FAKULTA MECHATRONIKY,
INFORMATIKY A MEZIOBOROVÝCH
STUDIÍ TUL

Diplomová práce

Development of a moving hand model

Studijní program:	N0714A270010 Mechatronika
Autor práce:	**Bc. Abdul Rahman Abdul Moghni**
Vedoucí práce:	Ing. Jan Koprnický, Ph.D. Ústav mechatroniky a technické informatiky

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INFORMATIKY A MEZIOBOROVÝCH
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Zadání diplomové práce

Development of a moving hand model

Jméno a příjmení:	**Bc. Abdul Rahman Abdul Moghni**
Osobní číslo:	M21000170
Studijní program:	N0714A270010 Mechatronika
Zadávající katedra:	Ústav mechatroniky a technické informatiky
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Zásady pro vypracování:

1. Familiarize yourself with the anatomy of the human hand.
2. Familiarize yourself with the 3D printing technologies used for the production of artificial hands.
3. Use a 3D scanner to obtain a 3D model of a human hand.
4. By appropriate modification in the CAD system, insert movable joints into the model to realize a simplified movable mechanical hand model.
5. Design a robotic hand system with appropriate control and action elements.
6. Realize the hand model using 3D printing technologies and open source electronic development platforms.
7. Test the created model using basic grip forms.

Rozsah grafických prací: dle potřeby dokumentace
Rozsah pracovní zprávy: 40-50 stran
Forma zpracování práce: tištěná/elektronická
Jazyk práce: Angličtina

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[1] ČIHÁK, Radomír. *Anatomie 1*. Třetí, upravené a doplněné vydání. Praha: Grada, 2011. ISBN 978-80-247-3817-8.
[2] ÖZKAYA, Nihat et al. *Fundamentals of Biomechanics: Equilibrium, Motion, and Deformation*. Cham: Springer International Publishing. ISBN 3319447378;9783319447377;
[3] BALASUBRAMANIAN, Ravi; SANTOS, Veronica J. (ed.). *The human hand as an inspiration for robot hand development*. Springer, 2014. ISBN 978-3-319-03017-3
[4] LIČKA, Antonín. *Využití 3D skenovacích technik pro 3D tisk protézy ruky*. Liberec, 2022. Diplomová práce. Fakulta zdravotnických studií Technické univerzity v Liberci. Vedoucí diplomové práce Jan Koprnický.

Vedoucí práce: Ing. Jan Koprnický, Ph.D.
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V Liberci dne 12. října 2022

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21. května 2023 Bc. Abdul Rahman Abdul Moghni

Development of a moving hand model

Abstrakt

Tato práce podrobně popisuje vývoj protetické ruky. Věnuje se pouze anatomii horní končetiny se zaměřením na předloktí. Pro zjednodušení bude práce rozdělena do několika fází. Jako první fáze je tedy zvolena amputovaná končetina. Ve druhé fázi je zdravá ruka naskenována přístrojem EinScan 2X pro plus, aby bylo možné provést správná měření pro protézu ruky. Třetí fáze se stará o změnu výstupních dat ze stroje EinScan 2X pro plus, což je tuhá naskenovaná ruka, a její následnou úpravu pomocí softwaru Fusion 360 přidáním kloubů do ní, aby byla kinematicky pohyblivá. Ve čtvrté fázi jsou do protézy ruky sloučeny aktuátory, které ji plně ovládají. Nakonec je na protetickou ruku aplikováno několik testů, které slouží k ověření její funkčnosti, schopností a omezení.

Klíčová slova: protetická ruka, EinScan Pro 2X, Fusion 360, předloktí, horní končetina, aktuátory, tuhá naskenovaná ruka.

Development of a moving hand model

Abstract

The thesis details the development of a prosthetic hand. It is devoted only to upper limb anatomy focused on the forearm. In order to facilitate this thesis, it will be divided into phases. So as the first phase, an amputated limb is chosen. In the second phase, the healthy hand is scanned with EinScan 2X pro plus machine to take the correct measurements for the prosthetic hand. The third phase takes care of changing the output data of EinScan 2X pro plus machine, which is a rigid scanned hand, and then modifying it using Fusion 360 software by adding joints into it to make it kinematically movable. For the fourth phase, actuators are merged into the prosthetic hand to fully control it. Finally, several tests are applied to the prosthetic hand as a verification approach of its functionalities, capabilities, and limitations.

Keywords: prosthetic hand, EinScan Pro 2X, Fusion 360, forearm, upper limb, actuators, rigid scanned hand.

Acknowledgements

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Contents

1 Introduction

Prosthetic hands have become increasingly advanced in recent years. Thanks to the fact that the design, hardware, and software have gone through great improvements and big achievements. The design of prosthetic hands is crucial, as it affects both the aesthetics and functionality of the device. Hardware, such as sensors and motors, is also important for enabling the prosthetic hand to move and interact with objects and the surrounding environment. Additionally, software plays a critical role in controlling the movements of the prosthetic hand and allowing it to respond to various inputs. In this context, this master thesis will explore the design, hardware, and software aspects of prosthetic hand, highlighting the current state of the art and potential future developments in this rapidly evolving field.

1.1 Motivation

The physical effects of limb amputations on patients can be severe, leading to psychological distress, economic hardship, social reintegration difficulties, and often low acceptance of conventional prosthetic replacements. The primary aim of prosthetic reconstruction is to assist in the reintegration of young and healthy individuals back into social and professional environments [1, 2]. However, The proportion of individuals who use prostheses over the long term is limited and can vary significantly according to various studies [3, 4, 5, 6]. Literature [3, 4, 6, 7, 8] reports a range of prosthetic usage rates in upper extremity amputees, varying from 9% to 81% depending on the level of amputation. The broad range could be due to the differences in the cohorts being studied, including factors such as the level of amputation and the type of terminal device used[3]. According to the most comprehensive study on the utilization and abandonment of upper-limb prostheses, it was found that, on average, one out of every five people rejects their prosthetic device [3]. Overall, prosthetic acceptance rates are generally higher for individuals with distal amputations, while above-elbow amputees have rejection rates of 60% or more when it comes to using prosthetics [3, 4, 5, 6]. Numerous surveys have been carried out to examine the rationales behind the usage or non-usage of prosthetic hands, as well as factors connected with successful prosthetic rehabilitation and patients' worries about various prosthetic characteristics [9, 10, 11, 12, 13]. Research has indicated that satisfaction with the functioning and comfort of a device is the most significant factor in predicting successful prosthetic rehabilitation in individuals with upper limb amputations [14, 15, 16]. Over the past decade, significant progress has been made to enhance device function and comfort, addressing the common concerns of prosthetic users. These advancements include a range of improvements, such as lightweight lithium batteries, realistic silicone glove material, personalized silicone sockets, multi-articulating hands, nerve transfers or advanced signal processing strategies for optimized control, Osseointegration for better mechanical attachment, and implanted interfacing sensors. These are just a few examples of the developments that have been made in this area [3, 17, 18, 19, 20, 21]. Although many of these advancements have become standard in clinical practice, there is no proof that they have significantly influenced the acceptance of prosthetics among individuals with upper limb amputations [22].

The prevalence of limb loss is higher than many individuals may think, and this number is on the rise. By becoming knowledgeable about the realities of limb loss, we can become better supporters of our loved ones, feel more connected during our own experiences with limb loss, and raise awareness by engaging in informed and impactful conversations.
In the following points we can observe facts and statistics about amputation [23].

- There are currently 2.1 million individuals in the United States who are living with limb loss, and this figure is projected to increase twofold by the year 2050 [1].
- Every year, approximately 185,000 individuals undergo amputations, equating to approximately 300 to 500 amputations being performed on a daily basis [24].
- Due to the wars in Afghanistan and Iraq, 1,558 military personnel experienced limb loss.
- Approximately 30% of individuals who have undergone limb loss are affected by symptoms of depression and/or anxiety.
- A foot ulcer typically precedes about 85% of lower limb amputations.
- Individuals with limb loss have a lifetime healthcare cost of $509,275, which is higher in comparison to the lifetime healthcare cost of $361,200 for individuals without limb loss.
- The likelihood of African Americans having an amputation is four times higher compared to that of White Americans [25].
- The total hospital charges for patients who had undergone an amputation in 2013 amounted to $8.7 billion.
- Up to 55% of individuals with diabetes who undergo a lower limb amputation may require amputation of their other leg within a period of 2 to 3 years.

- Roughly 50% of people who undergo amputation due to vascular disease will pass away within 5 years, which is a greater mortality rate compared to breast cancer, colon cancer, and prostate cancer within the same time frame.
- From 1988 to 2009, there was a 24% increase in the number of amputations caused by diabetes.
- The most frequent type of amputation is below-knee amputation, which accounts for 71% of Dysvascular amputations. It is projected that there will be a 47% rise in below-knee amputations from 1995 to 2020.
- The annual cost to both private and public insurance agencies in the United States is estimated to be $12 billion.
- Globally, there are over one million limb amputations that occur annually, which translates to one amputation every 30 seconds.
- The International Diabetes Federation (IDF) forecasts that the current worldwide incidence of diabetes, which is 285 million, will increase to 435 million by 2030.
- Within a span of 2 to 3 years, as many as 55% of people with diabetes who experience a lower extremity amputation may need to have their other leg amputated. [26].

To summarise what was written above. The number of people who loses their limbs are dramatically growing up. The cost of getting and maintaining a prosthetic limb is huge. Amputees suffer of psychological distress depression, and social reintegration difficulties. Hence, our golden goal as engineers is to mimic the human hand as close as possible and to make it as cheap as possible, so that it can be acceptable, affordable, accessible for the patients, and unique among the competitors.

2 Theory

As engineering students, we have to observe nature to fulfill our imagination with extraordinary ideas which for sure will help us to come up with remarkable solutions for our problems. Since our topic is a development of a movable hand we will dive into human nature (Anatomy).

2.1 Hand anatomy

Basically, the main parts that a human hand contains are the five fingers Joints between the fingers Palm region, and the Wrist region, which includes bones, ligaments, tendons, muscles, nerves, blood vessels, and skin. We can count the fingers starting with the thumb as the number one and finishing with the pinky as the number five. For a deeper understanding of hand anatomy, we will split the hand into pieces, so we can divide the hand into the frontal part which is called the palmar side, and the back of the hand is called dorsal side, both sides are shown in Figure 2.1 and in Figure 2.2.

Figure 2.1: Palmar side of the hand[27]

Figure 2.2: Dorsal side of the hand[27]

Also, we can divide the hand into boundaries based on the nerves that supply the hand and these boundaries are Ulnar, Median, and Radial more in Figure 2.3

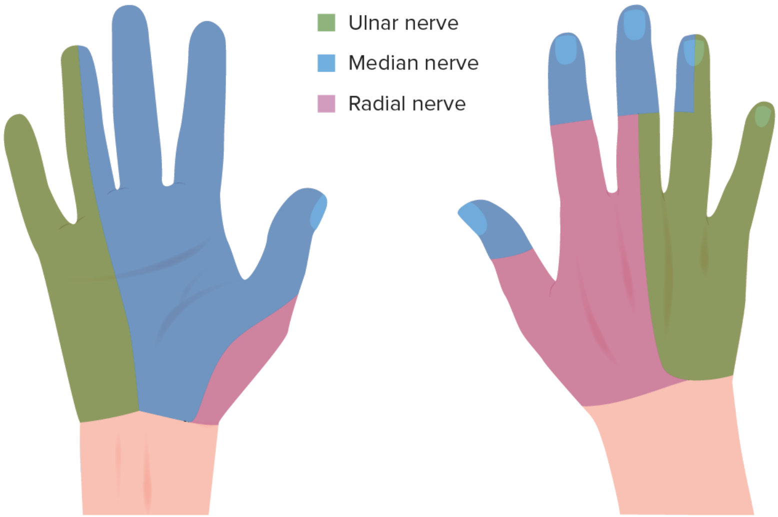


Figure 2.3: The Ulnar, Median, and Radial sides of the hand [28]

2.1.1 Bone system

A human hand-bones system can be divided into three groups Phalanges, Metacarpals, and Carpals, more in Figure 2.4.

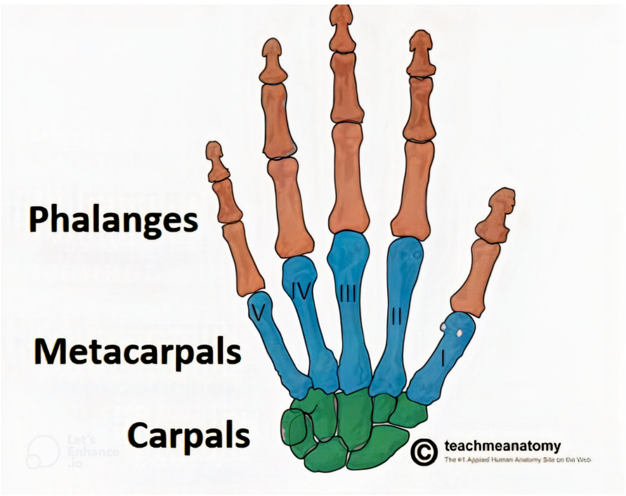


Figure 2.4: Overview of Carpals, Metacarpals, and-Phalanges[29]

The phalanges are the bones of the fingers and they are fourteen which can be divided into five Proximal bones, four Intermediate bones, and five Distal bones, as we can notice the thumb finger dose not have Middle Phalanges bone, more in Figure 2.5.

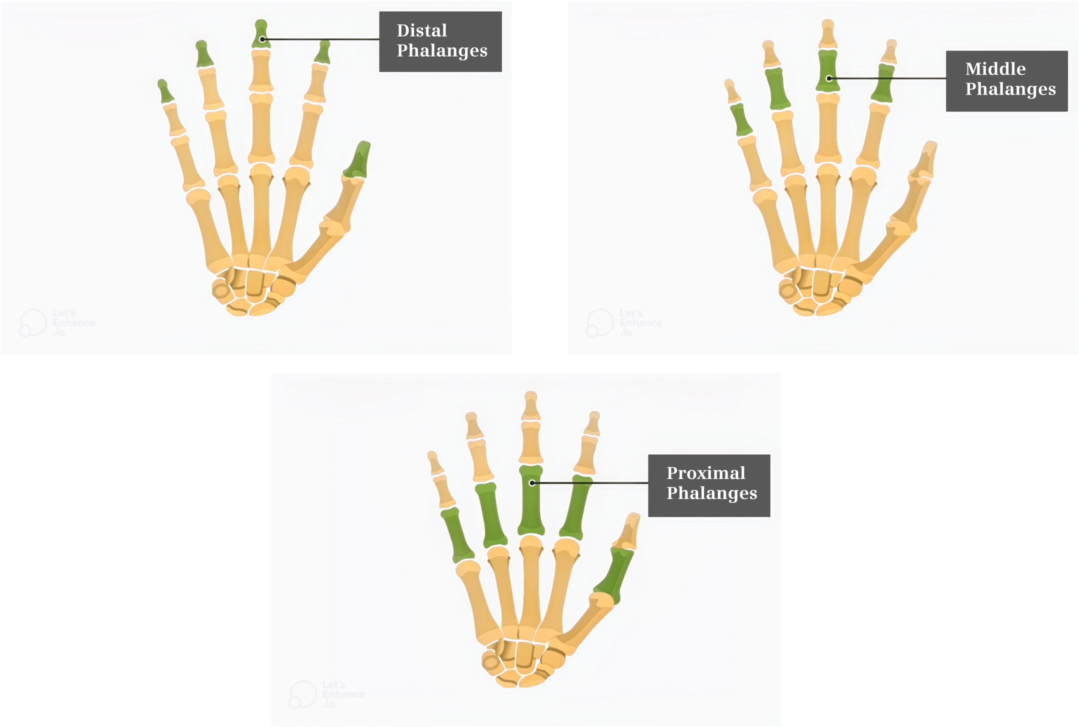


Figure 2.5: Phalanges Bones division

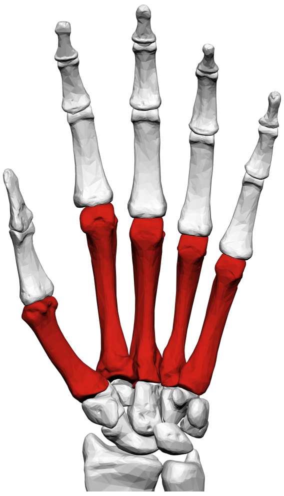


Figure 2.6: Caption

Metacarpals bones are five, if we take a look into the bones of the Metacarpals, they look like an extension of the fingers so they are numbered after them, starting with the Thumb as number one and finishing with the Pinky as number five more in Figure 2.6.

Carpals bones or the Wrist bones can be organized into two rows the Distal row and the Proximal row articulates the bones of the forearm, The Proximal row includes the Scaphoid, Lunate, Triquetrum, Pisiform. The Distal row includes Trapezium, Trapezoid, Capitate, Hamate. more in Figure 2.7.

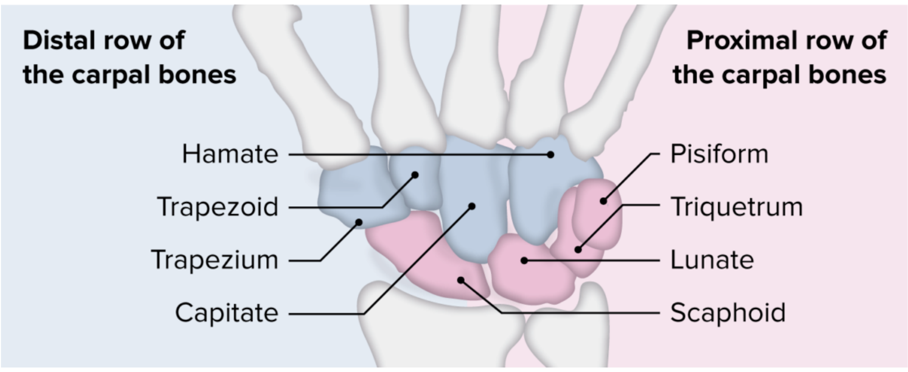


Figure 2.7: The proximal and distal rows of the carpal bones[30]

2.1.2 Muscular System

These muscles are called the intrinsic hand muscles because they are originate and inserted into the hand, They do not have much power. In fact, they are fatigued easier, but they have a lot of dexterity.

1. Thenar muscles
    - Thenar muscles are muscles that act on the Thumb and there are three of them, so we have Abductor of the Thumb, Flexor of the Thumb, and an Opposer of the Thumb, the Opposer helps Thumb to touch Pinky, More in Figure 2.8.

    (a) Abductor Pollicis brevis muscle
    (b) Flexor Pollicis brevis muscle
    (c) Opponens Pollicis muscle

2. Hypothenar muscles
    - Hypothenar muscles are muscles that act on the pinky finger and there are three of them, so the first are on Abducts the Pinky, the second is Flexes the Pinky, the last is oppose Pinky touching the Thumb, More in Figure 2.8.

    (a) Abductor digit minimi muscles
    (b) Flexor digit minimi muscles
    (c) Opponens digit minimi muscle

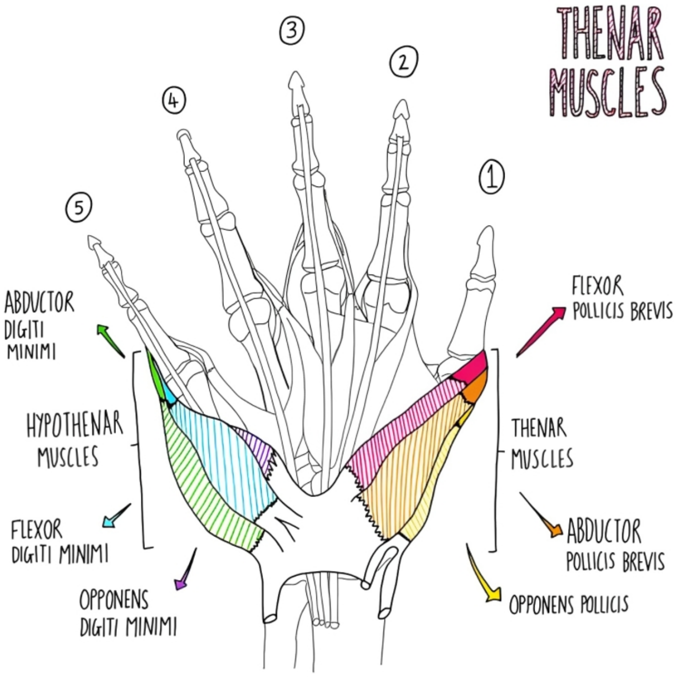


Figure 2.8: Thenar and Hypothenar muscles[31]

3. Lumbrical muscles
    - Lumbrical muscles are four in number. And these four muscles arise from the flexor digitorum profundus tendons and then these tendons course up, so they arise or they originate on the front of the hand, also called the Palmar surface. Then the tendons course to the back of the digits. The Lumbrical muscles flex the MCP joint and extend the IP joints. More in Figure 2.9.

