DESIGN AND FABRICATION OF PNEUMATIC ARM USING ARTIFICIAL MUSCLES

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Mohammed Najm Abdullah DALAALI

Thesis Advisor
Assoc. Prof. Dr. Daver ALI

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Mohammed Najm Abdullah DALAALI

Thesis Advisor
Assoc. Prof. Dr. Daver ALI

T.C.
Karabuk University
Institute of Graduate Programs
Department of Biomedical Engineering
Prepared as
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I certify that in my opinion the thesis submitted by Mohammed Najm Abdullah DALA ALI titled “ DESIGN AND FABRICATION OF PNEUMATIC ARM USING ARTIFICIAL MUSCLES” is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

Assoc. Prof. Dr. Daver ALI ....
Thesis Advisor, Department of Biomedical Engineering

This thesis is accepted by the examining committee with majority vote in the Department of Biomedical Engineering as a M.Sc. thesis. 22/12/2023

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Chaiman	: Assist. Prof. Dr. Ali EMİN (ATÜ)	....
Member	: Assoc. Prof. Dr. Daver ALI (KBU)	....
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Mohammed Najm Abdullah DALAALI

ABSTRACT

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Karabük University
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Assoc. Prof. Dr. Daver ALI
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The success of prosthetic arms for the human body relies on many factors. The main factor is the capability of the prosthetic part to fulfill at least one function of the lost limb, and this success is primarily influenced by the design of components, alongside the selection of materials. Servo-motors usually operate the active prosthetic hands. Although the use of servo-motors makes the control of prostheses easier, it increases their price, which limits the access of those in need. Therefore, the design of cheap and straightforward artificial arms that work with compressed air has attracted more attention in terms of cost-effectiveness. In this study, a pneumatic prosthetic forearm was designed and fabricated using artificial muscles. The artificial muscles were fabricated from an inner tube with high elasticity, and the outer shell was a flexible mesh material. The focus of this study was on the effects of muscle design parameters on forearm functions during operation. To this end, four models of artificial muscles were developed and tested to find the most effective models. The results showed that the most effective muscle models were those that can contract easily in length due to air pressure. Furthermore, the arm underwent testing to assess its biomechanical movement capabilities, as well as its capacity to carry and grasp various objects. The results showed that the pneumatic forearm can operate acceptably with some negligible limitations in movement, speed, and noise.

Key Words : Prosthetics, Forearm, Artificial hand, Artificial muscles, Pneumatic prosthesis

Science Code : 92504

ÖZET

Yüksek Lisans Tezi

YAPAY KASLAR KULLANILARAK PNÖMATİK KOL TASARIMI VE ÜRETİMİ

Mohammed Najm Abdullah DALAALI

Karabük Üniversitesi
Lisansüstü Eğitim Enstitüsü
Biyomedikal Mühendisliği Bölümü

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Protez uygulamaların başarısı birçok faktöre bağlıdır. En önemli faktör, protez parçasının kaybedilen uzvun en az bir fonksiyonunu yerine getirebilmesidir. Protez kolların başarısı öncelikle malzeme seçiminin yanı sıra bileşenlerin tasarımından da etkilenir. Aktif protez el veya kollar genel olarak servomotorla çalışır. Servomotorların kullanılması protezlerin kontrolünü kolaylaştırsa da fiyatını aşırı şekilde arttırır, bu da ihtiyacı olanların erişimini kısıtlamaktadır. Dolaysıyla, basınçlı havayla çalışan, ucuz ve basit yapay kolların tasarımı, maliyet etkinliği açısından daha fazla ilgi görmektedir. Bu çalışmada yapay kaslar kullanılarak pnömatik bir protez önkol tasarlanmış ve üretilmiştir. Yapay kaslar, yüksek elastikiyete sahip bir iç tüpten ve dış katman, esnek bir ağ malzemesinden yapılmıştır. Bu çalışmada, çalışma sırasında kas tasarım parametrelerinin önkol fonksiyonları üzerindeki etkilerini incelenmiştir. Bu amaçla, en etkili modelleri bulmak için dört farklı yapay kas modeli geliştirilip ve test edilmiştir. Sonuçlar, en etkili kas modellerinin hava basıncı nedeniyle kolayca kasılabilen kas modelleri olduğunu gösterdi. Ayrıca üretilmiş kol, biyomekanik hareket yeteneklerinin yanı sıra çeşitli nesneleri taşıma ve tutma kapasitesinin değerlendirilmesi için test edilip sonuçlar tartışılmıştır. Sonuçlar pnömatik önkolun hareket, hız ve gürültü açısından göz ardı edilebilir sınırlamalarla kabul edilebilir şekilde çalışabildiğini göstermiştir.

Anahtar Sözcükler : Protez, Önkol, Yapay el, Yapay kaslar Pnömatik protez.
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CONTENTS

Pages

LIST OF FIGURES

Pages

LIST OF TABLES

SYMBOLS AND ABBREVITIONS INDEX

SYMBOLS

A : pennatıon angle.
P : Pressure.
n : number of the moles.
V : Volume.
T : Temperature.
R : gas constant.
Kg : kilo gram.
K : kelvin.
Pa : pascal.
J : joule.

ABBREVITIONS

PTSD : posttraumatic stress disorder.
PLP : Phantom limb pain.
EMG : Electromyography.
atm : Atmospheric pressure unit.
PSI : Pounds Per Square Inch.
DRUJ : Distal radioulnar joint.
ERCL : Extensor carpi radialis longus.
EPB : Extensor pollicis brevis.
IP : Interphalangeal joint.
MC : Metacarpal.
MCP : MetaCarpoPhalangeal joınt.
PIP : Proximal InterPhalangeal joınt.
DIP : Distal interphalangeal joint.
FCU : Flexor Carpı Ulnarıs.
PALL : Palmarıs Longus.
PTER : Palmarıs Teres.
PQUAD : Pronator Quadratus.
ED : Extensor Digitorum.
APL : Abductor Pollicis Longus.
OP : Opponens Pollicis.
ECU : Extensor Carpi Ulnaris.
PCSA : Physiological cross-sectional area.
ROM : Range Of Motion.
EMG : Electromyography.

CHAPTER 1

INTRODUCTION

1.1. THE UPPER LIMB

The human body is a marvel of perfect symmetry and harmony, with the hand playing a crucial role in this perfect form. Its functional flexibility allows us to carry out everyday tasks and duties, making it a powerful tool for sensıng and ınteractıng wıth the envıronment. A large number of degrees of freedom (21 for the hand and 6 for the wrist) and thumb opposition play an essential role in enabling sophisticated movements, from strength to precision tasks.

Voluntary movement commands translate proprioceptive and external proprioceptive information into neural and muscle activity, allowing us to activate the limb thanks to the skeletal structure. The hand is necessary for social interaction and defines the boundaries between the self and the environment. Unfortunately, many people are subject to the loss of this vital part of their body.

1.2. LIMBS LOSING

Losing limbs is one of the most serious global health problems. Every year, about 1 million operations happen, which means that every 30 seconds, there is a limb loss. In 2005, there were 1.6 million amputations, with the projection that the number may double by the year 2050 [3]. The causes of loss of limbs vary, including congenital ones from birth or the process of amputation of this part for reasons such as [4]:

- Pathological causes such as cancer, peripheral vascular disease, infection, and diabetes complications can lead to irreversible loss of blood supply.

-Congenital malformations.

-External factors and trauma, such as accidents, thermal injuries from burns, electric shock, and frostbite.

Upper limb amputations can occur at various levels and rates (Figure 1.1). The loss of a complete limb or a part of it will cause the difficulty or impossibility of performing daily activities, and sources of pain and psychological stress for the patient: Postoperative pain, symptoms of anxiety, depression, (PTSD) posttraumatic stress disorder [5] and Phantom Lımb Paın PLP is defınd as "paınful sensatıon indıcating an absent lımb"[6].

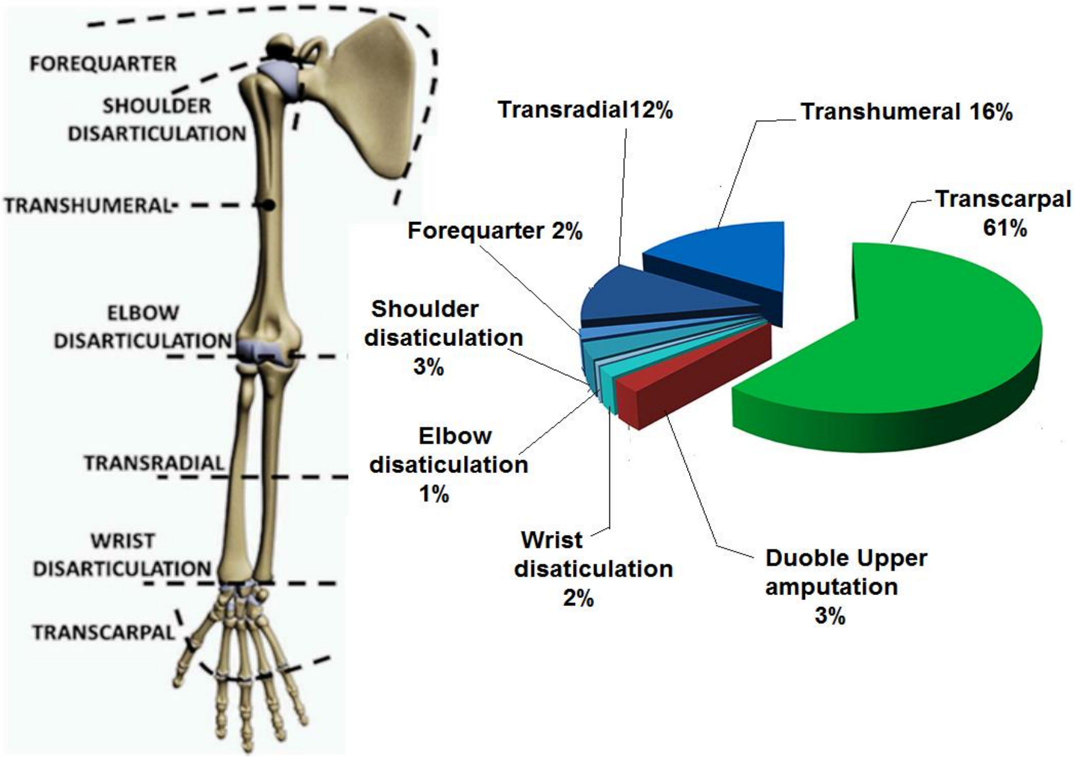


Figure 1.1. Upper limb amputatıon levels and statistics. (In ITALY and U K)[7]

The patient's mental and physical suffering varies from one person to another, where it is linked to individual and societal factors. In developed societies, where treatment and advanced care are available, the patient will be able to access necessary facilities and prostheses. However, having a good replacement for the lost limb comes with problems.

Various solutions have been tried to address this problem, including limb transplantation. However, the medical success of this operation is difficult to achieve and can cost more than 500,000 US dollars [8]. Also, many obstacles, such as finding a replacement limb and ensuring anatomical conformity, as well as ethical, religious, and psychological aspects, limited this solution [9]. Therefore, prosthetic limbs have been found to be an acceptable solution [10].

1.3. PROBLEM STATEMENT

The prosthetic limb industry is a large market that reached 0.398 billion US dollars in 2023. It is expected to grow to 0.929 billion US dollars in the next decade [8]. However, accordıng to the World Health Organization (WHO), there are at least 35 to 40 million people who require prosthetic limbs or related services[11]. Accessibility of these expensive services is the main challenge for many patients. Moreover, the practical models are closer to industrial models made of solid materials, making them difficult to adapt to every individual [12, 13].

1.4. THE AIM OF THE THESIS

Designing, implementing, and testing flexible artificial muscles that mimic biological muscles, with operating principles based on differences in internal air pressure.

Design, implementation, and testing of an artificial arm that mimics the anatomy of the human arm and is operated by pneumatic artificial muscles controlled by an electronic joystick. Ensuring the use of simple design and cost-effective materials to provide artificial arms at reasonable prices to a large group of people with missing limbs.

CHAPTER 2

LITERATURE REVIEW

2.1. PROSTHETIC LIMBS

An artıfıcıal upper extremıty lımb is manufactured to replace the missing part of the related limb that has been amputated or does not exist from birth. The prosthetic function may be cosmetic, functional, or both, and this prosthetic is made according to the necessities and deficiencies to complete the residual limb, which may be transhumeral (above the elbow), trans-radial (below the elbow), or partial hand. However, replacing any biological part with an artificial one is still a difficult task fraught with challenges [14].

2.2. HISTORY OF PROSTHETIC

Artificial limbs considered one of the first medical technologies used in human history. Back in ancient times, many stories describe that. In ancient Hindu writings, it is mentioned that a warrior called Vispalla lost her leg in a battle and was given an iron leg instead. Herodotus also mentioned a Persian soldier named Hegistratus Elius, who used an artificial leg [15]. He also wrote to Pliny the Younger that in the third century BC, there was a formidable soldier called Marcus Sergius, who had an iron left hand and fought with it against the Gauls [16].

However, the oldest physical evidence of prosthetic limbs was found in Egyptian mummy coffins, where an artificial foot was found; another mummy had an artificial forearm and right hand [17]. The remains of bones dating back to the sixth century in Lugoburd, Italy, showed deformities that may be due to the prolonged use of the prosthesis [18]. As for the eras that followed, there were many metal arms for knights and others. Perhaps the hook for the pirate’s hand was not created out of that, and there were likely other limbs made of wood and leather, but they could not resist the corrosion, so the models before the fifteenth century were almost non-existent [19].

The German knight Gotz von Berlichingen had a replacement hand for the hand that he lost in the early 1500s [20, 21] There was also a prosthetic limb for Von Berlichingen, which had a mechanism that allowed the fingers to bend through a release button. Although it was considered a shift in this field, and the design style that came after that is a set of copies from it.

The use of the prosthetic limb continued to require intervention from the other hand until the year 1812, when a German dentist, Peter Balliff, Made an artificial hand that moves under the influence of the movement of the remaining joints for the same arm, making it possible to close and open the hand without the need for the other hand [22].It represents the first model of a hand that works under the influence of the body.

Arms were designed on the same principle by adding belts attached to the patient’s body to move the prosthetic limb. However, it was difficult to wear or hide it under clothes, and this way remained until the beginning of the twentieth century ın 1904, when Wıllıam T.Carnes of Harmonsburg ,Pennsylvanıa designed an arm with joints in the fingers that bent into a mechanism that is a rack and pinion system that works with a cable attached to a belt at the shoulder, this mechanism registered as a patent. [23]. In 1912, he modified this model by using a worm-and-wheel system and adding a mechanısm to rotate and lock the wrıst. The Carnes hand gained significant importance during World War I [24]. After that, models were invented that had a separate source of movement, as in Germany in 1915, where they worked through pistons pushed by air to move the joints [25].

In 1919, the book Ersatzglieder und Arbeitshilfen for Kriegsbeschädigte and Unfallverletzte, which is considered the first compendium and reference for prosthetic limb designs, mentioned electromagnetic limbs that rely on the energy of electrical magnets to pull the joints of the hand [26].

World War II led to many casualties, as there were 17130 men, or 2.5% of all wounded American soldiers, suffering of the amputations, it is possible to imagine the number in Europe [27], which led to the necessity of establishing centers for the production and development of prosthetic arms, including the Army Prosthetics Research Laboratory (APRL), which had contributed to this field, including APRL Hand No.4, which was made of a cast magnesıum frame wıth a gripper to lock the fıngers in to get a affirm grıp, the hand was covered wıth a rubber cover that matched the patient's skin color[28].

In the late 1940s, Reinhold Reiter at Munich University invited Myoelectric control for the first time [29]. In the 1950s, research at the Unıversity of California,Los Angeles opened the door to muscular electrical control through electrical signals arriving from the brain, such as the Batty hand in the United Kingdom [30] that so-called Russian hand and the Bottomley hand that appeared later [31]. Johns Hopkins then created the first integrated arm system, which IBM experimented with in the 1960s, in addition to producing a control system linked to switches operated from the person's feet. In the seventies, the Boston's arm produced at the Massachusetts Instıtue of Technology (MIT), which became the fırst myoelectric arm in the USA. In addition, the first electric hook to become commercially available was the Michigan Arm. In Canada, work began on the Utah arm of the Utah University. At the same time, there was severe work on alternative limbs for children, such as Soribi in Sweden and the developing Systemteknik hand [30] In 1984, the technological problems and difficulties in this field were illustrated by the symposium "Current Clinical Concepts of Electrically Assisted Prosthetics" in Chicago, which highlighted the obstacles in this field. In the 1990s, microprocessors introduced in this field for the first time in the Boston Elbow.

