibit the 3D printing of Link 3, a complex yet vital connection within the exoskeleton hand's intricate network. These printed models provide invaluable insights into the physical interaction between various components.

Figure 9 3D Printing of Link 3.

Figure 10 3D Printing of Link 3

Serving as the foundation for the exoskeleton hand's structure, the Base Link is meticulously crafted in Solidworks, as showcased in Figure 11. Its sturdy design ensures a stable platform for the entire hand assembly. Figure 12 on the other hand illustrates the Base Link comes to life through the process of 3D printing, solidifying its position as a crucial structural element. The physical representation highlights the successful integration of design aesthetics and engineering principles.

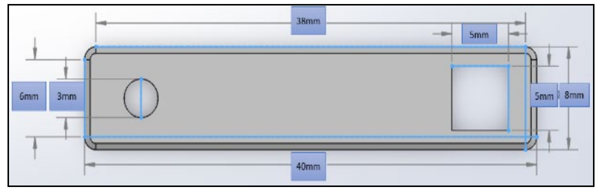

Figure 11 SolidWorks of Base Link.

Figure 12 3D Printing of Base Link.

Another significant component, the Motor Link, is meticulously designed using SolidWorks, as illustrated in Figure 13. This component is the driving force behind the exoskeleton hand's movements, delivering precision and fluidity to each gesture. When the servo motor gear is at 0 degrees, the motor link is in a specific position, and as the gear rotates towards 180 degrees, the motor link also follows suit, rotating in sync. This coordinated movement between the servo motor gear and the motor link allows for the transmission of rotational force, which is then transferred to the base link connecting rod.

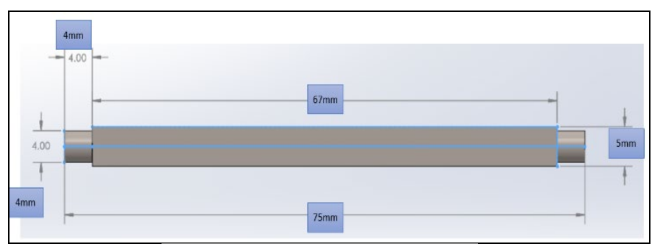

Figure 13 SolidWorks of Motor Link.

The base plate in the research serves a dual purpose: it provides a stable platform to hold the servo motor and support the motor link rod, which can rotate 360 degrees. Additionally, the base plate will be used to attach the exoskeleton hand to the back of the user's hand using Velcro tape. The Base Plate, featured in Figure 14, is strategically crafted to offer reliable support and stability for the entire exoskeleton hand. Figure 15 presents the physical embodiment of the Base Plate.

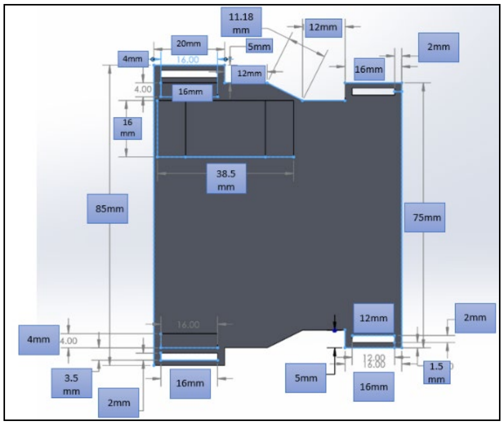

Figure 14 SolidWorks of Base Plate.

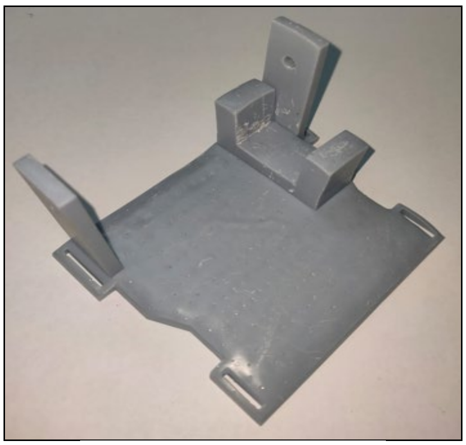
Figure 15 3D Printing of Base Plate.

Gears 35 and 15, depicted in Figure 16, epitomize the perfect synergy between SolidWorks' intricate design capabilities and 3D printing's precision manufacturing. These gears play a pivotal role in transferring motion and power throughout the hand. Meanwhile, Figure 17, depicted the 3D-printed Gear 35 and Gear 15. This gear is strategically positioned at the middle section of the motor link rod, where it forms an essential connection point. By coupling the gear to this location, it effectively translates the rotational force generated by the servo motor to the specific segment of the motor link rod, facilitating precise and controlled movements.