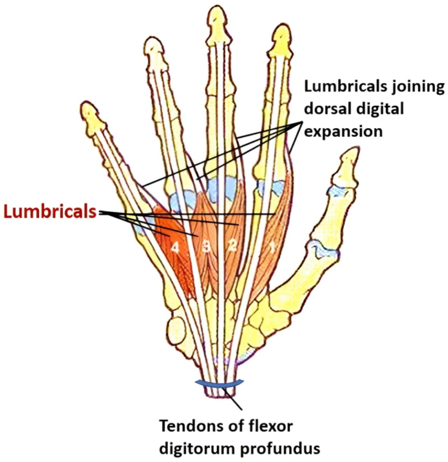


Figure 2.9: Lumbricals muscles[32]

4. Adductor Pollicis muscle

    - The Adductor Pollicis Muscle has a traverse head and an oblique head both of which come basically from the third Metacarpal and Carpal bones and go to the Proximal Phalanges of the Thumb. When this muscle contracts, it makes Thumb to Adduct. More in Figure 2.10

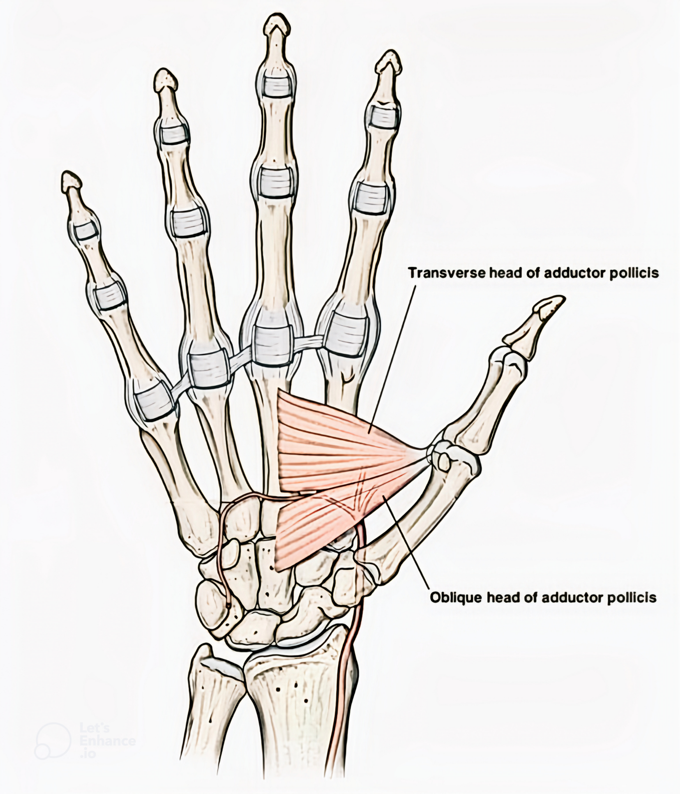


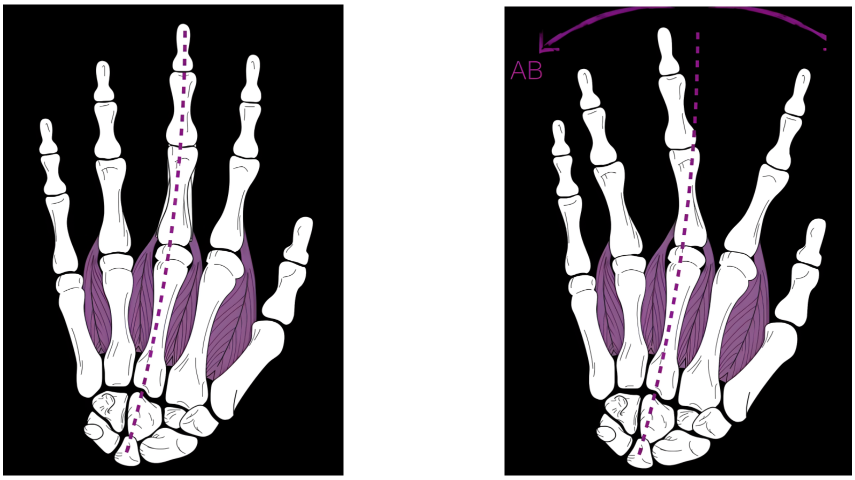
Figure 2.10: Adductor Pollicis muscle[33]

5. Dorsal Interossei muscles

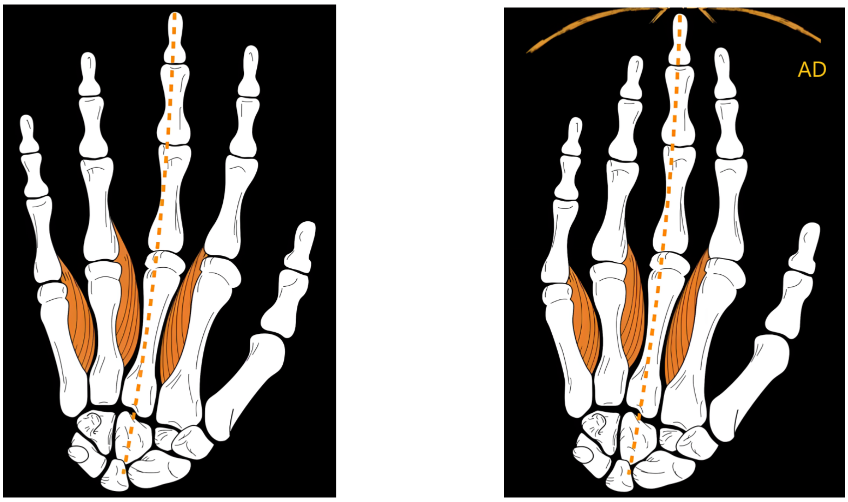
    - There are four of Dorsal Interossei muscles, so these muscles Abduct the Metacarpal Phalangeal joints. We can imagine a midline what's considered a B and a deduction going through the middle finger. When the Dorsal Interossei muscles contract the B duct, they pull the fingers away from the midline, As it is noticeable that the Pinky has its own abductor on the Hypothenar muscles. More in Figure 2.11a and in Figure 2.11b

6. Palmar Interossei muscles

    - There is three of Palmar Interossei muscles. And these muscles add ducting. In other word, they pull the fingers towards the midline. More in Figure 2.11c and in Figure 2.11d



(a) Dorsal interossei muscles (b) Dorsal interossei muscles-AB



(c) Palmar interossei muscles (d) palmar interossei muscles-AD

Figure 2.11: Dorsal and Palmar interossei muscles

2.1.3 Nerves System

The innervation of the hand depends on three nerves Median, Ulnar, and radial nerves. Each of these nerves is responsible for both sensory and motor functions in different parts of the hand.

- The median nerve. This nerve originates at the shoulder and controls the muscles we need to perform fine precision hand movements and pinching functions. The median nerve is the only nerve that enters the hand through the carpal tunnel; a spaced formed by the carpal bones of the wrist. This nerve controls sensation in the thumb, index finger, middle finger, and one side of the ring finger.[34]

- The ulnar nerve. The ulnar nerve runs through the arm into the hand and is the largest unprotected nerve in the human body. It connects to the little finger and adjacent side of the ring finger of the hand, providing sensation on the palm side of the hand. The ulnar nerve enables us to grasp objects. It travels along the elbow, between the bone and overlying skin at the Cubital tunnel. When we bump our “funny bone,” the painful sensation, we feel, comes from impact against this nerve. The ulnar nerve enters the palm of the hand through the Guyon’s canal.[34]

- The radial nerve. This nerve runs through the arm and controls our ability to extend our wrist and control the position of our hand. It also provides sensory feedback from the back of the little finger and the adjacent half of the ring finger.[34]

2.1.4 Ligaments

The human hand has a number of ligaments that help to support and stabilize the bones and joints. Ligaments are strong, flexible bands of tissue that connect bones to other bones, They are made of Collagen, and they play an important role in maintaining the stability and integrity of the hand.
There are several important ligaments in the hand, including:

- The collateral ligaments: These ligaments are located on the sides of the fingers and help to stabilize the joints.
- The volar ligaments: These ligaments are located on the palm side of the fingers and help to stabilize the joints.
- The interosseous ligaments: These ligaments are located between the bones of the fingers and help to stabilize the joints.
- The ulnar and radial collateral ligaments: These ligaments are located on the sides of the wrist and help to stabilize the wrist joint.
- The intercarpal ligaments: These ligaments are located between the bones of the wrist and help to stabilize the wrist joint.
- Distal radioulnar ligaments
  - Palmar radioulnar ligament
  - Dorsal radioulnar ligament
- Radiocarpal (wrist) ligaments
  - Palmar radiocarpal ligament
    - Palmar Radioscaphocapitate ligament
    - Palmar radioscapholunate ligament
    - Short Palmar radiolunate ligament
    - Long Palmar radiolunate ligament

    - Palmar ulnocarpal ligament
        - ulnocapitate ligaments
        - ulnolunate ligaments
        - ulnotriquetral ligaments
        - ulnopisiform ligaments
    - Triangular fibrocartilage complex
        - palmar ulnocarpal ligaments
        - palmar radioulnar ligament
        - articular disc
        - ulnomeniscal homologue
    - Collateral ligaments of wrist
        - radial collateral ligaments
        - ulnar collateral ligaments

- Intercarpal ligaments
    - Palmar intercarpal ligaments
        - scaphocapitate ligament
        - triquetrocapitate ligament
        - palmar capitohamate ligament
        - palmar trapezoideocapitate ligament
        - trapezocapitate ligament
        - palmar scaphotriquetral
        - palmar lunotriquetral
        - palmar triquetrohamate
        - pisotriquetral ligament
        - pisohamate ligament
    - Intercarpal interosseous ligaments
        - Scapholunate interosseous ligament
        - lunotriquetral interosseous ligament
        - trapeziotrapezoidal interosseous ligament
        - trapezoideocapitate interosseous ligament
        - capitohamate interosseous ligament

- Carpometacarpal ligaments
    - Dorsal carpometacarpal ligaments
    - Palmar carpometacarpal ligaments

- Intermetacarpal ligaments

  - Palmar metacarpal ligaments
  - Dorsal metacarpal ligaments
  - Interosseous metacarpal ligaments

- Metacarpophalangeal
  - Proper collateral metacarpophalangeal ligaments
  - Accessory collateral metacarpophalangeal ligaments
  - Phalangoglenoid ligaments
  - Palmar metacarpophalangeal ligaments
  - Deep transverse ligament

- Interphalangeal ligaments
  - Palmar interphalangeal ligaments
  - Proper collateral interphalangeal ligaments
  - Accessory collateral interphalangeal ligaments
  - Annular ligaments
  - Cruciform ligaments

2.1.5 Tendons

Tendons are fibrous tissues that connect muscles to bones. In the human hand, there are multiple tendons that help control the movement and positioning of the fingers and thumb. Some of the important tendons in the hand include:

- Extensor tendons: responsible for extending the fingers and wrist
- Flexor tendons: responsible for flexing the fingers and wrist
- Abductor tendons: responsible for abducting (moving away from the midline of the body) the fingers
- Adductor tendons: responsible for adducting (moving towards the midline of the body) the fingers

Injuries to the hand tendons, such as tendonitis or tendon tears, can lead to reduced hand function and pain.

2.1.6 Blood vessels

The blood supply of the hand relies on the Ulnar artery which is coming down from the Ulnar side of the wrist. It is jointed by the Radial artery on the other side, both these arteries are divided into a superficial and deep branch. The superficial branches unite to form the superficial Palmar arch. The major contributor to the superficial Palmar arch is coming form the Ulnar artery. Also the Ulnar and the Radial arteries unite to form the Deep Palmar arch. In this arch, it is primarily the Radial artery that participates in its formation. The Superficial arch and the Palmar arch, both of them, supply the rest of the hand by dividing it into multiple smaller branches. The Superficial Palmar arch gives off several branches typically somewhere between three to five and these run down the hand and then divide into what is known as digital arteries and run with the digital nerves on either side of the digits, so there is one for the Ulnar side of the digit and one for the medial side. Similarly, the Deep Palmar arch also gives rise to a number of smaller branches but primarily the branches running to the Thumb come from the Deep arch more in fig. 5.2, and fig. 5.3

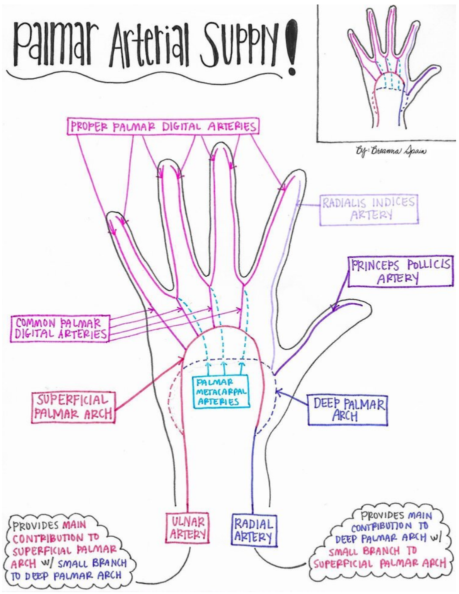


Figure 2.12: Palmar Hand Arteries

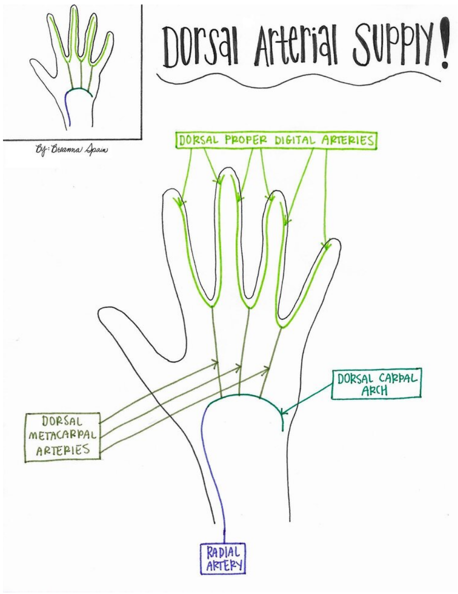


Figure 2.13: Dorsal Hand Arteries

2.1.7 Joints

Joints play a vital role in the functioning of the human hand. They allow for movement and provide stability to the bones of the hand. There are several types of joints in the human hand, each serving a different purpose and contributing to the overall function of the hand.

The carpometacarpal (CMC) joints are the joints that connect the bones of the wrist to the bones in the palm (metacarpal bones). These joints allow for a limited amount of movement, such as flexion and extension, which is important for activities such as typing and playing musical instruments.

The metacarpophalangeal (MCP) joints are the joints that connect the metacarpal bones to the bones in the fingers (phalanges). These joints allow for flexion and extension and are important for performing activities such as gripping and holding objects.

The proximal interphalangeal (PIP) joints are the joints located between the proximal (closest to the palm) and middle phalanges in each finger. These joints allow for a greater range of motion than the MCP joints and are important for activities such as playing the piano or manipulating small objects.

The distal interphalangeal (DIP) joints are the joints located between the middle and distal (furthest from the palm) phalanges in each finger. These joints have a limited range of motion but are important for maintaining the stability of the fingers and ensuring proper grip and dexterity.

The intercarpal joints are located between the bones of the wrist and allow for a small amount of movement in the wrist. These joints are important for maintaining stability in the wrist and allowing for activities such as wrist flexion and extension.

In conclusion, the joints in the human hand play a crucial role in its functionality and mobility. They allow for a wide range of movement and dexterity, which is important for performing everyday tasks and activities. Injuries to the hand joints, such as osteoarthritis or ligament sprains, can cause pain and limit hand function. It is important to protect and maintain the health of the hand joints to ensure proper hand function and prevent injury.

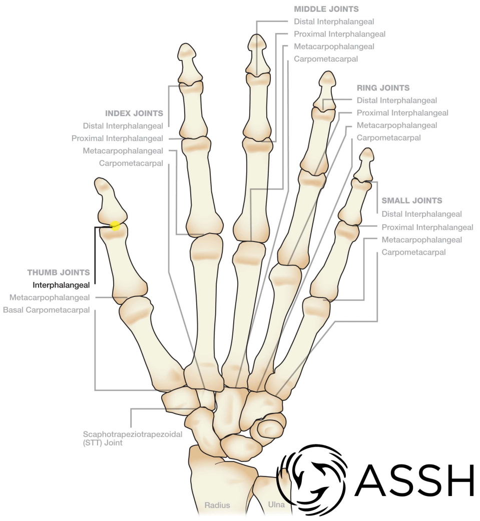


Figure 2.14: Hand joints[35]

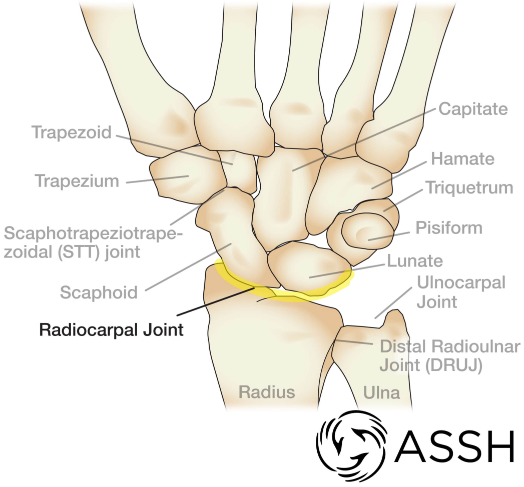


Figure 2.15: Wrist joints[35]

2.2 3D Scanning

3D scanning is a process of capturing the physical shape and appearance of an object in a digital format. This technology has revolutionized various industries, including manufacturing, product design, and entertainment. The process of 3D scanning involves using a specialized device or software to measure the dimensions and details of an object, and then converting that information into a digital model. In the manufacturing industry, 3D scanning is used to quickly and accurately capture the geometry of a product or part, which can then be used to create digital prototypes or produce exact replicas. This technology helps manufacturers save time and money by reducing the need for manual measurements and prototypes, and increasing the speed and accuracy of the design process. In product design, 3D scanning is used to create accurate digital representations of existing products, which can then be modified or used as a starting point for new designs. This technology allows designers to quickly and easily visualize their ideas in a 3D environment, allowing them to make changes and test different configurations without the need for physical prototypes.

In the entertainment industry, 3D scanning is used in the creation of computer-generated images (CGI) for film, television, and video games. This technology allows animators to accurately capture the details of real-world objects and environments, which can then be used as the basis for digital models in the production process. In addition to its benefits in various industries, 3D scanning has also found applications in medicine, archaeology, and engineering. Medical professionals use 3D scanning to create detailed images of the human body, which can be used for diagnosis, planning surgeries, prosthetics, and more. Archaeologists use 3D scanning to capture and preserve cultural heritage sites, while engineers use the technology to gather information about complex structures and systems. In conclusion, 3D scanning is a powerful technology that has transformed various industries by providing a fast and accurate method of capturing and reproducing the physical world in a digital format. With its wide range of applications and benefits, 3D scanning is likely to continue to play an important role in many areas of our lives for years to come.

In our thesis we used a product from SHINNING 3D, which was founded in 2004, and rapidly became China's first listed OTC stock company in the 3D digitizing and printing industries segment. SHINING 3D develops, manufactures, and commercializes a wide range of 3D technologies, including 3D scanners for multiple industries and applications, 3D printers for both additive manufacturing and consumer markets, 3D materials, 3D design and manufacturing services, and an online 3D cloud platform. SHINING 3D is well-positioned in the market and has the capacity to handle large sales volumes offer powerful 3D technologies, and provide strong service support. As the leader among Chinese 3D printing companies, SHINING 3D has currently extended a strong international influence with customers in more than 70 different countries in Asia and the Pacific, Europe, North America, South America, Africa and the Middle East. Therefore we used The EinScan Pro 2X plus, which is a handheld 3D scanning device produced by SHINING 3D. It is part of the EinScan Pro 2X series, which is designed for use by professionals in a variety of industries, including engineering, product design, reverse engineering, quality control, and education.

