



Final Report

Constructing and Analysing the Performance a Modified Prosthetic Hand **Rayang Termedate Mendrofa**

3rd Year Individual Project

I certify that all material in this thesis that is not my own work has been identified and that no material has been included for which a degree has previously been conferred on me.

Signed.....

College of Engineering, Mathematics, and Physical Sciences
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Final Report

ECM3175/ECM3149

Title: Constructing and Analysing the Performance of a
Modified Prosthetic Hand

Date of submission:

05/05/2023

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Abstract

Despite recent major breakthroughs in technology and medicine, the number of individuals who have body parts amputated for a variety of reasons continues to rise. Assistive equipment, such as prosthetic arms, can allow upper limb amputees to do restricted tasks and enhance their quality of life. This research intends to aid in the development of user-centred prosthetics by identifying user requirements and essential factors to consider when selecting prostheses. After receiving previous agreement, this study administered a questionnaire survey to people with disabilities who had upper limb amputations and visited orthosis firms, rehabilitation centres for the disabled, veteran's hospitals, and labour welfare corporations. Upper limb prosthesis users completed a modified questionnaire, and the findings were evaluated using descriptive statistics and the t-test.

The study's findings revealed that the primary reasons for terminating the usage of prostheses were pain (wear, weight, and difficulty of detachment) and design and function issues. Respondents expressed a need for varied prostheses built for certain purposes and situations, such as golf and cycling, as well as regular use. The majority of respondents said that buttoning clothes and tying knots were difficult or impossible to perform on their own. According to the findings of this study, the quality of life of upper limb amputees can be enhanced by developing a prosthetic arm with several functions that can meet both the user's demands and desires.

Keywords: prosthetic upper limb; user satisfaction; user-centred prosthetic upper limb; upper limb amputee; user's needs; user's requirements; assistive technology; technology development

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1. Introduction and background

It may be claimed that an individual's most valued possession is their human body. Restoring a missing biological limb, particularly a hand, is a challenging endeavor that makes one understand the complexities of the human body. For generations, pioneers have attempted to restore missing limbs with man-made technology. Several prosthetic devices from ancient civilisations around the world have been uncovered, indicating the continual advancement of prosthetic technology.

Until recent years, the development of prosthetic limbs was relatively gradual. Early discoveries like the lumber leg can be considered basic artificial legs. For a long time, prostheses have been passive devices that give nothing regarding control and mobility. Materials advanced over time, and designs proceeded to have hinges and pulley systems. This resulted in simple mechanical body-powered devices like metal hooks that open and close as a person bends their elbow.

However, nowadays have seen significant developments in prosthetic devices. The emphasis is not only on the physical characteristics of an apparatus but also on the control and biofeedback mechanisms. We are gradually approaching advanced transhuman fusion of machine and body. Maybe eventually, prosthetic technologies will be faster, stronger, and even healthier than our biological limbs. Throughout this final year project report, we will look at the designs of prosthetic arms. Its goal is to create a device that as closely as possible resembles the function of the human arm and can be controlled to some extent by muscular contractions.

1.1. Prostheses

The prostheses have been developed from ancient times to this modern day. Thus, there are several types of prostheses with difference in their adaptability, function, and mechanism. But in general, they are grouped by the way in which the device is controlled.

Passive Prostheses

This type of prosthesis has been dated back in ancient Egypt times. Passive prostheses are modest, non-moving implants that aim to restore an amputee's cosmetic appearance and have minimal functionality. A simple passive prosthetic is a simple wooden 'pirate' peg leg.



Figure 1.1 Capua Leg, wooden toe found in Egypt estimated from man living around 300 BC. (Courtesy Museum of Egyptian Antiquities in Cairo).

Mechanical Prostheses

Also called body-movement prostheses are operated by a harness that is attached to the user. They are often basic devices, such as a mechanical hook connected to elbow/shoulder movement. Despite their simplicity, these devices continue to be the most common form of prosthesis today.

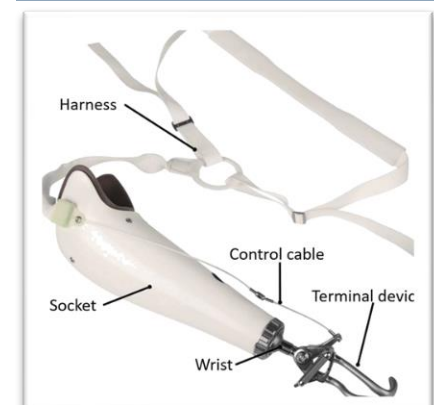


Figure 1.2. Mechanical hand prosthesis

Myoelectric Prostheses

Myoelectric prostheses measure electromyography (EMG) signals generated from the contraction of muscles near an amputee's residual limb. These signals are measured through electrodes placed on the surface of the skin or embedded directly into muscles. These signals are then amplified and sent to a microcontroller which analyses this information and controls the internal actuators. Myoelectric devices allow for far greater amounts of control than mechanical devices.

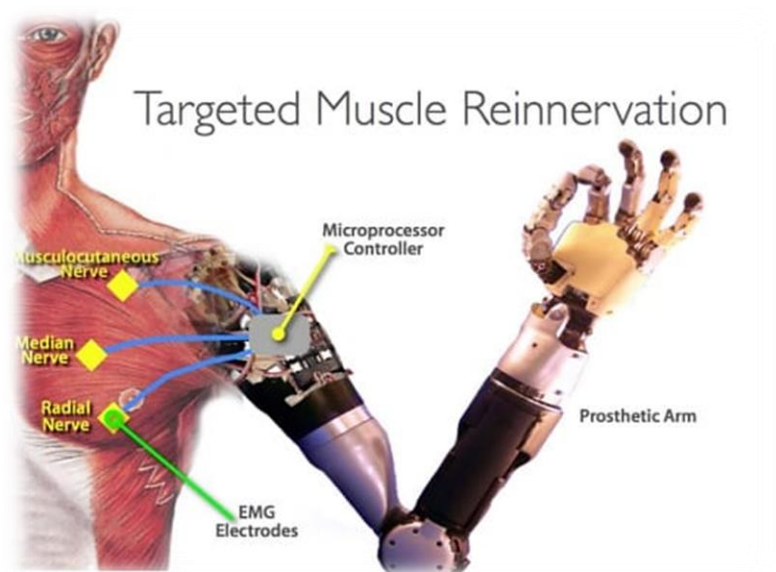


Figure 1.3. How myoelectric arm prosthesis work

Direct Brain interface

The most cutting-edge type of control is a direct brain neural interface. A surgical procedure places electrode arrays on the surface of the brain which are attached to pedestals implanted into the patient's skull. As the patient thinks of motion signals detected on the pedestals are used to control the movement of a robotic arm. This type of technology is still in its infancy but has already demonstrated disabled people controlling bionic devices with their thoughts alone.

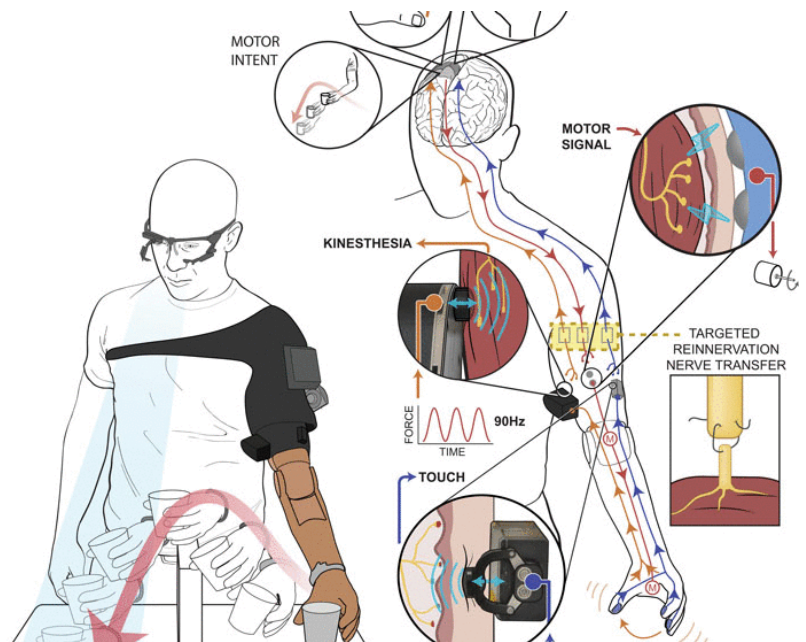


Figure 1.4. What a direct brain interface prosthesis work

1.2. Issue

There are various design and manufacturing obstacles to solve while creating a functioning prosthetic arm. The goal of this research is to analyse a mechanical prosthetic hand of suitable complexity and quality that may be utilised for further study in the field of prosthetics.

It is critical for the reader to understand that this work spans multiple technical disciplines. Each field will receive appropriate consideration, and we will strive to integrate all sectors into a single, strong, effective system.

The primary topics that will be covered in this thesis are listed below.

Physical Design

The mechanical and electrical systems' complexity determines how closely the gadget replicates the human arm and how much dexterity it can provide. The aim is to make the design as physically sophisticated as feasible.

Control Scheme

We would want a prosthesis that is as simple and natural to use as feasible. If the user has to struggle to execute even the most basic actions, such as gripping an item, the prosthesis is unlikely to be useful in practical sense.

Practicality

The equipment must be designed to be beneficial to amputees. It's unclear whether this technology will ever be used by an amputee, but the objective is to create a prosthetic that can help those who have lost their hands.

1.3. Plausible Solution

A prosthesis's overall purpose is to restore as much functionality as possible to a person who is missing a limb. The ultimate objective would be to be able to perfectly replace lost limbs one day. The goal of this project is to design and construct a 3D printed prosthetic hand. A user of this gadget will be able to manipulate the arm by detecting muscle flexing with surface electrodes put on the skin.

Modern 3D printers enable the creation and assembly of detailed mechanical components in a very short period of time. Other techniques of fabricating intricate patterns would be significantly more expensive and would not be achievable in such a short amount of time.

The first technique is to create a stiff joint connected system to regulate finger movement. Such a method is increasingly common in commercial prosthetic limbs; yet, designing a compact complicated gear linkage system is difficult. Another possibility is to create an artificial tendon network to actuate the device. This approach is utilised to control numerous robotic hands, which will be covered in the literature review part. The advantages of this device are its inexpensive cost and simplicity in manipulating fingers.

The inner workings of the system will be described in detail throughout this research. There are usually several solutions to every problem, and numerous compromises were made in the creation of this device.

1.4. Angle of Attack

Creating an excellent design from start is really challenging. Many solutions may appear plausible at first but later cause unanticipated problems. Trying to refine the original design over a period of months is not only a waste of time, but it also leads to a narrow-minded attitude.