An advanced prosthetic hand with five powerful fingers called the i-Lımb manufactured by Touch Bıonıc [32] opened the door to the use of more complex technologies in the twenty-first century as a reconstructive procedure Targeted muscle reinnervation (TMR), allows the patient to move the joints of the prostheses arm several times wıthout the need to use non-stereotactic procedures to swıtch between axes. It also provided huge budgets for projects for the prosthetic arm system, such as two projects from DEKA Integrated Solutions in Manchester ($18.1

million) and another from Johns Hopkins University. Applied ($30.4 million) for this research later became a product. In recent decades, technical development in the field of nanotechnology has led to the production of sensors and small electronic circuits that can be used to give prosthetic limbs a sense of temperature and even touch, with significant control over joint movements, with energy sources that are more durable and lighter. Also, recently, 3D printing has given greater accuracy and flexibility in producing parts for these limbs, as Hero Arm manufactured in the UK by Open Bionics [33], and there are more advanced myoelectric prosthetics like BeBiobic and the Michelangelo electronic hand by Ottobock Germany [34].

2.3. TYPES OF PROSTHETIC UPPER EXTREMITY

Prosthetic limbs can be classified into four general types according to the control mechanism and the functions that can be performed. It is called the TAXONOMY [35] classification. These types are:

Cosmetics prostheses are the simplest type that does not contain a power source and can be fixed or adjustable. The primary function of the limbs may be cosmetic, but they also can be used to perform simple and limited tasks and only with the help of the other hand. However, it has advantages such as low price, lightweight and no need for maintenance compared with other types [36].

Activity-specific is a prostheses limbs with an end that is designed in a way that enables a person to carry out a specific activity, such as swimming, riding a bike, fishing, and others [37]. These ends are also can be interchangeable with other forms according to the required activity, which means that they are more like tools, so they do not have a cosmetic aspect(Fig 2.1). However, they are desired products due to their relatively acceptable prices [38].

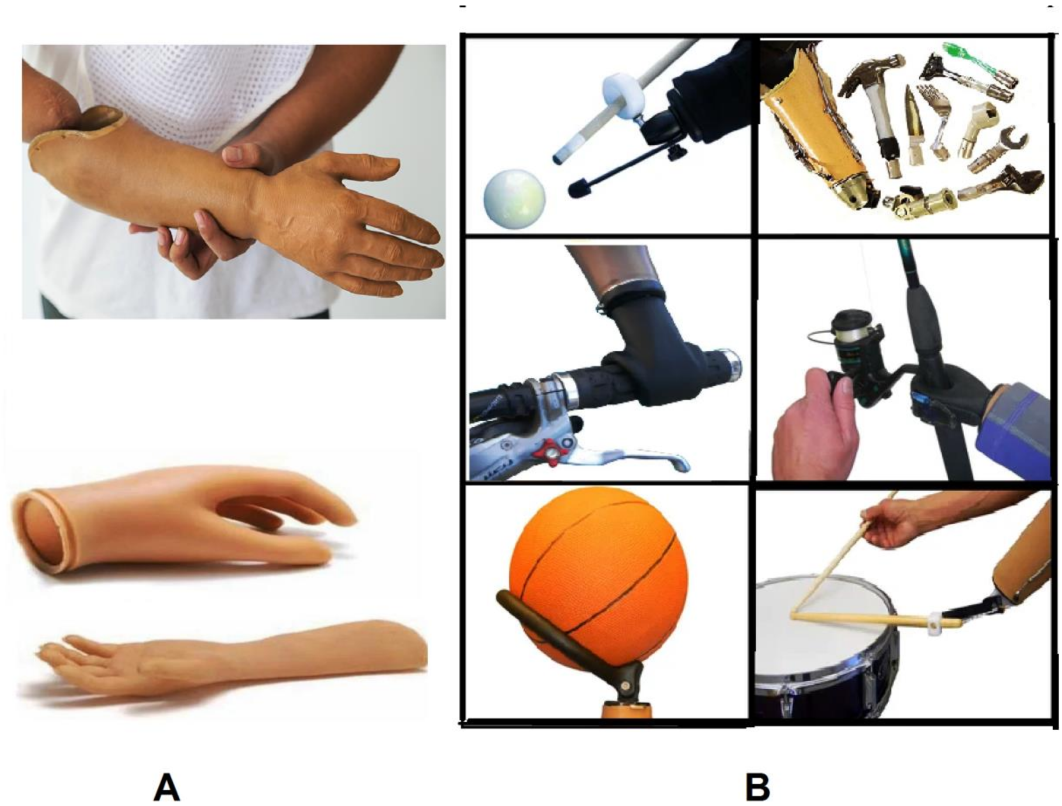


Figure 2.1. Prosthetics types: A- Cosmetics prostheses.B-Activity-specific prosthesis.

Body-powered prostheses, these limbs contain a specific working mechanism to move their parts by a wire tied to a belt that connects to the person body, such as the shoulder or parts of the remaining arm, so that they move due to the tension of the wire with the movement of the body [39]. This type has the advantage of being relatively lightweight and practical. It also provides feedback to the user, but it requires the provision of sufficient force to pull the wire, which makes it unsuitable for some cases, and obtaining the desired movement requires it to be in a specific position [40].

Externally powered prostheses that is made with an external power source that provides the energy necessary to move the various parts of the limb, which are usually derived by electric motors or by a magnetic or even through the force of fluid pressure. The method of controlling this type is according to specific inputs, either through a start button for each movement or by electromyography (EMG) indicators [41], or as it is called a myoelectric prosthesis, that depends on amplifying the nerve electrical signal from the remaining part of the amputated limb to control the prosthetic limb, which provides the ability of movement just by thinking. in addition it can be covered with artificial skin to resemble a human hand [42], so it has a cosmetic aspect. it may contain sensors that provide the user with a sense of temperature or touch [37]. This type is considered the most advanced type of prosthetic, which makes it too expensive [37], and it is necessity to train patients to operate it correctly (Fig 2.2) [43], Moreover, a long-term power source, small in size and weight, remains a challenge [44].

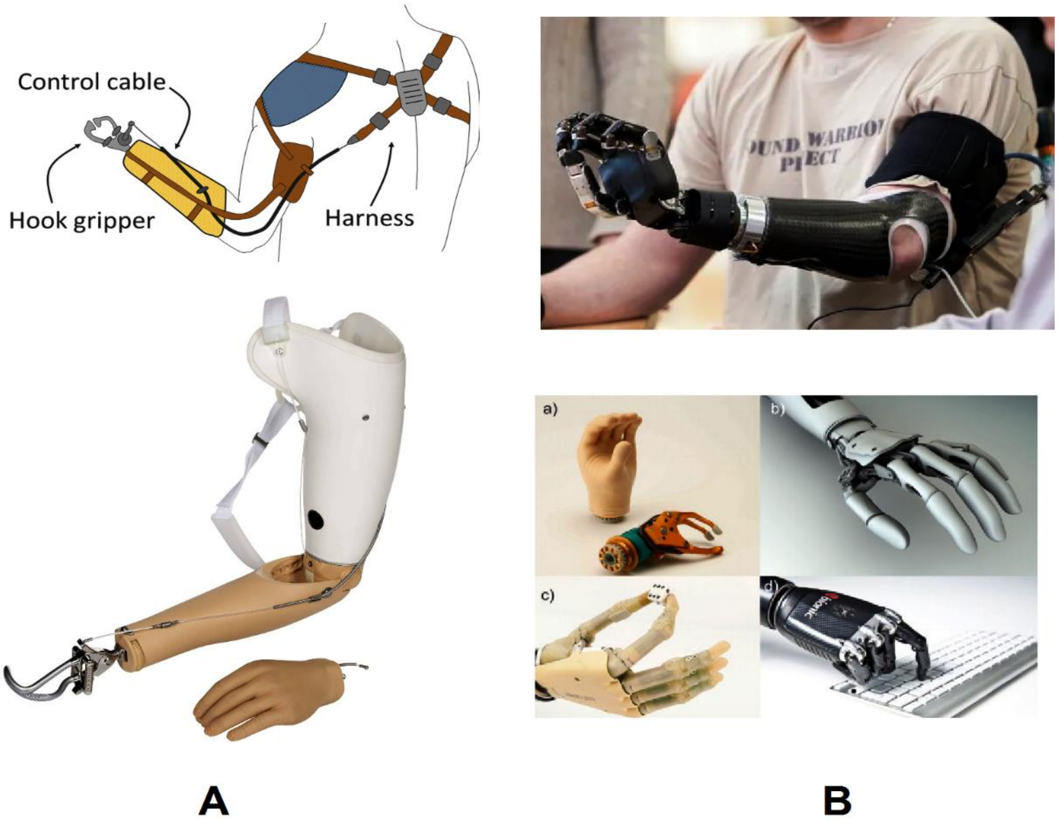


Figure 2.2. Prosthetics types: A- Body-powered prostheses B- Externally powered prosthesis.

2.4. PNEUMATIC PROTHESIS

Pneumatic systems use the force of air to do the work, which is transmitted through a system of pipes or cylinders to apply the generated energy, usually controlled by valves [45].

Most pneumatic prosthetics within the category of externally powered prostheses have been used in limb replacement since the early 20th century. However, the heavyweight, control difficulty, and technical issues prevented their widespread application. Still, the recent advancements in materials manufacturing, such as 3D printing, have contributed to a renewed interest in this type of prosthetic limbs.

Egyptian students succeeded in designing artificial limbs using artificial intelligence techniques and algorithms to create a lightweight prosthetic arm without a motor, which is controlled by brain signals and air pressure (Fig 2.3.A) [46].

In a similar work, a more sophisticated pneumatic prosthetic arm was developed in Japan. The finger movement was carried out with a pneumatic actuator in this arm, and a tendon-powered wrist was rotated with an electromotor. The pneumatic system was composed of an actuator for the finger's movement and two electric motors for the wrist rotation. The arm mass was about 255 grams, with a maximum lifting mass of 500 grams (Fig 2.3.B) [47].

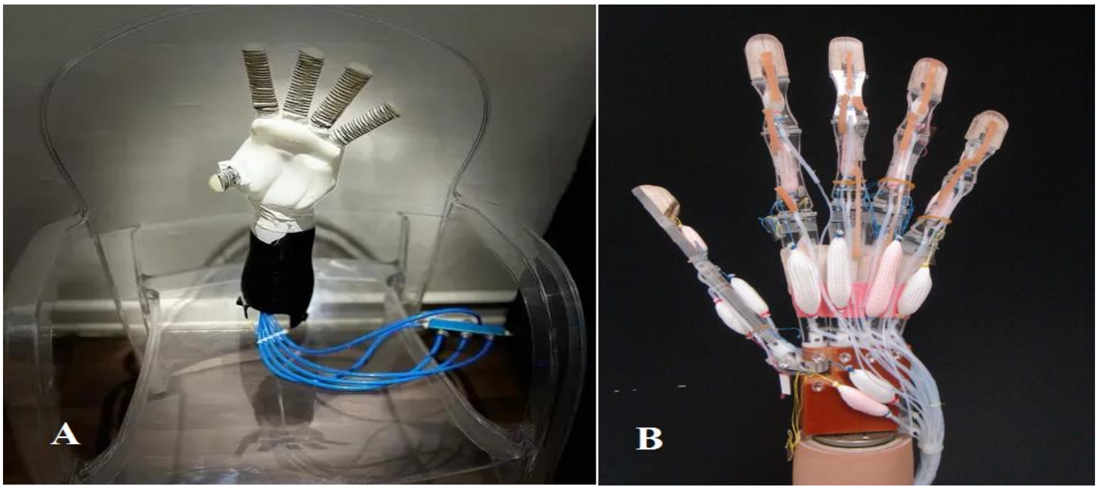


Figure 2.3. Pneumatic prothesis models.

- An inflatable robotic hand designed by Massachusetts Institute of Technology and Shanghai Jiao Tong University engineers gives amputees real-time touch control. The prosthetic fingers are made of a soft, stretchable material (Eco Flex commercial rubber) and are precisely inflated and flexed into specific positions using a simple pneumatic system. Thıs system ıncludıng a tıny pump and valves, can be worn at the waıst, wıch contrıbutes to reducıng the wıght of the pneumatıc hand (292g). This design also showed tremendous flexibility in holding objects and had EMG sensors that provide ease of use and training within a period not exceeding a few minutes. The hand is also planned to be sold at a reasonable price of about 500 $ [48].

However, it can be observed that the arm's movement is limited to bending the fingers, without any wrist movements or rotation of the arm (Fig 2.4).

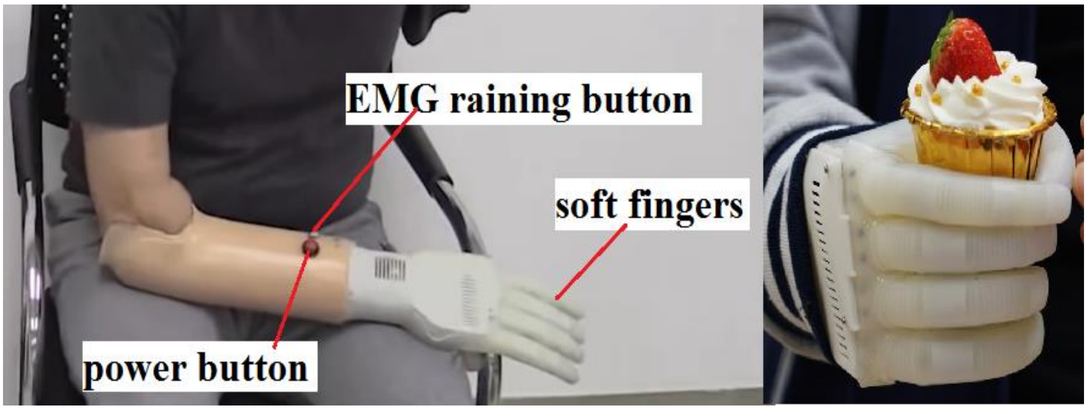


Figure 2.4. MIT and Shanghai Jiao Tong University's Inflatable Hand Model [48].

Researchers from three Japanese universities have developed a self-propelled five-finger pneumatic actuator. This arm contains five fingers bent by fourteen air bellows actuators supplied with air through an air pump that works mechanically through the effect of rotation of the forearm (Fig 2.5). There is also a digital processor that works to distribute the air through valves. The results of the grip tests for this model showed its superiority over those operating with electric motors [49].

This model can be considered a body-powered prosthesis type, and it is only valid for cases of trans-radial amputation; in addition, it requires the user’s ability to provide sufficient rotational energy to bend the fingers, and the model lacks wrist movements.