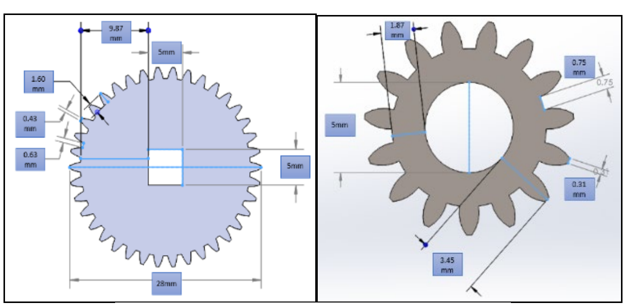
Figure 16 SolidWorks of Gear 35 and Gear 15.


Figure 17 3D Printing of Gear 35 and Gear 15.

3.2 Electrical Circuit Requirement

The MG90S Metal Geared Micro Servo is used in this project and for the actuators of the exoskeleton hand as seen in Figure 18. This micro servo is tiny and lightweight with high output power. Micro servo also can rotate approximately to 180 degrees. By using this micro servo, the exoskeleton hand can be controlled to grasp and ungrasp depending on the design of the exoskeleton hand.


Figure 18 MG90 S metal geared micro servo 180 degrees.

Figure 19 NodeMCU ESP8266 microcontroller board.

In this research, the Arduino IDE plays a vital role in programming the NodeMCU ESP8266 microcontroller board (see Figure 19). The NodeMCU ESP8266 receives the necessary code via the Arduino IDE. The servo motor is linked to the NodeMCU ESP8266 using Vin, ground, and D2 pins. The NodeMCU ESP8266 interprets the coded instructions and sends output to the servo motor. The servo motor's movement spans from 0 to 180 degrees, contingent on the code inputted into the NodeMCU through the Arduino IDE. This setup empowers users to manage the servo motor and its actions via the Blynk app on their mobile devices, allowing them to interact with and oversee the exoskeleton hand project. By modifying the code using the Arduino IDE, users can adjust the servo motor's movement and efficiently control the exoskeleton hand's gripping and releasing actions.

3.3 Coding

The following coding is used to control the servo motor using Blynk.

```
#define BLYNK_TEMPLATE_ID "TMPL1Uw8kWrE"
#define BLYNK_DEVICE_NAME "Servo Control"
#define BLYNK_AUTH_TOKEN "R5QJugfeHNQa8dT3XCyI5qLUM4i-Jyon"
#define BLYNK_PRINT Serial
#include <ESP8266WiFi.h>
#include <BlynkSimpleEsp8266.h>
#include<Servo.h>
Servo servo1;
char auth[] = BLYNK_AUTH_TOKEN;
char ssid[] = "ABCabc123456"; // Change your Wifi/ Hotspot Name
char pass[] = "abcdef123"; // Change your Wifi/ Hotspot Password
BLYNK_WRITE(V0)
{
 int s0 = param.asInt();
 servo1.write(s0);
 Blynk.virtualWrite(V5, s0);
}
void setup()
{
 Serial.begin(9600);
 servo1.attach(D2);
 Blynk.begin(auth, ssid, pass);//Splash screen delay
 delay(2000);
}
void loop()
{
 Blynk.run();
}
```

3.4 Blynk Application

Blynk is a popular Internet of Things (IoT) platform that empowers users to design and manage interconnected devices via smartphones and the internet. Within this reseach, the Blynk app is downloaded onto a mobile phone and functions as the interface for controlling a servo motor. This enables users to manipulate the motor's movements, such as gripping and releasing objects, as depicted in Figure 20.

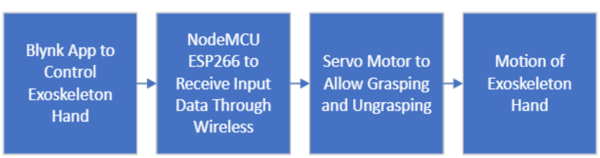

Figure 20 The Control Interface.