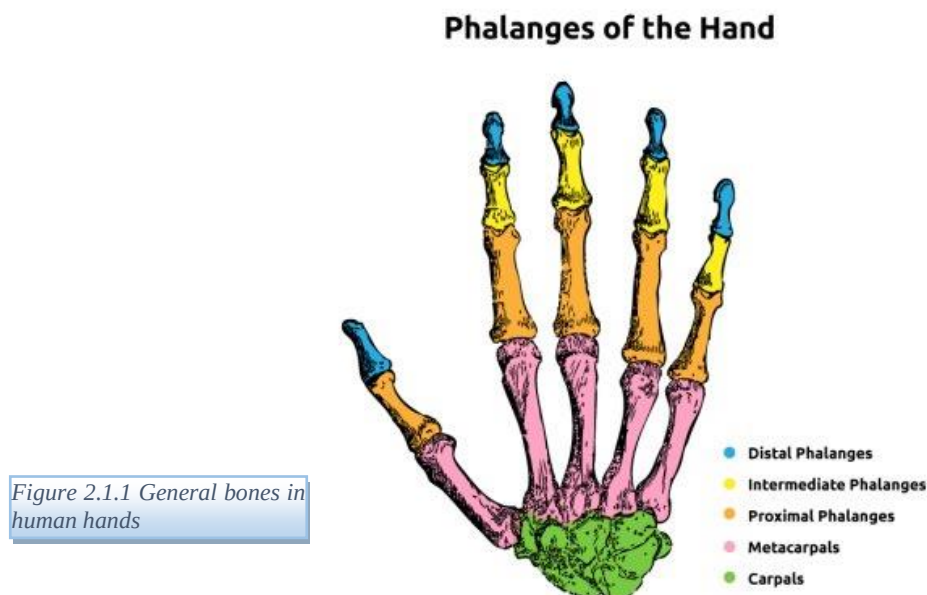
A far better strategy is to create the initial prototype as soon as feasible, study the system, and make changes. We can simply produce new and improved designs thanks to 3D printing.

2. Literature review

Various commercially available prosthetic arms, such as HeroArm [13] and iLimb, are myoelectric controlled robotic arms. Many more prosthetic arms are being developed in research labs around the world as prototypes to test advanced designs and concepts. Research prostheses are often more complicated in terms of mechanical design, control and monitoring systems, and resilience when compared to commercial devices [1]. From this knowledge, this section of this research will walkthrough the advantages and disadvantages of the known technology and help in to discover the perfect methodology, thus producing a good enough result.

2.1. *The Human hand*

The human hand comprises of at least 27 bones (depending on the individual) [2], more than 30 individual muscles [3] and over 100 named ligaments, nerves, and arteries [4]. Prostheses aim to replicate the functions of the human body and return functionality to persons with missing extremities. No current prosthetics can match the dexterity, flexibility, and fluidity of the human hand [1].



The fingers are composed of the distal, the medial and the proximal phalanges, connected by distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints and by a base whose function is twofold: it implements the 2-DOF metacarpal (MC) joint and allows an easy connection of the finger to the palm [5].

The thumb's anatomy differs greatly from those of the other fingers. It is shorter in length and more robust than the other fingers (as in the human hand) and is made up of three links: the distal phalange, the proximal phalange, and the metacarpal, which are linked by the interphalangeal (IP) and metacarpophalangeal (MP) joints, as well as a base that implements the 2-DOF carpometacarpal (CMC) joint with the palm itself.

Mechanical engineers are taught and studied about DOF during half of their courses. Let us define a degree of freedom (DOF) for this is necessary to continue reading this research/ project for a reader who does not have an engineering background.

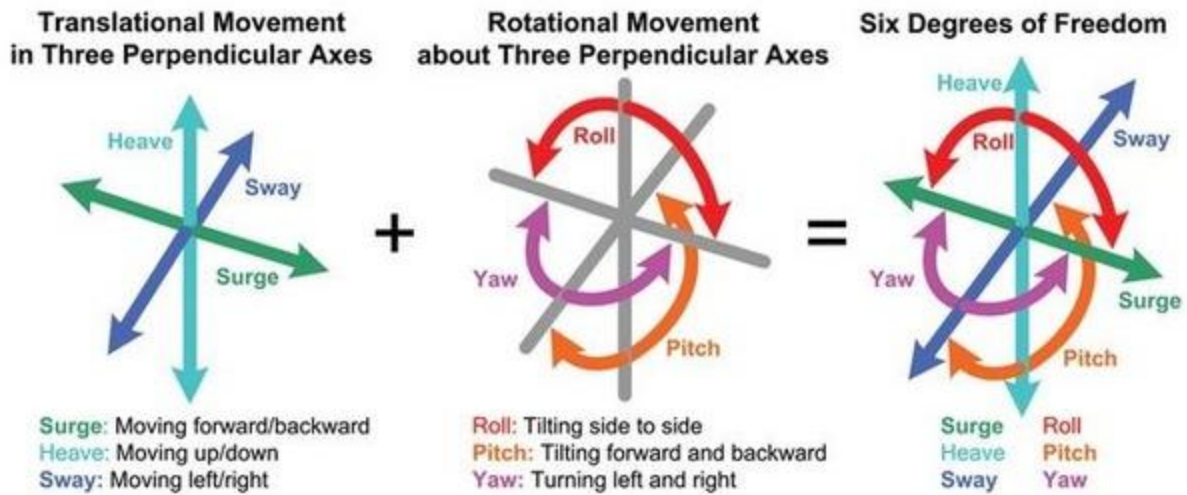


Figure 2.1.2 – Degrees of freedom at a single point (courtesy Ben Nelson, 2013)

Consider the illustration above as a point in space. From the vantage point, we can translate (move) along three different axes, namely forward/backward, up/down, and left/right. At the same time, we may rotate along three separate axes. As an example, the human neck has three degrees of rotational freedom: we may gaze left/right, up/down, and tilt our head sideways. So, a single point can have a total of six degrees of freedom (3 translational, three rotational).

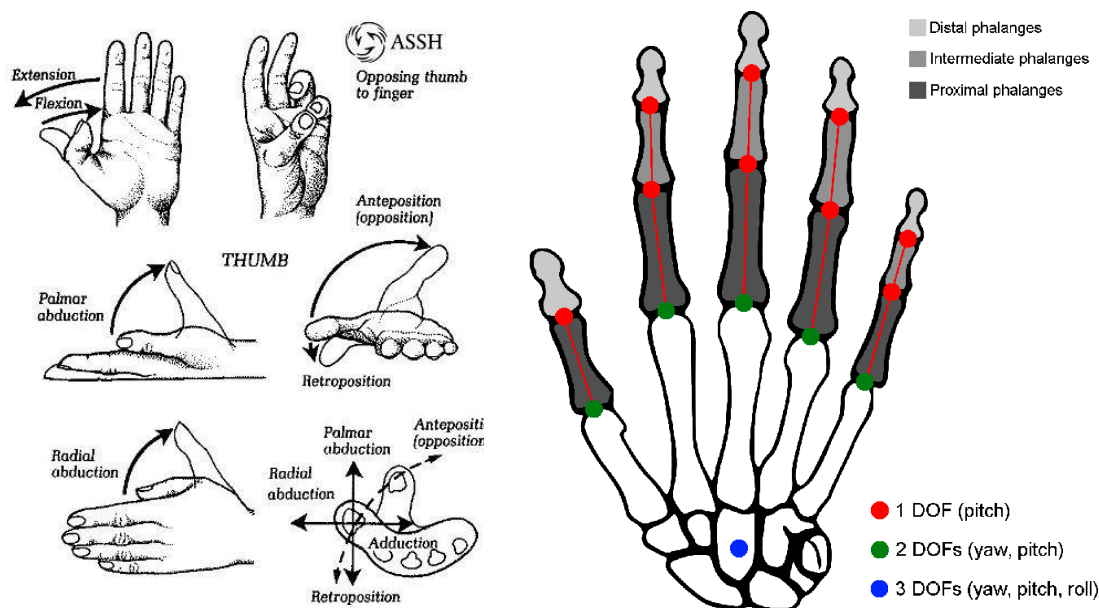
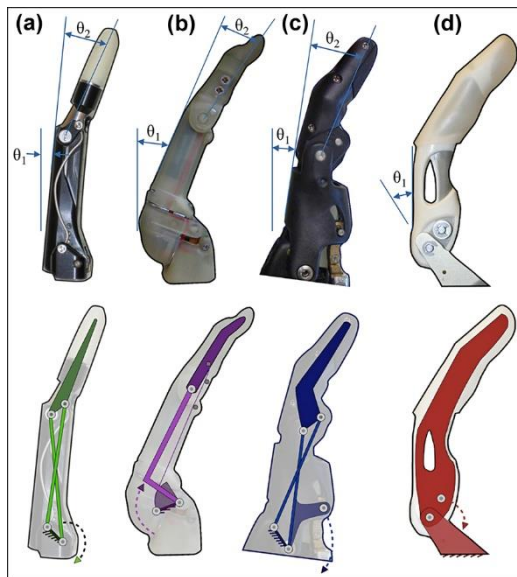


Figure 2.1.3 The Depiction of human hand vectors

The human finger as depicted in these illustrations above has four degrees of freedom [6]. Three of them are joint rotations (DIP, PIP, and MCP), which work together to govern finger flexion and extension. The knuckle (MCP joint) also allows for finger adduction along with abduction (wiggling from side to side). **In the thumb the lower CMC joint also allows for abduction/adduction – which gives 5 DOFs in the thumb [8].** Fingers, and all joints in the human body are actuated (moved) via contraction of muscles and tendons.

2.2 Capabilities of Prosthetic Hands

A significant number of commercial prosthetic fingers are operated by a DC electric motor-powered joint linkage system [1]. Below are kinematic models for various prosthetic fingers.



Their respective movements are limited with each finger features its own system of mechanically interconnecting joints. Rotating the metacarpal (knuckle) joint simultaneously rotates the upper phalange joint.

Figure 2.2.1 Commercial finger images (top) kinematic models of finger joint coupling mechanism (bottom) (courtesy of Yale University)

The drawback with this kind of structure is that no control over individual finger joints is provided. Because all joints in the finger are controlled by a single actuator, the entire finger has only one degree of freedom - these fingers can only open and close in one direction.

In actuality, a human finger exercises control over individual joints and may bend in a number of ways, displayed below. Although commercial prosthetic fingers may have the same number of joints as a human finger, they have fewer degrees of freedom. Usually, 1 or 2 compared to 4.