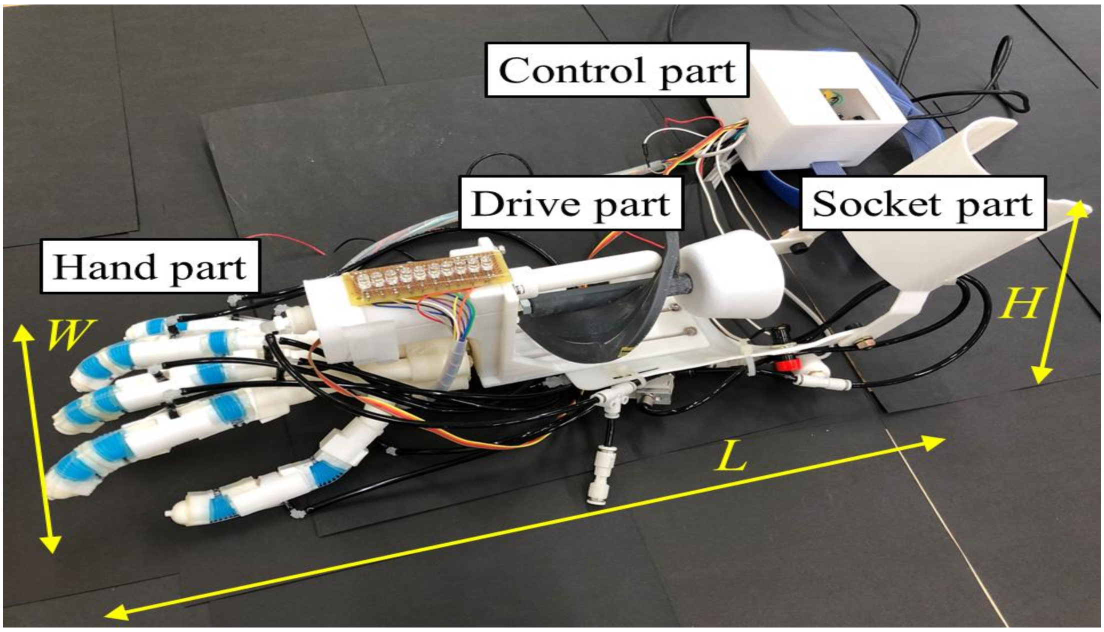


Figure 2.5. Self-propelled five-finger pneumatic actuator.[49]

Researchers have developed a soft hand made of flexible materials in the United Kingdom, using two silicone components that reınforced wıth polyester threads. The central part of the dvıce , which is the hand exoskeleton, is manufactured with a material called SmootOn SmoothSill 940 (ShoreA40), and soft actuators are made of fainter SmothOn EcoFlex0050(Shore00 50) material[50]. The hand contaıns six soft, pressure-drıven flexıble actuators that can be derived independently to bend the hand's five fingers and a sixth actuator for changing the thumb position. This design is characterized by ease of manufacture and low costs, with test results confirming its effectiveness. However, it is unclear how to attach it to the user, and it lacks wrist movements (Fig 2.6).

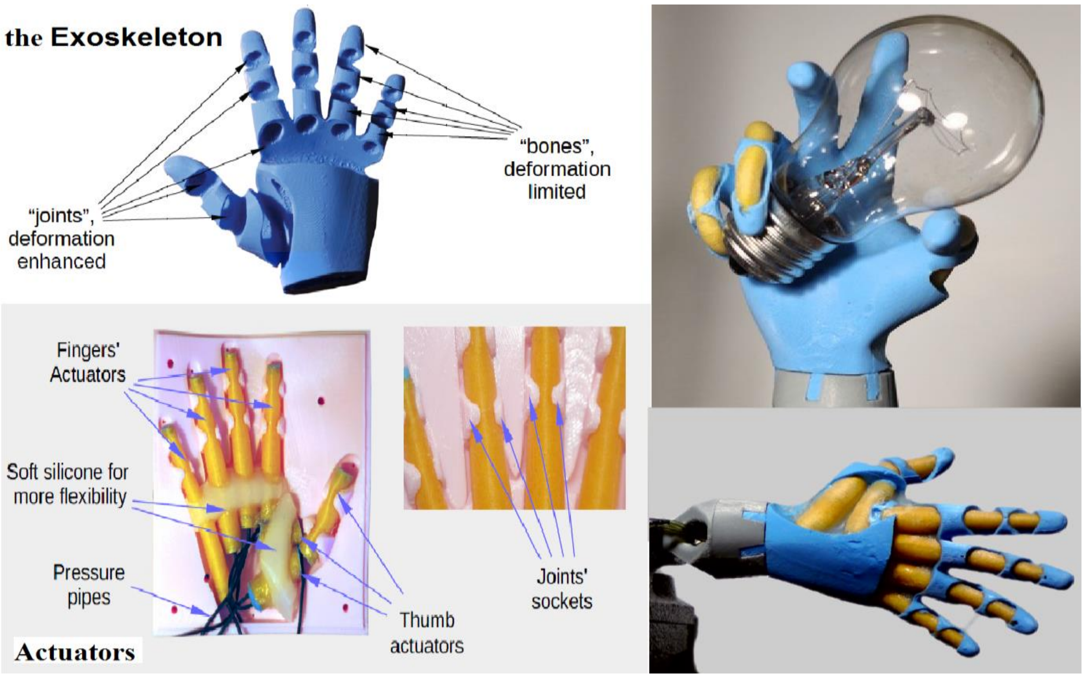


Figure 2.6. Soft hand made of flexible materials [50].

2.5. GAS LAWS:

Since the muscles in this study work with air pressure, it is necessary to understand the behavior of air under high pressure in a confined container.

The physics laws about gases [51]:
Boyle’s Law: At a fixed temperature, the volume of gas is inversely proportional to the pressure exerted by the gas.

Charle’s Law: The volume of a given mass of gas varies directly with the absolute temperature of the gas when pressure is kept constant.

Avogadro's Law: The volume of a gas sample increases linearly with the number of moles of gas in the sample

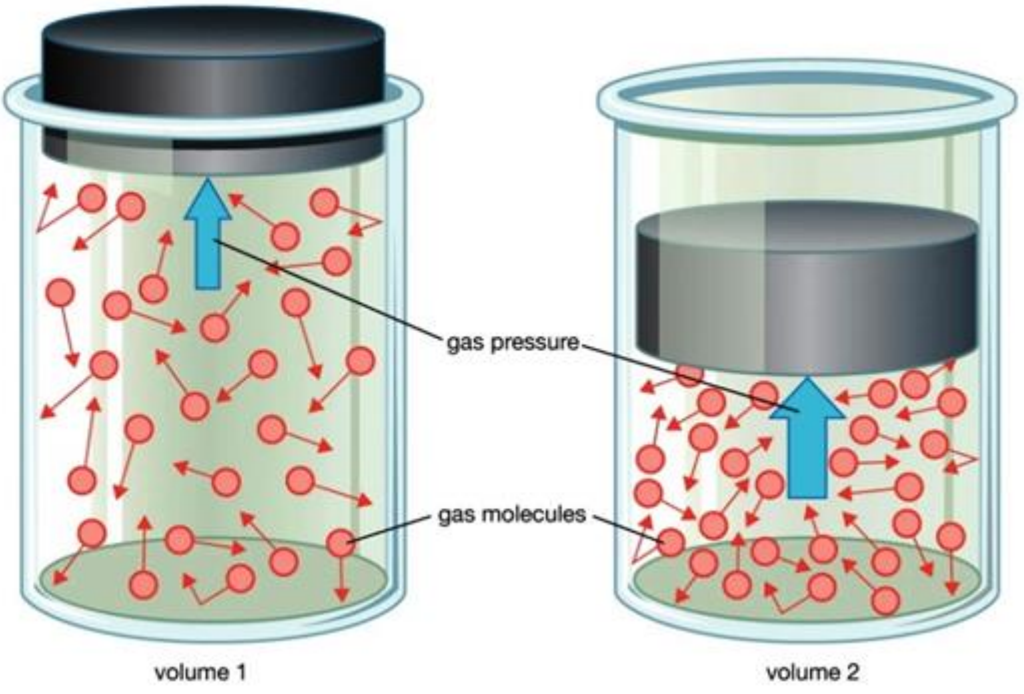


Figure 2.7. The relation between the volume and gas pressure.

It can be said that the air occupies any space that contains it, which is directly proportional to the temperature and the density of the gas and inversely to the volume or the container (Figure2.7) that the general law derived as a result of these three laws, also called the Ideal gas law and its mathematical formula [52]:

$$PV = nRT \tag{2.1}$$

Where:

P: pressure, V: volume, T: Temperature, and R: gas constant [8.314 J/mol·K].

So the R is the air density in S.I. units as: R = 8.314 J/mol·K, and can use the value R = 287 J/kg·K. The T temperature can be assumed constant with changes in P pressure and V volume for our sample by increasing the n moles of the particles through comprising more moles from outside. This pressure is Proportional inversely to the container volume and directly to the compressed volume of air, which introduces pressure force on the walls of the container from the inside direct to the outside, always taking the path of least resistance to expand the container, thus increasing its dimensions in parts and decrease others which can be used to produce a linear force in a specific direction.

2.6. THE FOREARM AND HAND

The upper extremity is one of the most complex parts of the human body and distinctions it from other creatures due to its ability to perform many movements with high flexibility, especially the part that extends from the elbow to the distal part of the upper extremity at the fingers which consist of the forearm and the hand.the forearm has two bones, and the hand has 27 bones. They have 34 muscles with many joints, ligaments, and tendons, in addition to nerves and blood vessels. Their parts are described according to their anatomical location, where the forearm extends beside the body with the hand facing us by its palm. This side called the anterior surface, the back side is the dorsal surface, the side that is close to the body is called the medial or ulnar, and the other side is called the lateral or radial side; the parts closer to the shoulder called proximal and farther away called the distal.

2.7. OVERVIEW ON THE BONES AND JOINTS

The human body contains 206 bones at adult age that provide the primary support for it, and protect the internal organs. The bones consist mainly of hydroxyl apatite with salts of calcium and phosphate, in addition to collagen, where the concentration and distribution of these materials vary in the areas of one bone, as they differ from one bone to another, which specifies the percentage of bone hardness and the bones differ in the shape and size, that classified into four types: long, short, irregular, and flat.

The bones articulate from their ends with other bones in what is called the joint (360 joints in the adult body), which are structurally classified into three types [53]:

Fixed fibrous joints exist between many fused bones and work to stabilize them. Examples of this type are the joints in the human skull.

Cartilaginous joints: are temporary, partially mobile joints found in young children and lasting until the end of puberty.

Synovial joints: are flexible and movable joints that give the bones the ability to slide, rotate, or bend over each other. They are the most common type in the body, such as those in the neck, hand, wrist, and others, and their ends are covered by smooth cartilage with the possibility of the presence of synovial fluid that provides smooth movement without friction. A ligaments interconnect these joints together. These joints have many types based on their movement that they provide and are functionally classified into six types (Fig 2.8):

Ball and Socket Joints: In this type, the shape of the bone's end is a circular is a spherical shape. This type of joint enables rotational movement, such as the shoulder and the hip joint rotation.

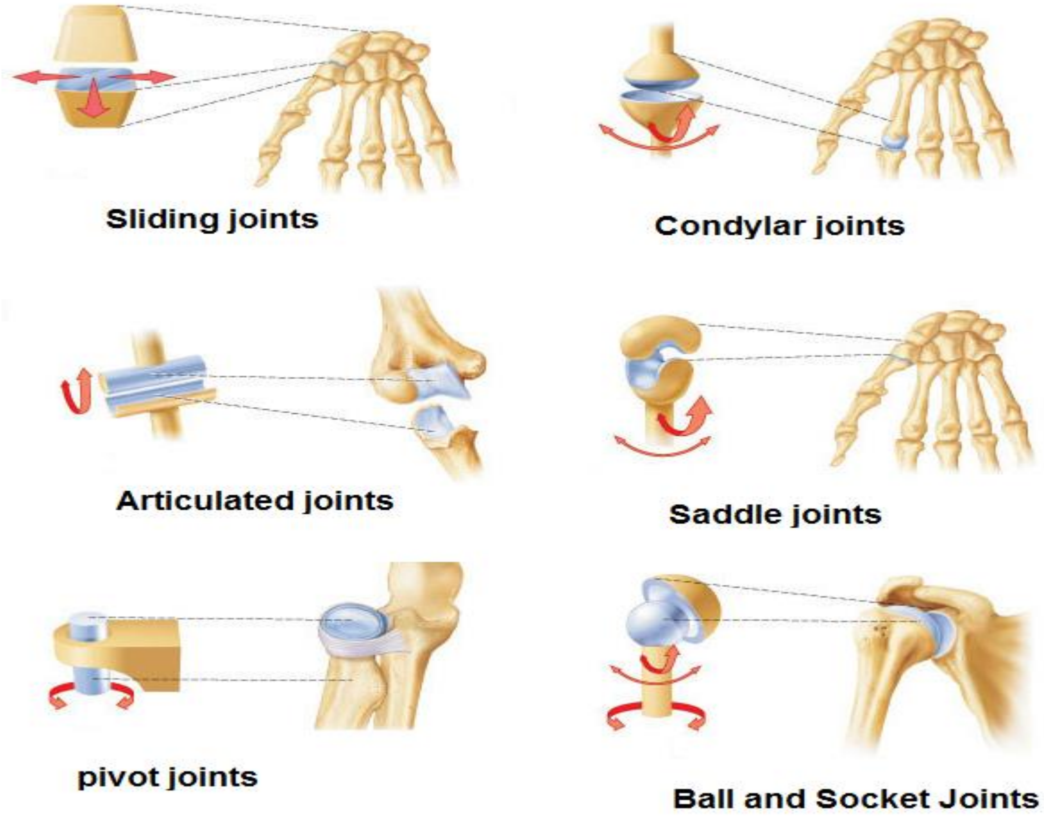
Pivot joints: The bones in this type are arranged above each other, as they articulate in a way that allows incomplete rotation around one axis with the possibility of lateral and posterior movement, an example of a pivot joint in the proximal radioulnar joint.

Articulated (Hinge) joints: This type has an arched cavity at the end of the bone that covers the convexity of the head of the other bone. This joint only provides rotational movement, like door hinges. Examples of this type of joint are the ankle, elbow, and knee.

Saddle joints: In this type, the ends of the bones have a mutual convexity and concavity, allowing movement in two planes, as in the movement of the base of the thumb in the hand.

Condylar joints: In this type, the end of the bone often has an oval surface that meets a cavity that provides movement in two coordinate planes in addition to rotation within a narrow angle. An example of condylar joints is the wrist and metacarpal-phalangeal joint.

Sliding joints: This type has smooth bone ends that articulate with each other in a way that allows them to slide over each other to produce a limited smooth movement without any rubbing or crushing of the bones. Examples of this type are the joints of the ankles, wrist, and spine.



Sliding joints

Condylar joints

Articulated joints

Saddle joints

pivot joints

Ball and Socket Joints

Figure 2.8. Upper extremity joints types.

2.8. ANATOMY OF THE FOREARM BONES AND JOINTS

It consists of two long bones called the Ulna and the Radius, their upper ends jointed with the elbow and their lower ends with the wrist (Fig 2.9). The bones extend together parallel, and in the lower and upper surfaces, some protrusions provide attachment points and paths for the ligaments and tendons of the forearm and wrist; each bone consists of the shaft region and two heads or ends [54].

2.8.1. The Ulna

It is longer than the Radius, and its anatomic position is located on the medial side. It is considered the stabilizer bone in the forearm.

2.8.2. The Radius

It is shorter than the Ulna lying at the lateral side the anatomic position, and it is the movement bone of the forearm during pronation and supination.

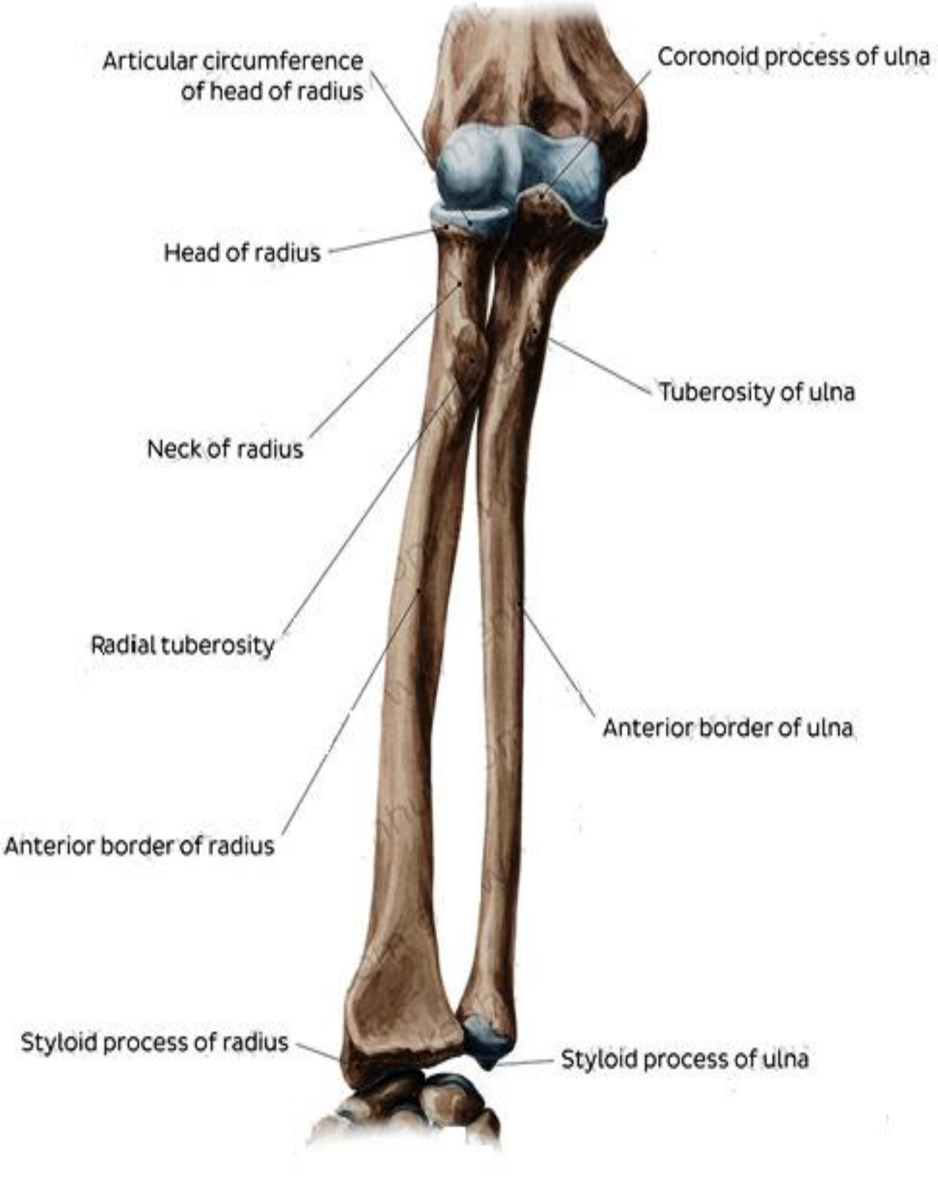


Figure 2.9. The forearm bones [1].