We use a NodeMCU ESP8266 as the brain of our research. It's programmed using the Arduino IDE and connected to the Blynk app for user input. The NodeMCU processes these inputs and controls a precise servo motor, a crucial part of the exoskeleton hand that moves accurately. The Blynk app makes operating the exoskeleton hand easy and efficient. Our research demonstrates how to control the exoskeleton hand using smartphones via Blynk, NodeMCU ESP8266, and the servo motor. The smartphone acts as a mini-computer and display for the Blynk app, allowing us to interact and control the servo motor. The NodeMCU connects to the Blynk cloud via Wi-Fi, letting it understand user commands. The Blynk app provides buttons and sliders to adjust the servo motor's angle from 0 to 180 degrees. This connection between the smartphone and NodeMCU through the Blynk app offers a simple and enjoyable way to control the servo motor.

4.0 RESULTS AND ANALYSIS

4.1 Exoskeleton Hand Assembly

Putting together the exoskeleton hand is the final step, requiring careful assembly of all the components mentioned earlier in Section 2. A visual depiction of the exoskeleton hand can be found in Figure 21. This illustration, skilfully created and assembled using SolidWorks, highlights the complex web of connections and mechanical relationships within the exoskeleton hand. To bring the exoskeleton hand from a digital design to a tangible and functional device, 3D printing technology is employed. Figure 22 portrays a 3D printing, culminating in the realization of the physical exoskeleton hand. The core components, including the servo motor, gear systems, NodeMCU (an electronic microcontroller), base plate, link 1, link 2, link 3, proximal phalanx, and middle phalanx, are meticulously interconnected to form a cohesive and functional set exoskeleton hand.

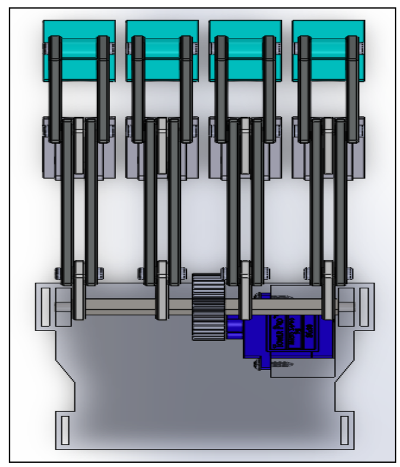

Figure 21 3D Printing of Exoskeleton Hand

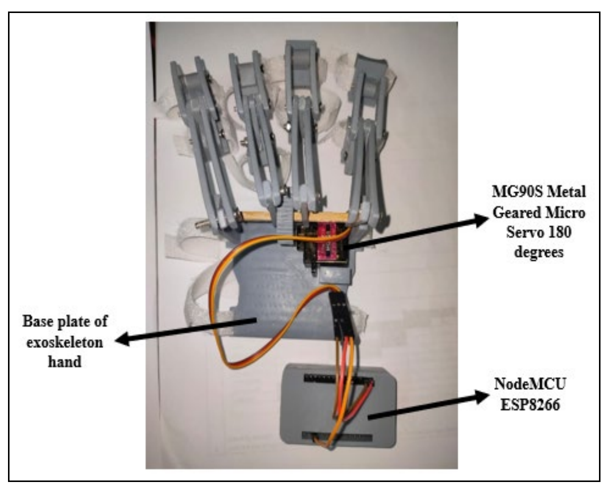

Figure 22 3D Printing of Exoskeleton Hand

Each element plays a crucial role in achieving the desired range of motion, precision, and functionality. The completion of the exoskeleton hand represents a remarkable achievement, made possible through the synergy of advanced digital design tools like SolidWorks and the transformative power of 3D printing.

4.2 Grasping Analysis

Both human phalanges and exoskeleton phalanges serve the purpose of enabling precise finger movements, but they perform in different ways. Human phalanges are part of the natural human hand structure, while exoskeleton phalanges are engineered components integrated into the exoskeleton to enhance hand capabilities for rehabilitation, assistance, or industrial applications. The design of exoskeleton phalanges is inspired by the anatomical and functional aspects of human phalanges, aiming to replicate and augment the hand's abilities for various practical uses [50]. In principle, the human finger consists of three types of phalanges: the distal phalanx, middle phalanx, and proximal phalanx. Each type of phalanx is crucial for the finger's intricate range of motion and dexterity. To analyze the joint angle for joint 1, joint 2 and joint 3 as depicted in Figure 23, a protractor is used. 0°, 90° and 180° motor rotation conditions are considered. 0° means ungrasping while 90° and 180° indicate grasping as shown in Figure 24. The variation of angles will be determined by Blynk Slider which is in this case is 0°, 90° and 180°.