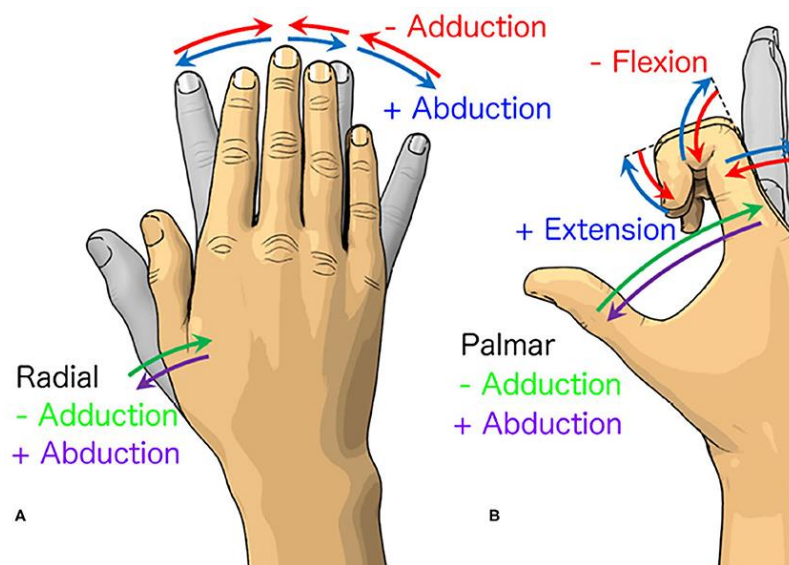


Figure 2.2.2 Various flexion arrangements of the human fingers – difficult or not possible with modern prosthetic

The various degrees of freedom of the human hand result in manoeuvrability. The exquisite motor control a person possesses over their individual finger joints enables them to do a wide range of difficult activities. On the other hand, commercial prostheses are confined to simple activities due to a lack of precise control within the fingers. Attempting to knit, sew, or play a musical instrument like a guitar with a current commercial prosthetic device, for example, would be exceedingly difficult, if not impossible [6].

Durability is a further significant aspect of design in commercial prostheses. As a result, commercially available prosthetic arms must be durable, lightweight, and packed in a closed system that can be affixed to an amputee. Mechanical complexity affects the degrees of freedom in the system; nevertheless, there is typically a trade-off because increasing complexity can increase device size while decreasing robustness and durability [1].

iLimb digits

A significant challenge in constructing prosthetic arms is that amputation can occur at any point along the arm and is unique in each occurrence. Touch bionics' iLimb digits include electric motors directly into the prosthetic fingers [7]. This permits the palm to fit into a socket connection, which connects the prosthetic fingers to the hand.

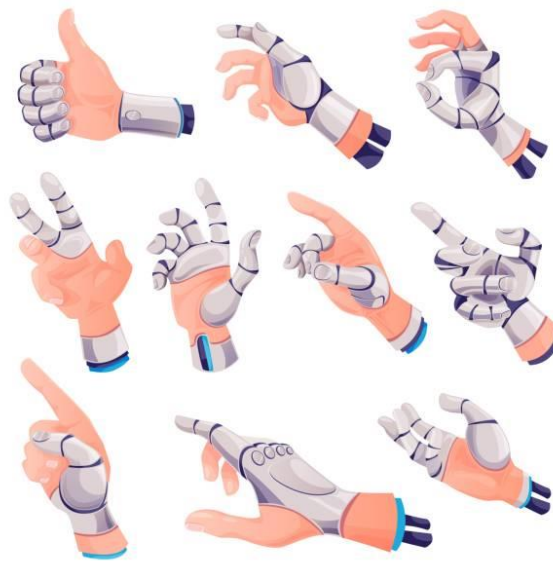


Figure 2.2.3 Different type of prosthesis that can be implemented in iLimb prosthesis design.

The illustration above depicts different amputations that might be used with the iLimb digits. A unique socket is built to fit around the remaining portion of the user's palm, and the device may accommodate as many digits as needed. The iLimb digits, are controlled by EMG electrodes placed over muscle areas in the palm. A small container containing the system's battery and controller must be worn around the user's wrist. A drawback of this method is that small motors must be employed in order to fit inside the fingers. As a result, the digits move slower and are weaker than in comparable commercial prostheses.



Figure 2.2.4 iLimb Prosthesis (courtesy of Touch Bionics)

Vanderbilt Hand

Advanced mechanical designs and sophisticated control mechanisms are tested in research prosthetic devices. Most research hands require an external power system, rendering them unsuitable for use as an amputee attachment [1]. Many research arms, including those at Vanderbilt [8], and Bologna [9] Universities, use artificial tendon designs to drive finger movements as opposed to a mechanical linkage system in commercial devices. The tendons (white wires) that go through the fingers and thumb are seen in the pictures below.

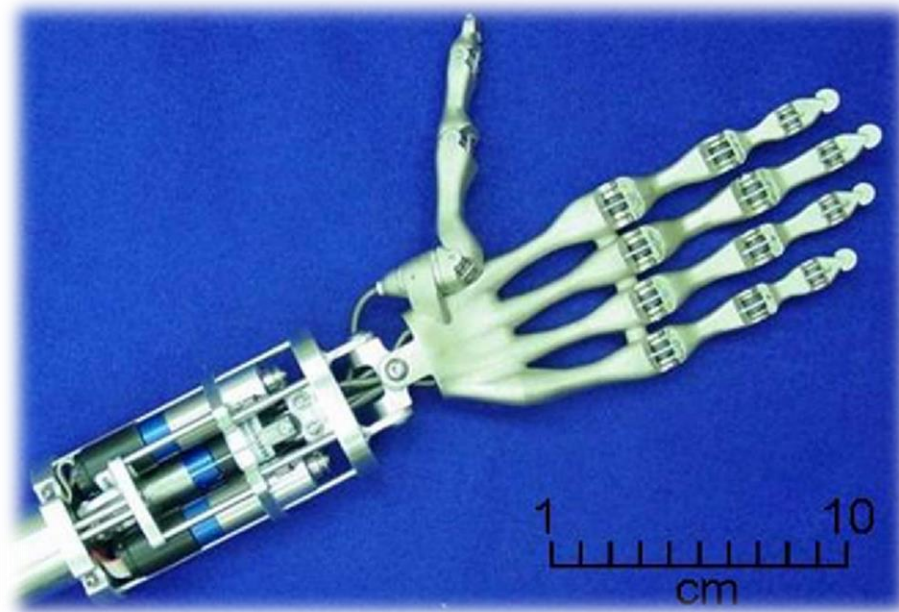


Figure 2.2.4. Artificial tendon in an anthropomorphic hand. (courtesy Vanderbilt University)

Brushed direct current motors power a pulley system that strains the tendons. This strain causes all three finger joints to close at the same time. Springs have been installed in each joint to allow the fingers to open. When the tendons' tension is released, these springs return the finger to its original open position. [10] The coiled steel springs included into each joint are seen in the figure to the right. The energy collected in the joints during the closure phase is employed to accomplish the opening phase without the need for further actuation by integrating springs.

The Bologna University (UB) hand uses a similar tendon/spring design to actuate fingers [9]. We can see in the next page that linear springs can be used to return fingers to an open position, or the spring mechanism can be directly incorporated into the structure. The UB hand IV has also experimented with a twisted string actuation system. A DC motor is basically used to twist two tendons together. This shortens the length of the tendons, causing tension and closing of the fingers. The main benefit of this technology is that rotational motion in the motors is directly converted to linear motion in the tendons; no intermediary pulley system is required to move the fingers. Another benefit is that the fingers can apply tremendous pressure. Fundamentally, the tendon pair may be twisted indefinitely, increasing the effort exerted by the finger - until, of course, a mechanical failure occurs somewhere. However, because many rotations are required to fully close a finger, this method of actuating fingers can take a longer time than it supposed to.

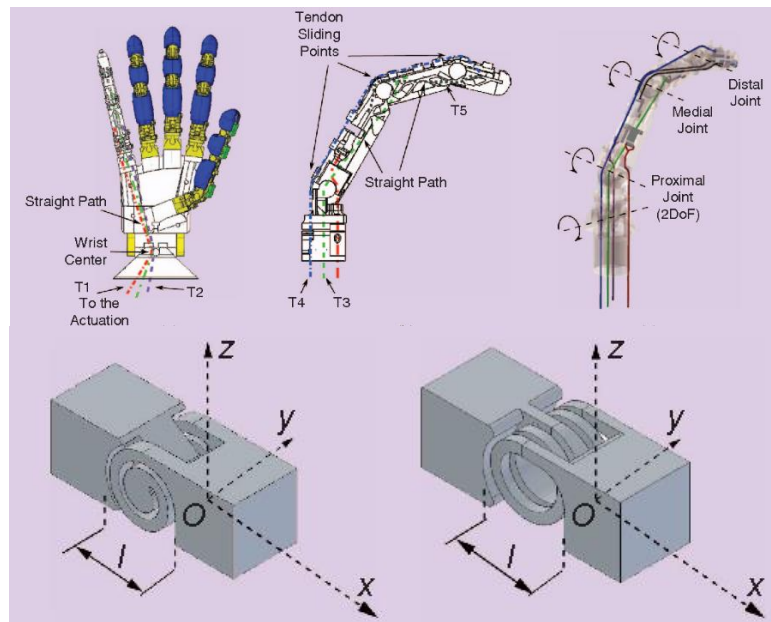


Figure 2.2.5. UB hand IV tendon network (courtesy of Bologna University)

The UB hand researchers appear to have shifted to utilising Servo motors to manipulate fingers in their most recently published video for faster motion. Myoelectric Prosthetic Arm 3D Printed 15 The UB hand IV achieves a high number of degrees of freedom by using a vast tendon network. The commercially available Shadow Hand likewise makes use of a vast tendon network and has 20 degrees of freedom [11]. The Shadow Hand, on the other hand, tensions its artificial tendons using pneumatic air muscles. In both circumstances, a huge area is necessary to drive all of the tendons, resulting in systems that are too big to be attached to an amputee.

Figure 2.2.6 Shadow Hand (courtesy of Shadow Robotics)

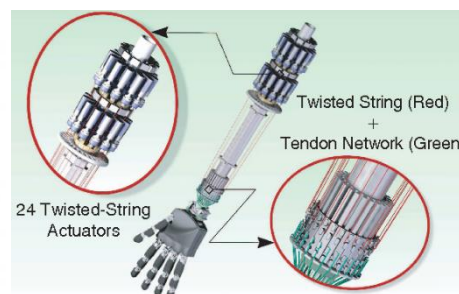


Figure 2.2.7 UB hand IV tendon network (courtesy of Bologna University)

Both of the systems necessitate a large amount of space to accommodate all of the actuators. One significant benefit of artificial tendon-driven prosthetic hands over previously mentioned mechanically joint-linked systems is joint conformance [1]. Fingers may adjust to the shape of the thing they are holding thanks to joint conformity. When joint-connected fingers shut, they are stiff and unyielding; tendon systems, on the other hand, have some flexibility at the joints, as seen below.

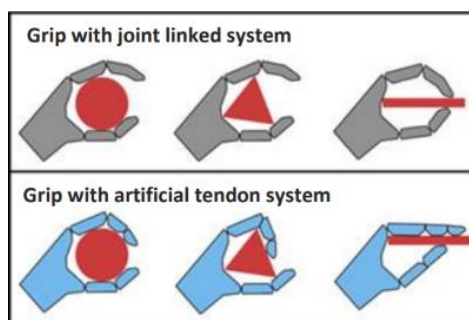


Figure 2.2.8 Depiction of joint conformity (courtesy Open Hand Project)

InMoov 3D Printed Bionic Arms

Developing 3D-printed bionic limbs has grown fairly popular in recent years. Many independent designers and ideas are established online in purpose to create a more advance, affordable, overall better prosthetics. InMoov is a self-funded project that is creating a life-like humanoid robot using 3D printing technology. The entire project is open source and gives excellent mechanical design insight into 3D-printed robotic body components [12]. Because this project is open source, the public can access computer-aided designs and step-by-step instructions on how to 3D print and assemble this system. Tendons operated by servo motors inserted in the forearm control the InMoov fingers.