One of the key features of the EinScan Pro 2X series is its dual-lens scanning system. This system uses two cameras, one of which is equipped with a structured light module, to capture high-resolution 3D data. This enables the scanner to produce detailed and accurate 3D scans, even of complex and irregularly shaped objects.The EinScan Pro 2X series is capable of scanning objects at up to 2 frames per second, making it a fast and efficient way to capture 3D data. Another key feature of the EinScan Pro 2X series is its ease of use. The scanners are handheld, meaning that they can be used to scan objects in a variety of positions and orientations, It offers a range of scanning modes, including auto scan, handheld scan, and fixed scan. The auto-scan mode allows users to capture a 3D model with a single button press, while the handheld scan mode allows for greater control and flexibility. The fixed scan mode is ideal for scanning larger objects that cannot be moved easily. The user interface is intuitive, and the software that comes with the scanner is designed to be user-friendly. The EinScan Pro 2X series also comes with a range of accessories, including a turntable, which makes it also easier to scan larger and more complex objects. The EinScan Pro 2X Plus generates 3D data in the form of point clouds or triangular meshes. A point cloud is a set of points in 3D space that represent the surface of an object. Each point in a point cloud has an X, Y, and Z coordinate, and can also have additional information, such as color or texture. Point clouds are used to represent the raw data generated by 3D scanning devices like the EinScan Pro 2X Plus. A triangular mesh, on the other hand, is a representation of a 3D object as a series of interconnected triangles. Triangular meshes are commonly used in computer graphics and 3D printing because they can be easily manipulated and rendered. The EinScan software, which is included with the EinScan Pro 2X Plus, provides tools for converting point cloud data into triangular meshes and vice versa. In addition to point clouds and triangular meshes, the EinScan Pro 2X Plus can also generate 3D models in other file formats, such as STL, OBJ, ASC, 3MF, P3 and PLY. These file formats are commonly used in 3D printing and computer-aided design (CAD) software such as in our case Fusion 360, and can be imported into a wide range of applications, making it a versatile tool for designers and engineers.

2.2.1 Specifications of The EinScan Pro 2X Plus

Model	**EinScan Pro 2x plus**			
Scan Mode	Handheld HD Scan	Handheld Rapid Scan	Fixed Scan with Turntable (With Add-on: industrial pack)	Fixed Scan without Turntable(With Add-on: industrial pack)
Scan Accuracy	Up to 0.05mm	Up to 0.1mm	0.04mm (Single shot accuracy)	0.04 mm (Single shot accuracy)
Volumetric Accuracy	0.3 mm/m (Markers Alignment)		N/A	N/A
Scan Speed	20 frames/sec 1.1 mil points/sec	30 frames/ sec 1.5 mil points/sec	Single Scan: <0.5sec	Single Scan <0.5sec
Point Distance	0.2mm ∼0.3mm	0.25mm ∼0.3mm	0.24mm	
Single Scan Range	208*136mm —- 312*204mm			
Depth of Field	+-100mm			
Working Distance	510mm			
light Source	LED			
Align Mode	Markers Alignment	Markers Alignment, Feature Alignment (geometrical features) Hybrid Alignment (Markers and Feature)	Turntable coded Targets, Feature, Markers, Manual Alignment	Markers, Feature, Manual Alignment
Texture Scan	No	Yes (With color pack add-on)		
Outdoor Operation	Set up shelter or cover to avoid direct sunlight			
Special Scan Object	For transparent, highly reflective or some dark objects, please spray with powder before scanning			
Printable Data Output	Able to export watertight 3D model directly to 3D printing			
Data Format	OBJ, STL, ASC, PLY, 3MF, P3			
Scanner Body Weight	1.13 kg (including the USB 3.0 cable)			
Supported OS	Win 7/Win 8/Win 10 64 bit			

Table 2.1: Specification of the scanner device[36]

2.2.2 PC requirements

Model	Requirements
Processor	Intel ® xeon E3-1230, Intel ®I5-3470, Intel ® I7-3770
Display card	Nvidia Quadro P1000 or higher, Nvidia GTX660 or higher
Display memory	> 4G
Memory Storage	8G
USB	At least one USB 3.0
Screen display	1920·1080 DPI: 100%, 120%. 3840·2106 DPI: 100%, 200%

Table 2.2: Required configuration[36]

Model	Requirements
Processor	I7-8700
Display card	NVIDIA GTX1060 or higher
Display memory	> 4G
Memory Storage	32G or more
USB	At least one USB 3.0
Screen display	1920·1080 DPI: 100%, 120%. 3840·2106 DPI: 100%, 200%

Table 2.3: Recommended configuration[36]

2.2.3 Scan Workflow

The scanning workflow of EinScan Pro 2X Plus 3D Scanner involves the following steps:

- Preparation: Assemble the scanner, connect to the computer, install the software and calibrate the device.
- Scanning: Place the object to be scanned on the rotating platform, and press the scan button in the software. The scanner will rotate the platform and capture images of the object from different angles.
- Data Processing: After the scanning is complete, the software will process the data captured by the scanner to generate a 3D model of the object. This process includes data stitching, error correction, and surface reconstruction.
- Post-Processing: The generated 3D model can be further edited, such as removing noise, filling holes, and smoothing the surface, to obtain a high-quality final model.
- Exporting: The final 3D model can be exported to various file formats, such as STL, OBJ, PLY, etc., for further use, such as 3D printing, reverse engineering, or virtual reality.

For a more detailed workflow of the scanning process from the beginning to the end in Fig. 2.16.

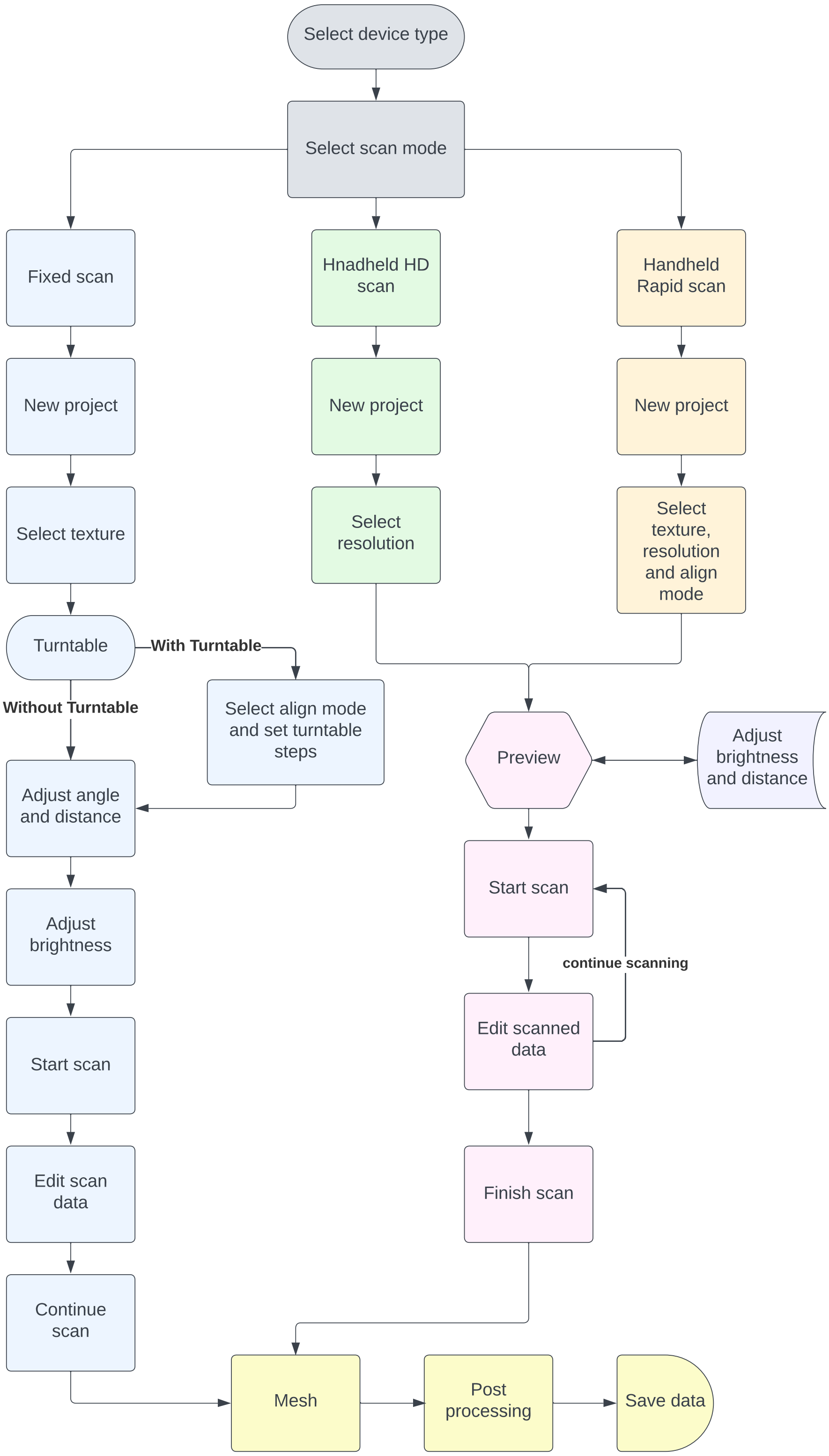


Figure 2.16: Scan Overflow[36]

2.3 3D Printing

Three-dimensional (3D) printing, also known as additive manufacturing, is a rapidly evolving technology that has gained significant attention in recent years. 3D printing is a process of creating three-dimensional objects from digital models by adding layers of material, such as plastic or metal, one on top of the other until the object is formed. This technology has revolutionized the manufacturing industry by enabling designers and engineers to create highly customized and intricate designs that were previously impossible or very costly to produce. One of the main advantages of 3D printing is the ability to create prototypes and functional parts quickly and cost-effectively. This is particularly important in fields such as aerospace and medicine, where custom-designed parts are needed for specific applications. Another significant advantage of 3D printing is the level of design freedom it offers. Traditional manufacturing techniques, such as injection molding or CNC machining, require the creation of molds or tooling, limiting the complexity of the designs that can be produced. 3D printing, on the other hand, allows designers to create intricate and complex shapes that would be impossible to create using traditional methods. However, like any technology, 3D printing has its limitations. One of the main challenges is the limited range of materials that can be used. While plastic and metal are commonly used, other materials, such as glass or ceramics, are more difficult to print. In addition, the quality of the final product can be affected by the type of printer used, the layer thickness, and other printing parameters.

In TULAB we are using Prusa printers, therefore we will print the prosthetic hand using one of those printers. The Prusa 3D printer is a popular brand of 3D printers that has gained a reputation for producing high-quality prints at affordable prices. Developed by Josef Prusa, the Prusa 3D printer has gained a loyal following among 3D printing enthusiasts and professionals alike. The printer is based on the open-source RepRap project, which allows for modifications and customization of the printer to suit specific needs. One of the key features of the Prusa 3D printer is its use of a heated bed, which allows for better adhesion of the printing material to the print surface. This, in turn, leads to better print quality and reduces the likelihood of print failures due to material detachment. The Prusa 3D printer also features a wide range of materials that can be used, including PLA, ABS, PETG, and nylon, among others. The Prusa 3D printer is also known for its ease of use and reliability. The printer comes with pre-configured profiles for different materials, making it easy for users to get started with printing without having to spend time configuring the printer. Additionally, the printer is designed to be self-calibrating, which means that it can automatically adjust the bed level and nozzle height, further reducing the need for user intervention. In addition to its ease of use, the Prusa 3D printer is also highly customizable. Users can modify the printer to suit their specific needs, such as adding additional extruders or upgrading the hot end to allow for higher temperatures. The printer also supports a wide range of software, including open-source slicers such as PrusaSlicer and Cura. 3D printing goes through several processes, The processes can be broken down into the following steps:

1. Design: The first step in 3D printing is creating a digital design using Computer-Aided Design (CAD) software. The design can also be created using 3D scanning, which involves scanning an existing object to create a digital model.
2. Slicing: Once the digital design is complete, it needs to be sliced into thin layers using specialized software called a slicer. The slicer software calculates the path that the printer nozzle will take to deposit the material layer by layer.
3. Preparation: Before printing, the 3D printer needs to be prepared. This involves setting up the printer and ensuring that the printing material is loaded and ready to use.
4. Printing: With the printer prepared, the printing process can begin. The printer deposits the material layer by layer, following the path calculated by the slicer software. The material can be deposited in different patterns and densities depending on the desired properties of the object.
5. Post-processing: Once the object is printed, it may require post-processing to improve its appearance or functionality. This can involve removing support structures, sanding, polishing, or painting.

The materials used in 3D printing can vary depending on the printer and the application. Common materials include plastics, metals, ceramics, and even food materials. There are many types of plastic materials that can be used for 3D printing. Each material has its unique properties, which make it suitable for different applications. Some of the most commonly used plastic materials for 3D printing include:

- PLA (Polylactic Acid): PLA is a biodegradable thermoplastic that is made from renewable resources such as corn starch or sugarcane. It is easy to print and is commonly used for making prototypes, toys, and household items.
- ABS (Acrylonitrile Butadiene Styrene): ABS is a thermoplastic that is strong, durable, and heat-resistant. It is commonly used for making automotive parts, toys, and electronic housings.
- PETG (Polyethylene Terephthalate Glycol): PETG is a thermoplastic that is strong, durable, and has good impact resistance. It is commonly used for making food containers, water bottles, and other consumer products.
- Nylon: Nylon is a strong and flexible thermoplastic that is commonly used for making parts that require high strength and durability, such as gears and bearings.
- TPU (Thermoplastic Polyurethane): TPU is a flexible and rubber-like thermoplastic that is commonly used for making phone cases, toys, and other consumer products.

- PVA (Polyvinyl Alcohol): PVA is a water-soluble thermoplastic that is commonly used as a support material for 3D printing. It can be dissolved in water, leaving behind a clean and polished print.
- PC (Polycarbonate): PC is a strong and durable thermoplastic that is commonly used for making parts that require high impact resistance, such as safety glasses and electronic housings.

These are just a few examples of the many plastic materials that can be used for 3D printing. The choice of material will depend on the specific requirements of the application, such as strength, durability, flexibility, or heat resistance. It is important to choose the right material to ensure that the 3D printed part meets the desired specifications. Overall, 3D printing is a versatile and powerful technology that allows for the creation of complex and customized objects with precision and accuracy.

2.4 Kinematics and degree of freedom

The human hand is a complex and versatile structure that has evolved over millions of years to enable us to interact with the world around us. With 27 bones, 27 joints, and numerous muscles, tendons, and ligaments, the hand has a high degree of freedom, which allows for a wide range of movements and functions. The degree of freedom of the hand refers to the number of independent degrees of movement that it can perform. In other words, it is the number of ways in which the hand can move without being restricted by the other parts of the hand or the body. The human hand has a high degree of freedom due to its complex structure, which allows for a wide range of movements and functions. The hand is made up of three main parts: the wrist, the palm, and the fingers. The wrist is a complex joint that allows the hand to rotate and move in multiple planes. This enhances the versatility of the hand's movements and enables it to perform a variety of functions. The palm of the hand is made up of five metacarpal bones, which connect the wrist to the fingers. The palm also contains numerous muscles, tendons, and ligaments, which are responsible for the movement and control of the fingers. The fingers of the hand have the most degree of freedom, as they can move independently in several directions. Each finger has three joints, which allow for flexion, extension, and rotation. The thumb, in particular, is highly mobile and can move in opposition to the other fingers, which allows for a powerful and precise grip. The degree of freedom of the human hand is also influenced by the nervous system. The brain sends signals to the muscles and joints, allowing for precise and coordinated movements. This neural control enables the hand to perform complex tasks with a high degree of accuracy and efficiency. The hand has a wide range of functions, including grasping, gripping, holding, manipulating objects, and fine motor skills. The degree of freedom of the hand is essential for these functions, as it allows for a high level of dexterity and precision. For example, when we grasp an object, the fingers and thumb move independently to adjust to the shape and size of the object.

This requires a high degree of coordination and control, which is made possible by the complex structure of the hand and the neural control of movement. Similarly, when we perform fine motor skills such as writing or typing, the hand must move in a precise and coordinated manner to produce the desired movements. The degree of freedom of the hand is essential for these skills, as it allows for the precise control of the fingers and the ability to make small adjustments to the movements.

In summary, each finger has two interphalangeal joints that allow for flexion and extension, as well as a metacarpophalangeal joint that allows for flexion, extension, abduction, and adduction. The thumb has an interphalangeal joint, a metacarpophalangeal joint, and a carpometacarpal joint that allow for various movements. The wrist has a joint between the carpals and radius that allows for flexion, extension, abduction, adduction, supination, and pronation, as well as the ability to move in three planes of 3D space. Altogether, the fingers provide 16 degrees of freedom, while the thumb provides 5 and the wrist provides 6, totaling 27 degrees of freedom.

3 Design of the prosthetic hand

In the design process of the prosthetic hand, we can choose one of two ways to get the mechanical part of the hand into physical life, the first one is common and a lot used which is to design it step by step, each component of the mechanical hand. The least common method yet more efficient and accurate is the 3D scanning method we easily scan the remaining hand and let's say adjust it in such a way to make it functional and meet our requirements.

3.1 3D scanning process

EinScan Pro 2X Plus has been used to get the data from the physical form into the digital form as a part of 3D scanning process. The scanned data can be affected by the light and the texture of the body, therefore the data can be defective during the scanning process as an example of possible defection that can happen to the model during the scanning are artifacts, Since learning how to use 3D scan an object was part of this thesis, Hence we tried to scan different objects one of them was a human head and during learning process some defection occurred, The most difficult defection to fix was artifacts because they can really create particles away from the wanted object or even they can create multiple surfaces on the object and we have to eliminate them carefully without affecting the surface of even the shape of the object. Another defection, that can occur in the scanned data, is holes. They appear as spots on the object and the scanning device can not fill them. They usually occur for a variety of reasons, including

- Occlusion: When an object is scanned, other objects or surfaces can block the scanner from capturing certain areas, resulting in holes in the 3D model.
- Reflective or transparent surfaces: 3D scanners may have difficulty capturing reflective or transparent surfaces, which can result in missing areas in the 3D model.

In order to fix these defections, we used software from Autodesk called Meshmixer, However, To minimize the occurrence of defections in 3D scanned objects, it is important to carefully prepare the surrounding area of scanning, adjust the lights and the object for scanning.
Next two pages we can observe the scanned human head with defection and without it, more is shown in fig. 3.10.