2.9. ANATOMY OF THE HAND BONES AND JOINTS:

The human hand consists of 27 bones and can be divided into three groups to form three regions: the wrist, palm, and fingers (Fig 2.10).

2.9.1. The Wrist

The wrist consists of eight irregular bones arranged in two rows, proximal and distal; the proximal row consists of four bones: the scaphoid, lunate, triquetrum, and pisiform (from the thumb side, respectively). The first two of them articulate on their proximal side directly with the radius bone, while the other two articulate with the radius and ulna with fibers to form the wrist joint; this row distally articulates with the distal row of carpal bones.

The distal row consists of four bones: trapezium, trapezoid, capitate, and hamate; these bones articulate with the palm bones distally and have surfaces and projections that provide points of attachment and passage for muscle fibers and ligaments; the bones articulate with each other in Sliding type joints that allow the two rows of the bones to slide towards and over each other, forming a shape that makes the wrist convex from side to side posteriorly and concaves anteriorly, This shape gives excellent shock resistance, in addition to high flexibility, which enables the hand to hold things tightly.

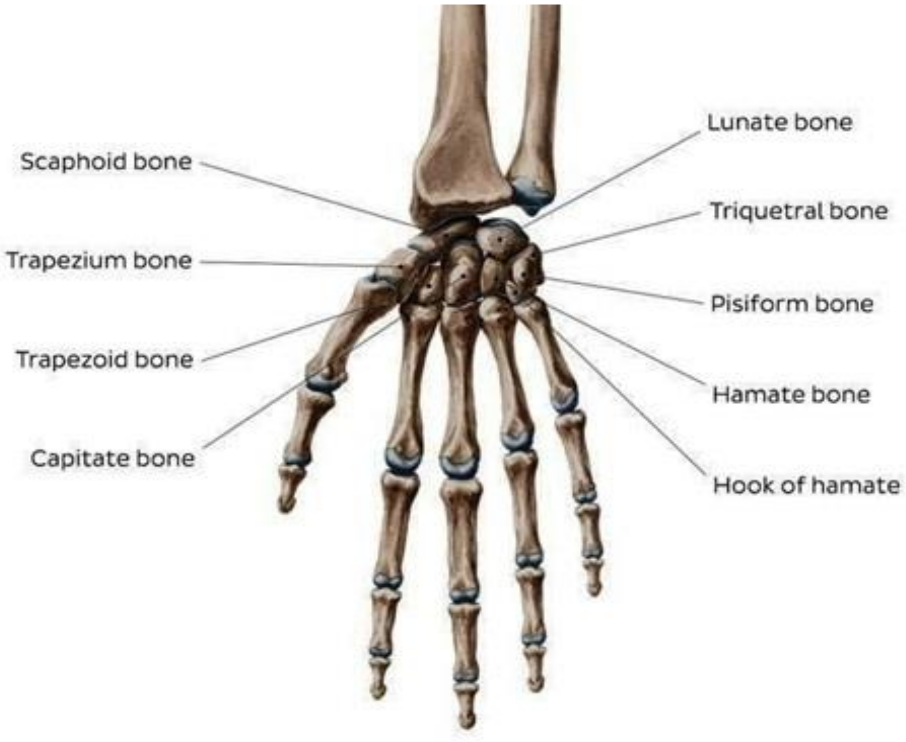


Figure 2.10. Wrist bones [1].

2.9.2. The Palm

Called also the Metacarpus consists of five long bones of different size that lies between the wrist bones and the phalanges of the fingers where the first connects to the thumb finger, the second connects to the index finger, the third connects to the middle finger, the fourth connected to the ring finger and fifth metacarpal to the little finger, each bone has a base, shaft and a head (Fig 2.11). The base is the widest part of the bone and differs in shape, with each bone in proportion to the irregular shape in the distal end of the carpal bone corresponding to it articulate with it. Among these five joints, the articulation of the first metacarpal bone with the trapezium is distinguished by the fact that the articular surface of the two bones is curved from the back to the front and from one side to the other at the side of the wrist with a Saddle type joint which gives the thumb more flexible movement in the hand with the ability to move at the lateral and frontal planes of the wrist. The shaft area is narrower than the base and the head, different in size and length for each metacarpal, and is the long middle part of it.

The head region is wider and is on the distal end of the metacarpal and has a convex shape that receives the concavity of the proximal phalanges' bases to form five separate metacarpophalangeal (MP or MCP) joints that connect each metacarpal bone to the corresponding proximal phalanges in hinge type joint.

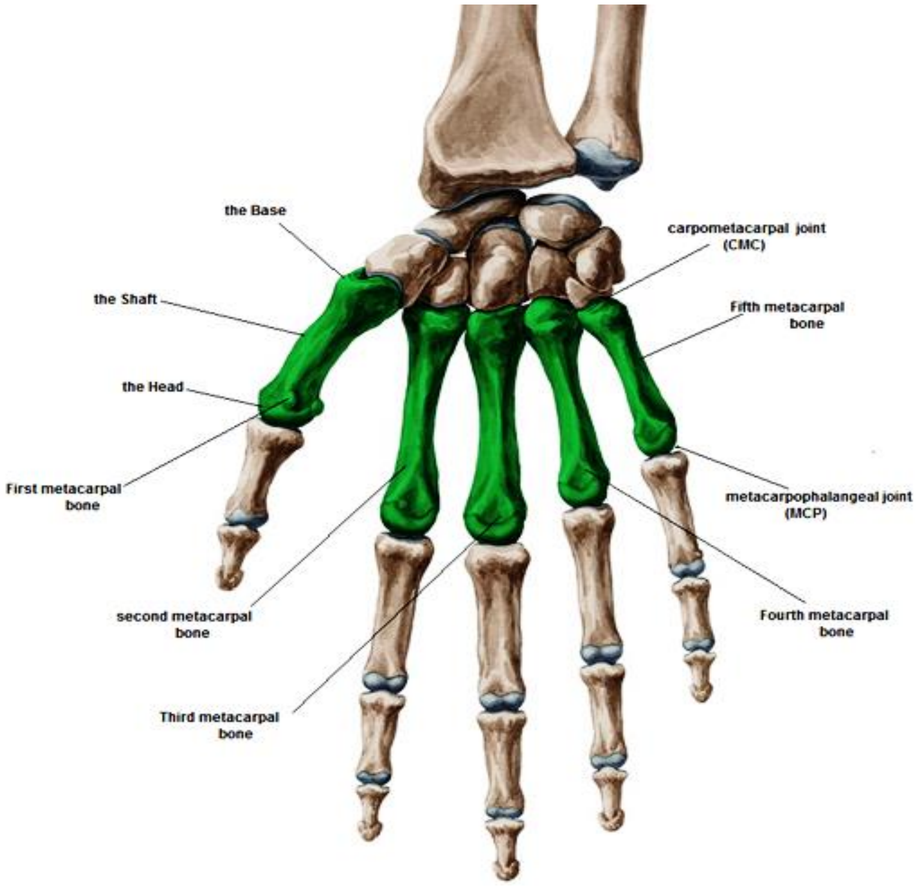


Figure 2.11. Palm bones [1].

2.9.3. The Fingers

The human hand has its distal end (thumb, pointer, middle, ring, and the little finger). Its position is from the radial to the ulnar side, respectively, and each finger consists of short bones called phalanges. The thumb consists of two phalanges, while other palmar fingers have three phalanges (proximal, middle, and distal) that are shorter distally, and these bones attach each other in a joint called the knuckle (Fig2.12).

The proximal and intermediate phalanges have a base, shaft, and head; the base is the widest and is at the proximal end. It contains a concavity that receives the convexity of the distal side of the metacarpal bones or of the next phalanx, where the proximal phalange has with the metacarpal bones the metacarpophalangeal joints (MCP), which is a condyloid type joint.

The shaft is the middle part of the phalange that becomes gradually thinner as we move away from the base; it has a round and smooth surface on its dorsal side, with convexity in the transverse plane, while it is flat and rough on its palmar surface that provides attachment points for the flexor fibrous sheaths of the digits.

The head is at the distal end of the phalanges, which is wider than the shaft. It has a pulley-like shape that appears on the palmar surface more than on the dorsal surface and in proportion to the concavity of the base of the next phalange end to make proximal interphalangeal joints (PIP), which is a synovial hinge-type joint.

The distal phalanges are located at the fingertip at the distal end. It is short with a flat shape and a broad base that articulates with the head of the intermediate phalanx in distal interphalangeal (DIP) joints, which is a hinge-type joint. The bone has an attachment point for the ligaments with a swollen bony lump tip under the nail area, which gives the finger its round appearance and provides a perfect hand's end to help in picking up the different objects.

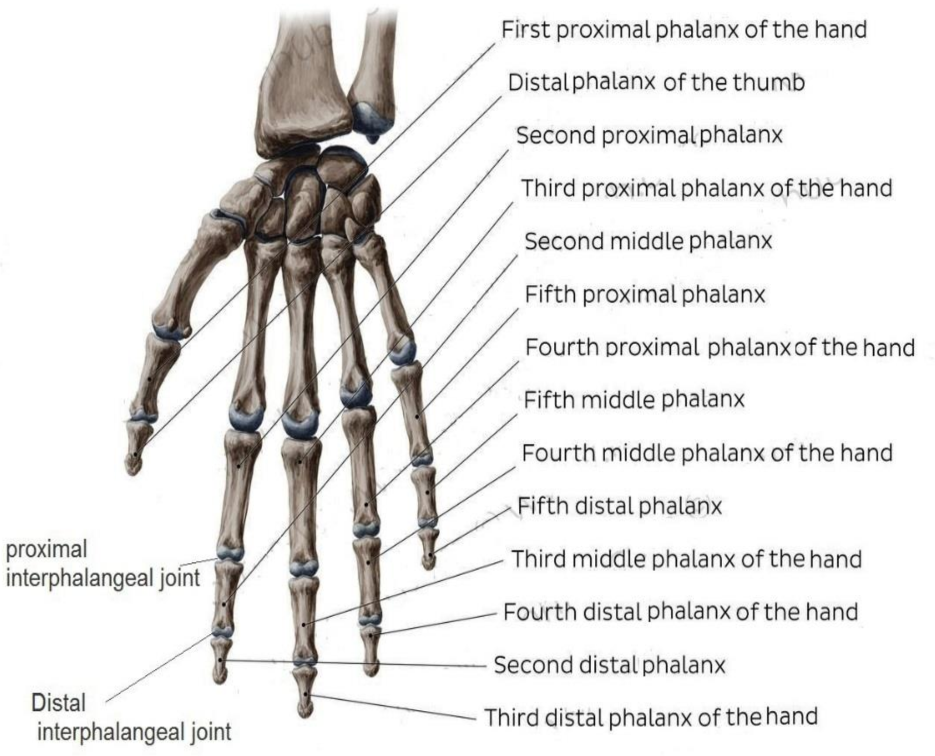


Figure 2.12. Fingers' bones [1].

2.10. THE MUSCLE

It is considered the motor of the movement in the human body through its ability to contract and relax to changes in length and dimensions. There are three types of muscles (skeletal, smooth, and cardiac muscles), including involuntary and voluntary.

The skeletal muscles for voluntary movement are soft tissue made up of many elastic fibers called muscle fibers that are longitudinal cells. The Protein represents the main component, and these fibers are grouped in parallel bundles surrounded by a thin transparent membrane. Moreover, each group of bundles is wrapped with a sheath of fibrous connective tissue called the muscle sheath to form what is called the muscle.

Muscles enveloped in another thicker sheath protect the muscles and extend to their distal ends to form the ligament, which is the attachment point to the bone; in addition, there are blood vessels that supply the muscle and nerves that provide the control (Fig 2.13) [55].

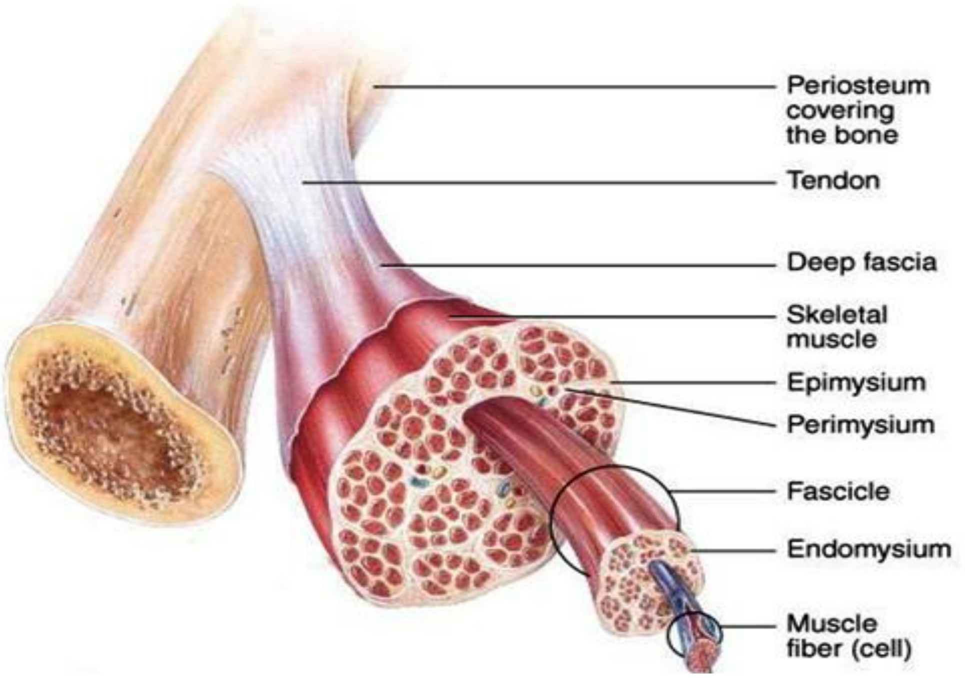


Figure 2.13. Structure of Skeletal Muscle.

2.11. THE MECHANISM OF THE MUSCLE ACTION

As it is known, what distinguishes the muscles is their ability to contract and relax, and this ability is due to the nature of the protein that makes up its cells.

There are many theories about the mechanism of muscle action; the most famous is the filamentous slip theory, which explains the arrangement of the protein in the form of longitudinally intertwined protein filaments, which are actin and myosin, where the myosin filaments contain Transverse protrusions resembling hooks, which work to pull the thin actin filaments, which makes the two filaments slide over each other longitudinally, approaching during the contraction and getting away during the expansion, consuming ATP energy molecules and this process is controlled by the neuronal electrical signal coming from the nerve and through the muscular sheath.