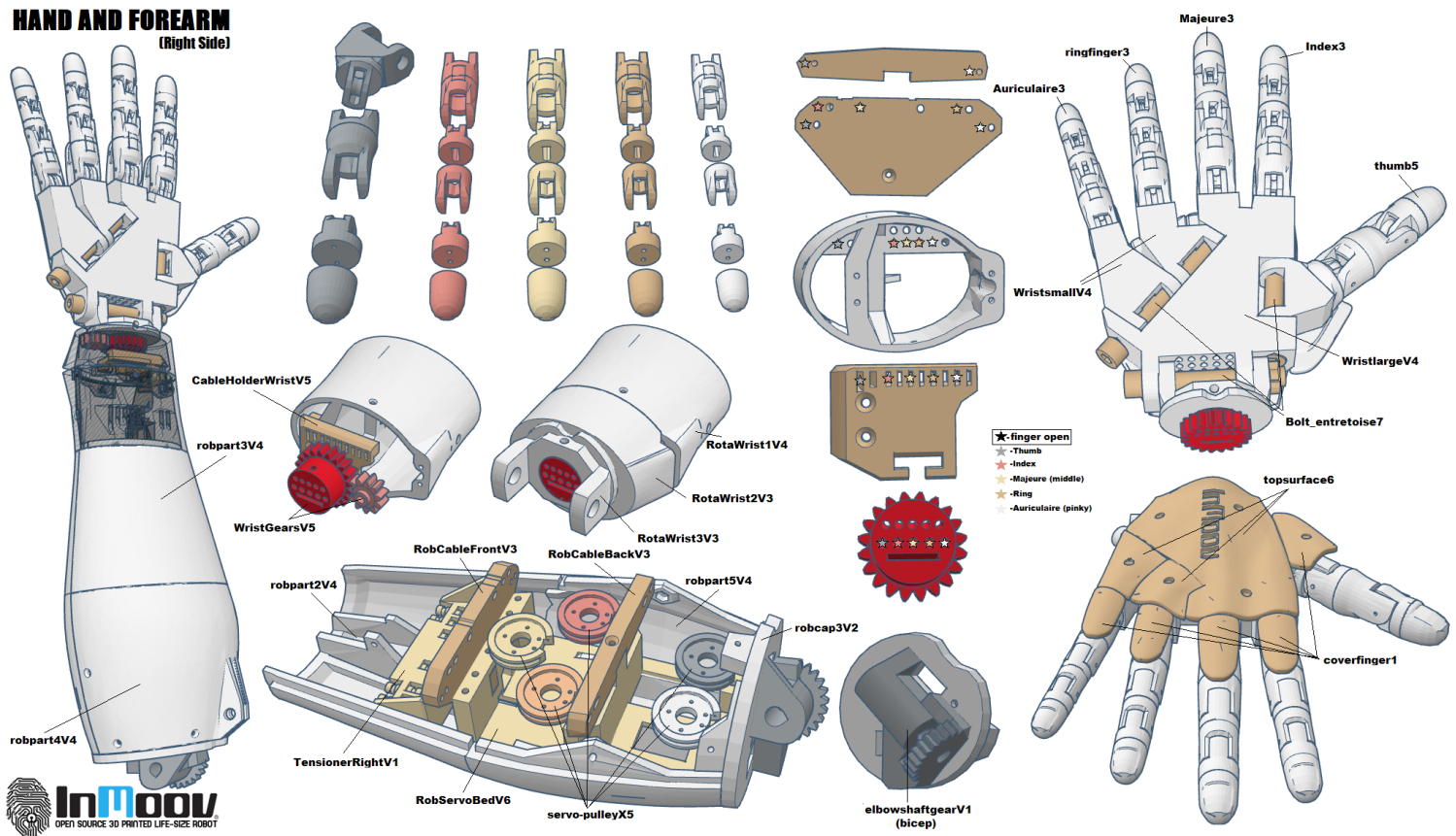


Figure 2.2.9 Bionic Hand (courtesy of InMoov Project)

The InMoov fingers (which involve the thumb) have just one degree of movement, limiting hand dexterity. However, this is a simple solution that has a significant benefit over other anthropomorphic hands in that it is low-cost and easily manufactured via 3D printing. The issue with the InMoov hand is that the Servos take up the whole forearm, leaving no place for it to be connected to a stump between the elbow and wrist.

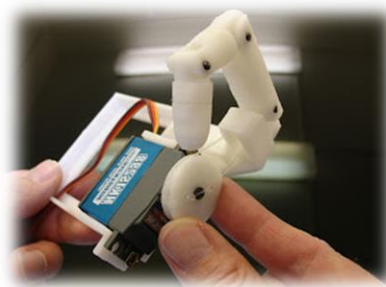


Figure 2.2.10. Finger Joint (courtesy of InMoov project)

2.3 User Control over the Prosthesis

Electromyography Sensing

Myoelectric pulses are electrical pulses generated within the organism by contracting muscles. Surface electrodes on the skin of the patient may detect these small impulses, which can then be utilised to operate the device, which in this case is the prosthetics [23]. Surface EMG approaches include a lot of crosstalk between muscle signals, which is an issue. Because muscle groups are physically close together, especially in the arm, it is difficult to determine which muscle is generating the measured signal via the surface electrodes.

Implanted Myoelectric Sensors

Through a surgical procedure, implanted myoelectric sensors (IMES) are inserted directly into targeted muscles. IMES provides for substantially cross-talk-free signals when used for EMG control. This implies that muscle impulses are more distinct, and deeper muscles can be employed for control as well [20]. As a result, this procedure gives the user greater control over their prosthetic device. IMES system users have been able to independently manipulate their prosthesis's thumb, fingers, and wrist rotation at the same time [25].

2.4 Sensory Feedback of the Prosthesis

One big issue with many prosthetic devices is that they offer no feedback to the user. The touching sensation is a natural feedback system that enables people to make physical modifications both consciously and subconsciously. A user must rely exclusively on eyesight to judge the location and force of their prosthesis in the absence of feedback.

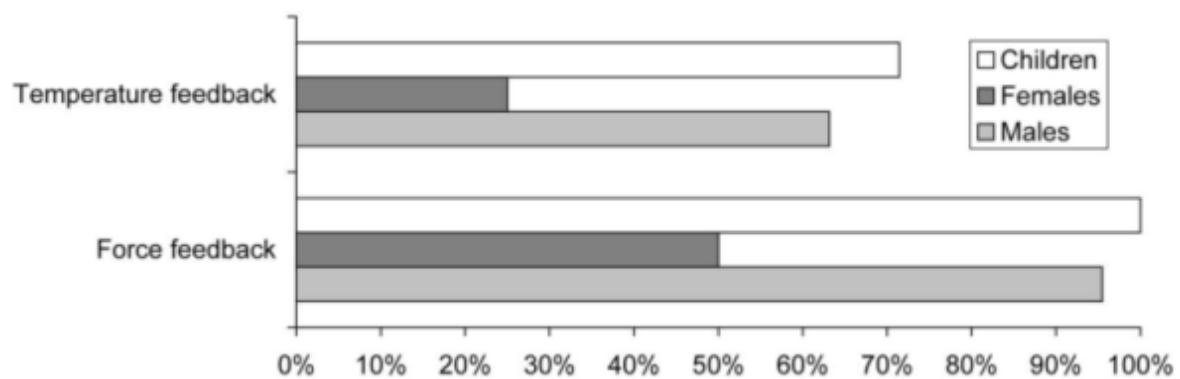


Figure 2.3.1 – Percentage of individuals that see sensory feedback on a survey on prosthetic arm users (courtesy International Society of Prosthetic and Orthotics)

According to survey data, practically of prosthesis users seek some type of contemporary sensory feedback [9]. Current prosthesis can provide feedback by activating senses in specific areas of the body. Sensory replacement is provided by vibration motors and temperature pads placed on the skin's surface. These types of feedback were useful to the majority of prosthesis users. Electro-tactile arrays are another new kind of feedback, it is a fake sense of touch can be manufactured by electronically activating arrays of electrodes [26]. An electro-tactile array on a smartphone screen, for example, may generate simulated surface textures of wood and stone. Electro-tactile patches might be wrapped over an amputee's stump to provide artificial perceptions of touch. Pressure sensors attached to the tips of the fingers might regulate the stimulating impulses. This would simply move the experience of fingertip touches to the stump.

3. Methodology and theory

Description of the methods/techniques used to include the building blocks for the research; all the methods for evaluating results and outcomes; and clear background for results (including math formulae)

3.1. *Biomechanical Principles of Human Hand*

Biomechanics analyses are divided into two perspectives which is kinetics and kinematics. For this research, the viewpoint is focused upon the certain movement that cover the dynamics of the limb. Thus, the equation and calculation that are going to be conducted will come from the kinematics perspective.

The hand consists of a sturdy wrist with at least two digits that can oppose each other with some strength [17]. One or both of the digits should be able to move so that gripping may be achieved. In its most basic form, one digit can be steady with one digit moving against that stable post. Digits benefit from having sensation and being pain-free since this facilitates their use. In terms of biomechanical motion, the hand contains seven manoeuvres that comprise the majority of hand functions.



Figure 3.2.1 The Precision/Terminal Pinch



Figure 3.2.2 The Opposition Pinch



Figure 3.2.3 The Key Pinch



Figure 3.2.4 Chuck Grip/Directional Grip



Figure 3.2.5 Hook Grip



Figure 3.2.6 Power Grasp



Figure 3.2.7 Span Grasp

3.2 *Biomechanical Analysis of Force Distribution*

Tendon Network

The finger extensor mechanism is shown as a network of linked tendons traveling along the phalanges. Each tendon component is depicted as a spring with a linear structure that can only transmit force when taut. As a result, its stiffness meets the following criteria.

$$k_i(l) = \begin{cases} K_i & \text{if } l_i \geq l_{i0} \\ 0 & \text{if } l_i < l_{i0} \end{cases} \dots (1)$$

where K_i is the spring stiffness dictated by the tendon's material characteristic, l_i is the length of the individual tendon component, and l_{i0} is the tendon component's slack length. The course of the tendon component along the bone surface between two tendon network nodes determines the length l_i . The tendon force F_i may be readily connected to its length change using the stiffness defined before:

$$F_i = k_i(l) \cdot (l_i - l_{i0}) \dots (2)$$

The Principle of Minimum Total Potential Energy is used to establish the locations of the nodes of the tendon network and, thereby determining, the forces in the separate components of the tendon network [18]. This is accomplished by minimising the total potential energy of the system Π , which is the sum of the strain energy stored in the system, U , and the potential energy of the external forces, V , which corresponds to:

$$\delta \Pi = \delta(U + V) = 0 \dots (3)$$

Applying the aforementioned method to the tendon network yielded a subsequent set of differential equations with regard to the node coordinates that determine the 3D geometry of the linked network:

$$\frac{\delta \left(\sum_{i=0}^m \left(\frac{k_i(l_i) \cdot (l_i - l_{i0})^2}{2} \right) - \sum_{i=0}^n (F_i \cdot S_i) \right)}{\partial P_{jk}} \dots (4)$$

$$(j = 1, 2, 3; k = 1, 2, \dots, l)$$

where S_i is the displacement of the tendon component and P_{jk} is the j^{th} coordinate of the j^{th} node of the tendon network.