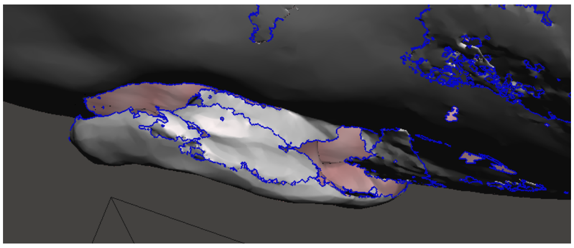


Figure 3.1: Defected ear

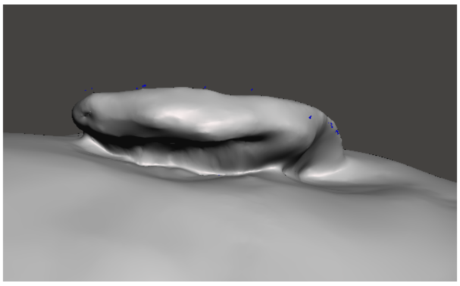


Figure 3.2: Fixed ear

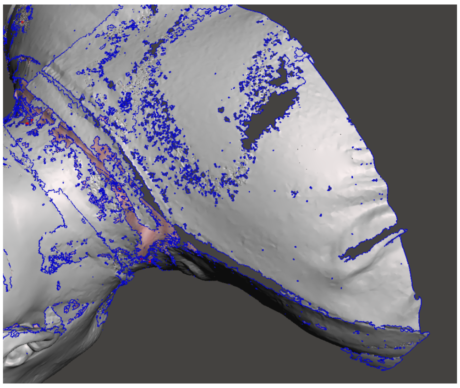


Figure 3.3: Defected Back and neck

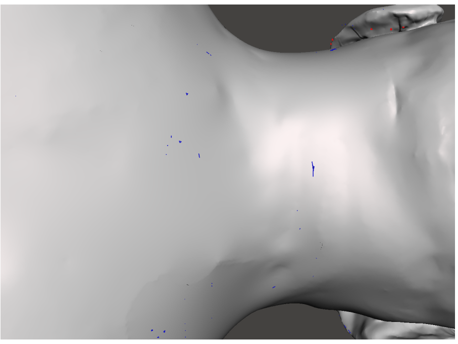


Figure 3.4: Fixed neck

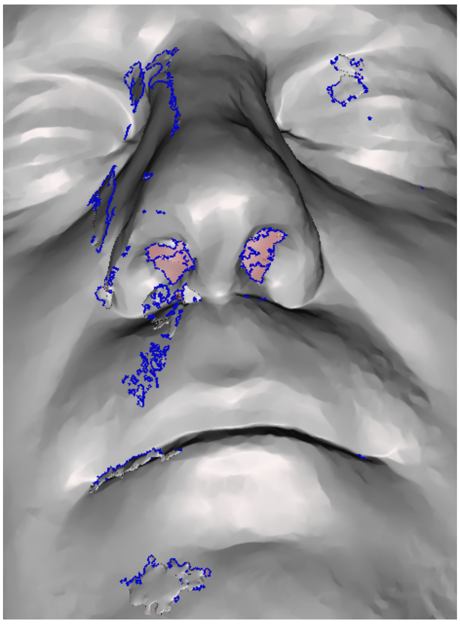


Figure 3.5: Defected face

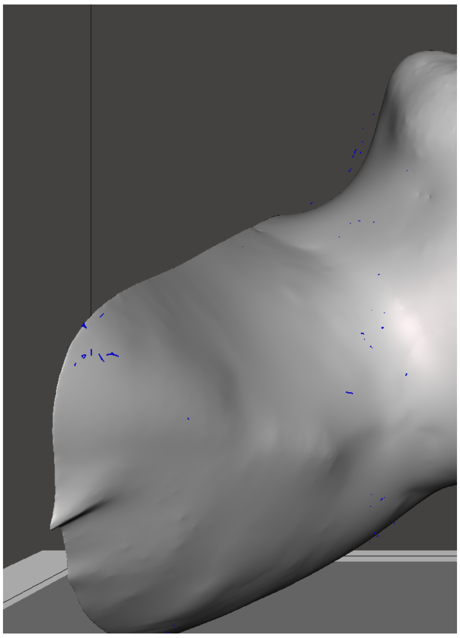


Figure 3.6: Fixed neck

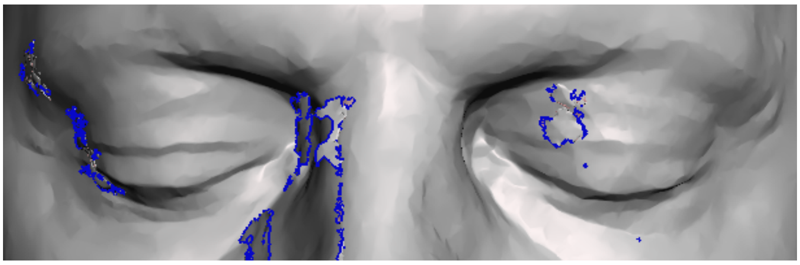


Figure 3.7: Closed eyes with artifacts

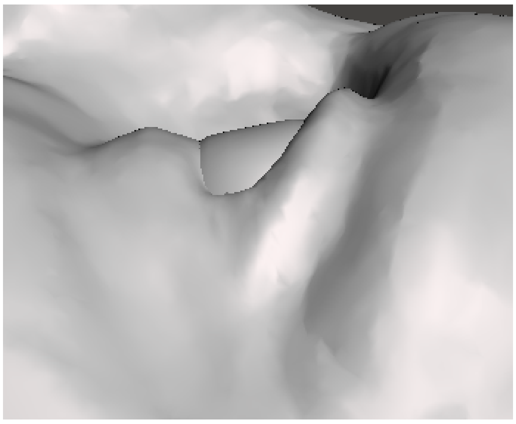


Figure 3.8: Opened left eye without artifacts

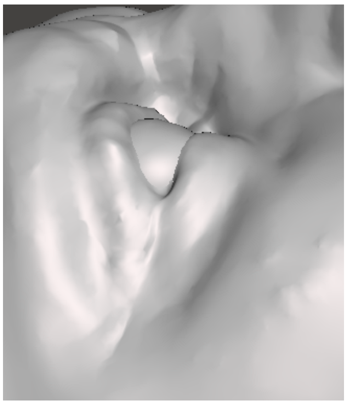


Figure 3.9: Opened right eye without artifacts

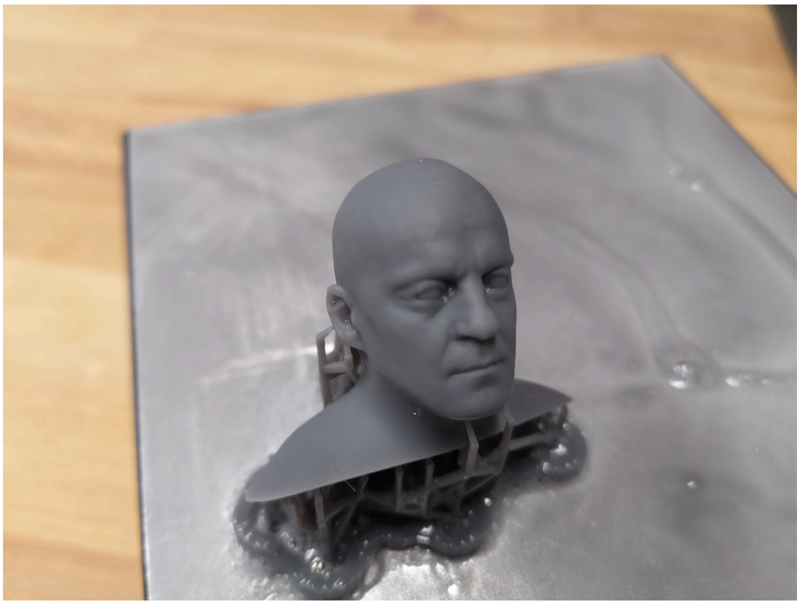


Figure 3.10: The final printed model after it has been fixed

3.2 Hand 3D scanned

After having an overview of the pros and cons of 3D scanning technology, the main process of this master thesis has been ignited. We tried a new approach to get the data into digital form which is Hand casting. After that, we can 3d scan the cast hand, For sure, we could directly 3d scan the hand skipping the casting step, but it is more likely to be affected by some defection, However, the cast is steadier during the scanning process which assures that the data will be better and have more details in it. Figures 3.11 and 3.12 show the raw data of the scanned hand. We can notice that the scanned data has a lot of details, clearly, it shows the nails, lines between the joints even tendons on the dorsal side of the hand. But by taking a closer look at the scanned hand we can notice some imperfections like wrinkles all over the hand especially between the thumb and the index and between all fingers which have to be fixed, another major imperfection is the line of action of individual fingers. If we notice the fingers as they close they will intersect which is not practical, Therefore, this hand will for sure need a lot of modifications in various soft-wares to make it fully functional.

Figure 3.11: Raw data of scanned hand dorsal side

Figure 3.12: Raw data of scanned hand palm side

3.3 Modification of the scanned data

The most important modification that was applied on the scanned hand is correcting the line of action of individual fingers. The best software we think is suitable for this assignment is Blender, because it has a very powerful function that allows us to modify the topology of the model, by using joints which refer to a type of object used in the process of rigging a 3D model for animation also. Joints are also commonly known as bones, and they are used to create a hierarchical system that controls the movement and deformation of the scanned hand. A joint in Blender is a simple object that consists of a head and a tail, or a root and a tip. These bones are connected together to form a chain, which can be used to simulate the movement of a skeleton or any other joint-based system as our scanned hand. Each joint can be manipulated in different ways depending on the movement requirements. For example, joints can be rotated or moved to create different poses or movements, and their position and orientation can be keyframed to create an animation. Additionally, joints can also be scaled or deformed to control the shape and volume of the mesh that they are attached to. In Blender, joints can be given a variety of properties that affect their behavior and their influence on surrounding vertices. For example, joints can be set to have a certain weight value, which determines how much influence they have on the vertices of the mesh. This allows for precise control over how the mesh deforms and moves as the joint is manipulated. In figures Figures 3.13 to 3.15 and **??** below we can see the main manipulations that joints allow.

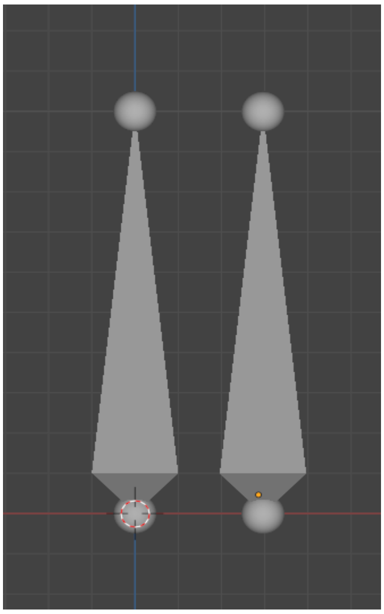


Figure 3.13: Joints-Bones

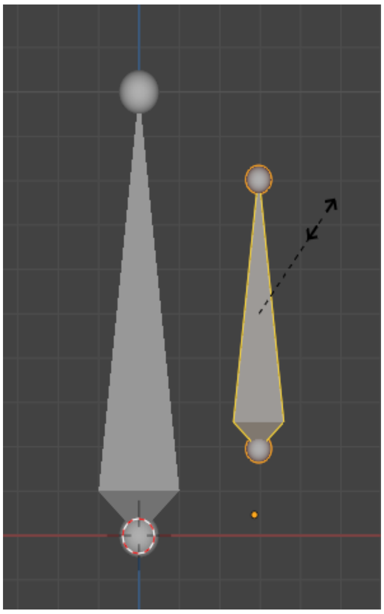


Figure 3.14: Scaled joint

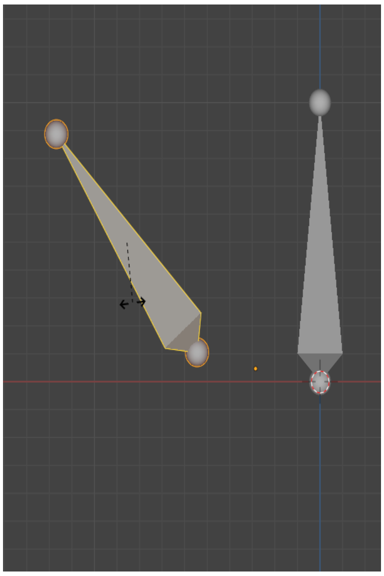


Figure 3.15: Rotation around Y-axis

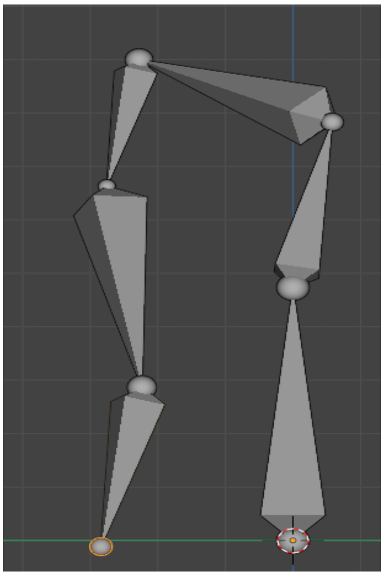


Figure 3.16: Chain of joints

The subsequent phase in the process involves integrating the joints into the scanned hand with great precision. This entails attaching the tip and tail to the rigid joint on the scanned hand and aligning the joints with one another based on the wrinkles that appear on the hand. These wrinkles serve as a guide for identifying the exact position of each joint on the hand. By successfully integrating the joints, a chain of interconnected Blender joints is formed.

This chain system enables the manipulation of the entire hand as a single unit, whereby any movement of a joint affects the entire chain. Consequently, by implementing the joints in this manner, we are able to achieve greater control and flexibility in manipulating the hand. After confirming the smooth and error-free operation of the chain system, the next step is to focus on the alignment of the lines of action. During hand casting or 3D scanning, it is nearly impossible for a person to keep their hand completely still for an extended period of time. As a result, there is a high possibility of losing the required position of the lines of action, which can have a significant impact on the final model.

Therefore, it is of utmost importance to align the lines of action as accurately as possible. This can be challenging, as the hand has a great degree of freedom compared to the model. However, by making small adjustments and carefully aligning the joints, it is possible to achieve optimal alignment of the lines of action.

One of the primary reasons why proper alignment of the lines of action is crucial is to prevent the occurrence of intersection between individual fingers. This can result in kinematic collapse, which would render the model impractical and unusable. Therefore, it is essential to ensure that the fingers are positioned accurately and do not intersect with each other when they close, in order to create a functional and realistic model.

Additionally, some fingers may need to be twisted, as they are not perfectly straight in their natural state. This is particularly relevant when working with scanned hand models, as the hand is a complex and intricate structure. Therefore, it is important to examine each finger in detail and make the necessary adjustments to achieve a natural and realistic appearance.

It is imperative that we give due consideration to another form of modification, known as surface modification, in addition to the 3D scanning method that captures intricate details and is well-suited for the identification of joints and the creation of a more lifelike hand. However, it is crucial to bear in mind that we must incorporate genuine joints that enable movement in the physical realm rather than solely in simulation. The implementation of such joints necessitates the introduction of a novel software program, namely Fusion 360. Therefore, we need to give equal weightage to surface modification and joint incorporation, and utilize Fusion 360 to achieve the desired outcome. In more simple words, we need to take a multi-faceted approach that combines 3D scanning, surface modification, joint integration, and software utilization to create a realistic and functional hand.

The scanned hand is currently in the form of a combinatorial surface or mesh consisting of vertices, edges, triangles, and tetrahedra. However, using mesh models in Fusion 360 can be more challenging than using traditional solid or surface models because mesh models are not a mathematical representation of an object's geometry. Instead, they are a collection of points and polygons that define the object's shape. Therefore, manipulating and editing mesh models can be more difficult due to their lack of precision and predictability.

Working with mesh models in Fusion 360 often involves converting them to solid or surface models, which can be a complex and time-consuming process. Furthermore, mesh models have larger file sizes than solid or surface models, causing the software to slow down, making it more challenging to work with.

Despite these challenges, mesh models can be beneficial in certain situations, such as working with complex organic shapes or importing models from other software programs that only output mesh files. Therefore, some had to reduce some details, The process of decreasing the level of detail in a 3D model can be accomplished by employing a powerful tool within Blender known as Sculpt mode. This highly versatile mode offers a plethora of brushes, each of which serves a distinct function. By intelligently selecting and combining these brushes, we could effectively modify the surface of our mesh while retaining the underlying mesh structure.

During the reduction process, some details may be lost, such as holes and finer intricacies that may have previously existed between fingers or other areas of the model. However, the overall shape and structure of the mesh are preserved, ensuring that the final product still's of high quality and visually appealing.

In Figure 3.17 we can observe the implemented and the correct positioning of Blenders joints into Hands joints, Moreover, In Figures 3.19 and 3.20 we can observe that it is evident that the incorrect application of Blender's joint features has resulted in a deformation of the middle finger. Figure 3.18 illustrates that the model is susceptible to significant deformations that can ultimately lead to its destruction.

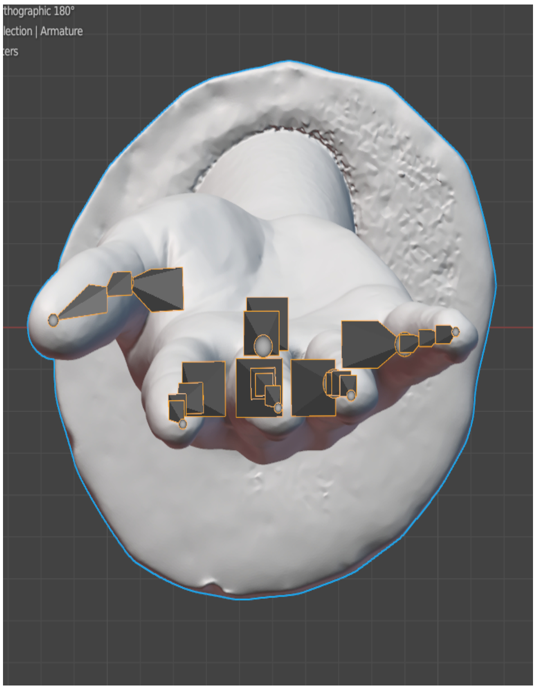


Figure 3.17: Implementation of Blender joints into Hands joints

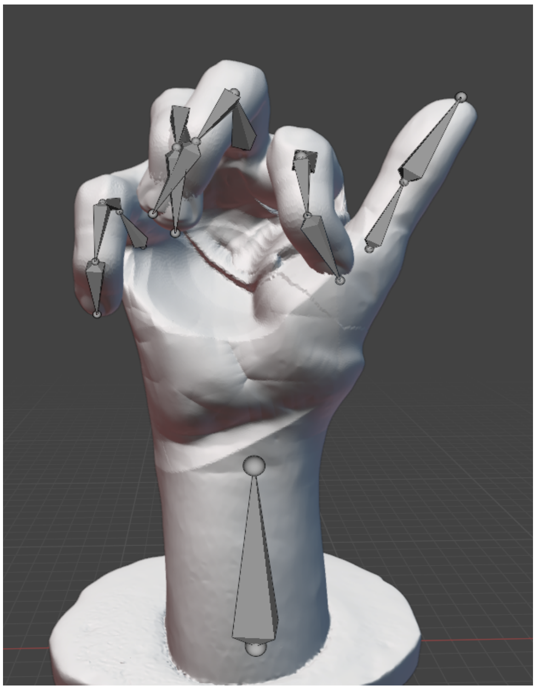


Figure 3.18: Hands deformation after wrong using of the Blender's joints

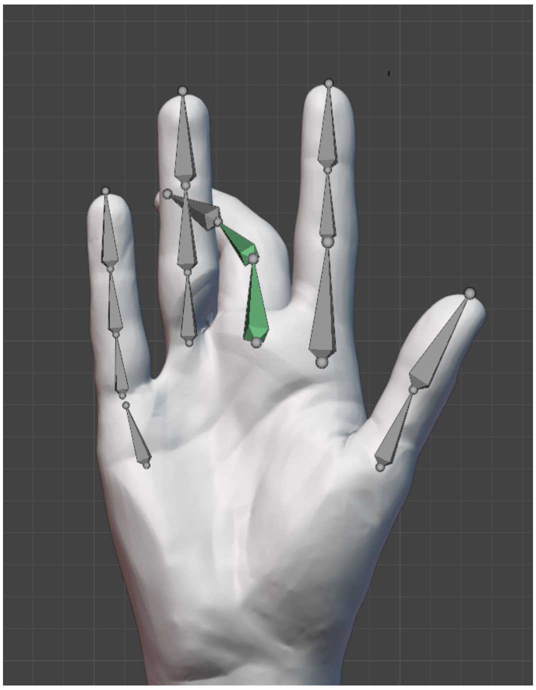


Figure 3.19: Finger deformation after wrong using of the Blender's joints Palmar View

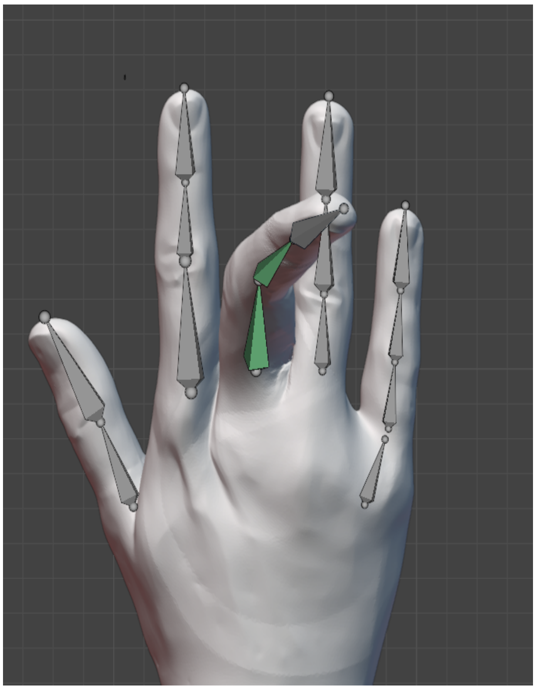


Figure 3.20: Finger deformation after wrong using of the Blender's joints Dorsal view

