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Design and Develop Motorized Soft Robotic Glove for Hand Rehabilitation

Agrisly Aban Siran[1,] **Mohamed Najib Ribuan**[1]*

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

*Corresponding Author Designation

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Abstract: Hand impairment is growing more widespread in the modern world as a result of an ageing population. The rising incidence of illnesses like stroke is putting an increasing strain on health care providers' limited financial resources and the ability of their physical therapy personnel. As a solution, this study presents the design and validation of a low-cost, customizable soft robotic hand exoskeleton for post-stroke hand rehabilitation. By integrating the same kinematic functionality as prior work on cable-actuated exoskeleton designs, the focus has switched to the simplicity of assembly and cost efficiency, allowing patients to manufacture and assemble the hardware required to perform the treatment. The prototype was subjected to motion analysis and force analysis to compare its performance with the hand in an assessment of grasping movement patterns and the force exerted on the fingertip while gripping a cup and tennis ball as an early review of the design's practicality. The findings of this study imply that the design theory is accurate. It might lead to a system that can successfully assist stroke patients through finger flexion and extension, and also allow patients to conduct rehabilitative tasks at home, lowering therapist effort while boosting patient freedom.

Keywords: Hand Impairment, Soft Robotic, Exoskeleton, Post-Stroke, Patient, Rehabilitation.

1. Introduction

One of the most silent contributors to disability and death in humans is stroke in the world [1]. A stroke or cerebrovascular accident is the sudden death of some brain cells due to a lack of oxygen when the blood flow to the brain is lost by blockage or rupture of an artery to the brain [2]. As for Malaysia, stroke was the second leading cause of death according to the latest World Health Organization data published in 2018 [3]. Due to stroke, humans lost the ability to move, walk, and talk, which are the most fundamental things in human life to perform daily tasks. To regain those abilities back, stroke patients have to go through physical rehabilitation. The standard rehabilitation process requires patients to perform repetitive exercises or actions to regain some of the previous motor functions [4]-[5]. The major

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*Corresponding author: *mnajib@uthm.edu.my*

problem with therapy regimens is time-consuming; the period for the patient-therapist to handle a patient per time is very long and uses lots of energy, which leads to higher costs. Moreover, not all hospitals provide therapy facilities and small clinics in remote areas.

Nowadays, the development of robots overgrows, impacting technology in many different ways, one of which is assisting patients' progress in the rehabilitation process. The immense complexities and small size of the human hand make building a robotic hand exoskeleton a unique design challenge. There are countless designs built in this field. Some keep the traditional way of using large and bulky robots for assisting stroke patients, which makes the patients discomfort due to it confining patients physically. More than that, it is costly and cannot be carried around. This may not be feasible for many patients due to locations, financial problems, and other constraints. In contrast, soft rehabilitation devices are lightweight and straightforward, easy to carry around compared to traditional ones. It solved the traditional way problems by using the natural exoskeleton of the hand and wearable gloves to control hand motion [6]. Uses deformable material, such as gels, soft polymers, and fluids that have better biomimetic qualities. [6] Soft rehabilitation devices had been proven to be successful for rehabilitation in the past years. However, the main problem is that most developers use pneumatic actuators as the actuation system, which are complex control systems and expensive components built. Users must be linked to a compressed air source through pneumatic hoses, thus restricting mobility

Most medical equipment and rehabilitation aids are marketed or purchased through a physical therapy practice or a medical supplier, generally at a significant expense to the patient. The open-source project has put manufacturing tools in the hands of regular people. Patients can now use their own medical gadgets instead of paying thousands of dollars for them from a medical supplier. This project intended to produce a simple-to-assemble, user-customizable robotic exoskeleton at a cheap cost, allowing patients to execute their therapy regimen without the need for repeated visits to physical therapists over the duration of our research and development. Present the design thoughts as well as an overview of the control system utilized in the hardware development of a robotic hand exoskeleton in this article.

2. Methodology

The development of the soft robotic hand exoskeleton platform made completely of commonly accessible and cheap components is the study's key contribution. The goal of the hardware development was to create a device that combined the desired properties of previously developed robotic hand exoskeletons with the primary elements of this study plan as shown in Table 1. Although adding more modalities to the exoskeleton and control system, such as more complicated controllers and sensors, might enhance the exoskeleton and control system, the exoskeleton design of this study purposefully eliminates complex and costly components for simplicity of use. The design depicts a platform that might be enhanced and complex through sensor fusion by end-users adding other modalities. The mechanical design and construction process for a robotic exoskeleton intended for end-user assembly must be simplified while prices remain affordable. A simple electronics kit, stationery items, and sports protective equipment are required for the construction procedure. Everything else in the soft robotic hand exoskeleton's mechanical architecture, including the tendons and the soft glove, is made of off-the-shelf components. This contains the arm plate placed on the motor bracket which holds the servo motor in a straight path to the exoskeleton, as well as the beads that are attached to the Velcro that holds the tendons in place.

Table1: Requirements for the motorized robotic hand glove.