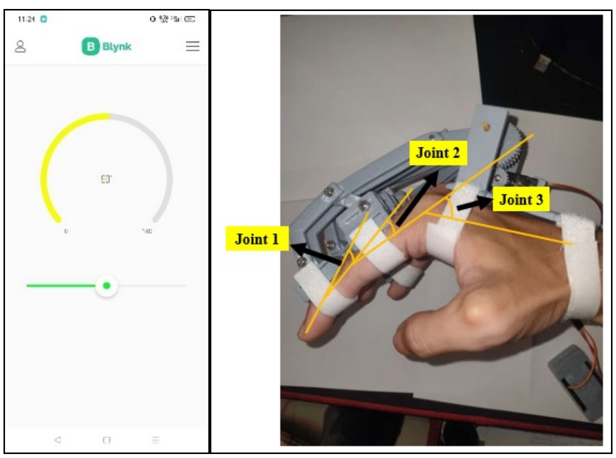

Figure 23 The analysis of joint angles for joint 1, joint 2, and joint 3 through the utilization of the Blynk Slider feature on a mobile phone.

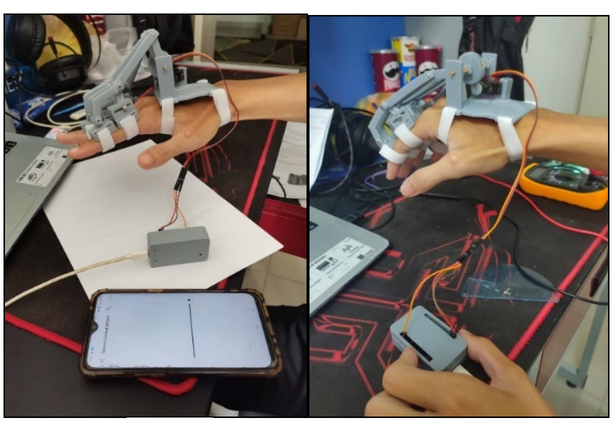

Figure 24 Ungrasping versus Grasping

Table 2 presented the angle measurements for each finger (Index, Middle, Ring, and Small) at three different joints (Joint 1, Joint 2, and Joint 3) for 90° motor rotation. These angle measurements represent the degrees of flexion or extension observed at each joint of the fingers. The significance of these angle measurements lies in their ability to provide valuable data about the mobility and flexibility of the fingers. In medical settings, such as hand therapy or rehabilitation, these measurements can help assess the health and function of the finger joints. They allow healthcare professionals to monitor progress during the recovery process and tailor treatment plans accordingly. For instance, the index finger exhibited angle measurements of 10°, 25°, and 30° at Joint 1, Joint 2, and Joint 3, respectively.

Table 2 Finger joint angle in condition servo motor rotate 90 degrees.

Finger Type	Joint 1	Joint 2	Joint 3
Index	10°	25°	30°
Middle	10°	24°	29°
Ring	10°	25°	30°
Small	10°	20°	25°

Table 3 Finger joint angle in condition servo motor rotate 180 degrees.

Finger Type	Joint 1	Joint 2	Joint 3
Index	15°	28°	60°
Middle	12°	27°	58°
Ring	14°	30°	59°
Small	10°	25°	56°

Meanwhile, when the servo motor undergoes a 180° rotation, the measurements for joint angles are documented in Table 3. A notable distinction between Table 2 and Table 3 emerges in the angle measurements for each finger joint. Upon rotating the servo motor to 180 degrees, the angles predominantly exhibit an increase compared to the 90-degree rotation scenario. For all finger types, Joint 1, Joint 2, and Joint 3 angles generally show higher values in Table 3 than in Table 2, implying a more pronounced finger flexion or extension when the servo motor reaches 180 degrees. The most substantial angle difference is observed in the Index finger at Joint 3, increasing from 30° in Table 2 to 60° in Table 3. This substantial alteration signifies a marked enhancement in finger extension when the servo motor completes a 180-degree rotation.

For further analysis, a digital multimeter is employed to measure the voltage and current at the input for each servo motor angle, as detailed in Table 4. The aim of these measurements is to delve into the electrical attributes of the system and verify that the servo motor receives the correct power supply at various angles. Based on the observations drawn from the measurements, the average input voltage is determined to be 5.002 volts, while the average current reads at 1.033 amperes. This data signifies that the power supply to the servo motor remains relatively stable, hovering around 5 volts, even as the motor rotates to 180 degrees.