Figure 3.21: Without modification

Figure 3.22: With modification

Figure 3.23: Without modification

Figure 3.24: With modification

Figure 3.25: Without modification

Figure 3.26: With modification

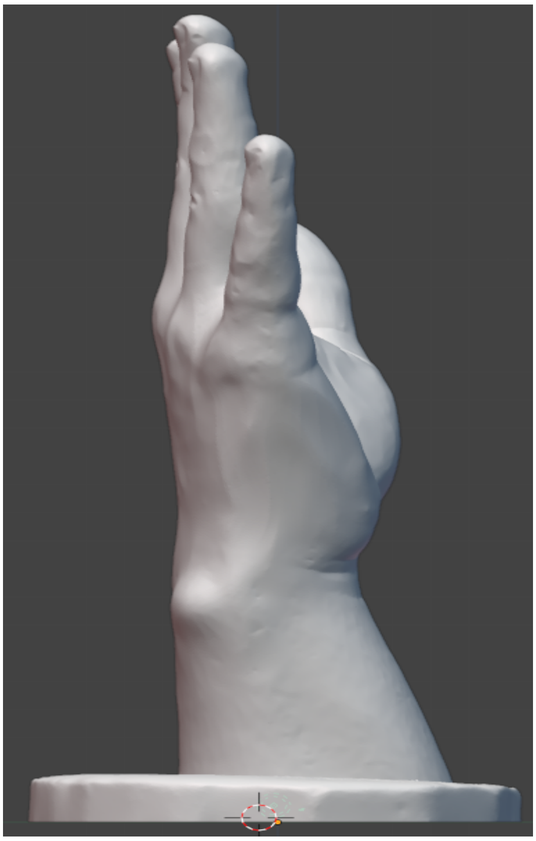


Figure 3.27: Without modification

Figure 3.28: With modification

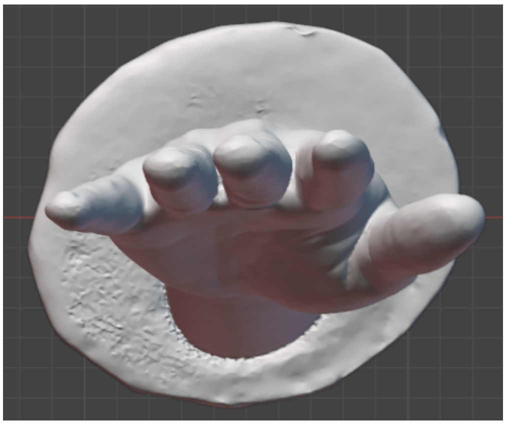


Figure 3.29: Without modification

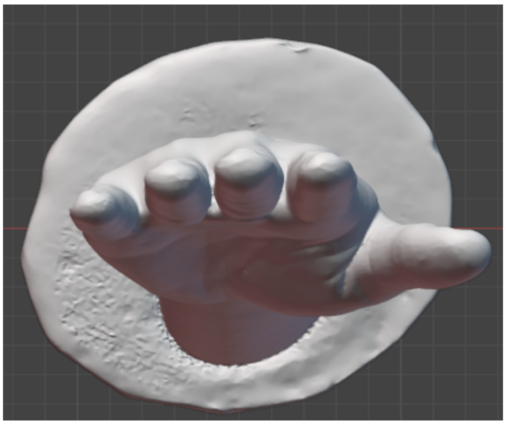
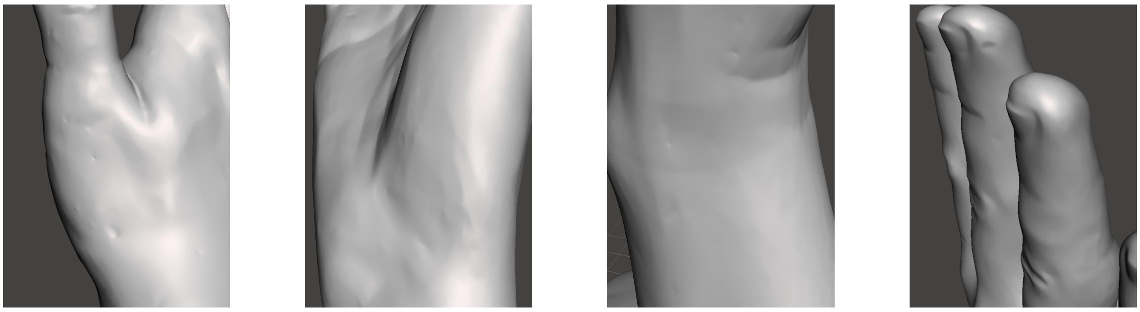


Figure 3.30: With modification

The labeled Figures 3.21, 3.23, 3.25, 3.27 and 3.29 represent the original scanned hand model, while Figures 3.22, 3.24, 3.26, 3.28 and 3.30 depict the modified version. The primary adjustment made to the model was focused on the fingers, wherein the line of action for each individual finger was altered, and some fingers were straightened to prevent intersecting during movement and enable smoother motion. It is noteworthy that the entire hand was slightly affected by the modifications. A helpful way to conceptualize how the hand reacts to the modifications is by envisioning the hand as a pliable clay dough. When working with clay, applying pressure or making changes in one area can affect the entire structure. In the same vein, modifications made to one part of the hand could have significant consequences on the overall functionality of the hand.



(a) Hole (b) wrinkles (c) wrinkles (d) Hole

Figure 3.31: Minor defections that was fixed later with smoothing brush via Blender

Figure 3.31 has some tiny but notable details. In the first image, marked 3.31.a, we can see the presence of holes created during the molding process under the thumb. Similarly, in Figure 3.31.d, a single hole can be seen on the middle finger. In addition, Figures 3.31.b and 3.31.d show some slight wrinkles which, although not major, were remedied at a later stage of work. These small imperfections were efficiently dealt with by using a smoothing brush tool within the Blender software.

3.3.1 Implementing Joint's using Fusion 360

Once the primary adjustments have been made to the inflexible scanned hand and its fingers are confirmed to open and close smoothly, the subsequent critical task is to import the model into a different software program known as Fusion 360. However, the data in our case is in mesh format not in solid or surface.

Solid modeling is typically used for designing parts and assemblies with precise dimensions and engineering tolerances. Solid models are based on mathematical representations of the object's geometry and can be easily modified and edited to meet specific design criteria. This makes them a great choice for manufacturing, prototyping, and simulation. On the other hand,

mesh modeling is often used for creating complex organic shapes or importing models from other software programs that only output mesh files. Mesh models are based on a collection of points and polygons that define the shape of the object, and can be more challenging to manipulate and edit than solid models. However, they can be useful for creating models for visualization, artistic purposes, or for 3D printing.

Hence, Using mesh models in Fusion 360 as we mentioned can be more challenging than using traditional solid or surface models because mesh models are created from a collection of points and polygons that define the shape of the object, rather than a mathematical representation of the object's geometry. All This means that mesh models can be more difficult to manipulate and edit because they do not have the same level of precision and predictability as traditional models.

In Fusion 360, working with mesh models typically involves converting the mesh to a solid or surface model, which can be a complex and time-consuming process. Additionally, mesh models often have a much larger file size than solid or surface models, which can slow down the software and make it more difficult to work with.

In general, If we are creating a complex organic shape or working with a mesh file from another software program, then mesh modeling may be more appropriate. But if we are designing a part or assembly that requires precise dimensions and engineering tolerances, it is better to use solid modeling. However, converting the mesh model to a solid model takes several steps for better results. These steps are converting from mesh to Quads then to T-splines then to BReb, going through these conversions step by step gives us more benefits from precision's perspective.

A quad mesh is a type of 3D mesh where all of the faces (or polygons) consist of four vertices, also known as quads. In contrast, a triangle mesh consists of faces with only three vertices.

The reason for converting a mesh to quads and then to a T-Spine before converting to BRep has to do with the underlying mathematical representations used to describe each of these geometries.

A mesh is a collection of triangles that represent a surface or solid object. While meshes are a popular choice for representing 3D models due to their simplicity and efficiency, they are not well-suited for many types of operations, such as boolean operations, filleting, and blending, which require a more structured geometry.

Converting a mesh to quads involves replacing the triangular faces of the mesh with quadrilateral faces using an Autodesk software called Recap, which can be more easily subdivided and manipulated. A quad mesh is more structured and regular than a triangular mesh, making it more suitable for certain types of operations.

A T-Spline is a type of surface representation that allows for more flexible control over the shape of a surface. It is a combination of a NURBS (Non-Uniform Rational B-Splines) surface and a polygonal mesh, where the mesh defines the topology and the NURBS surface defines the shape. By using a T-Spline, it is possible to create surfaces with smooth, curved shapes that are difficult to achieve with other types of geometry.

Finally, a BRep (Boundary Representation) is a solid modeling technique that represents 3D objects as a collection of simple geometric entities such as planes, cylinders, cones, and spheres. These entities are connected to each other to form a complete 3D object. BReps are well-suited for many types of operations, such as boolean operations. B-rep is a powerful technique for creating precise models with well-defined edges and vertices, but it can be difficult to use for modeling complex and organic shapes. One of the key differences between T-splines and B-rep is that T-splines are better suited for creating organic shapes, while B-rep is better suited for creating precise geometries. and since we already have an organic model for our hand and we want to implement the joint's into it and make the precise, Therefore we chose the BRep over T-spines

In Figure 3.32 we can observe that the mesh is in Quad form, and in Figure 3.33 is in a T-spline form, if we take a closer look to these two figures we can notice that the boundaries are improved in the T-spline form, and the last Figure 3.34 is the model in BRep form which we will continue working with it and implementing the joints into it.

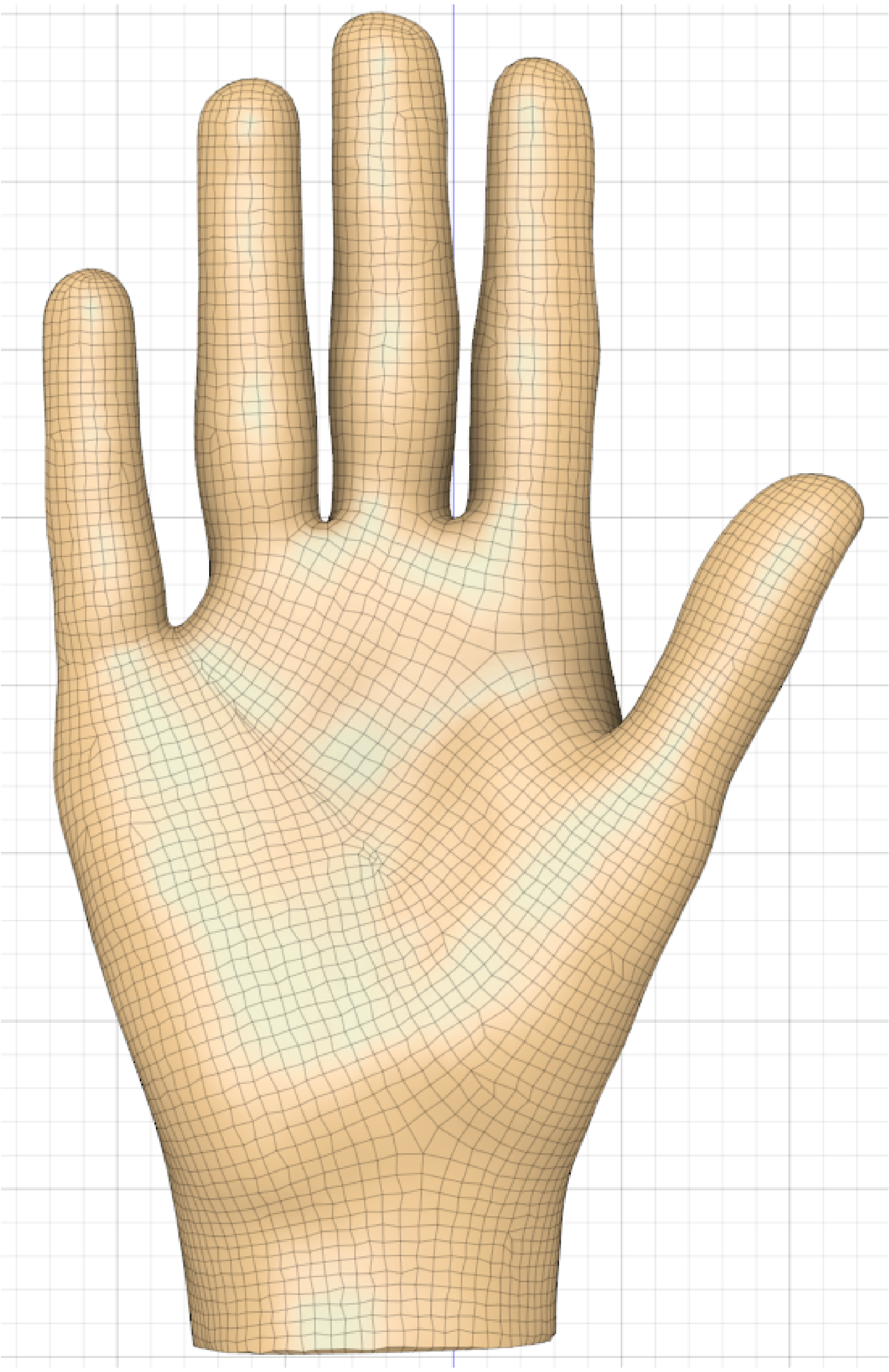


Figure 3.32: Quads

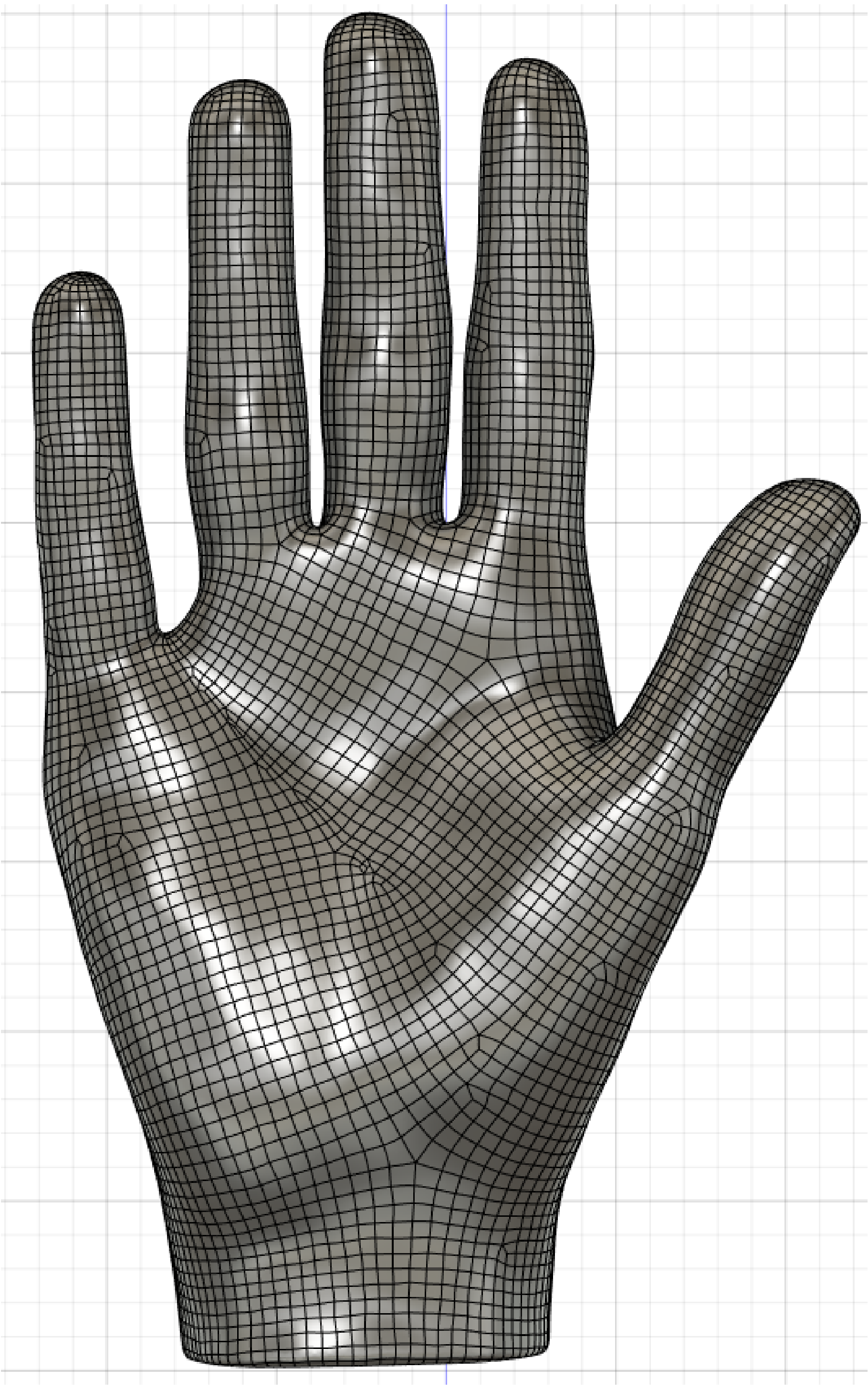


Figure 3.33: T-splines

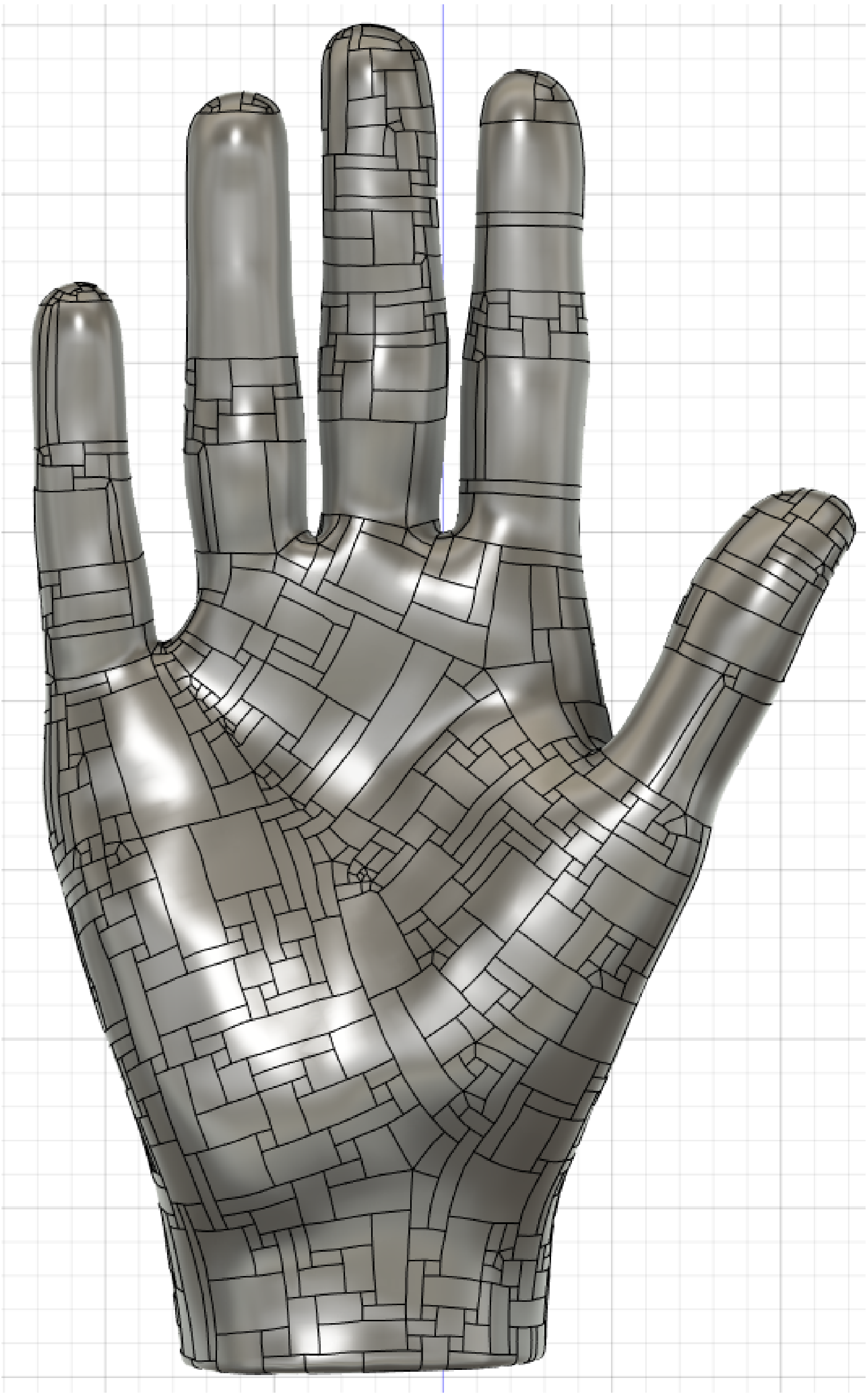


Figure 3.34: BRep

3.3.2 Shaping joints

Because this method of creating prosthetic hands is distinct, we needed to devise a unique approach for incorporating the joints by sculpting them into the hand. Once we had sculpted and molded the joints to fit each finger, we included holes to anchor them with shafts in place and prevent any undesired movements. Additionally, we created holes for wires that would run from the tip of each finger to the servo motor, enabling the fingers to move via the tension in the wires. Through the use of fusion simulation, we examined how the fingers and joints would interact with one another. This allowed us to identify certain areas where unintended contact could result in excessive friction or even impede joint movement. The intersection between the finger and the joint was found almost in all fingers and joints, As we can see in figs. 3.35 and 3.36, By moving the finger and examining its interior, we discovered an intersection. Than we can see in figs. 3.37 and 3.38, That the intersection was successfully removed which leads to smooth movement of the joint.