	Requirement
Design	Simple mechanical and electrical built
Manufacturing	Using low-cost and off-the-shelf components
Weight	< 300 g
Price	< RM 150

2.1 Actuation system

The design presented here is a jointless construction that depends on the patient's skeleton's natural mobility and joint restrictions. Eliminating the mechanical and structural linkages substantially simplified the mechanical design and the assembly process of this exoskeleton. The palmar side of the hand was actuated by tensioning artificial tendons attached to the fingers, as shown in Figure 1. The opposing force required for the abduction was provided by elastic prosthetic tendons on the dorsal side of the hand. The elastic and inelastic tendons were created to replicate how the human hand works in gripping actions. A single custom-designed actuator mechanism was used to move each finger. The kinematic design of a finger was greatly influenced by the structure of a healthy human hand in order to produce realistic mobility. A tendon running down the palmar side of the fingers generated the actuation force.

The actuated design of this glove is controlled based on the length of the palmar tendon/cable. The palmar tendon is modified to allow complete finger extension at its maximum value during rest. The angle bent for each of the DIP, PIP, and MCP finger joints bend when enough force is given to the tendon, and the length of the palmar tendon decreases as the tendon is spooled by the motor.

The disadvantage of an underactuated design is that the joint's angle position is not immediately adjustable. However, since the system is meant to imitate the functioning of a healthy human, this is not a serious concern. Due to the muscular structure of the finger, the maximum angle bend by each joint is approximately not more than 90°.

The design for tendon attachment sites or known as anchor points followed the concept discussed in the tendon routing section. The finding results by [7] demonstrate that the anchor point or tendon attachment point design is effective as it shows the force normal to the finger normal to finger changes with the angle of the distal phalanx. The anchor point of the finger is shown in Figure 2. The brown line represents the artificial tendon used, and the green rectangles represent the anchor points [8].

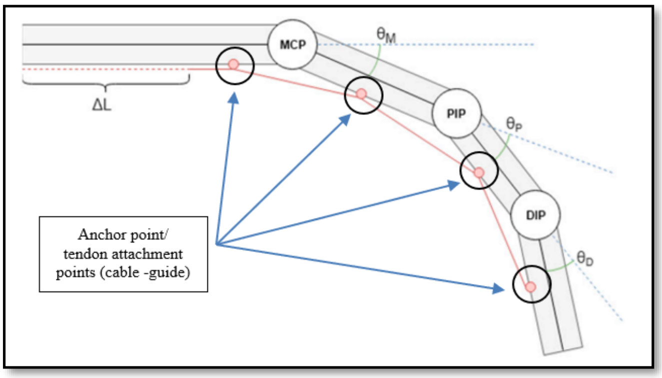

Figure 1: The design of tendon attachment points from [7]

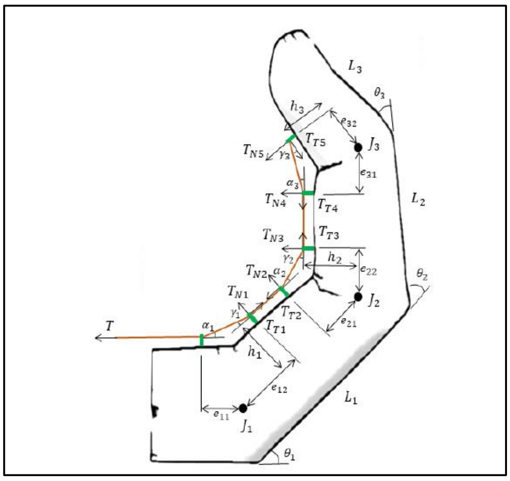

Figure 2: the design of finger anchor point by [8]

Anchor points or tendon attachment sites were used using the same approach as [7] and [8], as indicated in Figure 1. When a force is applied to the tendon, it produces a force on the anchor perpendicular to the finger and tangential to the finger. The anchor points are set to create the greatest torque in all three joints. Tension is a pulling force that equals the force at the actuators' ends. The torque delivered to the joints, and therefore the force applied tangential to the radius of the circle centered on the joints that contain the anchor point for the tendon, rises as the actuator force is given to the palmar tendon and the finger is flexed. It can only happen if there are no bends in the cable, which affects the design of the artificial tendon's course in order to apply the highest stresses to the fingertip. To create a linear actuation stroke, this notion significantly impacts the design of this motorized soft robotic hand glove.

The linear stroke motion was generated by pulling the palmar tendon around a spool with the rotating motion of a 360-servo motor. It can spin 360 degrees. Throughout the servo travel range, there is continuous torque. It weighs 55g and measures 40.7 x 19.7 x 42.9mm in size. The motor’s stall torque is 8.5kgf.cm when supplied by 4.8V and 10kgf.cm when supplied by 6V. The servo motor’s working speed is determined by the voltage given; when the input voltage is 6V, it takes just 0.16 seconds to attain a 60° angle, however, when the supply is 4.8V, it takes 0.20 seconds. Between 4.8V and 7.2 V is the operating voltage range.