Muscles differ in shape and terms of the strength of their expansion and contraction, depending on their size, length, and the nature of the work, and the frequent use and exercise increases the size of the fibers, which increases the muscle size and strength. Muscle biomechanics calculation is not that easy due to a large number of influencing factors, but studying the muscle structure and architecture through resonance imaging and ultrasound, such as the angle of arrangement (pennation angle) and fiber length, gives the ability to calculate the length of the group of interconnected fiber bundles, or what is called the fascicle, through the equation [56]:

$$\boldsymbol{Fascicle\ length(mm) = muscle\ thickness(mm) \times \alpha^{-1}} \tag{2.2}$$

Where α = pennation angle

Also, through the experimental study, it shown that the tension force produced is directly proportional to the summation of cross-sections of the fibers, or what is called the physiological cross-sectional area (PCSA) for this muscle can be calculated theoretically through the equation (Fig 2.14):

$$\boldsymbol{PCSA(mm^{2}) = \frac{muscle\ mass(g) \times cos\ (\alpha)}{muscle\ density(g/mm^{3}) \times fiper\ length(mm)}} \tag{2.3}$$

Where PCSA represents the summation of the cross-sectional area for all muscle fibers and the density of muscle is approximately 0.001056 g/mm3, so the architectural design of the muscle with big mass and pennation angles, and short muscle fibers gives a big PCSA and large force production [57] [58].

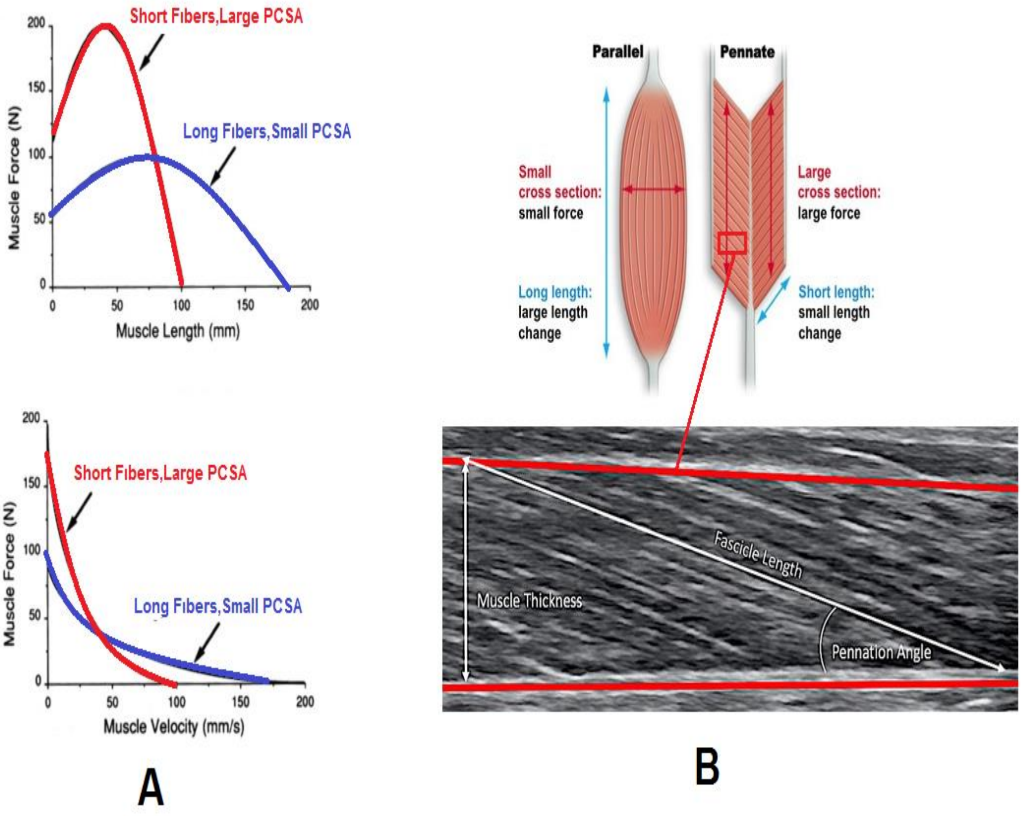


Figure 2.14. A- PCSA relation with muscle’s length and velocity [58].
B- The muscle’s Pennation angle[59].

2.12. THE ANATOMY OF THE FOREARM AND THE HAND MUSCLES

The forearm and the hand have more than 30 muscles distributed on different aspects, and in each aspect, there are three groups: the proximal, intermediate, and deep muscles [2, 60].

2.12.1. FOREARM MUSCLES

2.12.1.1. The Anterior (Flexor) Compartment

■Superficial Group:

It represents the muscles that lie above the other layers of muscles and directly under the skin on the front side of the forearm, and it consists of four muscles [2]:

• Pronator teres muscle: It has a cylindrical shape with two heads, the first attaches to the head of the ulna, and the second to the end of the humerus bone and the muscle extends obliquely to attach at its distal end with the radius bone near its middle. The contraction of this muscle works to pull the radius bone, making it, with the help of other muscles to rotate the radius above the ulna in a semi-circular motion, which rotates the entire forearm in a motion called the pronation.

• Flexor carpi radialis muscle (FCR): It relatively a thin muscle originates from the upper end of the humerus bone and extend with a long fusiform shape, tapering near the last third of the radius bone to form a tendon that attaches to the bases of the second and third metacarpal bones in the palmar aspect of the wrist. Its primary function is to flex the wrist and serve as a dynamic stabilizer of the scaphoid, aiding in the abduction of the hand and wrist.

• Palmaris longus muscle: It has a fusiform shape, wider in the middle and thinner at its ends, originates from the medial attachment point of the humerus bone at the radial carpal muscle and the flexor carpal ulnar muscle's common attachment point and extends between them, its ends near the middle of the forearm bones, then extends in the form of tendons to enter the midline of the wrist.

In addition to its role in flexing the wrist, this muscle attaches and helps in the tension of the Flexor retinaculum and the palmar aponeurosis (a fibrous band near the wrist over the carpal tunnel) which strengthens the grip of the hand. It is worth noting that this muscle is present only in 14% of the world's population, especially among the peoples of Africa and Asia and the indigenous people of America and sometimes exist only in one arm for the same person, so it has an auxiliary role in the hand.

• Flexor Carpi Ulnaris muscle: It is in the most medial position relative to the superficial muscles and has two heads, the first attaching medially to the humerus bone's end, and the second attaching to the posterior side of the ulna bone. These heads unite to form a tendon arc that represents the beginning of the muscle which becomes in a fusiform shape and tapers towards the end, extending into a tendon that attaches to the medial carpal bones and the base of the fifth metacarpal bone. This muscle is widely regarded as the strongest muscle for abduction and flexion of the wrist and hand (Fig 2.15).

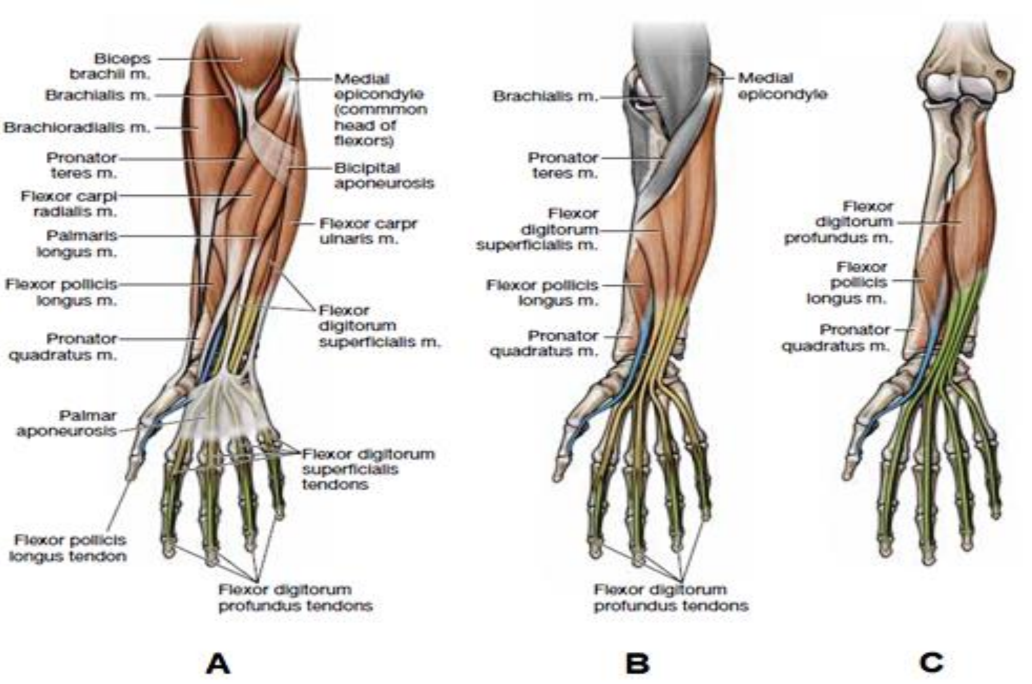


Figure 2.15. Superficial (A) intermediate (B) and deep (C) muscles of the anterior compartment of the forearm [2].

■ Intermediate Group:

It represents the intermediate layer located between the superficial and deep muscles and consists of only one muscle.

•Flexor Digitorum Superficialis muscle (FDS): Also known as the flexor digitorum sublimis, it is the largest flexor muscle in the anterior aspect and has two heads.the first head is medially attached to the humerus above the elbow joint. The second head is on the anterior oblique line of the radius bone shaft, giving it a shape similar to a checkmark at the upper beginning of the muscle. It later widens to cover the two forearm bones and extends to the distal ends of the bones.The muscle continues in the form of a tendon tape that enters the tendon channel and branches into four branches in the wrist. Each of these branches enters the four middle fingers and then branches into two branches after the metacarpal-phalanges joint to attach to the palmar side of the phalange bones at the middle joint. This form of connection provides stronger bonding of the fingers and also creates a channel for passing the flexor digitorum profundus (FDP) muscle tendons.

The primary function of this muscle is to flex the fingers (excluding the thumb) at the proximal joints of the phalanges by pulling the middle phalanges towards the palm, in addition to its role in assisting with wrist flexion.

■ Deep Group:

It represents the muscles that lie below the muscles of the other layers, so its location is closest to the forearm bones, and it includes three muscles:

•Flexor pollicis longus muscle (FPL): It is a long muscle that originates from the inner side of the proximal end of the radius bone and the membrane between the two bones of the forearm. Additionally, it is attached to the upper medial side of the Gantzer's muscle. It extends over the radius bone and enters the wrist as a tendon through the carpal tunnel, ultimately connecting to the distal phalange of the thumb from its palmar side.

This muscle serves a critical function in the movement of the thumb, contracting to flex the thumb at the metacarpophalangeal (MP) joints and the interphalangeal (IP) joint.

•Flexor Digitorum Profundus muscle (FDP): is a lengthy muscle that originates from the inner side of the proximal head in the ulna bone and the membrane between the two bones of the forearm. It extends towards the ulnar side of the hand and tapers at its end at the last third of the ulna, where it connects to four tendons that enter the palm at the wrist through the carpal tunnel. Each of these tendons then extend to attach to the distal phalanges of the middle four fingers, passing under and through the two branches of the Flexor Digitorum Superficialis muscle (FDS).

This muscle is responsible for flexing the Metacarpophalangeal (MCP) and distal (DP) joints of the four middle fingers (index, middle, ring, and little fingers).

•Pronator Quadratus muscle (PQ): is a short, quadrilaterally shaped muscle with flat muscle fibers running in parallel. It extends over the two forearm bones at its distal quarter in a transverse manner, from the oblique edge of the front side of the ulna bone to the lateral border of the radius. Its strong attachment to the bone occurs through a deep-seated area where the ligaments of the other anterior forearm muscles pass over it towards the wrist.

This muscle contraction pulls the distal end of the radius over the Ulna, resulting the turning of the wrist at the radioulnar joint. This movement is known as the Pronation, which is the function of this muscle.

2.12.1.2. The Posterior Compartment

■ Superficial Group:

• Brachioradialis muscle: A muscle with a fusiform shape, it is one of the largest muscles located in the upper lateral end of the forearm. Despite its appearance of having only one head, it is anatomically found to have a deep head, resulting in two heads on its upper side with a broad attachment point to the humerus. The brachialis muscle originates from the lateral margin of the humerus. It extends across the elbow joint and along the lateral side of the radius, attaching to the distal end at the base of the styloid process (Fig 2.16).

The primary function of the brachialis muscle is to flex the forearm on the humerus. Additionally, it plays a role in the rotation of the forearm to assist other muscles in supinating the forearm from the pronated position and pronating from the supinated position.

- **Extensor carpi radialis longus muscle (ECRL):** A long, fusiform-shaped muscle has many points of contact at its upper end, mainly on the posterior and anterior sides in the distal third of the humerus. It is also attached to the lateral epicondyle of the humerus; it extends at

the lateral side of the radius and tapers approximately at the middle of the forearm to a flat tendon that reaches the radial styloid process and passes behind it toward the wrist to attach to the posterior aspect of the second metacarpal bone’s base (metacarpal of the index finger)

This muscle may help to flex the elbow joint. Also, it is one of the main muscles that control the movements of the wrist, where its oblique path enables it to pull the hand close and forward. Thus, it helps other muscles extend the wrist as well as abduct the hand (radial deviation). This also helps in tightening the hand grip by stabilizing the hand and giving sufficient tension to the ligaments of the finger flexor muscles while using the hand.

- **Extensor carpi radialis brevis muscle (ECRB):** A fusiform muscle that originates from the lateral epicondyle below the attachment points of the extensor carpi radialis longus (ECRL) and brachioradialis muscles. Despite being shorter than these two muscles, it is one of the long muscles that run along the side of the radius, crossing from the posterior side towards the wrist in the form of a tendon to attach to the bases of the phalanges of the second and third fingers as an extensor for these fingers. Additionally, this muscle aids in the extension of the wrist and abduction of the hand (radial deviation).

- **Extensor digitorum muscle (EDB):** It is a long muscle attached from its upper end to the lateral epicondyle of the humerus bone and extending to become wider near the distal quarter of the ulnar shaft bone, where four tendons arise from it that enter the wrist, and each tendon is attached to the lateral side of the middle and distal phalanges bases of the four fingers (index, middle, ring, and the little fingers).

The function of this muscle is to extend the four fingers except the thumb, and it also plays a role in extending the wrist.

• Extensor digiti minimi (EDM) muscle: a long, slender muscle that originates from the lateral epicondyle of the humerus and extends towards and along the ulna. It continues as a long tendon in the lower half of the forearm and attaches to the wrist laterally, where it is connected to the phalanges of the little finger.

The primary function of this muscle is to extend the little finger at the metacarpophalangeal joint, facilitating the extension of the finger from a clenched fist. Additionally, the muscle contributes to the movement of the dorsal aspect of the hand towards the dorsal forearm, playing a role in extending and bending the wrist in a posterior direction.

• Extensor Carpi Ulnaris muscle (ECU): is a fusiform muscle with two heads, one originating from the lateral epicondyle of the humerus (from the common extensor tendon) and the other from the posterior side of the ulna. The muscle extends towards the wrist to the side of the ulna to enter the wrist in the form of a tendon that attaches to the wrist at the base of the little finger.

The primary function of the muscle is the extension and ulnar deviation of the wrist, and its location and function also contribute to the stability of the distal radial joint, maintaining a balanced extension of the wrist without deviation of the hand in the transverse plane.

• Anconeus muscle: A small muscle located at the back of the elbow, it has a triangular shape on its surface and is attached at its pointed head to the posterior surface of the lateral epicondyle of the humerus, at its broad base attached to the lateral section of the ulna.

The primary function of this muscle is to control the ulna during pronation, and it also contributes to elbow extension.