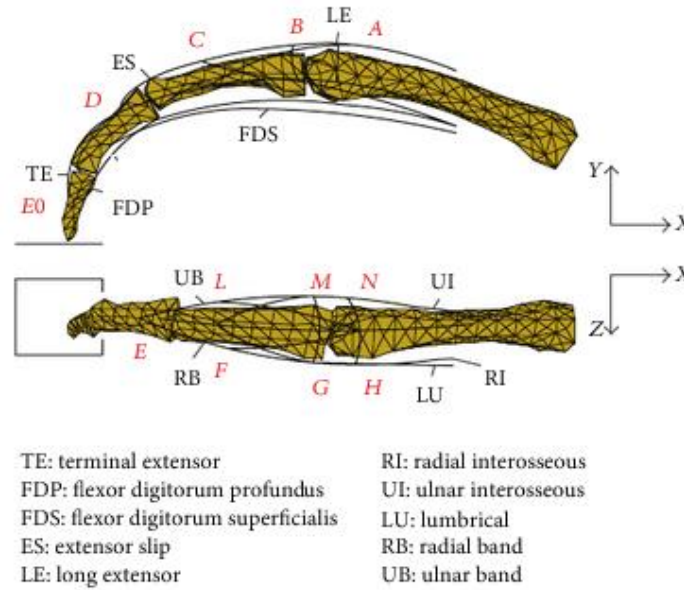


Figure 3.1.8 A three dimensional multisegmented of human index finger
(Courtesy of BioMed Research International)

Each tendon component's journey is simplified for this research by assuming it follows a straight line between two nodes in the tendon network. The nodes are limited to being on the bone surface and moving along a line between the node and one specific vertex of the bone facet holding the node. The selected vertex is the one that corresponds to the node direction of motion being closest to the direction of the tendon force.

Immediately following that, the Lagrange multiplier method is combined with previous *Principle of Minimum Total Potential Energy* (Eq.3) while satisfying the "node stays on bone surface" constraint. The equation below will define the minimisation issue and the accompanying Lagrange function,

where $L_s(P_{jk}) = 0$ is the equality constraint that "keeps the node on the line between the node itself and a vertex," and λ_s is the Lagrange multiplier.

$$\Lambda(P_{jk}, \lambda_s) = \prod (P_{jk}) + \sum_{s=1}^r \lambda_s L_s(P_{jk}) \dots (5)$$

This leads to the following set of equations, which are used to solve for the coordinates of the nodes in the tendon network.

$$\left(\delta \left(\sum_{i=0}^m \left(\frac{k_i(l_i) \cdot (l_i - l_{i0})^2}{2} \right) - \sum_{i=0}^n (F_i \cdot S_i) + \sum_{s=1}^r \lambda_s L_s(P_{jk}) \right) \right) (\partial P_{jk})^{-1} = 0 \dots (6)$$

$(j = 1, 2, 3; k = 1, 2, \dots, l)$

Multisegmented Finger Model.

External stresses delivered to the tendon network acted along the RI, LU, LE, and UI lines of the muscles (refer to figure 3.1.8) [18]. A multisegmented finger model was built to provide kinematic and kinetic inputs to the tendon network model. It is possible to express the following in terms of moment equilibrium around each degree of freedom (DOF) of the three joints with,

$$F_{FDP} \alpha_{FDP, DIP, FL} - F_{TE} \alpha_{TE, DIP, FL} + P_x l_1 \sin \theta_1 - P_y l_1 \cos \theta_1 = 0 \dots,$$

$$F_{FDP} \alpha_{FDP, DIP, FL} - F_{ES} \alpha_{ES, PIP, FL} - F_{UB} \alpha_{UB, PIP, FL} - F_{RB} \alpha_{RB, PIP, FL} + P_x (l_1 \sin \theta_1 + l_2 \sin \theta_2) - P_y (l_1 \cos \theta_1 + l_2 \cos \theta_2) = 0 \dots,$$

$$F_{FDP} \alpha_{FDP, MCP, FL} - F_{LE} \alpha_{LE, MCP, FL} + F_{RI} \alpha_{RI, MCP, FL} + F_{UI} \alpha_{UI, MCP, FL} + F_{LU} \alpha_{LU, MCP, FL} + P_x (l_1 \sin \theta_1 + l_2 \sin \theta_2 + l_3 \sin \theta_3) - P_y (l_1 \cos \theta_1 + l_2 \cos \theta_2 + l_3 \cos \theta_3) = 0 \dots,$$

$$F_{RI} \alpha_{RI, MCP, AD} - F_{UI} \alpha_{UI, MCP, AD} + F_{LU} \alpha_{LU, MCP, AD} + P_z (l_1 \cos \theta_1 + l_2 \cos \theta_2 + l_3 \cos \theta_3) = 0$$

Where as F_{TE} , F_{RI} , F_{UI} , F_{LU} , F_{ES} , F_{UB} , F_{RB} , and F_{LE} are the load resulted from the movement of the major muscles and tendons of the finger extensor mechanism. While F_{FDP} is the load of the finger flexor muscle that spans the three joints. α is the expression for flexion/extension or adduction/abduction.

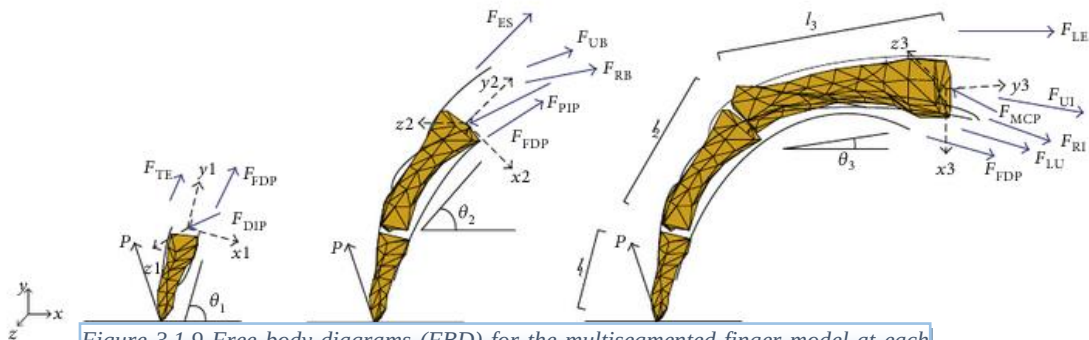


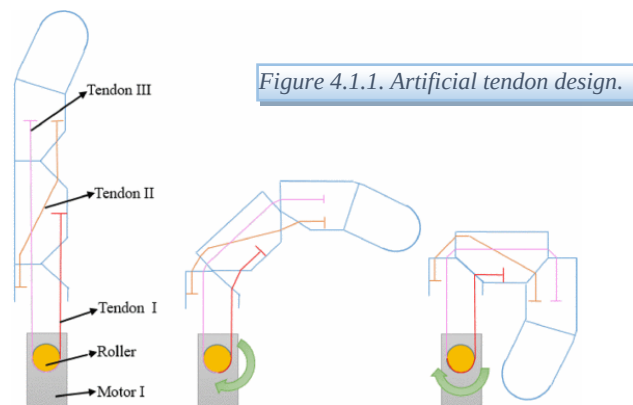
Figure 3.1.9 Free body diagrams (FBD) for the multisegmented finger model at each joint during static pressing (courtesy of BioMed Research International)

4. Design and Analytical Investigation

4.1. Mechanical Design

This research examined the following existed design from the web suitable to be a prosthetic hand. The designs that are appeared in this research study is not practically used as prosthetics but with some adjustments it could technically work as a cheaper and easy to craft (DIY-ness) alternative to the known modern prosthetics such as iLimb, Bebionic 3, ShadowArm, and HeroArm. Its components are also commercially available online as construction parts of a five-fingered robotic hand..

4.1.1. Early Idea and Concept Drawings



a) complete extension b) partial flexion c) complete flexion

Originally, the design of the prosthetic hand in this research is heavily inspired by tendon network-based designs which is quite a unique design and concept. It uses a fishing line as tendon network of the hand to remove weight and also it is an innovative idea. After exploring numerous actuation mechanisms for prosthetic arms. Artificial tendons are a feasible technique of actuating bionic hands, as evidenced by the literature evaluations of the Shadow Hand, UB Hand, and InMoov. Any high-strength line that does not stretch when strained can be a tendon. These wires link to the fingers and are tensioned by forearm motors. When you pull on the tendons, the fingers open and close.

Unfortunately for this research, the idea is scraped and back to joint linkage system. The movement of the finger will be shown to be similar with this illustration below. To be lightweight and attachable to an amputee, the electric motors controlling these joints must be adapted and be one with the device. These motors will be as close to the fingers as possible, fortunately, we are able to put them within the palm area.

Though the movement network idea is changed, the decision to drive the tendons using ordinary servo motors was determined early on. Servo Motors are geared direct current electric motors that may be programmed to rotate to particular angular locations.

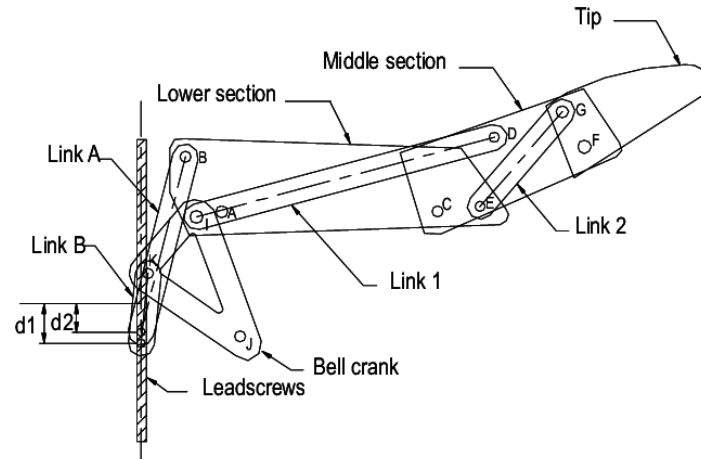


Figure 4.1.2 Joint linkage system finger design

4.1.2. Computer Assisted Design

Solidworks is a computer design software program that is used to represent solid mechanical components and assemblies. Solidworks is a prominent engineering program that has been extensively utilised in the design and analysis of mechanical components. Although, the design is also sketch and designed using Shapr3D due to its application is available on portable devices such as an Ipad.