2.2 Mechanical design

The mechanical design of the glove in this study was based on the hand's resting position, with the motor system actuating the hand's closure and a passive system returning the hand to its resting position. This specification necessitated using an inelastic material on the bottom of the hand connected to a motor system with position monitoring through an infrared sensor to close the hand and an elastic material on the top of the hand to restore the hand to its neutral state. The flexion and extension of the finger are controlled by a cable-driven push and pull mechanism. Artificial tendons linked to the fingers are used to activate the palmar side of the hand. The opposing force necessary for abduction on the dorsal side of the hand was given by artificial elastic tendons. As illustrated in Figure 3, the inelastic tendon was fastened to the fingers using cable guides, while the elastic tendon was sewn to the rear of the distal phalanx glove's finger. To reduce friction loss between the cables and the glove's surface, beads were employed as cable guides for the palmar tendon passage. The first joint is the proximal interphalangeal (PIP), the middle joint is the distal interphalangeal (DIP), and the last joint is the metacarpophalangeal (MCP). Except for the thumb, the PIP and MCP are the only joints.

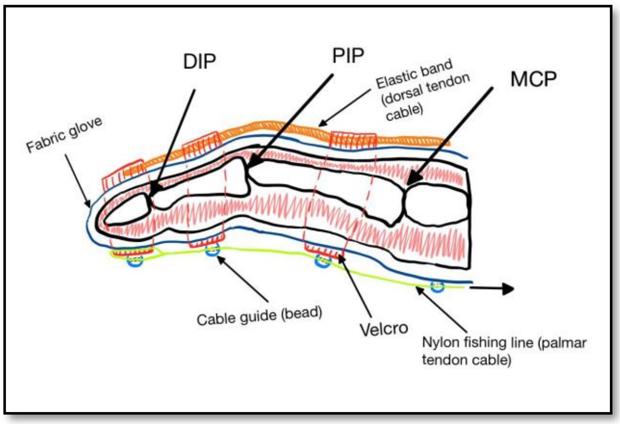

Figure 3: Cable guide and tendons attached to the glove

In addition, the ability to adapt to a wide range of hand and finger sizes was a key consideration during the design process. To allow the fitment for a wide range of hand and finger sizes, eight Velcro with beads stitched on the top were cut and attached to each finger phalanges, as shown in Figure 4. Artificial tendons that provide actuating and restoring force to the fingers can be easily customized to the user’s kinematics. Trim the monofilament fishing line to the correct length before securing it to the cable guide with the fingers fully extended to customize the length of the finger stroke of the palmer's tendon. The software performs a calibration after it has been secured. In a similar way, the rehabilitative force provided by a 1/8" shock cord can be tailored.

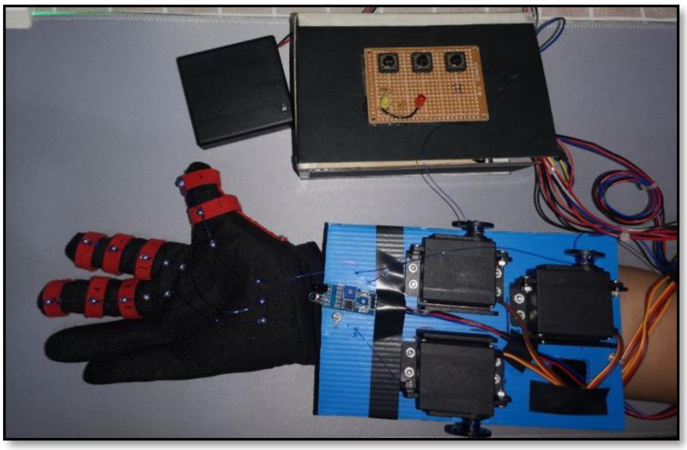

Figure 4: A fully assembled soft robotic hand glove to the microcontroller via wire.

2.3 Control system

The Arduino/Genuino Uno is a microcontroller board based on the ATmega328P. It features 14 digital input and output pins, with six PWM output pins. The Arduino is broadly helpful since it is readily available and inexpensive. It also has a vast user and development community and access to code libraries, enabling a range of interface options, making it the best choice for this device. The Arduino Uno acts as the central platform to control all the communication, data processing, and signal processing for this device's system.

2.3.1 Electrical design

Circuit design is the main control to move the finger mechanism to get the result of the handgrip. The Arduino UNO microprocessor is the main controller used to control the servo motor movement. This circuit design section will explain each component used in the circuit and diagram of the main circuit. The motorized soft glove uses three servo motor that only requires moving three of the fingers (thumb, index and middle) that solely focus on rehab in this study. The servo motor is connected in parallel to an external voltage DC power supply that supplies 6V. While Arduino Uno is supplied with 9V from a 9V battery connected through a battery snap clip connector, the IR sensor directly uses the power supply from the Arduino Uno board with the supply of 5V. The full schematic diagram of the glove's finger control system is shown in Figure 5.

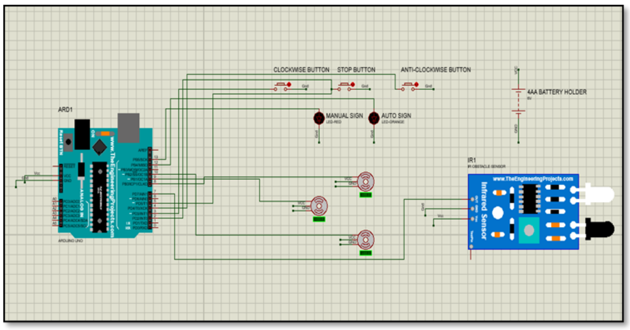

Figure 5: The schematic diagram of the Motorized Soft robotic Hand

2.3.2 Position Control

The hardware control system was designed uniquely. The control system operates in two modes: manual and automatic control mode. The patients can choose whether they want to use automatic control or manual control.