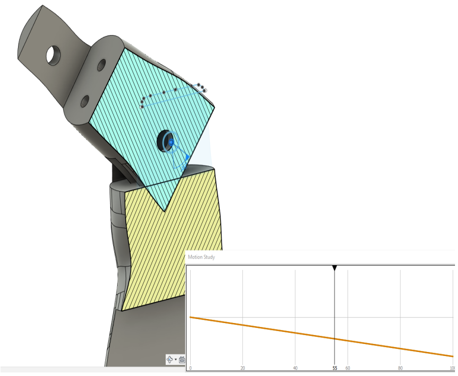


Figure 3.35: Intersection of finger and joint

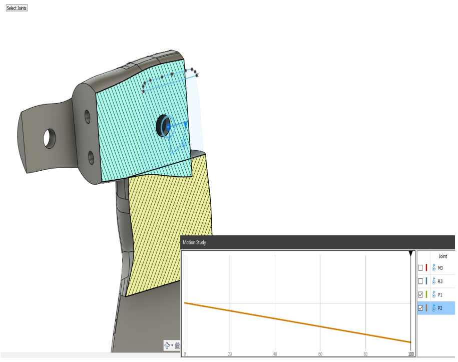


Figure 3.36: Intersection of finger and joint

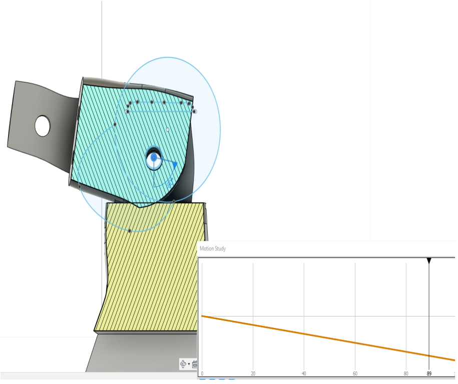


Figure 3.37: Removing the intersection

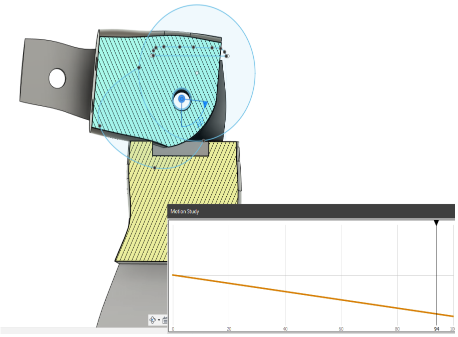


Figure 3.38: Removing the intersection

The outside of the fingers is another common intersection that has been found. In figs. 3.39 to 3.41, We can observe the finger after the solution have been applied.

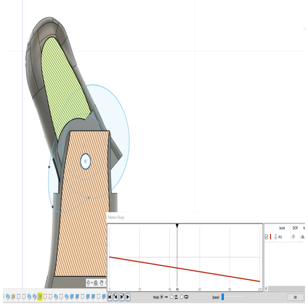


Figure 3.39: Removing exterior intersection

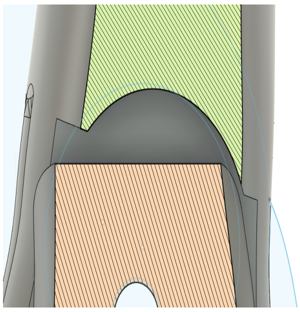


Figure 3.40: Closer look into the solution

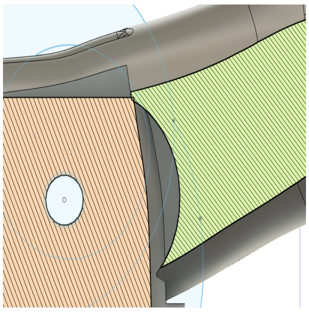


Figure 3.41: Joint under different angle

As it was mentioned we added holes to attach the fingers with the servos using wires, We can see some of those holes in figs. 3.42 to 3.44.

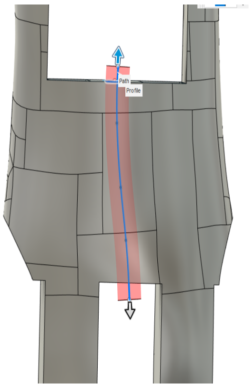


Figure 3.42: Curved hole

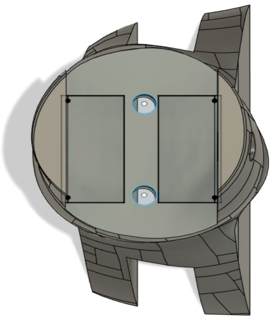


Figure 3.43: Hole upper view

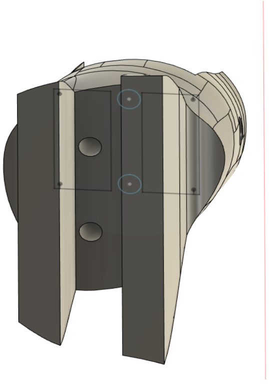


Figure 3.44: Hole bottom view

The final step in hand modeling involves creating room for the servos. This is necessary because the prosthetic hand must be formed from the wrist as the requirements were given in the thesis, which means that the servos cannot be placed in the forearm area as usual. To solve this problem, we decided to place the servos in the palm area more in fig. 3.45. We then downloaded a 3D model of the desired servo and tested whether it would fit in the palm area, as shown in figs. 3.47 and 3.48. Based on our findings, we concluded that we needed to choose smaller servos that could fit in the palm area. After testing the servo fitting in the palm area we had to create a cover for the palm as shown in fig. 3.46.

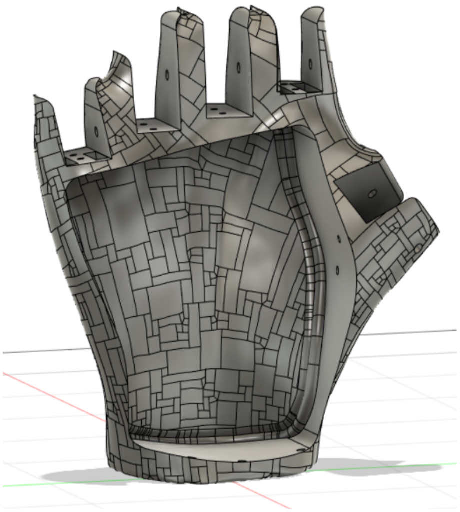


Figure 3.45: Room in palm for servos

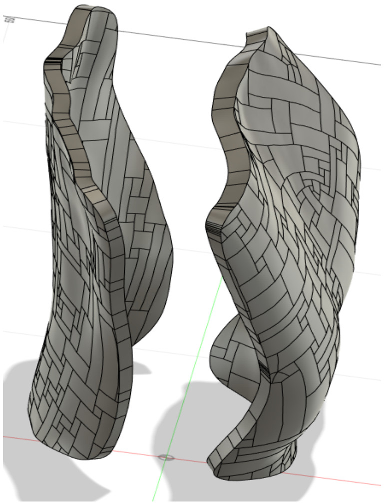


Figure 3.46: Palm cover

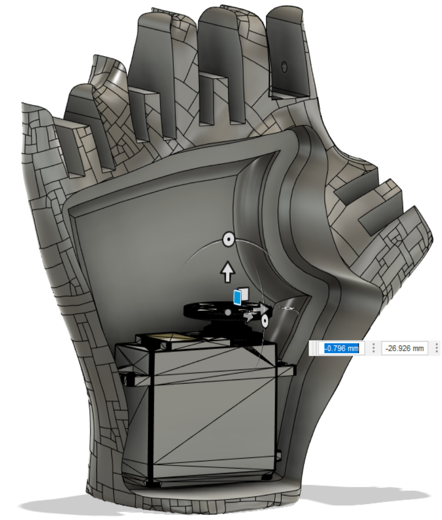


Figure 3.47: Fitting servo model into palm area

Figure 3.48: Fitting servo model into palm area side view

4 System Controller

In the field of prosthetics, the development of advanced technologies has revolutionized the way we design and control prosthetic devices. The use of software to control a prosthetic hand is one such important step. In our thesis, we aim to model and control a prosthetic hand using the Arduino microcontroller board. We need to use software because it allows us to program the Arduino board to control the movements of the prosthetic hand, and it helps us to create complex algorithms that can interpret signals from the user's limb and translate them into movements of the prosthetic hand. If we look at fig. 4.1, we can observe the workflow of our whole system, it starts with electrodes placed on the patient's forearm and using the EMG sensor, we collect the raw signals, then send them to Arduino Nano, which processes the signal using software, then control the prosthetic hand using servos.

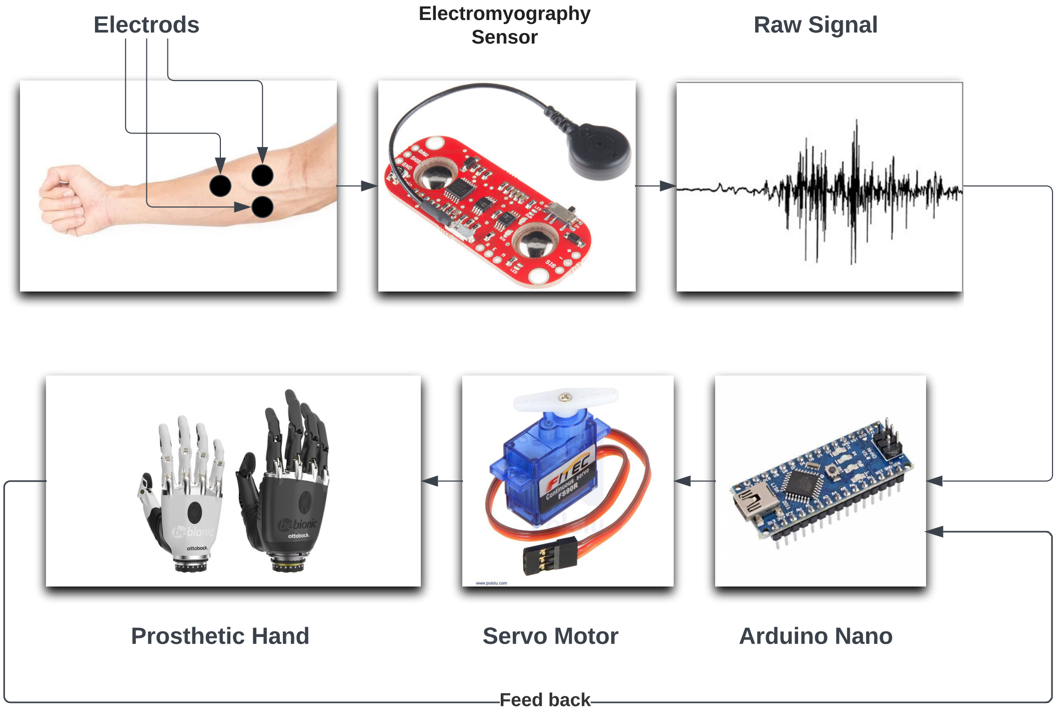


Figure 4.1: System block diagram

4.1 Electromyography Sensor

A biomedical signal is an electrical signal acquired from any organ that represents a physical variable of interest. Typically, this signal is a function of time and can be described in terms of its amplitude, frequency, and phase. The EMG signal is an example of a biomedical signal that measures the electrical currents generated in muscles during contraction, representing neuromuscular activities. Muscle activity is always controlled by the nervous system, making the EMG signal a complex signal that depends on the anatomical and physiological properties of muscles. During transmission through different tissues, the EMG signal can acquire noise, and if detected on the surface of the skin, the signal can collect signals from different motor units simultaneously, leading to signal interaction. Powerful and advanced methodologies are required for the detection of EMG signals, particularly for clinical diagnosis and biomedical applications. Management and rehabilitation of motor disability are some of the important areas of application. With the availability of appropriate algorithms and methods for EMG signal analysis, the signal's nature and characteristics can be understood, and hardware implementations can be developed for various EMG signal-related applications such as prosthetic limbs .

In 1666, Francesco Redi recorded the beginnings of EMG, which involved the observation of the electric ray fish's highly specialized muscle that produced electric currents[37]. In 1773, Walsh managed to exhibit that the muscle tissue of the Eel fish had the ability to produce a spark of electricity. A publication titled ”De Viribus Electricitatis in Motu Musculari Commentarius” was published in 1792, written by A. Galvani, which demonstrated that muscle contractions could be initiated by electricity[38]. In 1849, Dubios-Raymond made a breakthrough discovery that it was feasible to document electrical activity while a person voluntarily contracted their muscles. The first-ever recording of this activity was accomplished by Marey in 1890, who also coined the term electromyography[39]. Gasser and Erlanger utilized an oscilloscope in 1922 to display the electrical signals produced by muscles. However, due to the random nature of the myoelectric signal, only rudimentary data could be gleaned from its observation. The ability to detect electromyographic signals progressed gradually from the 1930s to the 1950s, and improved electrodes were increasingly used by researchers to examine muscles[40]. The utilization of surface EMG for treating particular disorders in a clinical setting started in the 1960s. The initial use of sEMG by practitioners was carried out by Hardyck and his research team in 1966[39]. During the early 1980s, Cram and Steger presented a clinical technique that involved utilizing an EMG sensing device to scan a range of muscles[39]. The production of small and lightweight instrumentation and amplifiers, using advanced integration techniques in electrodes, did not reach a sufficient level until the mid-1980s.

Nowadays, several appropriate amplifiers are accessible commercially. Artifacts that are produced in the microvolt range by cables became available in the early 1980s. Over the last 15 years, studies have led to an improved understanding of the characteristics of surface EMG recording. In current times, surface electromyography is more commonly employed for recording from superficial muscles in clinical protocols, while intramuscular electrodes are utilized solely for deep muscle recording[41, 42]. EMG has numerous applications. It is utilized clinically to diagnose neurological and neuromuscular issues, and is also used for diagnostic purposes by gait laboratories and clinicians who are trained in biofeedback or ergonomic evaluation. Additionally, EMG is employed in various research laboratories, including those involved in biomechanics, motor control, neuromuscular physiology, movement disorders, postural control, and physical therapy.

4.1.1 Driving motors and power supply

Servo motors are electric motors that can be used in a wide range of applications where precise control of position, speed, and torque is required. There are different types of servo motors available, each with its own unique characteristics and applications. Such as,

- DC servo motors: These are the most basic type of servo motors, and they are commonly used in small and low-cost applications that require precise control of the angular position. They typically have a permanent magnet rotor and a wound stator, and they are controlled by a pulse width modulation (PWM) signal.
- AC servo motors: These motors are similar to DC servo motors, but they use an alternating current (AC) power source instead of a direct current (DC) power source. They are commonly used in industrial applications, such as robotics and CNC machines.
- Brushless servo motors: These are high-performance servo motors that are commonly used in applications that require high speed and torque. They do not use brushes, which reduces friction and increases efficiency. They are often used in the aerospace, defense, and medical industries.
- Linear servo motors: These are specialized servo motors that can provide linear motion, as opposed to rotary motion. They are commonly used in applications such as positioning systems, robotics, and industrial automation.
- Stepper motors: These are a type of servo motor that operates by dividing a full rotation into a number of equal steps. They are commonly used in applications that require precise control of position and speed, such as CNC machines and 3D printers.

These are just a few examples of the different types of servo motors available. The choice of servo motor will depend on the specific requirements of the application, including the required precision, speed, torque, and cost.

The main part of the prosthetic hand that is responsible for the movement is the motor. There is a seemingly endless selection of DC, stepper, and servo motor products on the market, each with its own advantages and drawbacks. Also jointed arm robots require the perfect actuator to power their specialized movement with the right type and amount of force.
There are various factors to consider when selecting a motor to power a prosthetic hand with movable joints.

1. What type of movable joints is used?
   There are five types of robotic joints: linear, orthogonal, rotational, and twisting. For our hand, rotational joints were used, since we need just a rotation motion with one degree of freedom.

2. How much noise is tolerable in the application?
   Based on our application, the level of noise is not a significant factor as we are looking for a cost-effective solution, and the servos we can utilize are small in size, which inherently means they are less likely to produce excessive noise.

3. How much Force is necessary?
   To adequately respond to this inquiry, it is crucial to possess knowledge of the minimum grip force. The minimum grip force refers to the amount of force exerted by the fingers to securely grasp an object and counteract the effects of gravity. Our project involves the use of a prosthetic hand to handle various food items, including a cup of soft drink. Among these items, the cup of soft drink is the heaviest object that the hand needs to lift. Consequently, the design of the hand system must ensure that an adequate grip force is provided to securely hold the cup of soft drink.

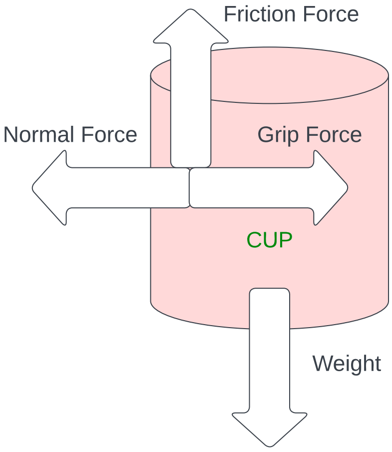


Figure 4.2: Cup free body diagram

The arm's acceleration is negligible and considered to be zero. Rapid upward movement of the arm would result in additional weight being exerted on the cup due to acceleration. However, our prosthetic system is designed to lift the cup at a slow speed, disregarding acceleration in the calculations.

According to the free body diagram, to prevent the cup from slipping out of the hand, the static friction force must be equal to the weight of the cup.

$Fy = FrictionForce - Weight = 0$
$Fx = GripForce - NormalForce = 0$

The friction force can be determined using the equation: $FrictionForce = \mu \cdot N$, where µ represents the coefficient of static friction and N represents the normal force. The normal force is equal in magnitude but opposite in direction to the grip force exerted by the prosthetic hand system.
$Weightofcup = m \cdot g$, Where m is the mass of the cup and g is the gravity acceleration. When calculating the forces acting on the cup both vertically and horizontally, we can solve the equation $\mu \cdot N = m \cdot g$, to calculate the mass of the cup we have the following equation, $Mass = Volumeofcup \cdot density = 621ml \cdot 1.1g/ml = 683grams$.
We assume that the prosthetic hand and the cup are made of plastic material. Therefore, the Static friction coefficient between them will be $\mu = 0.5$
$MinimumRequiredGripForce = m \cdot g/\mu = 0.683 \cdot 9.8/0.5 = 13.4N$.

After answering all these three questions, it has been decided to choose servo motors. Therefore, let's take a hint of how servo does its work. Inside a typical hobby servo motor, we will typically find three main components: a DC motor, a controller circuit, and a feedback mechanism such as a potentiometer. The DC motor is connected to a gearbox and output shaft, enhancing the motor's speed and torque. The DC motor propels the output shaft. The controller circuit interprets signals from the controller, while the potentiometer provides feedback to the controller circuit, enabling it to monitor the position of the output shaft. Most hobby servos employ a standard three-pin connector with 0.1" spacing for power and control. While the color coding may vary among brands, the pin order is typically consistent. By combining these components, we can utilize just three wires to provide power and control over the direction, speed, and position of the output shaft. for more understanding in Fig 4.3. To control the movement of a servo, whether it is to position it along its movement arc or to manage the speed and direction of a continuous rotation servo, a precise and timed signal must be sent by the controller. Hobby servos typically expect a pulse every 20 milliseconds (ms), with the width of the signal determining the position. This width generally ranges from one to two milliseconds. This method of signal control is commonly known as Pulse Width Modulation (PWM). A servo controller is typically a specialized hardware component that receives input from other devices such as a joystick, potentiometer, or sensor feedback to generate the control signal for the servo. Alternatively, one can utilize the PWM-capable pins on a microcontroller to directly send the signal to the servo.