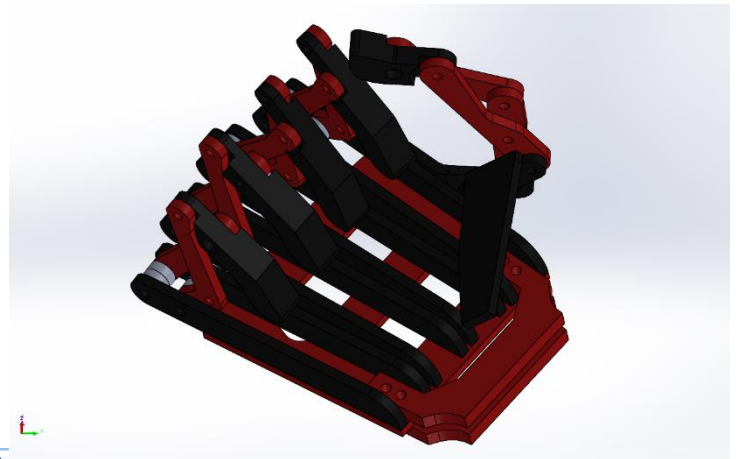
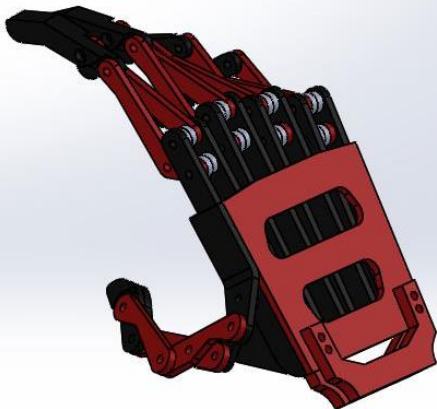


Figure 4.1.3. Hana prosthesis prototype CAD

This design will be modified again after printing it using a 3D printing method as there are some parts of the components that are yet to be added, such as the servo motors, screws, and miscellaneous cable part. Each finger was created as a separate module. As a result, depending on the arrangement of the severed fingers, finger modules can be readily joined and deleted throughout the assembling process. Driving power is generated in each finger module by a direct current (DC) motor and delivered to the joint frames in the distal, middle, and proximal phalanxes through linkage. The linkage are connected to the actuator by means of a rotator.

Each finger consists of three individual printed components linked together with metal pins. The artificial tendon loops around the inside tip of the finger to create a linkage locking point. This joint is located beside the bone outside the finger to form an harmonic bond. When the joint is pulled, rotational forces are applied to all the joints and the finger curls up.

4.1.3. Mechanical Calculations

Finger Actuation Speed

The anti-blocking servo has an operating speed of 0.15 s/60°. A full wrist rotation from a palm up to a palm down position (180°) therefore takes $(0.15/60) \times 180 = 0.45\text{s}$.

It has been measured that a tendon must move about 2cm to move the finger from fully extended to fully flexed. Using the arc length formula,

$$\text{length} = \frac{n^\circ}{360^\circ} \times 2\pi r$$

Where length is 2cm, r is the radius of the custom servo horns (7mm). It is calculated that the Servo must rotate 160° to completely open/close each finger. We find that the maximum time to open/close a finger is $(0.15/60) \times 160 = 0.4\text{s}$.

4.2. Electrical Design

Signal Flow Overview

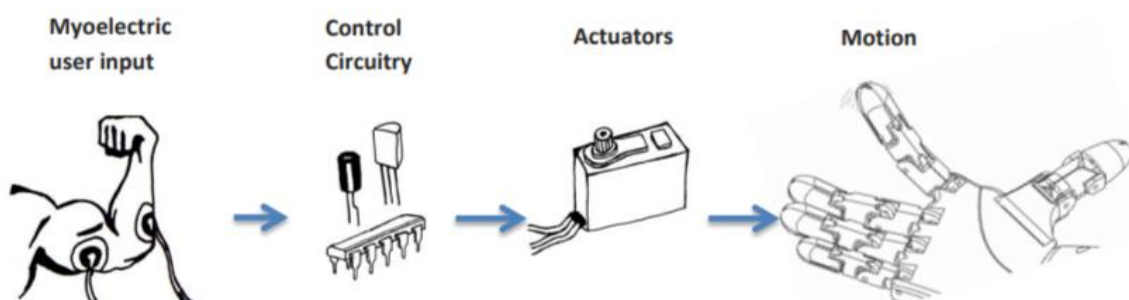


Figure 4.2.1 Signal Flow Diagram

The EMG sensor board amplifies, rectifies, and smoothes an analogue signal generated by user flexing. This analogue signal is used by the microcontroller to create a pulse width modulated signal. This activates servo motors, which tighten the tendons and cause the fingers to curl up.

Actuation



The actuators in this system, as previously stated, are anti-blocking servo motors. These motors may be programmed to rotate to angles of up to 180 degrees from rest. Because the joint linkage moves relatively more to open and close each finger, the angular precision of each servo influences how precisely the fingers can be controlled.

Microprocessor



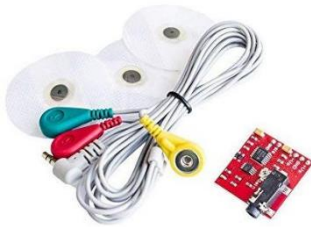
The Arduino Mega 2560 is to be used as the central computer for this system. This beast of a processor has everything needed to support the microcontroller and definitely is more than adequate for this design. In order to program the device, a dupont wire has to attach to the microcontroller circuitry and is passed data through a USB connection to a PC.

Voltage Regulators

Power regulators were utilised to regulate the voltage and power provided to the servos and microprocessors. These voltage regulators prevent a servo from stalling and taking a considerable amount of electricity from the battery. In the worst-case situation, if this happened to all six servos at the same time, it could easily destroy the electronics or possibly start a fire. Due to a lack of available 5V surface mount regulators, 5V surface mount regulators were utilised to power the servos, and a 3.3V regulator was used to power the microcontroller.

The particular regulators utilised provide a maximum current of 1A. It is reasonable to assume that each servo will require at least 500mA of electricity to function. As a result, each 1A power regulator powers two servos. These particular regulators keep the output steady at 5V. As ideal servo power is around 6.5V, this results in slightly slower and weaker servo performance.

Electromyography (EMG) Sensing



Single-channel EMG sensor boards that are simple to use have been utilised to detect and quantify muscle activity. A tiny PCB and three surface electrodes are included in this kit. Two of these electrodes assess the voltage potential across a muscle, while the third serves as a ground reference point on a bony structure. The muscle sensor kit is intended for use with a microcontroller. As a user flexes, an internal amplification system converts minute electrical pulses into an addressed and smoothed signal that can be fed into an analogue to digital converter on a microcontroller.

Power Supply

The power supply used in this research are one 9V1A adapter. Servo motors draw a lot of current when they're running. Disposable batteries would not be a good option since the servos would waste power too quickly, necessitating regular replacement. The muscle sensor kits use very little power; however, the servos and microcontroller use a lot. To provide a positive and negative voltage reference, the muscle sensor kits require two power sources. These sensors are sensitive to spikes in the input voltage and require a consistent power source to provide high-quality readings. Because of this, the EMG sensor boards are powered by 9V adapter. This adapter should keep the experiment going for a long time. A more advanced electrical system might connect all components to a single power source by generating a negative voltage for the EMG sensors. This would reduce the size, weight, and clutter of the current power supply system.

4.3. Kinematics Analysis

Position Analysis

Because of the diameter of the tendon fixing frame is equal to the diameters of the joint frames in the DIP, PIP, MCP joints, in natural motion, the angles of each phalange will be defined as $\theta_1, i = 1, 2, \text{ and } 3$ while the positions of the nodes P_1, P_2, P_3 is represented and mapped using cartesian coordinate frame.

$$P_1 = (l_1 \cos \theta_1, l_1 \sin \theta_1)$$

$$P_2 = (l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2), l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2))$$

$$P_3 = (l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3),$$

$$l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3))$$

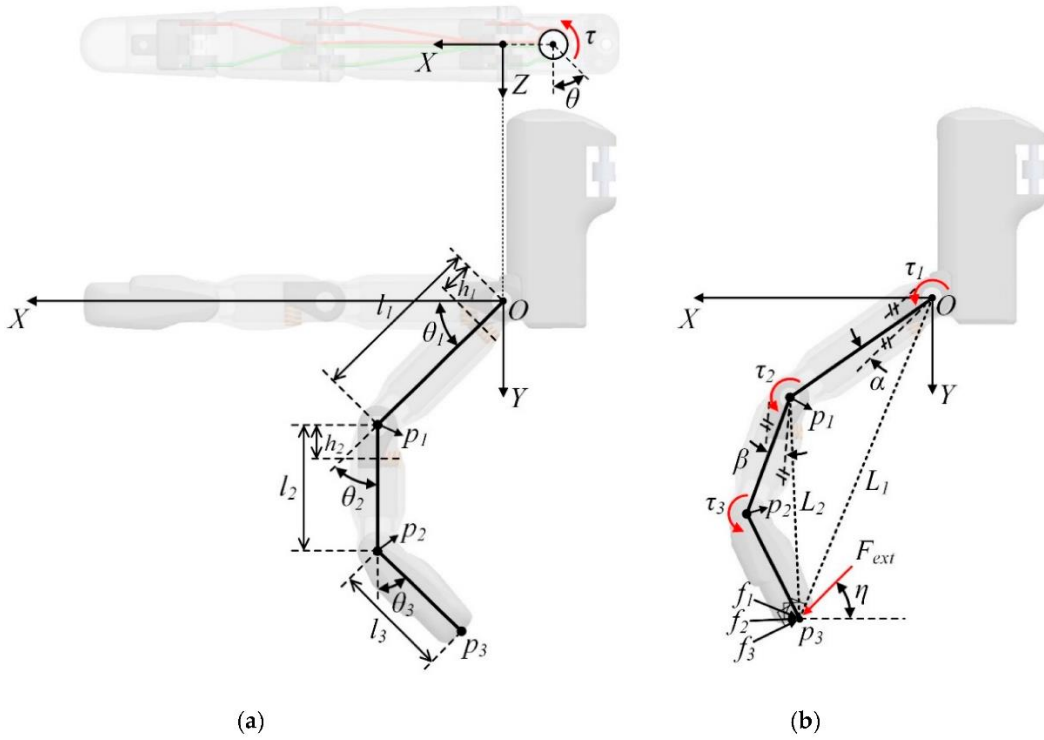


Figure 4.3.1 Coordinate system and variable in natural and grasping motion

α and β are angle that exist due to grasping method, thus the nodes P_1, P_2, P_3 derives as:

$$P_1 = (l_1 \cos(\theta_1 - \alpha), l_1 \sin(\theta_1 - \alpha))$$

$$P_2 = (l_1 \cos(\theta_1 - \alpha + l_2 \cos(\theta_1 - \alpha + \theta_2 - \beta), l_1 \sin(\theta_1 - \alpha) + l_2 \sin(\theta_1 - \alpha + \theta_2 - \beta))$$

$$P_3 = (l_1 \cos(\theta_1 - \alpha) + l_2 \cos(\theta_1 - \alpha + \theta_2 - \beta) + l_3 \cos(\theta_1 - \alpha + \theta_2 - \beta + \theta_3),$$

$$l_1 \sin(\theta_1 - \alpha) + l_2 \sin(\theta_1 - \alpha + \theta_2 - \beta) + l_3 \sin(\theta_1 - \alpha + \theta_2 - \beta + \theta_3))$$