Sustaining a consistent voltage input holds paramount importance for the seamless operation of the servo motor. This stability ensures that the motor maintains a dependable power source, enabling it to sustain its performance and functionality across its full range of motion. Moreover, a constant voltage supply mitigates abrupt voltage fluctuations that might potentially harm the servo motor or compromise its precision in various positions. Through the measurement and analysis of voltage and current data, the project assures the dependable and efficient operation of the servo motor, guaranteeing uniform motion and control for the exoskeleton hand research.

Table 4 Voltage and current value for each angle of servo motor.

Angles of servo motor rotate (degrees)	Voltage input	Current input
10°	5.02V	0.9A
20°	5V	0.9A
30°	5V	1A
40°	5.01V	1A
50°	5V	1A
60°	5.01V	1A
70°	5V	1A
80°	4.99V	1A
90°	5V	1A
100°	5.01V	1A
110°	5V	1.1A
120°	4.99V	1.1A
130°	4.99V	1.1A
140°	5V	1.1A
150°	5V	1.1A
160°	5V	1.1A
170°	5V	1.1A
180°	5.01V	1.1A
Average:	5.002V	1.033A

4.3 Cost

Utilizing affordable and readily available components underscores the cost-effectiveness of the proposed exoskeleton design and implementation. Table 5 provides an inventory of components along with their respective quantities and unit costs for crafting an exoskeleton hand steered by a NodeMCU ESP8266 board and a servo motor.

Table 5 Cost the exoskeleton hand project

No.	Component/Product	Quantity	Unit cost (RM)	Total cost (RM)
1.	NodeMCU ESP8266 + USB cable	1	19.70	19.70
2.	MG90S Metal Geared 180 degrees Micro Servo	1	12.80	12.80
3.	Female to male jumper wire, 10cm (40piece)	1	3.70	3.70
4.	Velcro tape (1meter)	1	2.50	2.50
5.	Flat Head Screw 8mm, 12mm, and 20mm (10pieces)	3	2.50	7.50
6.	Nuts for flat head screw (10pieces)	1	2.50	2.50
7.	3D printer UV Curable Resin (1liter)	1	120	120
	Total cost:			**RM168.70**

The collection of components detailed in the table underscore a meticulously planned endeavor aimed at fashioning a functional exoskeleton hand that can be controlled via the Blynk app on a smartphone. The amalgamation of the NodeMCU ESP8266 board, the MG90S servo motor, and mechanical fixtures such as screws and nuts, coupled with the utilization of 3D printing capabilities, showcases a holistic and inventive approach to producing a practical and user-friendly exoskeleton hand. Additionally, the presence of jumper wires emphasizes the importance of proper circuit connections and the need for seamless communication between the NodeMCU board and the servo motor for accurate and precise control of the exoskeleton hand's movements.

5.0 CONCLUSION

First, we gathered and examined a range of significant exoskeleton hand designs. These notable examples underwent a comprehensive analysis to comprehend their distinct features, functions, and advancements. This methodical exploration enriched our understanding of diverse approaches and innovations in exoskeleton hand technology.

Second, we successfully designed and produced a tailored exoskeleton hand for individuals with paralyzed fingers. This wearable device empowers users by facilitating grasping and ungrasping actions, enabling them to perform daily tasks despite finger paralysis. To create the exoskeleton hand, we utilized 3D printing with the Creality Halot-One 3D printer. This choice ensured precise customization, resulting in a comfortable fit while maintaining mechanical strength. Micro servo motors were selected as actuators, offering precise control for smooth and accurate exoskeleton hand movements. These servo motors can rotate up to 180 degrees, aligning perfectly with the required range of motion.

Third, a significant accomplishment is the successful integration of IoT into the proposed exoskeleton hand. The NodeMCU ESP8266 board played a pivotal role as the central controller. Its built-in Wi-Fi capabilities facilitated seamless communication with the Blynk app, enabling users to remotely control the servo motor for grasping and ungrasping actions. The user-friendly interface of the Blynk app elevated the overall experience, allowing intuitive interaction with the exoskeleton hand using smartphones.

To enhance the exoskeleton hand's functionality, a few recommendations are proposed for future improvements. First, the movement of the exoskeleton hand should closely mimic the natural motion of human fingers to ensure comfortable and intuitive control for users. Second, the quality and durability of the device need further enhancement. Using high-quality materials and advanced construction techniques during manufacturing will ensure the exoskeleton hand's longevity and reliability, establishing it as a dependable assistive tool for individuals with paralyzed fingers. In summary, the future direction for these recommendations involves further research and development to enhance the exoskeleton hand's design and construction, with a focus on natural motion and improved durability. This is in line with the goal of making it a more effective and reliable tool for users with paralyzed fingers.

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