The stop PB (pushbutton) needs to be pushed once to switch control mode, then the mode control changes. Therefore, every time the stop PB has been pushed, the control mode switches. Due to the 360° servo motor used, the code system uses the ASCII table to control the servo motors' stopping and rotation direction. When stopping the motor, the decimal number of 89 is the most precise. Whereas the most precise decimal number from the ASCII table to rotate the servo motor clockwise is 0, while for rotating anticlockwise, the decimal number is 116. As a result, there won't be any delay during the stopping and rotating of the servo motor. But in actuality, there will always be a delay after using the battery for quite some time. The speed and precision of the servo motor depend more on the voltage supply. Therefore, when the voltage drops, it affects the servo motor precision and causes some delay of 0.5s to 1s. The flowchart of this hardware control system is shown in Figure 6.

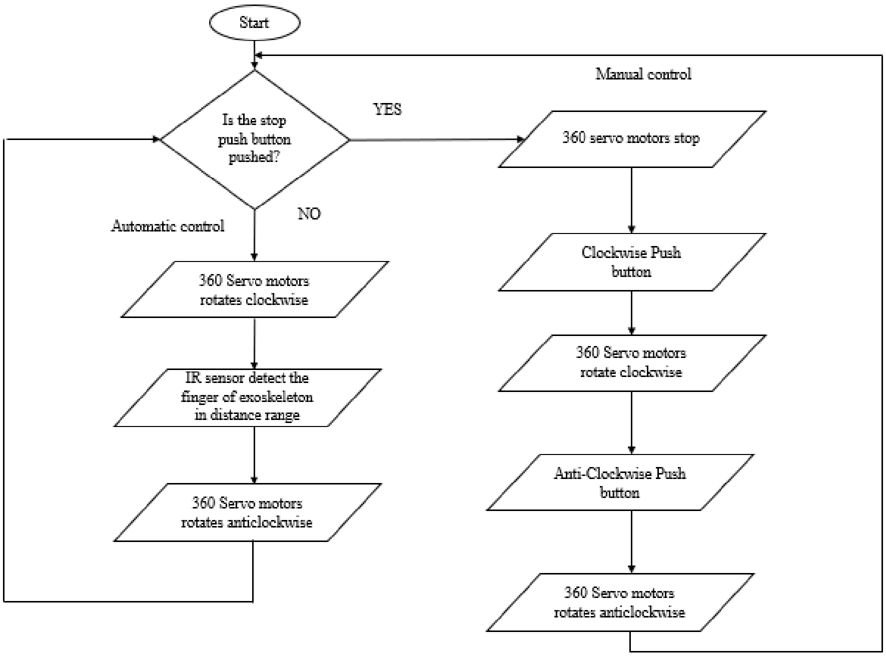

Figure 6: The flowchart of the hardware control system

2.4 Experiment

2.4.1 Gripping experiment

The gripping experiment is done in order to determine if the design could be useful in helping patients to complete daily tasks. For the gripping experiment, the mode used to control the servo motors is manual control, enabling the user to control the rotation of the servo motors and stop it. The gripping motion is manually stopped when the servo motors cannot spool the palmar tendon anymore while gripping the object. This indicates that it has reached the maximum grip. Each of these finger grips has a force driven by a servo motor operating with a maximum of 6V. A battery holder for 4AA batteries that gives 6V is used as an external supply to power up the servo motors. As a result, the DC voltage supply is stable, enabling the servo motors to operate to their max strength functionally.

In this experiment, the object used is hard plastic and a tennis ball. The weight of the hard plastic cup is 28 g, whereas the weight of the tennis ball is 55 g. During the gripping experiment for under-actuated conditions, the prosthetic hand was placed at rest while the palm was facing upward, and the objects were attached beforehand using Velcro. This is because the beads used as a cable guide for the palmar tendon are glossy, making it slippery and unable to grip the object correctly. Therefore, the object's weight is not a concern in this experiment.

2.4.2 Bending experiment

The primary reason this experiment is being conducted is to determine whether the glove's feat can imitate the patterns of movement that a person without a disability do when making a grasping motion. The mechanism design of this glove is done well; the cable guide can direct linear stroke thru the pulley process from the motors to the glove's finger without the fingers misaligning. The control mode used is automatic. The automatic mode control enables continuous extension and flexion of fingers, required for repeated finger exercises. As it is mentioned that the goal is to have high repetition hand/finger exercise for stroke patients as it helps to stimulate the brain and encourage neuroplasticity [9]. This bending experiment is done by grasping movement involving three fingers to bend simultaneously.

There is no object applied to the glove for this experiment, both under-actuated and un-actuated. The data was acquired from recorded videos using a Huawei P20 Pro camera. Three different camera positions were deployed to capture each finger's movement. The recorded videos of bending fingers were then analyzed in Kinovea software. The glove's joints for DIP and PIP are marked using thumbnails to act as a midpoint between each phalange enabling the Kinovea software to track the angle bend.