Velocity Analysis

When the angular velocity of the actuator during natural motion is ω , the velocities of the nodes P_1, P_2, P_3 are calculated as follows:

$$V_1 = \omega(-l_1 \sin \theta, l_1 \cos \theta)$$

$$V_2 = \omega(-l_1 \sin \theta - 2 \cdot l_2 \sin 2\theta, l_1 \cos \theta + 2 \cdot l_2 \cos 2\theta)$$

$$V_3 = \omega(-l_1 \sin \theta - 2 \cdot l_2 \sin 2\theta - 3 \cdot l_3 \sin 3\theta, l_1 \cos \theta + 2 \cdot l_2 \cos 2\theta + 3 \cdot l_3 \cos 3\theta)$$

Where $\theta = \theta_1 = \theta_2 = \theta_3$

Static Analysis

When the torque τ produced by an actuator is divided into each joint equally, $\tau_1 = \tau_2 = \tau_3 = \frac{\tau}{3}$. The relations between each force that generated by each joint and the external load F_{ext} generated by contact with an object node P_3 can be analysed accordingly with the ranges of α and β . The value of the spring force f_{s_j} ($j=1$ and 2), produced by the torques (τ_1 and τ_2) after an object is contacted at P_3 is derived as follows.

$$f_{s_j} = k_j x_j$$

Where k_j and x_j are the spring constant and compressed length of the j^{th} linear, respectively. Then, the produced forces (f_1 and f_2) are formed by the spring forces at the range $0^\circ < \alpha$ and $\beta < 25^\circ$. After the compression of the springs (α and $\beta = 25^\circ$), f_j is determined by the sum of each spring force and the force produced by τ_j . Thus, the relation between the forces by joints and the external force is derived by,

$$F_{ext} = \sum_{i=1}^3 f_i = \left[\frac{\tau_3}{l_3} \cos \theta_{f_3} + h_2 \frac{f_{s_2}}{L_2} \cos \theta_{f_2} + h_1 \frac{f_{s_1}}{L_1} \cos \theta_{f_1}, \frac{\tau_3}{l_3} \sin \theta_{f_3} + h_2 \frac{f_{s_2}}{L_2} \sin \theta_{f_2} + h_1 \frac{f_{s_1}}{L_1} \sin \theta_{f_1} \right]^T$$

for $0^\circ < \alpha$ and $\beta < 25^\circ$

$$F_{ext} = \sum_{i=1}^3 f_i = \left[\frac{\tau_3}{l_3} \cos \theta_{f_3} + \frac{\tau_2}{L_2} \cos \theta_{f_3} + \frac{\tau_1}{L_1} \cos \theta_{f_3} + h_2 \frac{f_{s_2}}{L_2} \cos \theta_{f_2} \right. \\ \left. + h_1 \frac{f_{s_1}}{L_1} \cos \theta_{f_1}, \frac{\tau_3}{l_3} \sin \theta_{f_3} + \frac{\tau_2}{L_2} \sin \theta_{f_3} + \frac{\tau_1}{L_1} \sin \theta_{f_3} + h_2 \frac{f_{s_2}}{L_2} \sin \theta_{f_2} + h_1 \frac{f_{s_1}}{L_1} \sin \theta_{f_1} \right]^T$$

for α and $\beta = 25^\circ$

Where θ_{f_i} is the angle of between X-coordinate and the i^{th} force and h_j and L_j are the distances between the axis of each revolute joint and the j^{th} linear spring and the fingertip P_3 respectively. In equation above, the external force is calculated to be:

$$F_{ext} = [f_{ext} \cos \eta, f_{ext} \sin \eta]^T$$

Where F_{ext} is the value of the external force and η is the angle between X-coordinate and the external force. By using the equation calculated above, the specifications of the actuator and gearbox can be calculated when the derived payload and the velocity of the finger module are given.

5. Presentation of experimental results of the final constructed product

A clear presentation of experimental and/or theoretical results obtained, highlighting any trends or points of interest. Provide a detailed, logical analysis of your results, and critically analyse your data. Discuss your findings in detail.

5.1. *Modified Prosthetic Hand*

Fingers



Figure 5.1.1 Thumb



Figure 5.1.2. Finger

Complete Hand



Figure 5.1.3 Back palm

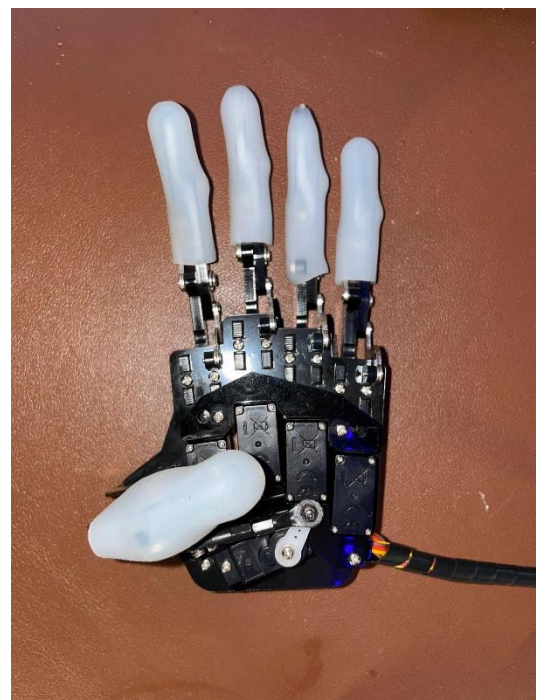


Figure 5.1.4 Palm

The final system is a bionic hand with five degrees of freedom that can be operated by myoelectric impulses. The overall design is made up of thirteen distinct 3D printed components.

All of the fingers move separately and can make different variation of movements. A set of EMG electrodes put on the forearm and/or bicep allows the user to control the mobility of their arm. At this point, two electrode sets allow for basic control of the arm's range of motion.

System Properties	Description
System Weight	300 g
Material	Acrylic
Joint Linkage	Metal pins and screws
Power Source	9V1A adapter
Microcontroller	Arduino MEGA
Servo Voltage Regulators	AP1117 – 5V output, maximum current 1A

Table 1. System Specification

5.2. Achievable Grasp



Figure 5.2.1 Power Grip Palm View



Figure 5.2.2 Power Grip back palm view

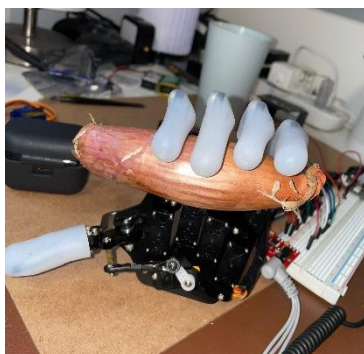


Figure 5.2.3 Handle Grip



Figure 5.2.4 Pinch Grip

5.3. Actuation

Fluidity

The fingers move reasonably smoothly and naturally. The fluidity of finger motions is determined by various elements, including friction between moving plastic components, servo control, and the tension of the tendons.

Strength

Using small kitchen scales, testing shows that the fingers can deliver at least 500g of force apiece. The servo motors might indeed be turned further to increase the stress on the joint. This would effectively boost each finger's closing force. The strength of the printed acrylic resin components, rather than the torque of the servo motors, is the limiting element in finger force. If we kept raising the servo tension, either a finger component would break, or a fracture would occur.

5.4. Control

The simple Boolean EMG control cycled through and activated distinct states. One stage permitted wrist rotation, whereas another permitted finger actuation. The hand might be instructed to close, rotate to a specific place, rotate back, and then reopen. A similar motion might be used to grip and pour liquid from a bottle. Using this basic EMG control, however, switching between the two states made the job slow and monotonous.

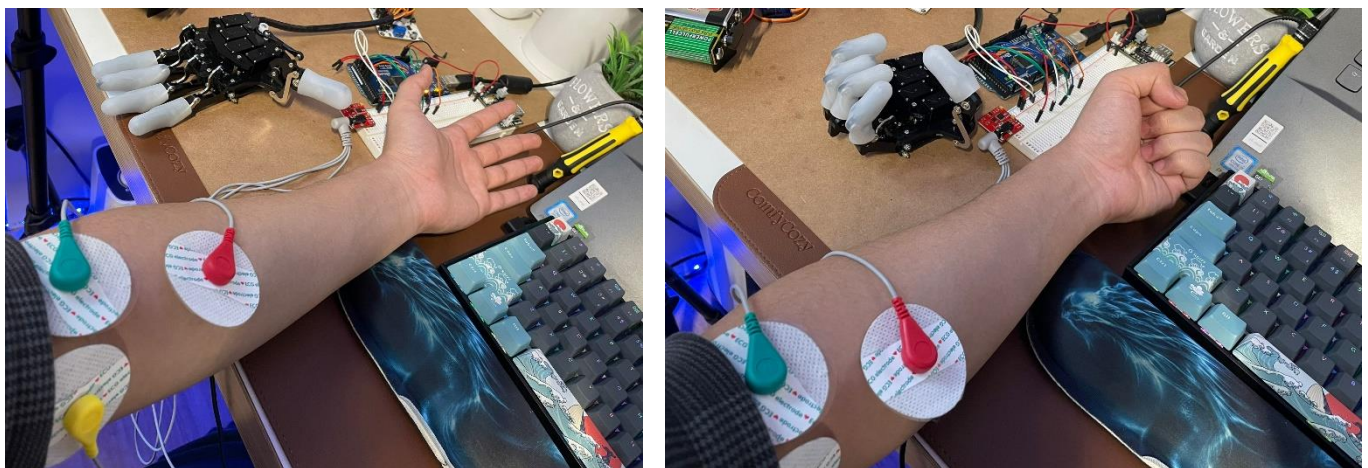
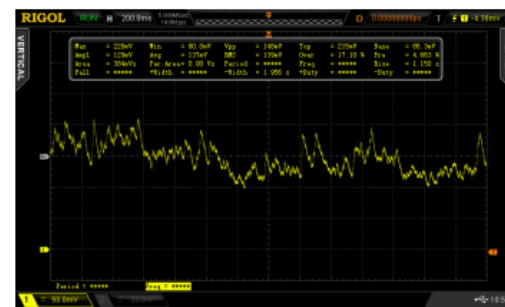
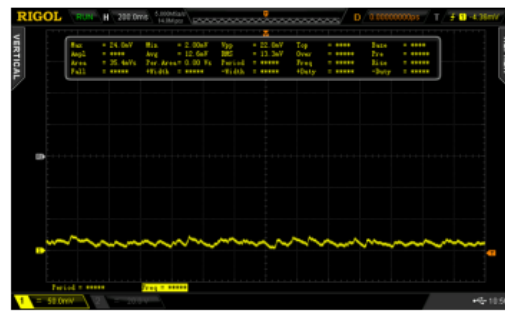


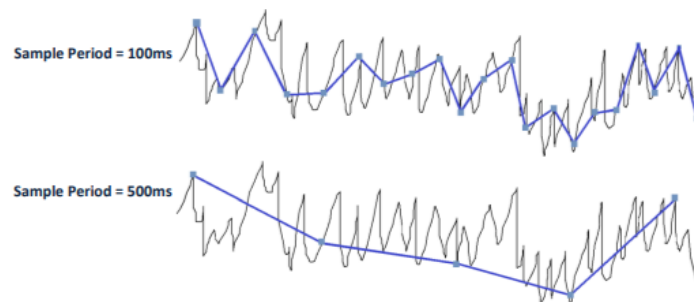
Figure 5.4.1 User controlling the opening and closing of the hand through muscle flexing.