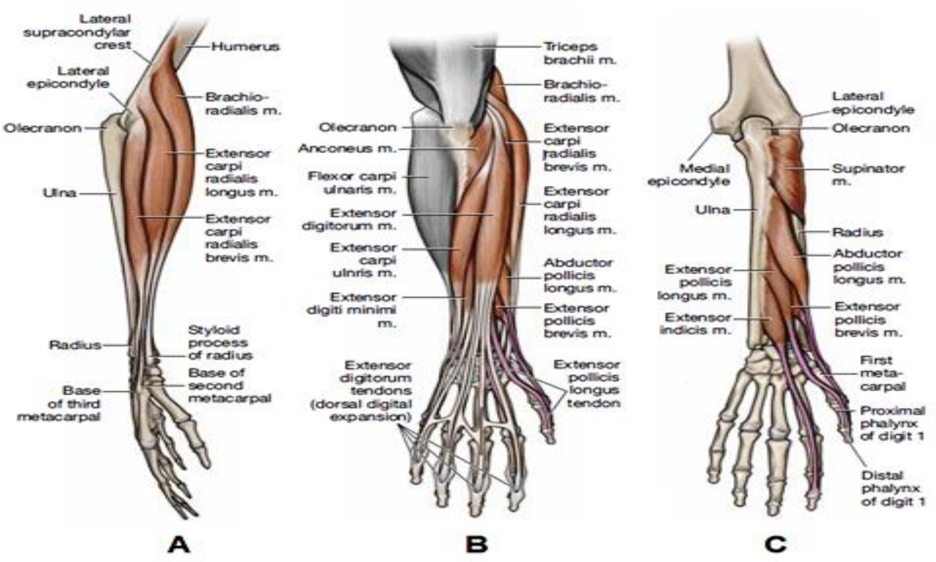


Figure 2.16. A.lateral view of the forearm.superificial (B) and deep (C) muscles ofthe posterior compartment of the forearm [2].

■ **Deep Group:**

• Supinator muscle: A broad muscle with a cylindrical shape located at the elbow and linked to several places around it, where it has an attachment to the humerus bone at the lateral epicondyle and with the radial collateral ligament and the annular ligament, the muscle also wraps around the lateral, posterior and anterior surfaces of the radius at its proximal third and connects it to the ulna at the upper ulnar crest (Supinator crest) and near the ulnar fossa.

The function of this muscle, as is its name, is supination of the forearm, where it rotates the radius horizontally at the proximal radial joint to become parallel to the ulna bone, which makes the palm upward.

• Abductor pollicis longus muscle: A Medium length muscle that arises from the Posterior surface at the upper part of the radius shaft and attaches in a wide area as it has attachments to the interosseous membrane; the muscle extends in the middle part of the forearm closer to the radius towards the hand and enters the wrist in the form of a tendon that attaches at its end to the distal phalanx of the thumb.

The primary function of this muscle is in the abduction and extension of the thumb at the thumb-carpal joint, and it also has a role in flexing the hand and abducting the wrist (radial deviation).

• Extensor pollicis longus muscle: That muscle arises from the inner borders of the ulna bone at its middle third part, and it attached to the interosseous membrane, forming a broad base and it extends towards the hand in the middle of the forearm, closer to the radius, its end be tapered at the distal end of the radius, and extends from it a tendon passing deeply through the carpal to attach the base of the distal phalanx of the thumb posteriorly.

Its primary function is to extend the thumb at the metacarpophalangeal and interphalangeal joints. It can also assist in adduction of the thumb and extension and abduction of the wrist joint.

• Extensor pollicis brevis muscle: A muscle originating from the inner edge of the ulna at the distal third of the radius to the lowest of the origin for the extensor pollicis longus and attached to the interosseous membrane. The muscle extends obliquely towards the ulna and the wrist and ends at the end of the forearm with a tendon that enters deep into the wrist to attach the base of the proximal phalanx of the thumb dorsally.

The function of this muscle is to extend the thumb at the metacarpophalangeal and carpometacarpal joints.

• Extensor indicis muscle: A narrow muscle originating from the posterior surface of the ulna, and the interosseous membrane extends towards the hand in the middle part of the forearm. Then, it becomes narrow at its end to enter the wrist deeply through its ligament, which is attached to the posterior part of the proximal phalange of the index finger by the extensor expansion tendons.

The function of this muscle is to extend the index finger at the metacarpophalangeal and interphalangeal joints; it also produces weak extension in the wrist joint.

2.12.2. HAND MUSCLES

The hand is the most distal part of the upper limb and consists of the palm and five fingers; the fingers do not contain muscles. Instead, they move through ligaments associated with the muscles that are distributed in the forearm, as we explained previously, and in the palm. The distribution of muscles in the palm can be divided into three groups or compartments [60, 61]:

2.12.2.1. Muscles in the Thenar Compartment

This area is located at the base of the thumb on the inner side of the hand. It includes three muscles (Abductor pollicis brevis, Flexor pollicis brevis, and Opponens pollicis muscle).

■ **Abductor pollicis brevis muscle:** A Flat and thin triangular muscle, and it is the most lateral and superficial site in the thenar muscles; it has a base that arises from the transverse carpal ligament; it also has two heads that are attached to the scaphoid and trapezium bones, then extends towards the thumb to attach the lateral side of the proximal phalanx base in the thumb by a thin, flat tendon.
The function of this muscle is to abduct the thumb at the carpal joint.

■ **Flexor pollicis brevis muscle:** A short, internal muscle located at the radial border of the palm, it has superficial attachment points with the flexor retinaculum and tubercle of the trapezium and deep attachment points with the trapezoid and the capitate bones, the muscle extends towards the thumb and taper at the radial side of the proximal phalanx base to attach Lateraly the base of the proximal phalanx in the thumb by a short tendon. Its function is to flex the thumb at the metatarsophalangeal joint and the metacarpophalangeal joint.

■ **Opponens pollicis muscle:** A small, relatively thin, triangular muscle located on the radial side of the hand, originating from the tubercle of the trapezium bone and the flexor retinaculum of the hand extending laterally and downward towards the thumb to attach the radial side and along the entire length of the metacarpal bone of the thumb.

The function of thismuscle, as is its name, is to produce a thumb movement opposing the movement of the two muscles of the pollicis, which gives a proximal flexion and rotation of the thumb medially in the first carpal joint; this procedure gives the thumb the ability to touch the tip of the four fingers, which enables the hand to do precise tasks such as gripping and picking up small objects with high efficiency (Fig 2.17).

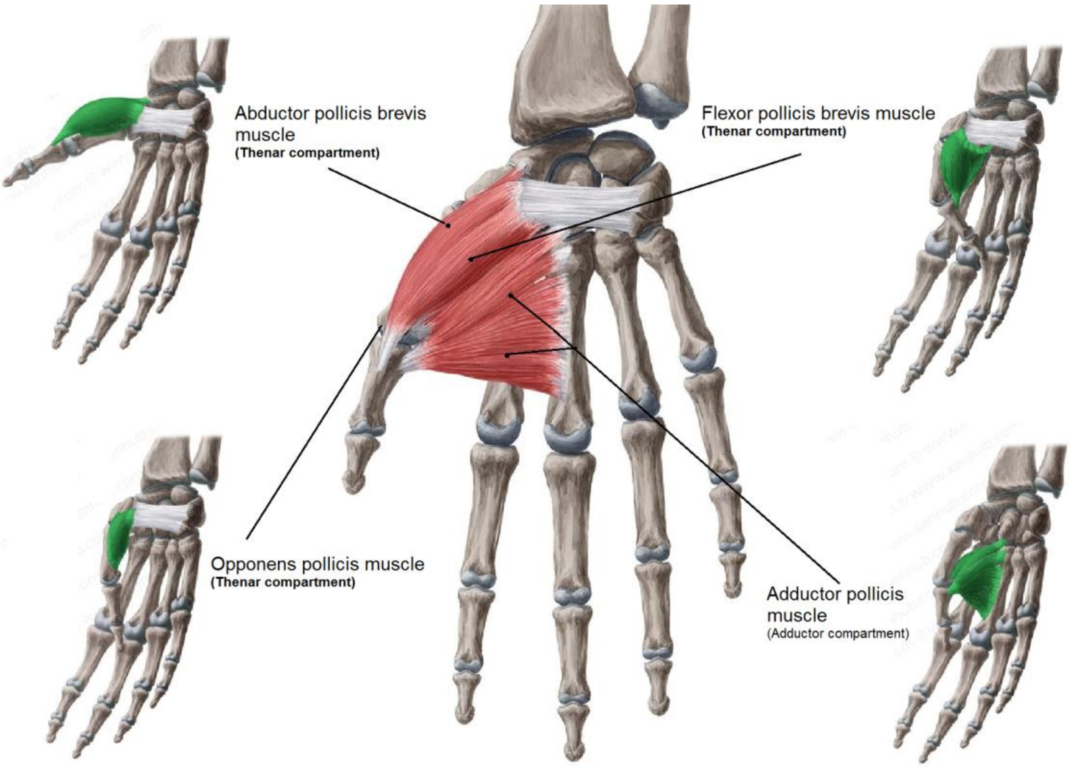


Figure 2.17. Thenar and Adductor compartments muscles [1].

2.12.2.2. Muscles in the Adductor Compartment

It is one of the hand areas in its deep compartment at the palmar side (some sources consider it to be a part of the thenar compartment). It includes one muscle called the Abductor pollicis muscle, which is a triangular-shaped muscle located between the center of the palm and the thumb. It has two heads: a transverse head attached to the base of the third metacarpal palmar bone and an oblique head attached to the bases of the second and third palmar metacarpals and the capitate bone. The muscle extends towards the thumb and tapers at its end to form the triangular head, which is attached to the middle base of the proximal phalanges in the thumb.

The function of this muscle, as its name suggests, is to adduct the thumb at the carpometacarpal joint. This procedure is one of the essential movements that give the thumb in the human hand this unique ability and flexibility in holding things or performing various actions. [60, 61] [1].

2.12.2.3. Muscles in the Hypothenar Compartment

It represents the muscles located at the base of the little finger on the palmar aspect(Fig 2.18), which are three primary muscles [60, 61] [1]:

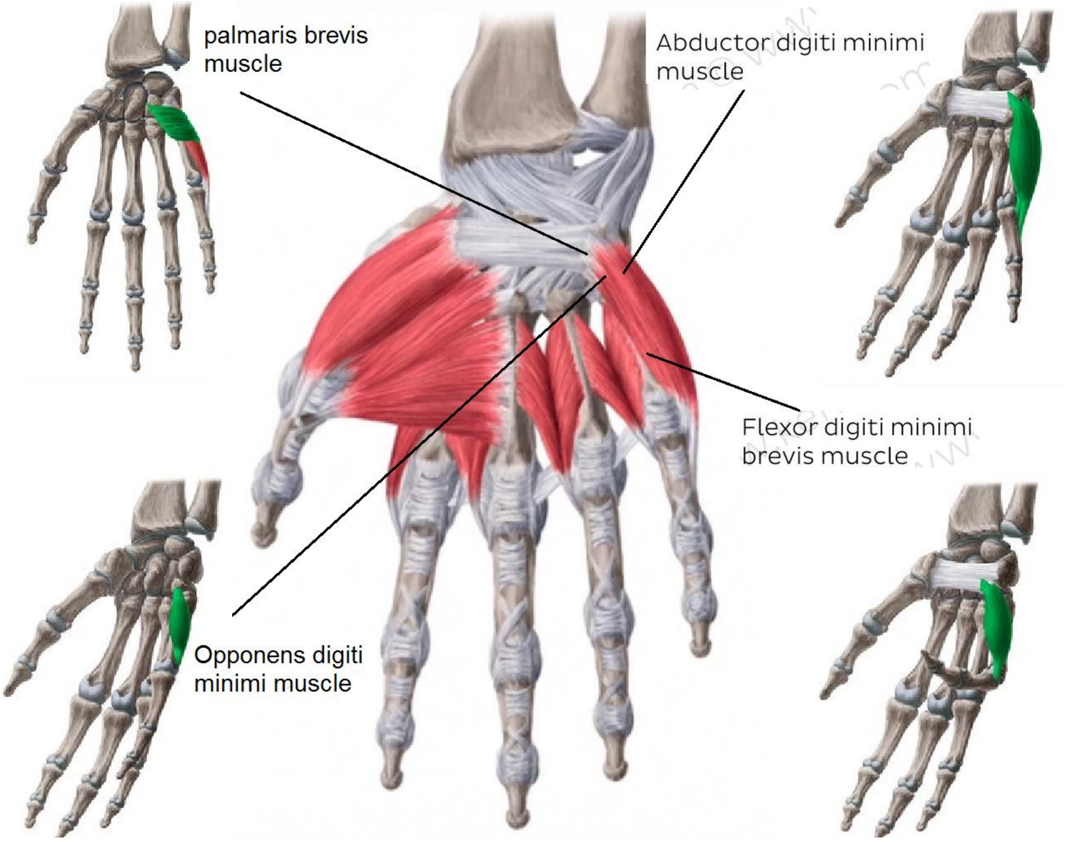


Figure 2.18. hypothenar compartment muscles [1].

■ Abductor digiti minimi muscle: A short, spindle-shaped muscle located on the medial side (ulnar border)of the palm and is the most superficial of the hypothenar muscles, this muscle has many points of origin in the anterior aspect of the palm, as it arises mainly from the Pisiform bone and it is also attached to the pisohamate ligament, and the flexor retinaculum, In addition, some fibers originate from the tendon of the flexor carpi ulnaris, which is also attached to the piriformis bone, the muscle extends towards the fifth finger at the ulnar border of the hand where the tendon of the muscle attaches to the proximal phalanx in the little finger at its ulnar side.

The primary function of this muscle is to flex and abduct the little finger at the metacarpophalangeal joint, which is due to moving it away from the other fingers. This procedure is necessary to have a hand with separate fingers to grasp large objects.

■ Flexor digiti minimi brevis muscle: A short muscle located on the medial side of the palm. The origin of the muscle is a short tendon that is attached to the hook of the Hamate bone and the medial side of the flexor retinaculum; the muscle extends towards the fifth finger to attach to the bases of its proximal phalanges on its palm side.

The function of this muscle is to flex the fifth finger at the metacarpophalangeal joint. Also, it has a role in lateral rotation and resistance for this finger.

■ Opponens digiti minimi muscle: A small triangular muscle arising from the hook of the hamate bone and the flexor retinaculum, the muscle extending obliquely towards the little finger to attach the adjacent palmar and ulnar side of the metacarpal bone of the finger.

The function of the muscle is to flex the little finger at the metacarpophalangeal joint. Also has a role in the lateral rotation and provides opposition to the movement of the other two little finger muscles; this action is essential to get a firm grip as well as help to pick up small or irregular objects.

2.12.2.4. Muscles in the Central Compartment

The muscles located in the center of the palm called the lumbrical muscles, are four short muscles with a worm-like shape that lie between the metacarpal bones of the four middle fingers and originate from the radial side of the tendons of flexor fingers deep (FDP) muscle, where the first and second muscles are from the tendons of the index and middle fingers, while the third is from the tendons adjacent to the middle and ring fingers. The fourth is from the tendons adjacent to the ring and little finger. Each muscle extends radially towards each finger that corresponds to it and has a fusiform end at the proximal phalanges of the four fingers, which attach to the lateral border of the tendons of the extensor muscles of the fingers (Fig 2.19).

These muscles extend the fingers at the interphalangeal joints (IP) and bend them at the metacarpophalangeal joints (MCP), as this procedure is necessary to obtain the deformation of the hand known as the lumbrical plus finger [60, 61] [1].

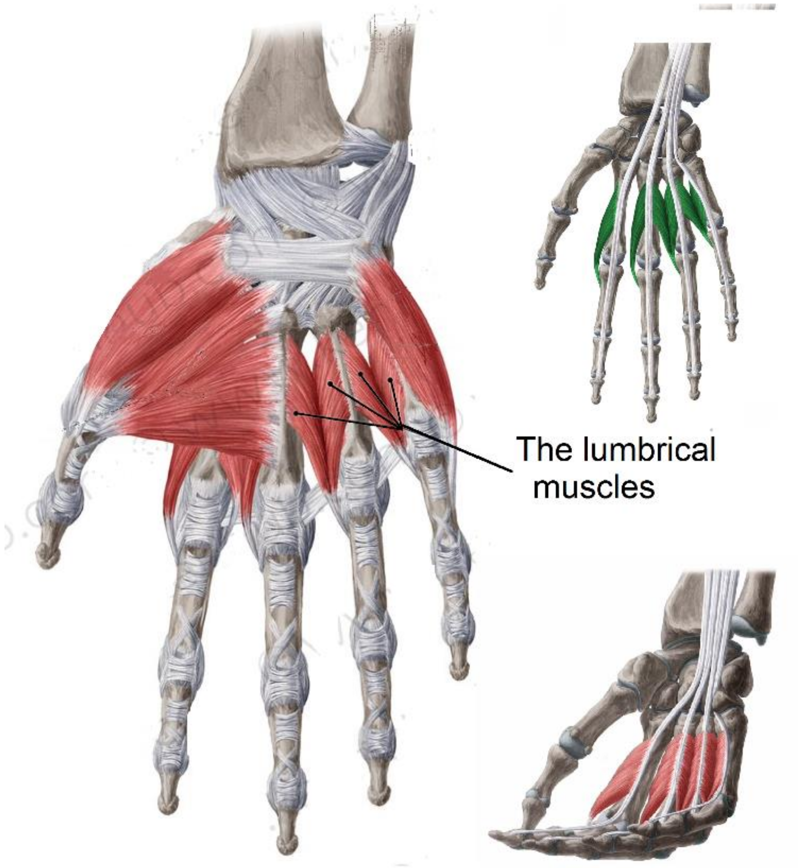


Figure 2.19. The limbrical muscles [1].