3. Results

3.1 Gripping Experiment

The graph in Figure 7 and Figure 8 shows the difference in force exerted on each finger actuated and unactuated. The data were acquired during the actuated grip experiment utilizing a test setup that kept the wrist and finger straight while the motors were activated.

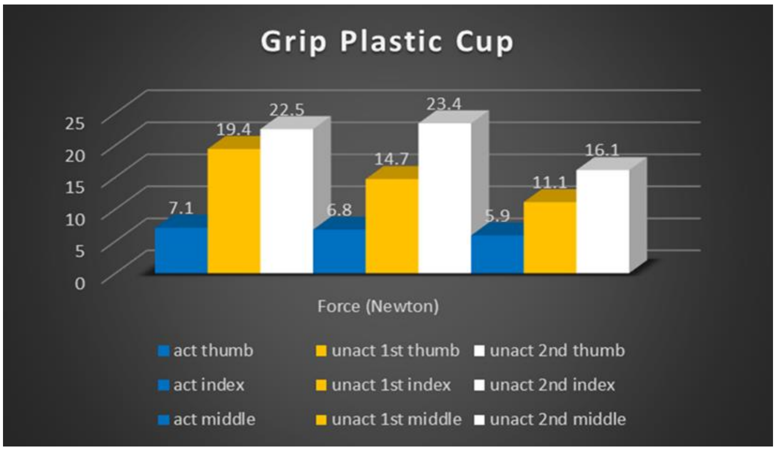

Figure 7: The normal force exerted on fingertip while gripping plastic cup

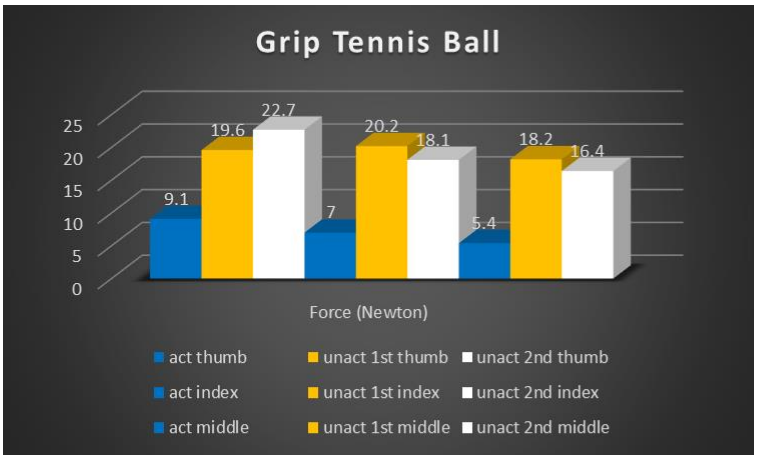

Figure 8: The normal force exerted on the fingertip during gripping a tennis ball

3.2 Bending Experiment

Figure 9 to Figure 16 presents the sample patterns of three of the finger's joint angles observed during making the grasping motion. The test was performed for seven seconds each, where each finger would first curl and then uncurl. The testing began with establishing two baselines for two healthy individuals' unactuated movement in orange and white lines, followed by the actuated movement in the blue line.

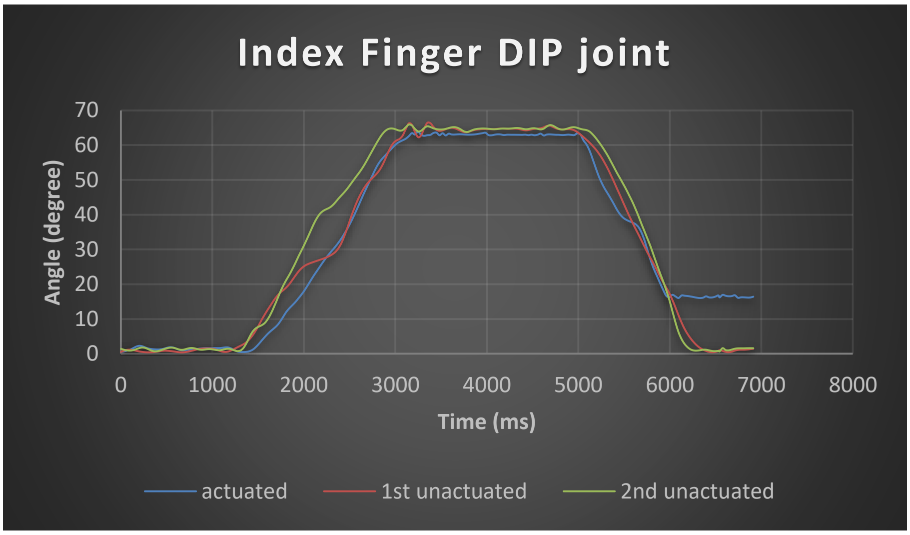

Figure 9: Motion analysis data of the distal interphalangeal (DIP) joint for index finger