Finger proportional control worked rather well; the harder the user flexed, the more the fingers closed. However, due to the use of noisy signals to control servo positions, this proportional control caused the fingers to shake when attempting to close. Initially, the EMG signals were sampled every 100ms, and the magnitude of the signal was converted to a decimal number. Every 100ms, the servos were likewise updated.

The EMG signals are rather noisy, as seen in the oscilloscope visualisations on the next page. This implies that the signal voltage level can considerably spike or drop in 100ms, causing the servos to be ordered to move around to different places. This is especially true for high-level signals.



The sampling points utilised for servo control, as seen below, are continually changing up and down. A smooth signal is sought, which means that these EMG outputs should be filtered to enhance control characteristics. Increasing the duration between ADC samples and servo updates reduces finger shaking but does not solve the problem.



Proportional control requires an EMG signal that grows linearly with flex intensity. The user concentrated on beginning at rest, gradually increasing flex intensity to a maximum, and then releasing to create the screen shot below.



With increased flex strength, the size of this signal seems to rise linearly. This is necessary for precise proportional control.

6. Discussion and conclusions

Overall System Performance

The final system provides relatively good performance and characteristics for a prototype 3D printed model. The device is fast and responsive to electro-myography user input but offers limited strength. Over the course of testing the system has proven to be reliable and has required minimal maintenance since being assembled. The biggest downfall of this design is its lack of toughness. In the real world a practical prosthetic hand must be able to absorb sudden shocks and support heavy loads without failing.

Benefits to an Amputee

At this point, the exhibited prosthetic hand is not ready for usage by an amputee; rather, it is a low-cost robotic hand. The University may be able to organise partnership with a medical institute to allowing the device to be tested and used by amputees. Such testing would be extremely beneficial in studying and enhancing the device's performance.

Implications & Contribution to the Field

The device provided here serves as a foundation for future research by final-year engineering students to build and test advanced prosthetic designs such as complex EMG control algorithms, integrated pressure feedback, and other advanced bio-mechatronic concepts and designs.

With the rise of the 3D printing industry in the future, better printers and materials will enable students to design more 'commercial-like' prosthetic devices - sturdy and lasting systems that might serve a wide spectrum of patients with a missing limb. Continuous research will hopefully result in a system that is more durable and provides better dexterity and control. Perhaps a future design will benefit amputees and improve people's quality of life.

6.1. *Future Research/Improvements*

Mechanical Design & Manufacturing

This research has exclusively used acrylic resin for 3D printing. Nylon may also be used for 3D printing and has substantially higher strength than flexibility. A variety of 3D printed materials, such as unique 3D printed rubber fingertip grips, might be utilised to improve the device.

The artificial tendon finger actuation system outlined in the literature study would be flexible, more affordable and unique than an Joint linked network. However, it could be more weaker and easily tear to use in the servo motors.

Future students interested in experimenting with different actuation methods should print and construct the open-source prosthetic arm accessible on the InMoov website. This research is pushing the boundaries of 3D printed prosthesis, even developing a joint-linked actuation system powered by miniature electric motors in the palm.

Custom PCB/Servo Controller

Custom printed circuit boards are far more reliable than prototyped circuits. A bespoke PCB will be required to construct a board small enough to fit within the gadget as the circuitry grows more sophisticated by including multiple pressure sensors and vibration motors.

AMME High School is hoping to acquire an electronic 3D printer. It is recommended that future students practise with this machine before submitting any PCB designs for fabrication. It may also be beneficial to utilise a servo controller board, which would minimise the microcontroller's overhead and eliminate the requirement for voltage regulators.

Advanced EMG Algorithms and Processing

Future students are urged to create more complex EMG control algorithms that allow for the simultaneous control of several arm motions. A control system of this type would have to include some form of calibration mechanism to allow the system to respond to each individual user's myoelectric signals.

Complete Arm Design

As this research is only limited to human hand and certain fingers, future students should be able to design the whole complete arm with tendon in the wrist. Movable biceps and triceps might also be beneficial for an amputee who lost an arm.

7. Project management, consideration of sustainability and health and safety

The fundamental source of project management was the use of a Gantt chart, as displayed in the figures below, to support the time history of the project, ensuring that work flows smoothly and without pressures on health. The goal of the Gantt chart is to provide a visual reference of realistic time-based milestones for finishing project portions. The original Gantt Chart is supposed to evolve over time to truly reflect the project, with parts updated, added, or removed. Every step taken in the project was subjected to a risk assessment to ensure that the project meets the expected milestones on time and that any risks or possible difficulties with the experiments that might cause a delay or incompleteness of work are reduced. Because of the experimental technique, the initiative involves health and safety hazards.

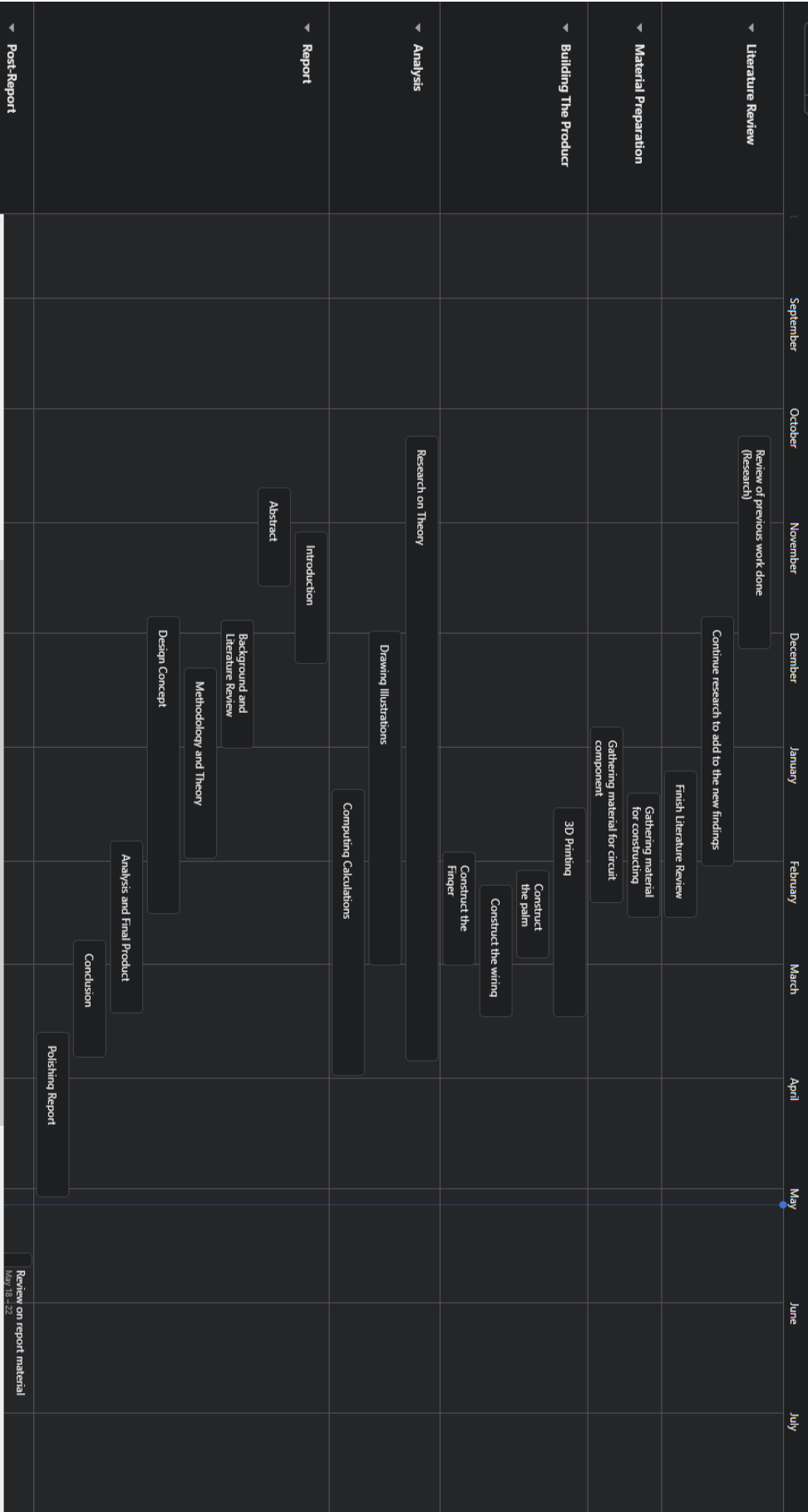
Modelling work necessitates the usage of the man-hour required to visit the computer station. Computer-related ailments include back difficulties from poor posture for long periods of time, eye strain from focusing on a pixelated screen, and repetitive strain injury. Due to the potential risks issued, periodic pauses were taken every two and a half hours to rest the eyes and the body, and a workstation with a comfortable chair was chosen to complete the project, with a soft cushion supporting the arms, wrist tests, and regular typing breaks to reduce the risk of RSI.

Table 2. Risk Assessment

Risk Item	Effect	Cause	Likelihood	Severity	Action to minimise risk
Unforeseen delays in analysis/experimental procedure	Delays in the completion of the project, or enabling after hours work to accommodate the deadline	Unfamiliarity with the Biomechanics topics, electrical components, and certain programming language like Arduino.	M	M	Organise work time, set a deadline on work progress well, time management of other assignments in different module, and refer to Gantt Chart on progression
Loss of work	Setback in project and report completion	Failure in hardware or loss of working materials	L	H	Punctually save work on multiple sources
Illness	Hinders the ability to focus on work and may degrade the quality of the report	COVID, other airborne diseases and genetics disease such as Asthma	M	H	Adjust the project, accordingly, taking breaks, eat healthy, such that the project carries merit

L – Low, **M** – Moderate, **H** – High.

7.1. Gantt Chart



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