2.12.2.5. Muscles in the Interossei Compartment

Intrinsic muscles of the hand are located between the metacarpal bones (Fig 2.20) and consist of two groups of muscles, palmar and dorsal [60, 61] [1].

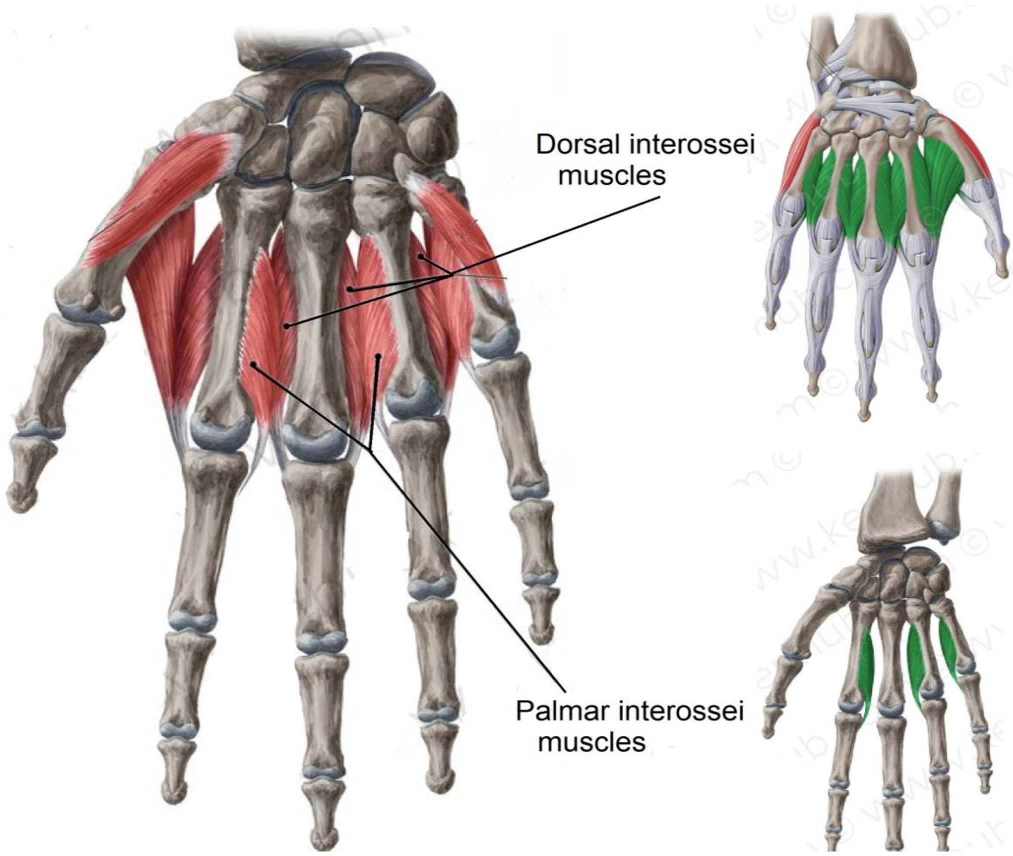


Figure 2.20. Interossei muscles [1].

■ **Dorsal interossei muscle:** A short, paired, feather-like muscle on the dorsal side of the hand fills the space between the five metacarpals.

-The first dorsal muscle, which is the largest located between the thumb and index, arises from the lateral surfaces of the metacarpal bones of the two fingers, and the muscle fibers extend obliquely to meet in a common tendon that attaches radially to the base of the proximal phalanx in the index finger.

-The second dorsal muscle arises from the adjacent surfaces of the metacarpal bones of the index and middle fingers. It extends between them, where the fibers are as in the first muscle, which has a common tendon that is attached radially to the base of the proximal phalanges in the ring fingers.

-The third dorsal muscle arises from the adjacent surfaces of the metacarpal bones of the middle and ring fingers. It extends between them, where the muscle fibers are formed in the same way as in the two previous muscles, to attach by its tendon medially to the base of the proximal phalanges in the ring finger.

-The fourth dorsal muscle arises from the adjacent surfaces of the metacarpal bones of the ring finger and the little finger. It extends between them with muscle fibers from the same dorsal muscles to attach its tendon to the base of the proximal phalanges in the ring finger.

These muscles work mainly to abduct the middle fingers (index, middle, and ring fingers) in a longitudinal axis and pull them away from each other. In contrast, the first and second muscles work to abduct the index and middle fingers radially. In contrast, the third and fourth muscles work on the ulnar abduction of the middle and ring fingers; in addition to the primary function of these muscles, they have a role in stabilizing the joints of the fingers during flexion and extension.

■Palmar interossei muscle: Short, internal, and unipennate muscles, where their fibers extend to unite in a common tendon on one side; these muscles occupy the spaces between the metacarpal bones on the palmar surface of the hand and extend between the adjacent surfaces of the metacarpal bones to the lateral base of the phalanges in the fingers, which are four or three muscles:

The first interossei of this muscle may not be present in many cases. However, if it is present, it arises from the base of the metacarpal bone of the thumb and extends distally to attach to the ulnar side of the proximal phalanges on the same finger.

The second interossei muscle arises from the metacarpal bone of the index finger. It extends in the space between it and the middle fingers to attach to the extensor expansion of the index finger.

The third interossei muscle arises from the radial side of the second metacarpal bone. It extends between the middle and the ring finger to attach its tendon radially to the proximal base of the phalanges in the ring finger.

The fourth interossei muscle originates from the radial aspect of the fifth metacarpal bone. It extends between the ring finger and the little finger to attach to the base of the proximal phalanges of the little finger.

We note from above that there is no palmar interossei muscle for the middle finger, where the primary function of these muscles is to adduct fingers by pulling the other fingers closer towards the middle, so their action is opposite to the dorsal muscles also have an essential role in extension in the metacarpophalangeal joints of the second, fourth, and fifth fingers, and flexion in the interphalangeal joint.

• Brachioradialis muscle: A muscle with a fusiform shape, it is one of the largest muscles located in the upper lateral end of the forearm. Despite its appearance of having only one head, it is anatomically found to have a deep head, resulting in two heads on its upper side with a broad attachment point to the humerus. The brachialis muscle originates from the lateral margin of the humerus. It extends across the elbow joint and along the lateral side of the radius, attaching to the distal end at the base of the styloid process.

The primary function of the brachialis muscle is to flex the forearm on the humerus. Additionally, it plays a role in the rotation of the forearm to assist other muscles in supinating the forearm from the pronated position and pronating from the supinated position.

• Extensor carpi radialis longus muscle (ECRL): A long, fusiform-shaped muscle has many points of contact at its upper end, mainly on the posterior and anterior sides in the distal third of the humerus. It is also attached to the lateral epicondyle of the humerus; it extends at the lateral side of the radius and tapers approximately at the middle of the forearm to a flat tendon that reaches the radial styloid process and passes behind it toward the wrist to attach to the posterior aspect of the second metacarpal bone’s base (metacarpal of the index finger).

This muscle may help to flex the elbow joint. Also, it is one of the main muscles that control the movements of the wrist, where its oblique path enables it to pull the hand close and forward. Thus, it helps other muscles extend the wrist as well as abduct the hand (radial deviation). This also helps in tightening the hand grip by stabilizing the hand and giving sufficient tension to the ligaments of the finger flexor muscles while using the hand.

- **Extensor carpi radialis brevis muscle (ECRB):** A fusiform muscle that originates from the lateral epicondyle below the attachment points of the extensor carpi radialis longus (ECRL) and brachioradialis muscles. Despite being shorter than these two muscles, it is one of the long muscles that run along the side of the radius, crossing from the posterior side towards the wrist in the form of a tendon to attach to the bases of the phalanges of the second and third fingers as an extensor for these fingers. Additionally, this muscle aids in the extension of the wrist and abduction of the hand (radial deviation).

- **Extensor digitorum muscle:** It is a long muscle attached from its upper end to the lateral epicondyle of the humerus bone and extending to become wider near the distal quarter of the ulnar shaft bone, where four tendons arise from it that enter the wrist, and each tendon is attached to the lateral side of the middle and distal phalanges bases of the four fingers (index, middle, ring, and the little fingers).

The function of this muscle is to extend the four fingers except the thumb, and it also plays a role in extending the wrist.

- **Extensor digiti minimi muscle:** a long, slender muscle that originates from the lateral epicondyle of the humerus and extends towards and along the ulna. It continues as a long tendon in the lower half of the forearm and attaches to the wrist laterally, where it is connected to the phalanges of the little finger.

The primary function of this muscle is to extend the little finger at the metacarpophalangeal joint, facilitating the extension of the finger from a clenched fist. Additionally, the muscle contributes to the movement of the dorsal aspect of the hand towards the dorsal forearm, playing a role in extending and bending the wrist in a posterior direction.

- **Extensor carpi ulnaris muscle:** is a fusiform muscle with two heads, one originating from the lateral epicondyle of the humerus (from the common extensor tendon) and the other from the posterior side of the ulna. The muscle extends towards the wrist to the side of the ulna to enter the wrist in the form of a tendon that attaches to the wrist at the base of the little finger.

The primary function of the muscle is the extension and ulnar deviation of the wrist, and its location and function also contribute to the stability of the distal radial joint, maintaining a balanced extension of the wrist without deviation of the hand in the transverse plane.

- **Anconeus muscle:** A small muscle located at the back of the elbow, it has a triangular shape on its surface and is attached at its pointed head to the posterior surface of the lateral epicondyle of the humerus, at its broad base attached to the lateral section of the ulna.

2.13. THE BIOMECHANICS OF THE FOREARM AND THE HAND

The human hand's role is evident in carrying out the activities of daily life because of the high coordination between its parts to apply many actions where the bones of the hand and forearm move at their joints with the effect of contraction and relaxation of the muscles, due to producing movements with a range of motion (ROM), differ in flexibility and range from one person to another, according to use, age, gender, and the anatomical structure of the hand.
By taking the body in the anatomical position (the palm facing upwards), we mention the most important of these individual movements [62-64]:

2.13.1. Forearm Pronation

Is the movement of the forearm bones by shifting the distal end of the radius from the lateral side to the medial side by its rotation over the ulna and changing the position of the two bones from parallel to each other to form similar to the cross sign. That causes the forearm to rotate almost 90 degrees at its radioulnar joints from the normal position which causing the anterior side of the palm facing posteriorly or downward (Figure 2.21).

2.13.2. Forearm Supination

It is an opposite movement to pronation by returning the two forearm bones to a parallel position with each other and the anterior side of the palm facing anteriorly or upwards.

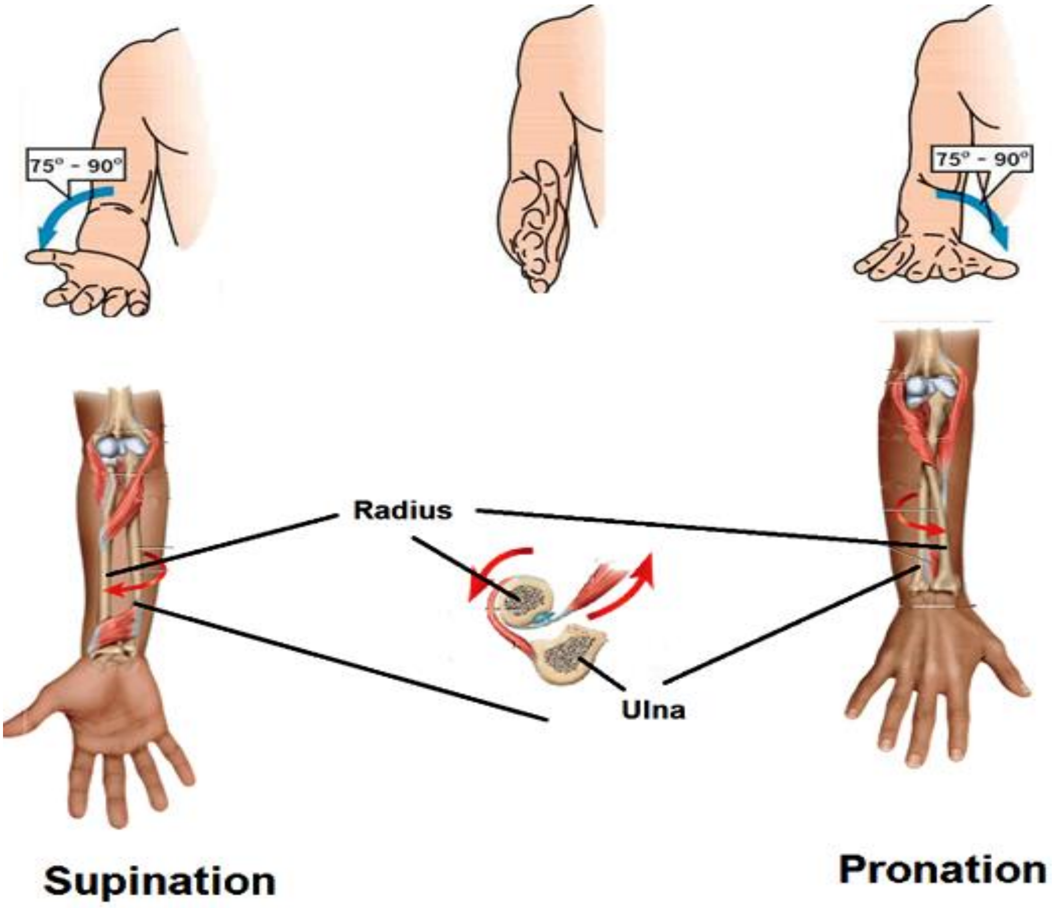


Figure 2.21. Supination and Pronation movement [2].

2.13.3. Wrist Flexion

It is moving the entire hand at the wrist joint towards the anterior side of the forearm on the same axis and different coordinate plane, where this movement can be done in a range of angles shown in Table 2-1.

2.13.4. Wrist Extension

An opposite movement to the hand flexion is done by moving the hand toward the posterior side of the forearm at the wrist joint (Figure 2.22), and this movement can be done in a range of angles, as in Table 2-1.

2.13.5. Wrist Adduction

It is also called ulnar deviation, and it is the movement of the entire hand towards the little finger, which means towards the outer aspect of the ulna bone at the wrist joint within the same coordinate plane of the forearm and in a different axis within an angle range shown in the table below.

2.13.6. Wrist Abduction

It is also called radial deviation, which is the opposite movement of hand adduction. It is the movement of the entire hand towards the thumb (Fig 2.22), which means towards the outer aspect of the radius at the wrist joint, within an angle range, as shown in Table 2-1.

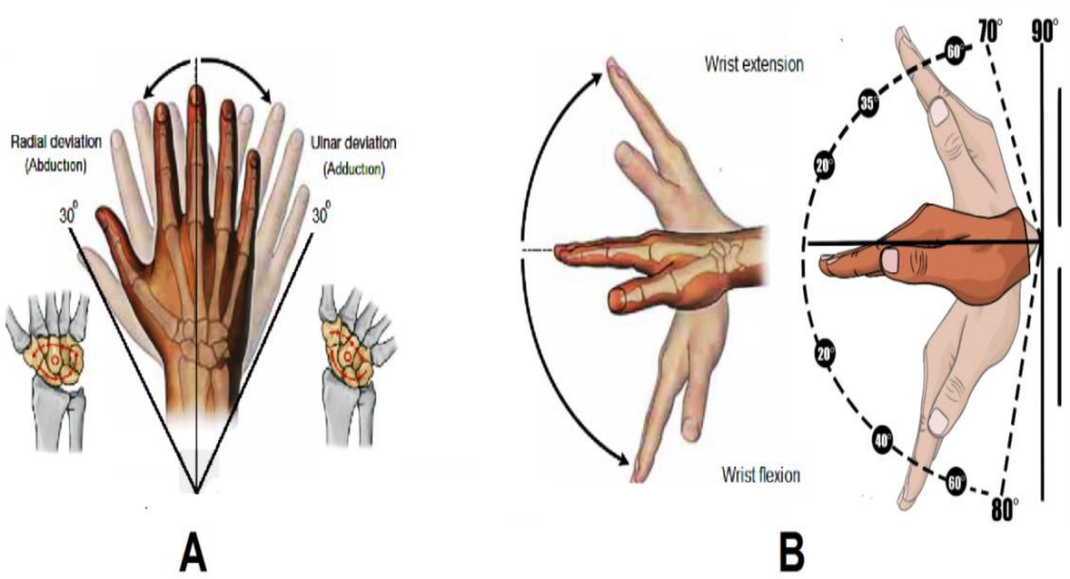


Figure 2.22. A-Wrist Abduction and Adduction.B-Wrist Flexion and Extention [2].