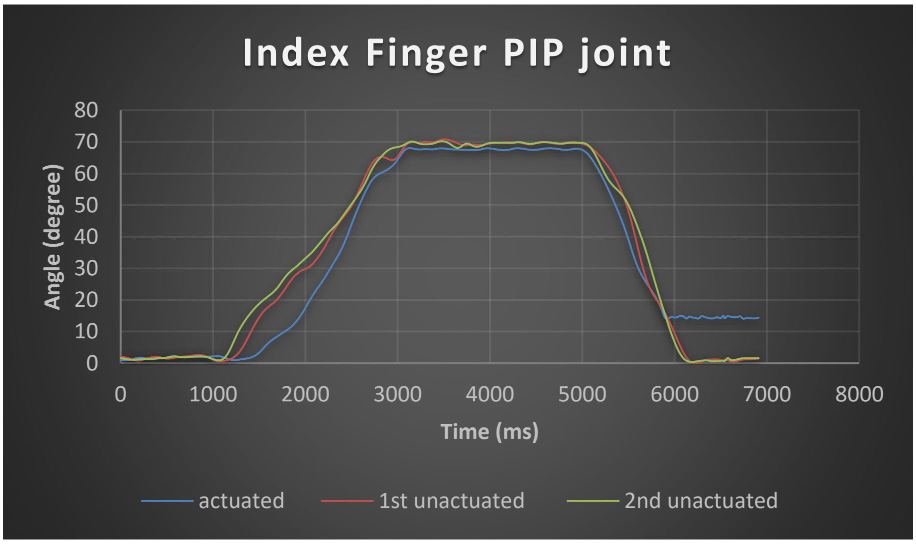

Figure 10: Motion analysis data of the proximal interphalangeal (PIP) joint for index finger

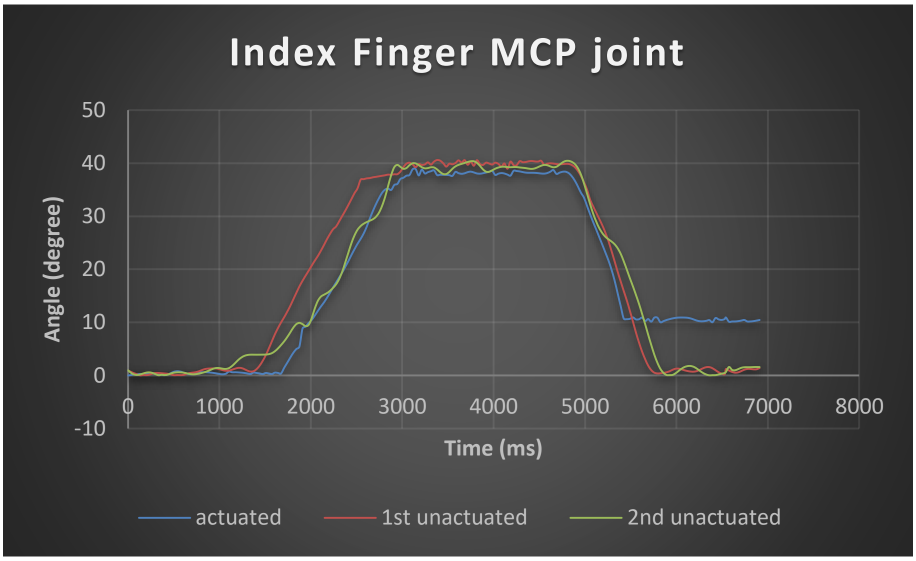

Figure 11: Motion analysis data of the metacarpophalangeal (MCP) joint for index finger

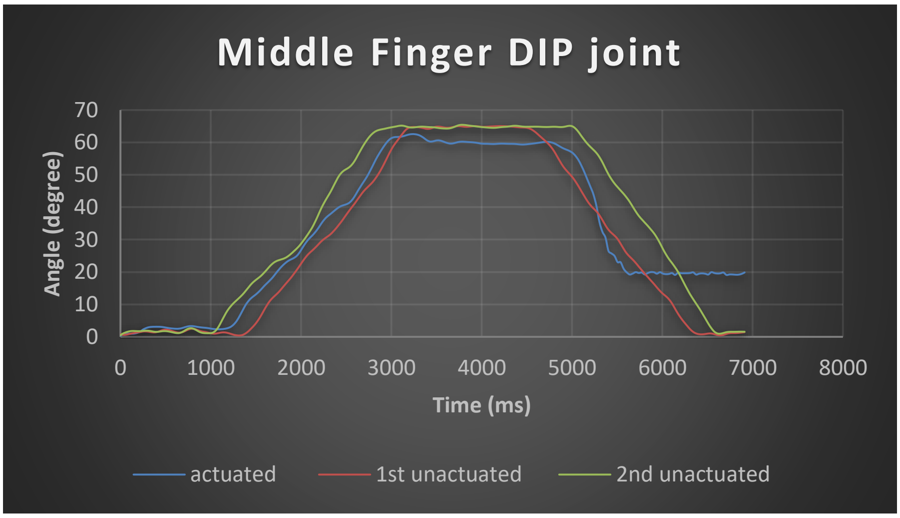

Figure 12: Motion analysis data of the distal interphalangeal (DIP) joint for the middle finger