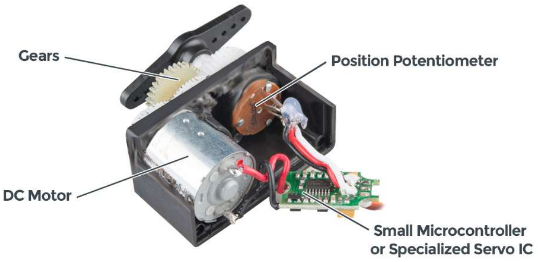


Figure 4.3: Inside a standard hobby servo[43]

Types of Servos

- A typical hobby servo, also known as a ”closed-loop” servo, typically offers a movement range of either 90 or 180 degrees. However, it’s important to note that some servos may have a slightly larger or smaller range, so it’s advisable to review the motor’s specifications before incorporating it into your project. Standard servos provide feedback to the controller regarding their position along the movement arc through the control signal wire. This feedback enables you to accurately move the servo to specific positions by using the appropriate pulse length from your controller. Fig 4.4
- Continuous rotation or ”open-loop” servos operate differently from standard servos. In these servos, the control signal solely governs the direction and speed of the servo, rather than the position. As a result, they allow for convenient control over the speed and direction of the drive shaft. However, since there is no feedback mechanism for position control, they are not recommended for applications that necessitate precise movement between specific points along the rotation arc.Fig 4.5

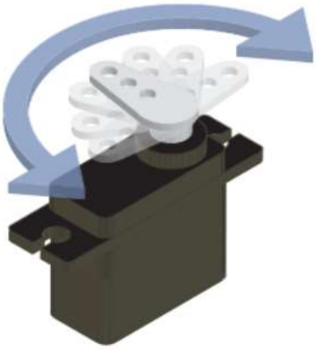


Figure 4.4: standard hobby servo[43]

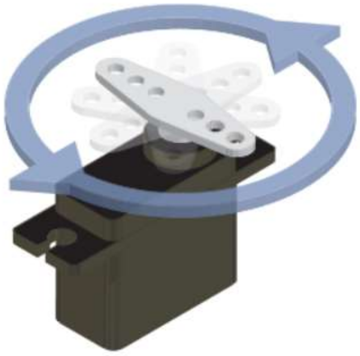


Figure 4.5: continuous rotation[43]

Servo sizes

Hobby servos are typically categorized based on their size, although there may be slight variations in how manufacturers classify them. In general, they can be classified into three types: micro, standard, and giant. These classifications indicate not only the physical dimensions of the servo but also the output torque and the power needed to generate that torque.
Each type has its own advantages and disadvantages. A giant servo can generate a significantly higher amount of torque compared to a micro servo. However, it requires more space and power to generate such force. On the other hand, standard-sized servos provide a balanced option, with moderate power requirements and reasonable output torque suitable for most applications. More in fig 4.6.

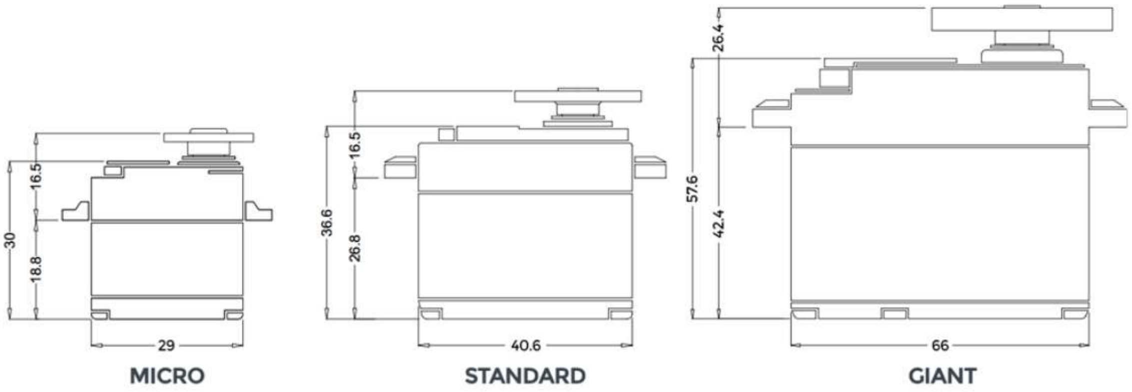


Figure 4.6: A size breakdown from the Hitec HS-85MG, Hitec HS-425BB, and Hitec HS-805BB in millimeters

As we already noticed in figs. 3.47 and 3.48, It is not possible to implement the standard servo motor because of our limited space, therefore, we will have to compromise and use the MICRO servo, for more specification about the MICRO servo in data sheet [44].

4.1.2 Controller code implementation

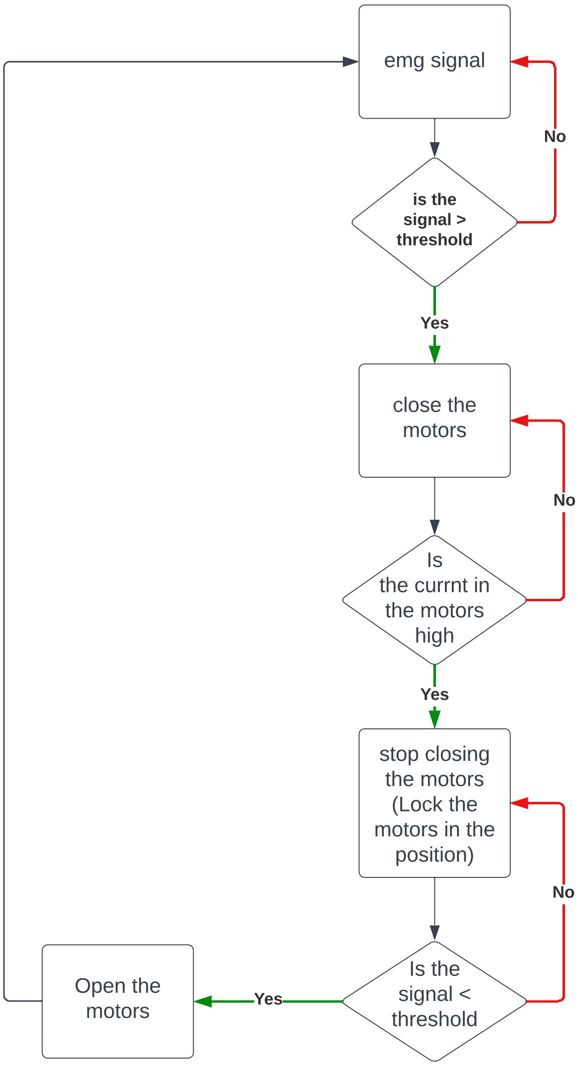


Figure 4.7: Program workflow

Going through coding

The control algorithm functions as a state machine, beginning in an idle state where all servos are stationary. In this state, it awaits a start command, typically triggered by the EMG sensor. The assumption is made that the hand's initial position remains unchanged. Once the start command is received, the movement initiates. The servos are controlled individually, enabling the grasping of objects with varying

shapes. The grasping process concludes when the EMG signal surpasses a predetermined threshold. The signals captured from EMG sensors undergo amplification and rectification. Fig. 4.8 provides a depiction of the original EMG signal, while Fig. 4.9 shows the filtered signal. The input amplitude of the EMG signal is measured in millivolts. Upon receiving the EMG signal, it is necessary to apply a low-pass filter to remove any noise from the signal. This filtering process helps to enhance the quality of the signal. The amplification is then calculated using the following formula:
$x[n] = \alpha * y[n] + (1 - \alpha) * y[n-1]$.
The smoothing factor α, ranging from 0 to 1, is used to calculate the resulting filtered discrete signal x[n] from the received discrete EMG signal y[n]. Fig. 4.9 demonstrates an example of an EMG signal after filtering with a smoothing factor of $\alpha = 0.05$. Various values of α ranging from 0.05 to 1 were tested on the EMG signal. When $\alpha = 0.05$, the filter is slower but yields a clear output. In Fig. 4.9, the filtered signal is visualized in green.

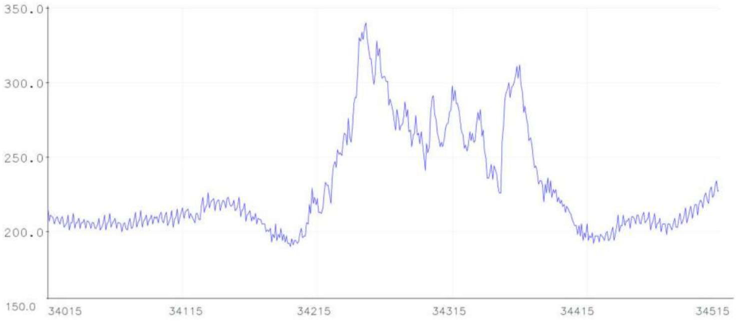


Figure 4.8: Raw EMG signal

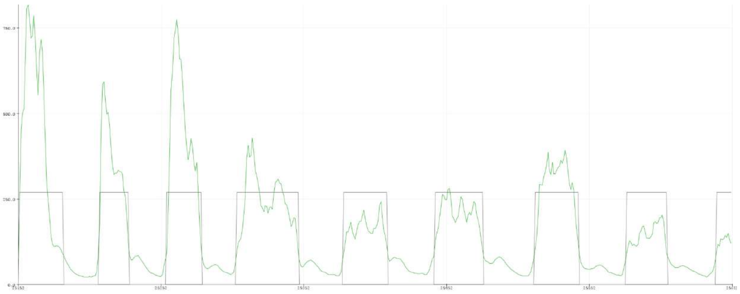


Figure 4.9: Filtered EMG signal

Subsequently, the filtered signal undergoes classification and analysis to detect finger flexion and extension. The features relevant to finger movements are extracted and distinguished from the EMG signal. The focus of the current study includes the assessment of power related to grasping movements.

To expedite the computation of the EMG signal, the features are extracted in the time domain. Additionally, the grasping function initiates based on the amplitude of the EMG signal. Grasping action commences when the amplitude of the EMG signal surpasses a predefined threshold. Fig 4.9 presents, in black rectangle, the grasping movement, When the EMG exceeds the threshold it activates the servos.

Feedback

One of the main important topics is feedback. In other words, knowing when to stop the servo during the grasping process is a very important step, Therefore, feedback has been taken into our consideration.

To improve the controllability of our system, there are multiple methods to obtain feedback and integrate it into the microcontroller. We can utilize various sensors such as current sensors, voltage sensors, and force sensors. These sensors allow us to gather information about the current levels, voltage levels, and force exerted within the system, respectively. By incorporating this feedback into the microcontroller, we can enhance the overall control and performance of our system.

Considering our financial and spatial constraints, we explored an alternative method for obtaining feedback that is cost-effective and space-efficient. In this regard, we opted for the utilization of a shunt resistor. The shunt resistor serves as a more affordable and compact solution to gather the necessary feedback data. By implementing the shunt resistor, we can overcome the limitations posed by our financial and spatial restrictions while still acquiring essential feedback information.

Shunt resistors are electronic components used for measuring electric current within a circuit. They are connected in parallel with the circuit element under measurement, and the current passing through the shunt resistor generates a voltage drop across it. This voltage drop is subsequently measured using a voltmeter, and the obtained value is utilized to determine the current flowing through the circuit.

Shunt resistors operate by generating a voltage drop across a resistor with a ”known value” when current passes through it. This voltage drop is subsequently measured using a voltmeter and typically amplified to calculate the current flowing through the circuit. To measure the current in a circuit, the voltage drop across the shunt resistor is initially calibrated using a known current, and the output voltage is adjusted by removing resistive material until the values align. However, as the current requirements increase, the resistance needs to decrease, making it increasingly challenging to calibrate smaller current measurements due to the diminishing amount of material available for adjustment.

In summary, the objective is to identify any variation in behavior and transmit it to the microcontroller. To achieve this, we utilize the shunt resistor to detect the voltage drop when the servo encounters an obstacle. Through calibration, we establish a threshold to halt the motor if the voltage surpasses it. This approach allows us to detect and respond to obstacles by monitoring the voltage fluctuations and taking appropriate actions in real-time.

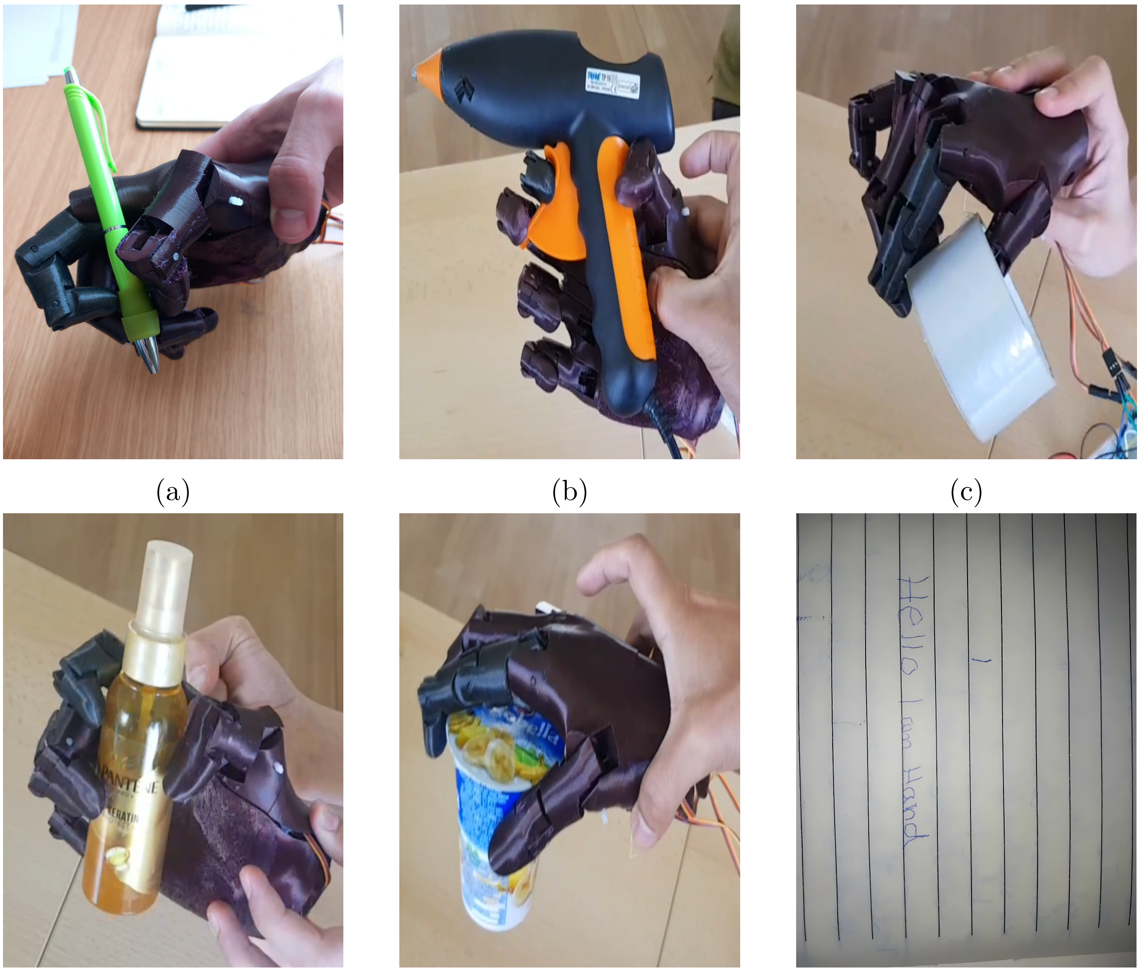
5 Results and Performance Evaluations

The evaluation of the production and functionality of this prosthetic hand has undergone various stages. grasping capabilities of our design, and 3D printed model.

grasping capabilities of our design

We used multiple grasping techniques to assess the upper extremity function of individuals with hand impairments or disabilities. We tested the design's ability to grip various objects, including performing power grip, cylindrical grip, tip grip as a substitute for tripod grip, lateral grip, and extension grip. Since we did not have volunteers with forearm amputation during the test and evaluation phase, we held the prosthetic hand with our own hand to perform the tests. The objects used for testing included transparent tape, a glue gun, a writing pen, a cylindrical oil bottle, and a yogurt can. Our hand demonstrated the capability to form various grips, except for the extension grip we tried to hold a cellphone especially when the palm is facing the ground but it is a bit better when the palm is facing the sky, and the tripod grip is typically performed by a healthy hand when writing. However, we propose that in our case, a tip grip can be substituted for the tripod grip when holding objects such as a pen. This is further supported by the fact that our prosthetic hand is not specifically designed for complex tasks like writing or using chopsticks. Fig 5.1 in our documentation depicts our hand holding various objects.

Based on our evaluation results, we can confidently assert that our design demonstrated efficient performance of 90% in diverse test cases. Our affordable body-controlled prosthetic hand offers the simplicity of use, as it merely requires the reception of signals from the EMG sensor to initiate a grasping motion. Although this prototype represents an initial iteration of our model, we anticipate that with the recommended adjustments outlined in Chapter Seven on future work, it can be easily prototyped and locally mass-produced without encountering any obstacles. It will have the potential to assist with everyday tasks, including tasks like floor sweeping and hanging laundry on a drying rack, as well as participating in certain sports activities. Additionally, it can serve as a conversation starter in public settings like trains or buses, contributing to increased self-assurance and confidence.



(a) (b) (c)

(d) (e) (f)

Figure 5.1: Grasping various objects using our designed hand: (a) tip grip as a substitute of tripod grip, (b) power grip, (c) tip grip, (d) cylindrical grip, (e) lateral grip, (f) writing test

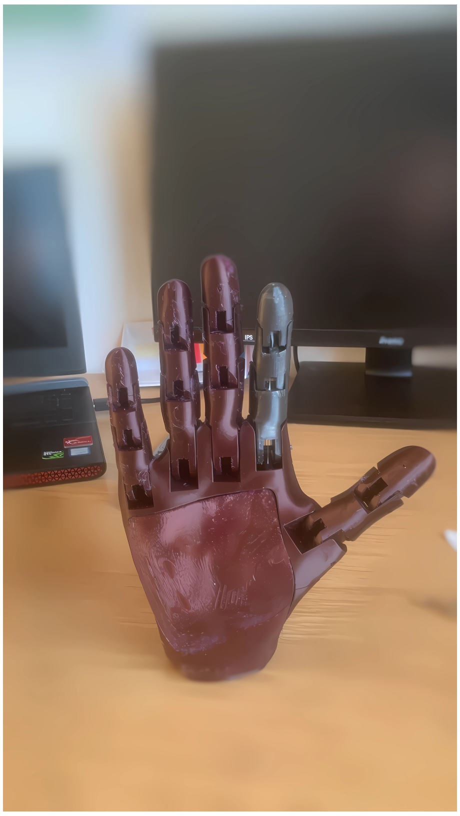


Figure 5.2: Palmar 3D printed Hand view

Figure 5.3: Dorsal 3D printed Hand view

3D printed model

The hand was printed using Prusa printers and PLA material. Upon examination, minor imperfections and a lack of intricate details were observed in the palm area. This can be attributed to the curved shape, necessitating the addition of supports during the printing process. Furthermore, three layers shifted due to material refilling, resulting in undesired friction between the joints during the tests. we tried To address this issue, and the common contact area was meticulously polished. Additionally, the shafts were subjected to polishing as they were also printed components since the Prusa 3d printers have problems printing perfectly rounded shapes.

6 Conclusion

The number of amputees is rapidly increasing around the world for different reasons like Wars, accidents, diseases, etc. Amputee people can suffer of different kinds of problems like depression, social reintegration difficulties, and often low acceptance, Therefore, the main goal of this Thesis is to create a functional prosthetic hand that will replace a real hand in case of amputation. The main focus is to make the prosthetic hand as real as possible. Basically, our golden goal is to mimic the human hand, therefore the first step is to look deeply at the anatomy of the hand to understand its functionality, The human hand is made basically of bones which can be divided into three groups Phalanges, Metacarpals, and Carpals, These Bone systems are responsible for the rigidity of the hand and mainly they are giving the hands shape. Also, its made of muscles and they are as follows, Thenar muscles, Hypothenar muscles, Lumbrical muscles, Adductor Pollicis muscle, Drosal Interossei muscles, and Palmar Interossei muscles, the muscular system are responsible for the motion of the hand providing the force to conduct the motion. Also, it has Ligaments which are very important because they bound the bones together, otherwise they will be flouting with no bound, also they stabilize the bones with joints. It contains also Tendons which are responsible to connect the muscular system to the bones system. A human hand contains a lot of lineaments and tendons. They are approximately over 100. It also has 27 joints which play a very important role in allowing the hand to move cretin movements and make different types of grasping and etc. It contains also Blood vessels that supply the hand with blood to keep it alive, lastly, the main system is the Nerves system which is responsible for sensory and motor functions in different parts of the hand.

After getting to understand what is Hand made of and how it does its work the next step is to model the hand to bring it to the real world. There are several ways to approach this step and the best approach since we are trying to mimic the real human hand is through utilizing 3D scanning technology which is basically the process of capturing the physical shape and appearance of an object in a digital format. In TULAB, we have a magnificent 3D scanner called Einscan Pro 2X plus which helped to make a model of the main hand, the model had to go through some processing and modification for sure because the output of the 3d scanner is a rigid body, we applied surface modification to entire hand one of them is quality reduced the reason of doing that is when working with the model in fusion 360, it can handle the model without any problems since we are applying a lot of functions and modification to it, the lines of actions of individual fingers had to be modified also the main reason causing this problem is during molding or scanning the person can not hold his hand and fingers still for a longer period to finish the molding or 3D scanning process. After putting the hand into the right position, then we could design the joints into the hand. The used method was sculpting and slicing the hand. Since the hand is driven by the tension, holes were added for the wiring. In order to make this model general, we add a room into the palm area to put into it all the servos, microcontrollers, and batteries, for sure this move decreased our choice of servos motors to fit into the space we have.