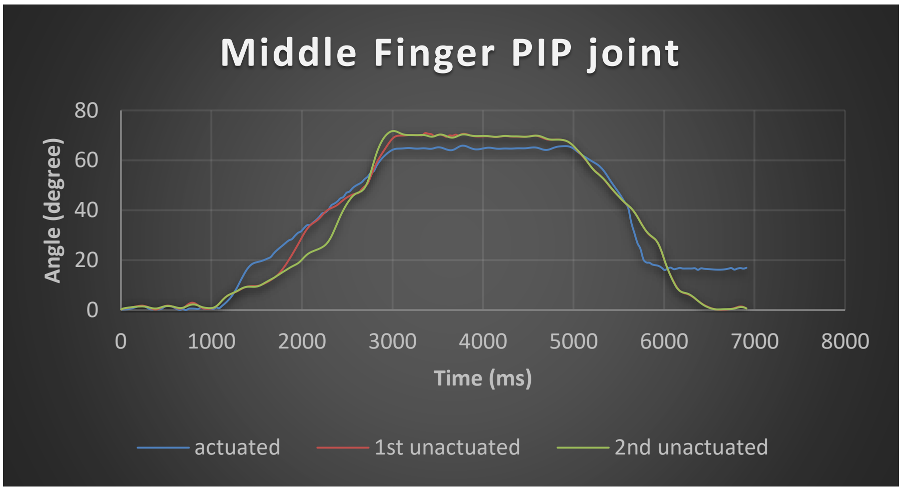

Figure 13: Motion analysis data of the proximal interphalangeal (PIP) joint for the middle finger

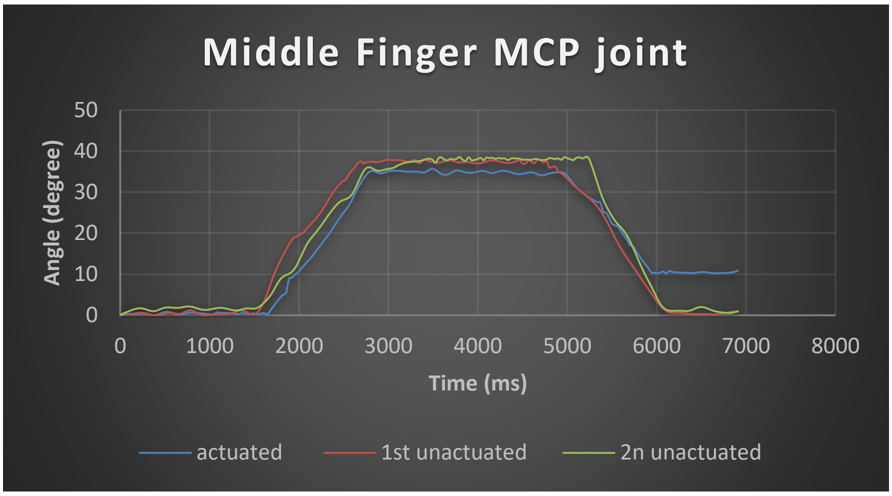

Figure 14: Motion analysis data of the metacarpophalangeal (MCP) joint for the middle finger

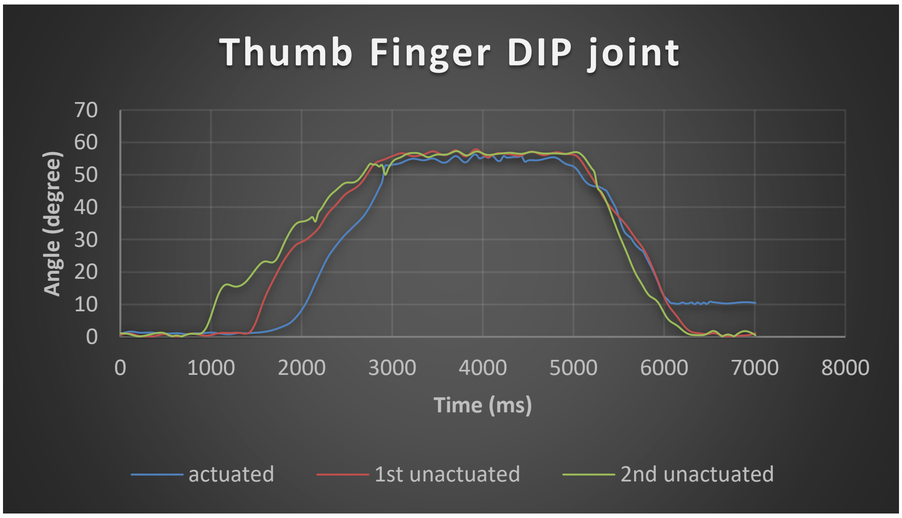

Figure 15: Motion analysis data of the distal interphalangeal (DIP) joint for the middle finger