The hand was fabricated using Prusa printers and PLA material. The printing process involved multiple stages to assess the functionality of individual parts and make necessary adjustments to the model's parameters in case needed. However, the shafts required additional polishing due to the challenges and intricacies involved in achieving a precise round shape during the printing process.

After getting the model ready it is like a body without a soul, Therefore, we have to add the soul by implementing the controller and the servos into it. The control algorithm functions as a state machine. In the beginning, we wait for the signal from the EMG sensor, these signals have to be processed in real-time, since the raw signal is useless for us because we have a sensitive controlling system so the signal goes through a low-pass filter to eliminate the unwanted noises. A threshold was used to determine when to activate the servo motors and when to deactivate them. The threshold can vary from one person to another since the muscular system of a human can also vary from one person to another. Therefore, the threshold had to be adjusted experimentally when it come to the change of users, also it is important to know when to stop the servo motors from closing and let them hold still in position during holding a cup or any other object. Thus, we used a shunt resistor to detect the voltage drop and feed this signal back into the microcontroller as a feedback signal to create a close loop in our system. Hence, a function in our program was created which had one job detect the voltage drop when the servo hits an obstacle, again a threshold was determined. And if the signal exceeds the threshold, the servos stop at the position they are currently in, and when the signal goes below the threshold, the servos are released.

Subsequently, we proceeded to integrate the components of the hand, including the servo motors and the EMG sensor, in order to conduct a comprehensive performance evaluation. The results obtained from the evaluation were highly promising. We conducted a series of tests involving different grasping techniques on various objects, such as transparent tape, a glue gun, a writing pen, a cylindrical oil bottle, a yogurt can, and a cellphone. The prosthetic hand exhibited a remarkable level of efficiency, achieving a success rate of 90%. It's important to mention that the prosthetic hand in question has not undergone testing or received approval from the European Medicines Agency (EMA).

According to Fourie's (2017) master's thesis, it is stated that ”The 3D image is saved on the computer as a .STL file which is the same file format used in 3D printing but can't really be manipulated or used in the mainline CAD software” (p. 58). Furthermore, Fourie mentions that ”The 3D scan of the author's own hand come out fairly well but the information was not sufficient to be used in the design although accurate it was only used as a comparison model and could not be used in the modelling of the hand” (p. 58)[45]. Based on the results presented in this master thesis, it can be concluded that the findings presented here contradict the conclusions made in Fourie's master's thesis and proves him wrong.

7 Future work and recommendations

This master thesis is the first prototype and exhibits both strengths and weaknesses, thereby presenting numerous opportunities for improvement in various areas.

- The 3D scanning process was done manually and it can be automated.
- The process of creating the joint is done manually and in the future I believe that it can get automated using AI
- The hand was 3D printed utilizing PLA material and Prusa printers, resulting in a noticeable deficiency in achieving the desired level of detail outlined in our thesis. As a recommendation, it is highly advised to employ resin printers or alternative printers known for their ability to maintain high-quality printed models.
- The current design of the prosthetic hand does not possess water resistance capabilities. It is strongly advised to incorporate a water-resistant feature into the hand, considering its intended use in domestic tasks, various sports activities, and the potential exposure to rain when used outdoors.
- The current setup involves using a single EMG sensor to control all fingers collectively, resulting in simultaneous movement of all fingers. However, this approach may not be ideal for certain grips and objects. Therefore, it is recommended to consider employing individual EMG sensors for each finger, enabling independent control and facilitating a wider range of grasping techniques.
- In order to accommodate the limited space available in the palm area of this prosthetic hand, hobby servo motors were selected. However, it is suggested to explore alternative options to address the challenge of limited space. One possible solution is to enlarge the palm area towards the forearm direction, allowing for the use of larger servo motors with increased torque. Alternatively, considering different types of motors may also prove beneficial in optimizing the design and functionality of the prosthetic hand.
- To establish the connection between the servos and the tips of the fingers, we initially used industrial sewing threads. However, we encountered a challenge where the string tended to elongate under high tension, resulting in imperfect positioning. To address this issue, we opted to replace the string with dental

floss. Dental floss proved to be a more suitable alternative as it does not elongate like regular string and offers a silky texture that aids in maintaining the desired position. Nevertheless, it is advisable to consider using fishing wires as a potential enhancement to further improve the stability and reliability of the connection.

List of Figures

List of Tables

References

[1] ZIEGLER-GRAHAM, Kathryn et al. Estimating the prevalence of limb loss in the United States: 2005 to 2050. *Archives of physical medicine and rehabilitation*. 2008, vol. 89, no. 3, pp. 422–429.

[2] SALMINGER, S et al. Prosthetic reconstruction to restore function in transcarpal amputees. *Journal of Plastic, Reconstructive & Aesthetic Surgery*. 2016, vol. 69, no. 3, pp. 305–310.

[3] BIDDISS, Elaine A and Tom T CHAU. Upper limb prosthesis use and abandonment: a survey of the last 25 years. *Prosthetics and orthotics international*. 2007, vol. 31, no. 3, pp. 236–257.

[4] ØSTLIE, Kristin et al. Adult acquired major upper limb amputation in Norway: prevalence, demographic features and amputation specific features. A population-based survey. *Disability and rehabilitation*. 2011, vol. 33, no. 17-18, pp. 1636–1649.

[5] JONES, LE and JH DAVIDSON. The long-term outcome of upper limb amputees treated at a rehabilitation centre in Sydney, Australia. *Disability and rehabilitation*. 1995, vol. 17, no. 8, pp. 437–442.

[6] WRIGHT, Thomas W, Arlene D HAGEN, and Michael B WOOD. Prosthetic usage in major upper extremity amputations. *The Journal of hand surgery*. 1995, vol. 20, no. 4, pp. 619–622.

[7] YAMAMOTO, Michiro et al. Cross-sectional international multicenter study on quality of life and reasons for abandonment of upper limb prostheses. *Plastic and Reconstructive Surgery Global Open*. 2019, vol. 7, no. 5.

[8] ØSTLIE, Kristin et al. Prosthesis use in adult acquired major upper-limb amputees: patterns of wear, prosthetic skills and the actual use of prostheses in activities of daily life. *Disability and Rehabilitation: Assistive Technology*. 2012, vol. 7, no. 6, pp. 479–493.

[9] ATKINS, Diane J, Denise CY HEARD, and William H DONOVAN. Epidemiologic overview of individuals with upper-limb loss and their reported research priorities. *Jpo: Journal of prosthetics and orthotics*. 1996, vol. 8, no. 1, pp. 2–11.

[10] BURGER, Helena and Črt MARINČEK. Upper limb prosthetic use in Slovenia. *Prosthetics and orthotics international*. 1994, vol. 18, no. 1, pp. 25–33.

[11] DUDKIEWICZ, Israel et al. Evaluation of prosthetic usage in upper limb amputees. *Disability and rehabilitation.* 2004, vol. 26, no. 1, pp. 60–63.

[12] KEJLAA, GH. Consumer concerns and the functional value of prostheses to upper limb amputees. *Prosthetics and orthotics international.* 1993, vol. 17, no. 3, pp. 157–163.

[13] KYBERD, Peter J and Wendy HILL. Survey of upper limb prosthesis users in Sweden, the United Kingdom and Canada. *Prosthetics and orthotics international.* 2011, vol. 35, no. 2, pp. 234–241.

[14] SCHULTZ, Aimee E, Susan P BAADE, and Todd A KUIKEN. Expert opinions on success factors for upper-limb prostheses. *Journal of Rehabilitation Research and Development.* 2007, vol. 44, no. 4, p. 483.

[15] BIDDISS, Elaine and Tom CHAU. Upper-limb prosthetics: critical factors in device abandonment. *American journal of physical medicine & rehabilitation.* 2007, vol. 86, no. 12, pp. 977–987.

[16] ØSTLIE, Kristin et al. Prosthesis rejection in acquired major upper-limb amputees: a population-based survey. *Disability and Rehabilitation: Assistive Technology.* 2012, vol. 7, no. 4, pp. 294–303.

[17] ROCHE, Aidan D et al. Prosthetic myoelectric control strategies: a clinical perspective. *Current Surgery Reports.* 2014, vol. 2, pp. 1–11.

[18] FARINA, Dario and Oskar ASZMANN. Bionic limbs: clinical reality and academic promises. *Science translational medicine.* 2014, vol. 6, no. 257, 257ps12–257ps12.

[19] ORTIZ-CATALAN, Max, Bo HÅKANSSON, and Rickard BRÅNEMARK. An osseointegrated human-machine gateway for long-term sensory feedback and motor control of artificial limbs. *Science translational medicine.* 2014, vol. 6, no. 257, 257re6–257re6.

[20] SALMINGER, Stefan et al. Long-term implant of intramuscular sensors and nerve transfers for wireless control of robotic arms in above-elbow amputees. *Science Robotics.* 2019, vol. 4, no. 32, eaaw6306.

[21] KUIKEN, Todd A et al. The use of targeted muscle reinnervation for improved myoelectric prosthesis control in a bilateral shoulder disarticulation amputee. *Prosthetics and orthotics international.* 2004, vol. 28, no. 3, pp. 245–253.

[22] SALMINGER, Stefan et al. Outcomes, challenges, and pitfalls after targeted muscle reinnervation in high-level amputees: is it worth the effort? *Plastic and reconstructive surgery.* 2019, vol. 144, no. 6, 1037e–1043e.

[23] PROSTHERICS, Access. *15 Limb Loss Statistics that May Surprise You.* Access prostherics, Oct 18, 2017. Available also from: https://accessprosthetics.com/15-limb-loss-statistics-may-surprise/.

[24] OWINGS, Maria and Lola Jean KOZAK. *Ambulatory and inpatient procedures in the United States, 1996.* US Department of Health and Human Services, Centers for Disease Control and ..., 1998. No. 139.

[25] GOODMAN, David C, Amitabh CHANDRA, and Elliot S FISHER. Disparities in health and health care among Medicare beneficiaries. 2008.

[26] PANDIAN, G. Rehabilitation of the patient with peripheral vascular disease and diabetic foot problems. *Rehabilitation medicine: principles and practice*. 1998, pp. 1517–1544.

[27] SCIENCIA58. *Back and palm of the hand of a man*. wikimedia, 4 November 2021. Available also from: https://commons.wikimedia.org/wiki/File:Hand_male_both_sides.jpg.

[28] LECTURIO. *Sensory innervation of the hand*. lecturio, July 7, 2022. Available also from: https://app.lecturio.com/#/article/3594.

[29] ANATOMY, Teach Me. *Bones of the Hand: Carpals, Metacarpals and Phalanges*. By TeachMeSeries Ltd (2022), 2022. Available also from: https://teachmeanatomy.info/upper-limb/bones/bones-of-the-hand-carpals-metacarpals-and-phalanges/.

[30] LECTURIO. *Bones of the Wrist*. lecturio, July 14, 2022. Available also from: https://app.lecturio.com/#/article/2866.

[31] THE-LITTLEMEDIC. *Thenar Muscles*. medizzy, 2017. Available also from: https://medizzy.com/feed/109538.

[32] AHMEDABAD. *Lumbricals*. Samarpan Physiotherapy Clinic, 2022. Available also from: https://mobilephysiotherapyclinic.net/lumbricals-muscle/.

[33] LAB, Earth's. *ADDUCTOR POLLICIS MUSCLE*. Earth's Lab, 2016. Available also from: https://www.earthslab.com/anatomy/intrinsic-muscles-hand/?dc=upperlimb-muscles-test&rm=true.

[34] PLÍVA, Zdeněk et al. *Guidelines for Writing Bachelor or Master Thesis*. 2nd ed. Liberec: Technical University of Liberec, Faculty of Mechatronics, 2019. ISBN 978-80-7494-456-7. Available from DOI: 10.15240/tul/002/978-80-7494-456-7.

[35] SURGERY OF THE HAND, American Society for. *Hands joints*. American Society for Surgery of the Hand, 2021. Available also from: https://www.assh.org/handcare/safety/joints.

[36] 3D, SHINING. *USER MANUAL EinScan Pro 2X / 2X Plus / EP/EXScan Pro Software V3.3*. 2nd ed. Road, Kowloon Bay, KLN, HK, China: SHINING 3D, July 2019. Available also from: https://cdnimg.shining3d.com/software/5598fb28d2e10227837abecf6464a80e.

[37] BASMAJIAN JV, de Luca CJ. *Muscles Alive*. Baltimore: The Functions Revealed by Electromyography. The Williams & Wilkins Company, 1985. Available also from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2482044/.

[38] KLEISSEN, RFM et al. Electromyography in the biomechanical analysis of human movement and its clinical application. *Gait & posture*. 1998, vol. 8, no. 2, pp. 143–158.

[39] CRAM JR Kasman GS, Holtz J. *Introduction to Surface Electromyography*. Gaithersburg, Maryland: Aspen Publishers Inc., 1998. Available also from: https://dl.uswr.ac.ir/bitstream/Hannan/138995/1/9780763732745.pdf.

[40] S, Shahid. *Higher Order Statistics Techniques Applied to EMG Signal Analysis and Characterization*. Jacqueline Walke, 2005. Available also from: https://www.researchgate.net/publication/7703552_Application_of_Higher_Order_Statistics_Techniques_to_EMG_Signals_to_Characterize_the_Motor_Unit_Action_Potential#fullTextFileContent.

[41] NIKIAS, Chrysostomos L and Mysore R RAGHUVEER. Bispectrum estimation: A digital signal processing framework. *Proceedings of the IEEE*. 1987, vol. 75, no. 7, pp. 869–891.

[42] KLEISSEN, RFM et al. Electromyography in the biomechanical analysis of human movement and its clinical application. *Gait & posture*. 1998, vol. 8, no. 2, pp. 143–158.

[43] SOMTHING, sparkfun start. *SERVOS EXPLAINED* [online]. 2022. [visited on 2022-09-10]. Available from: https://www.sparkfun.com/servos.

[44] SG90, SERVO MOTOR. *SERVOS MOTOR SG90 DATA SHEET* [online]. 2022. [visited on 2022-09-10]. Available from: http://www.ee.ic.ac.uk/pcheung/teaching/DE1_EE/stores/sg90_datasheet.pdf.

[45] (201508888), Riaan Gerard Fourie. *Mechanical design of a biologically inspired prosthetic hand, The Touch hand 3*. 2017. MA thesis. University of KwaZulu-Natal.

8 Appendix A

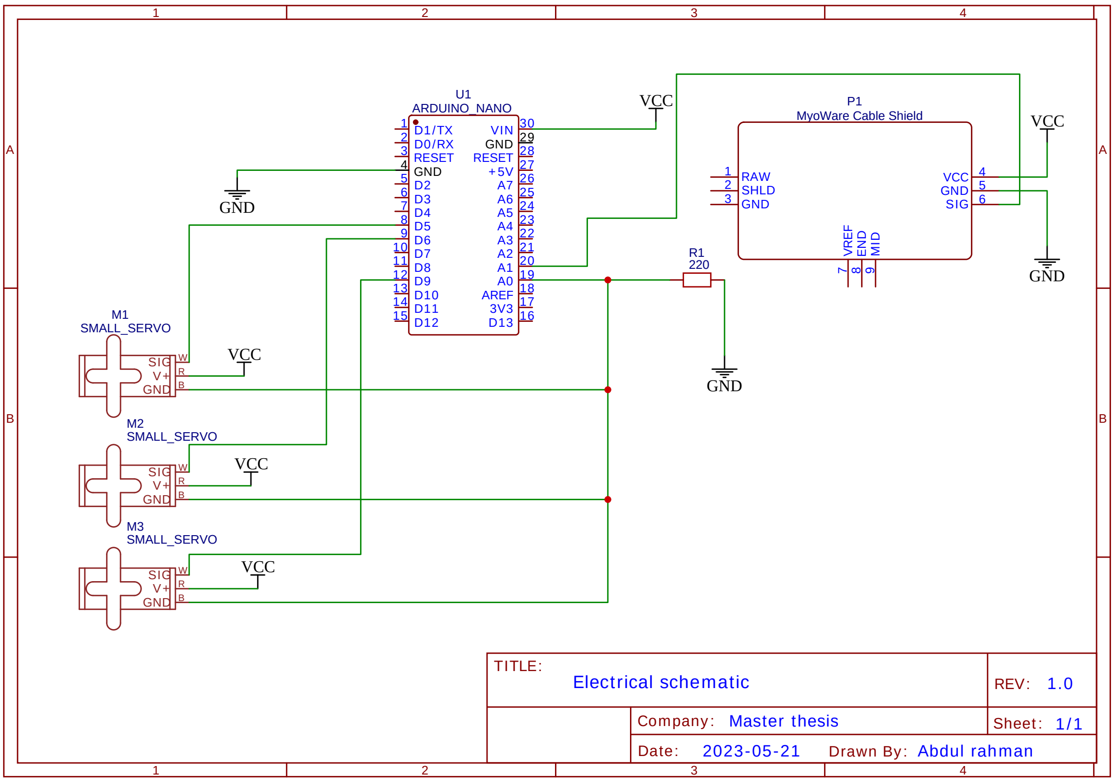


Figure 8.1: Electrical schematic

```
#include<Servo.h>Servo myservo;
Servo myservo1; Servo myservo2;
int pos = 0;
int val;
int emg_pin =2;
//shunt
int sensorpin = A0;
//int sensorvalue;
int threshold_res = 1000;// was 100
//filtering parameters of shunt sensorfloat
alpha_res = 0.05;
int snsorvalue_filter =0;
int sensorvalue_prev =0;
int sensorvalue_raw =0;
//filtering parameters of emg sensorint emgPin =
A1;
int emgRaw = 0;
int emgFiltered = 0;int emgSmoothed
= 0;int emg_state = 0; int emgPrev
= 0;
float alpha = 0.05; //was 1int
threshhold_emg = 90; int pinoutput = 0;
int dig=0; void setup() {
```

```
myservo.attach(9);
myservo1.attach(6);
myservo2.attach(5);
Serial.begin(9600);
pinMode(emg_pin,INPUT);
pinMode(8,OUTPUT);
}


void loop() {
emg_sensor();
val = digitalRead(emg_pin);
Serial.println(pos);
Serial.println(val);
Serial.println(sensorvalue_filter);
   if (val==1){
    myservo.attach(9);
    myservo1.attach(6);
    myservo2.attach(5);
    for(pos ; pos<=180; pos+=10){
      sensor_shunt();
      if(sensorvalue_filter >
        threshold_res){myservo.attach(9);
        myservo1.attach(6);
        myservo2.attach(5);
        break;
        }
      else{
myservo.write (pos);
```

```
        myservo1.write(pos);
        myservo2.write(pos);
        delay(50);//was50
                 }
    }
   }
    else{ myservo.attach(9);
    myservo1.attach(6); myservo2.attach(5);
    for(pos ; pos>=0; pos-=10){ sensor_shunt();
      if(sensorvalue_filter > 200){
        myservo.attach(9);
        myservo1.attach(6);
        myservo2.attach(5);break;
                 }
               else{
        myservo.write(pos);
        myservo1.write(pos);
        myservo2.write(pos);delay(50); //was
        50
        }
}
    }
}
void sensor_shunt() {
  sensorvalue_raw=analogRead(sensorpin);
  sensorvalue_filter = (int)( alpha_res *
sensorvalue_raw + (1 - alpha_res) *
sensorvalue_prev);
```

```
  sensorvalue_prev = sensorvalue_filter;
  Serial.print("shunt_resistor_value");
  Serial.println(sensorvalue_filter);
}
void emg_sensor(){
 emgRaw = analogRead(emgPin); // read the EMG sensor
value
  emgFiltered = (int)(alpha * emgRaw + (1 - alpha) *
emgPrev); // apply a low-pass filter
  emgSmoothed = (2 * emgFiltered + emgPrev) / 3; //
apply a smoothing filter
  emgPrev = emgFiltered;
  if(emgSmoothed > threshhold_emg){
                pinoutput = 100;
            digitalWrite(8, HIGH);
    }else{      pinoutput = 0;
              digitalWrite(8,
              LOW);
      };
  Serial.print("EMG value: ");
  Serial.println(emgSmoothed);
  Serial.print(", Servo position: ");
  Serial.println(pinoutput);
  Serial.println(sensorvalue);// servo feedback
  delay(20);} // wait for the servo to move
```