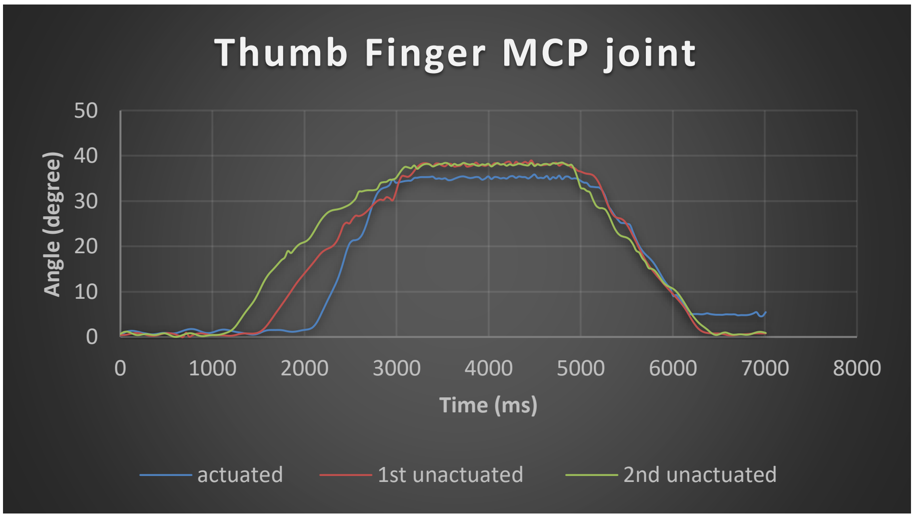

Figure 16: Motion analysis data of the metacarpophalangeal (MCP) joint for thumb finger

3.3 Discussion

The results show measurable parameters that have been generated, such as the extent to which the linear movement of the motorized soft glove design operates. Apart from the gear actuation supplied by the servo motor, the soft glove design significantly impacts each finger's movement. According to the investigation results, the motorized soft glove was able to mimic the natural range of a human hand gripping action even though it doesn’t achieve a function equal to 100 percent.

The DIP, PIP, and MCP activities drop when the prosthetic hand uses the motorized soft glove during the bending experiment, as demonstrated in Figure 9 to Figure 16. Due to the homemade prosthetic used, the under-actuated finger is unable to flex fully, which is crucial to show the design's full capability both for gripping and bending experiments. The equipment and tools used to conduct these experiments are only affordable and can be easily obtained. This does considerably affect the output for each result, such as the joint angle is unable to be fully bent due to the homemade prosthetic hand used, which also affects the under-actuated data for force analysis, the type of camera used to record the bending experiment is not asynchronous, which causes some starting delay as being pointed out in the motion analysis. Therefore, to obtain the exact and compelling findings for the under-actuated finger bending and force analysis, it is better to use a QualisyCamera that synchronous several cameras when taking videos and a 3D-printed prosthetic hand with a real human hand dimension and DOF. But due to a lack of resources and circumstances, this was not possible.

The gripping experiment result also demonstrated that the glove could generate a sufficient grip force when grasping an object. It can be seen in Figure 10 and Figure 11 that the grip force increases approximately 2N and 0.2N for the under-actuated thumb and middle finger when it is grasping the tennis ball. But the grip force for the middle finger decreases by about 0.5N. This will be the result of the tennis ball's round shape, where the majority of grasping work will be performed between the thumb and index finger, leaving a supporting role for the middle finger to stop the ball from slipping. In contrast when the prosthetic hand is gripping the hard plastic cup. The shape of the plastic cup is spherical, due to the lack of joints and restraint the homemade prosthetic has. It makes it difficult for it to grip the cup correctly, which leads to the lesser force exerted during the gripping process.

While the maximum grip force applied on the under-actuated finger during grasping the tennis ball and hard plastic cup is much lesser than the force applied to the human hand when wearing a soft glove. Since the force delivered to the fingertip is determined by the arrangement of the fingers and the moment the motor is contracting the palmar tendon, the force applied to the sensor will always be less when the cable's pulling force than the healthy human hand. Moreover, due to friction, the system demands more energy consumption which leads to lower efficiency. In addition, the prosthetic hand used does not have the same joints as a human hand. It is merely a low-cost homemade prosthetic hand that could not be compared to a realistic 3D printed prosthetic hand or an actual human hand. As the homemade prosthetic hand lacks actual joints which do not provide the same DOF as an actual human hand. There is another issue that this soft glove faces during the gripping experiment, the beads used as the cable guide for the soft glove are glossy and considered quite large, they protrude from the Velcro preventing the motorized soft glove from fully gripping the object. These issues will be addressed in future versions of the exoskeleton.

4. Conclusion

Every study that is conducted has flaws, there is no denying that. But from the initial research, there is an improvement from the recommendation in the previous study. Studies on this motorized soft glove still have a lot to test its functionality. The design of the motorized soft glove builds upon past work done on cable-actuated exoskeletons. The motorized soft glove was created with generally accessible off-the-shelf components while controlling the actuators via a specially designed shield to assist ease of wiring with a commonly available open-sourced microcontroller. The experiments were done to verify that the range of motion and the forces applied at the actuated fingertip corresponded with those of a healthy human hand. The design and findings mentioned in this research yielded a favorable result. It was also proved, in the findings section that this motorized soft glove design was able to create the fingertip grab forces needed to execute various daily living chores. Despite with using only easily found components and basic experiments to evaluate the performance of the motorized soft glove. The result and analysis of this research are very important for future studies.

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