Table 2.1. Ranges of the motion ROM in the wrist [65, 66].

Wrist	Value
flexion	65° - 70°
Extension	70° - 80°
Abduction (Radial deviation)	15° - 25°
Adduction (Ulnar deviation)	40° - 45°

2.13.7. Fingers Abduction

It is moving the fingers at their metacarpal-phalangeal joints away from the line or the middle finger in the hand within one coordinate plane (the index and the thumb towards the radius, the ring finger ,and the little finger towards the ulna), which leads to separate of the fingers from each other, fingers abduction can be individual or combined.

2.13.8. Fingers Adduction

It is opposite to a fingers abduction movement, which is by moving the fingers toward the middle finger in the hand, which is due to bringing the fingers closer to each other.

2.13.9. Fingers Flexion

Is the movement of the anterior side of the fingers towards the palm at their metacarpal-phalangeal joints and or the movement of the anterior side of the phalanges towards each other at the interphalangeal joints within the same axis of the hand but with a different coordinate plane. Flexion can be done for each phalanx and joint individually, or the movement of closing the whole hand, which means bending all the bones of the fingers at all their joints (Fig 2.23).

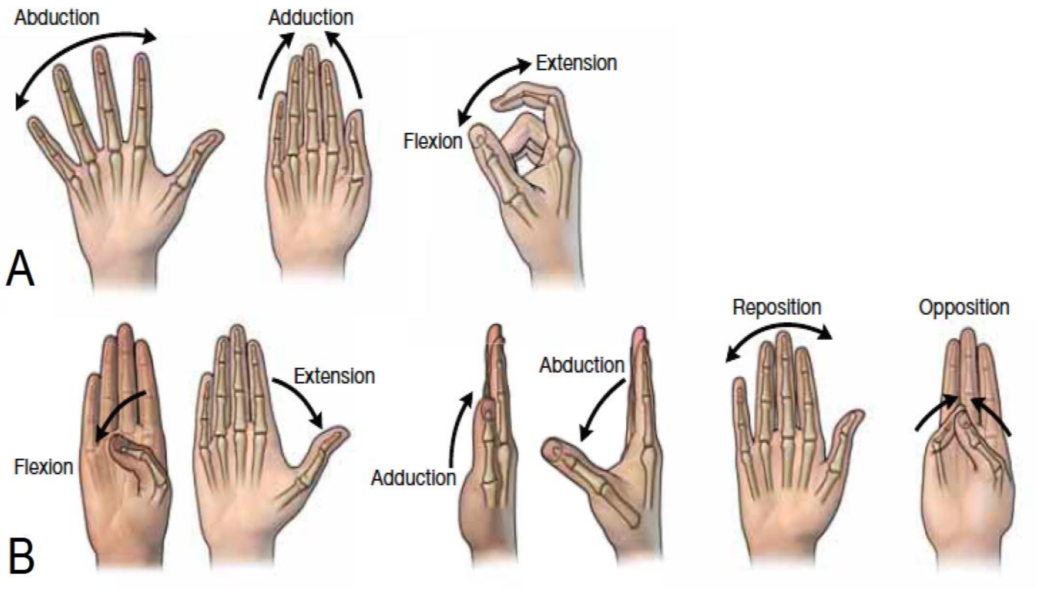


Figure 2.23. A-fingers movements.B-thumb movements.[2].

2.13.10. Fingers Extension

Opposite movement to finger flexion represents the expansion of the phalanges of the fingers at their joints individually or the opening of the whole hand which means the expansion of all fingers at all its joints.

2.13.11. Thumb Opposition

It is the movement of the metacarpal bone of the thumb towards the palm at the MCP joint in a way that enable the tip of the thumb touch the tips of the fingers in the same hand. This movement characterizes the thumb where it is provided by its saddle-type joint.

2.13.12. Thumb Anteposition

Also known as palmar abduction, this is the movement of the thumb away from the index finger at an average angle of about 40 degrees. This movement aims to open more space in the hand to pick up objects.

2.13.13. Thumb Reposition

It is a movement opposite to the Thumb Opposition movement of the thumb towards the outside of the hand at the MCP joint and back to its position in the coordinate plane of the palm (Table 2.2).

Table 2.2. Ranges of motion in the finger joints [65].

Finger	**Flexion**	**Extension**	**Abduction/adduction**
Thumb			
Trapeziometacarpal	50- 90°	15°	45° - 60°
Metacarpophalangeal(MCM)	75- 80°	0°	0°
Interphalangeal (IP)	75- 80°	5- 10°	0°
Index			
Carpometacarpal (CMC)	5°	0°	0°
MCP	90°	30- 40°	60°
Proximal interphalangeal (PIP)	110°	0°	0°
Distal interphalangeal (DIP)	80- 90°	5°	0°
Middle			
CMC	5°	0°	0°
MCP	90°	30- 40°	45°
PIP	110°	0°	0°
DIP	80- 90°	5°	0°
Ring			
CMC	10°	0°	0°
MCP	90°	30- 40°	45°
PIP	120°	0°	0°
DIP	80- 90°	5°	0°
Little			
CMC	15°	0°	0°
MCP	90°	30- 40°	50°
PIP	135°	0°	0°
DIP	90°	5°	0°

CHAPTER 3

METHODOLOGY

3.1. THE DESIGN OF MUSLES

In this study, the forearm parts for a right-hand prosthesis replacement were designed and assembled using the SolidWorks program. The parts were selected based on the author’s right hand. Also, the forearm's muscles and solid parts were modeled carefully before manufacturing.

3.1.1. The Muscle Structure

The muscles were designed to include an air chamber and an outer shell. The air chamber is a hollow cylinder made of a material with a hipper elasticity. They were closed at one end, with the other containing a passage for pressurized air. We tested cylindrical mesh (polyester) and two relatively spiral covers (metallic and nylon) for the outer shell. Covers surrounded the chamber, and the ends were connected to the chamber ends (Fig 3.1 and 3.2).

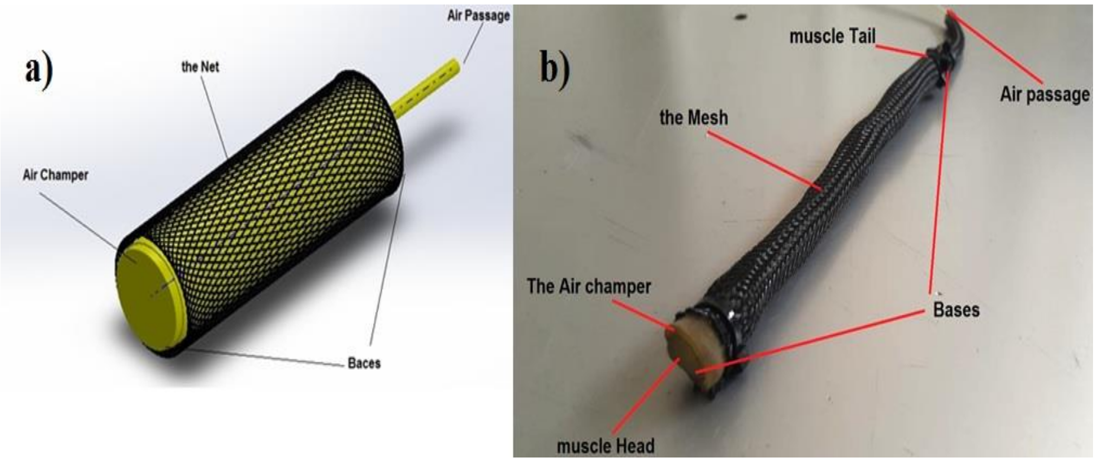


Figure 3.1. The artificial muscle structure; a)3D modelling, b) shell and cover details.

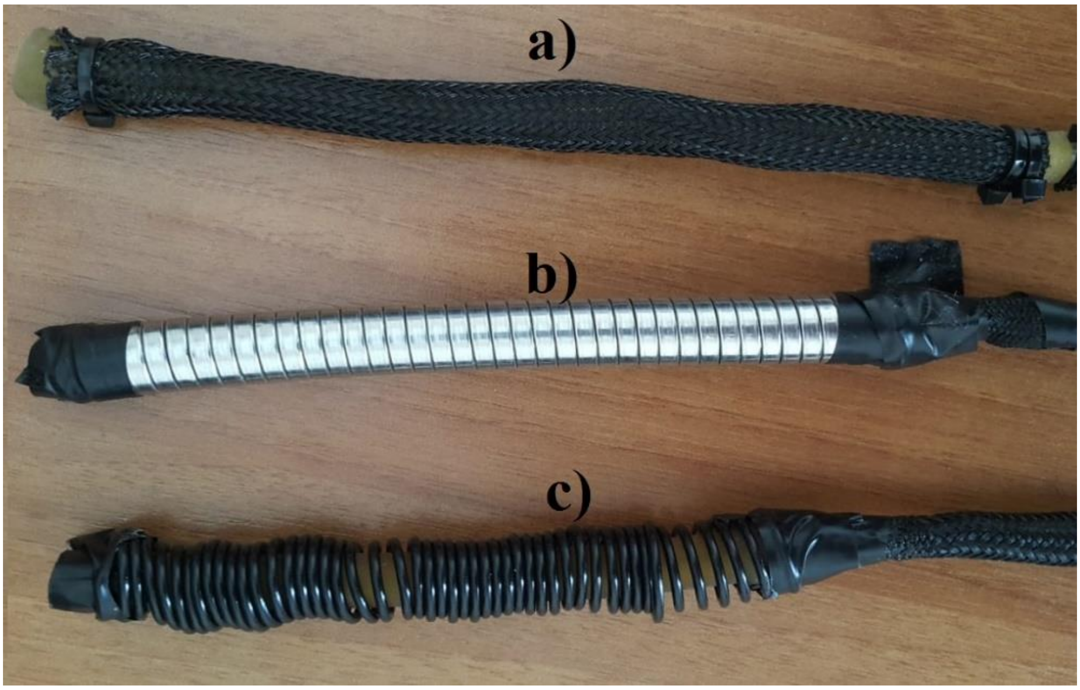
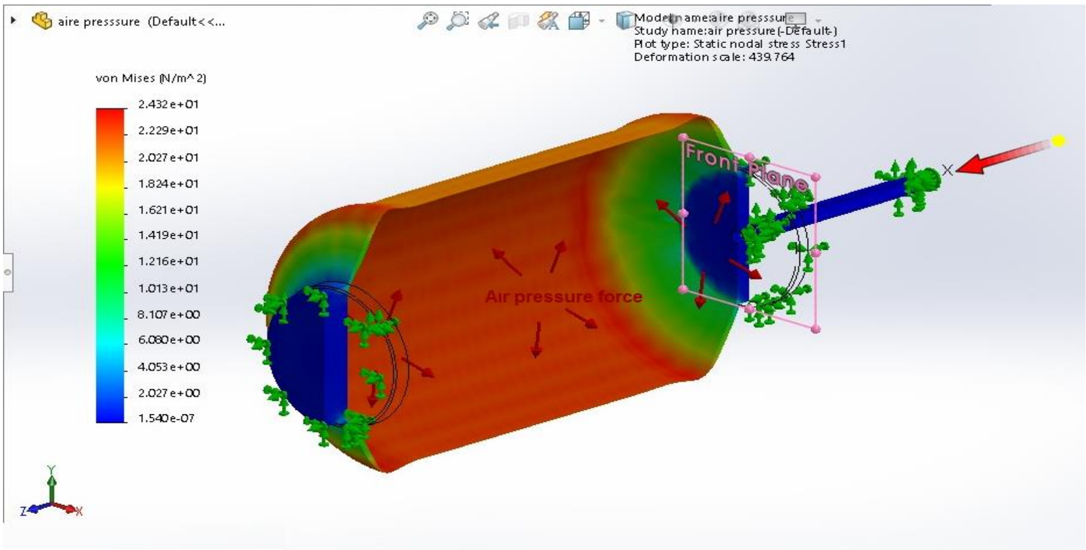


Figure 3.2. The shell covers; a) mesh (polyester), b) metalic spiral and c) nylon spiral.

The muscles with mesh cover showed better performance among the three different muscles in terms of weight, power production, lengthening ratio, and time responsibility. It was selected to use the prosthetic hand muscles in this study.

3.1.2. Muscle Working Principle

The general gas law explained in the previous chapter shows a relationship between air pressure and container volume. The air chamber was a thin silicon, and its bases were made of non-flexible materials. The flexible walls of the chamber were covered with a nylon mesh that could expand easily with the volume change in the polymer chamber, resulting in an increase in diameter and a decrease in height. With the combination of hyperelastic polymer volume change and mesh shape deformation, a muscle contraction could be mimicked (Fig 3.3).



Model name:aire presssure

Study name:air pressure(-Default-)

Plot type: Static nodal stress Stress1

Deformation scale: 439.764

Figure 3.3. The air pressure and muscle contraction simulation.

3.1.3. The Fingers and Fingers Bases

Each finger was designed in three parts, representing a phalange with a semi-cylindrical shape and a flat on the dorsal and palmar sides. The distal phalange end means the tip of the finger, and the proximal phalanx has an end to set in the finger’s base. Between them is the middle phalange, connected to these two phalanges from its dorsal side by a rubber that represents a flexible joint.

On the lateral side, the phalanges appear with an inclined end towards the palm side. These ends are also concave; their counterparts are convex when the finger is bent. This design strengthens the finger's grip and prevents it from descending when carrying weight.

Additionally, the proximal end of the distal phalange is attached to an elastic band that works as a tendon extending across the finger through a canal along the proximal and middle phalanges to reach the finger's flexion muscles (Fig 3.4).

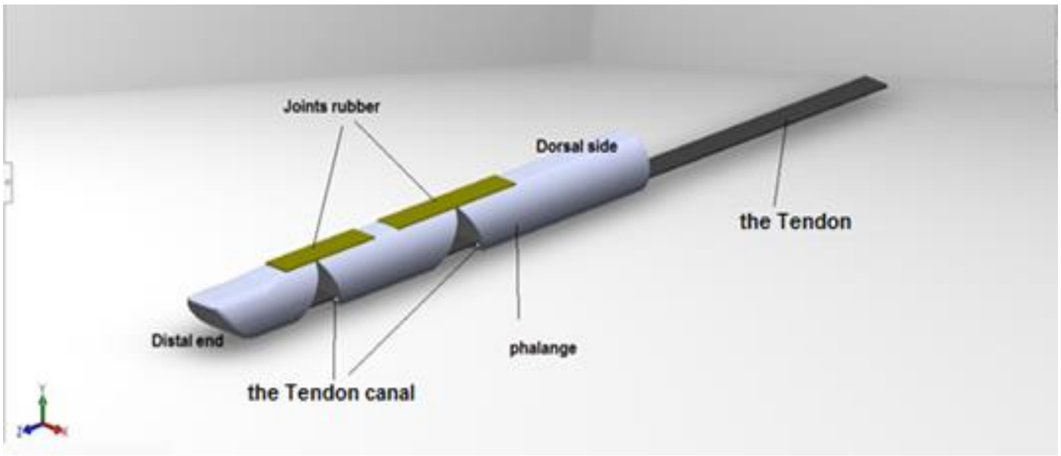


Figure 3.4. The finger structure.

The finger bases from its distal are connected to the proximal ends of the fingers. Their unique shape allows the peripheral bases to slide under the medial bases, creating a sliding-type joint. The proximal end of the finger bases is cylindrical, with holes from the dorsal side to the palm (the middle and ring fingers have slots). These holes are the attachment points with the palm through the stud bolts (Fig 3.5).

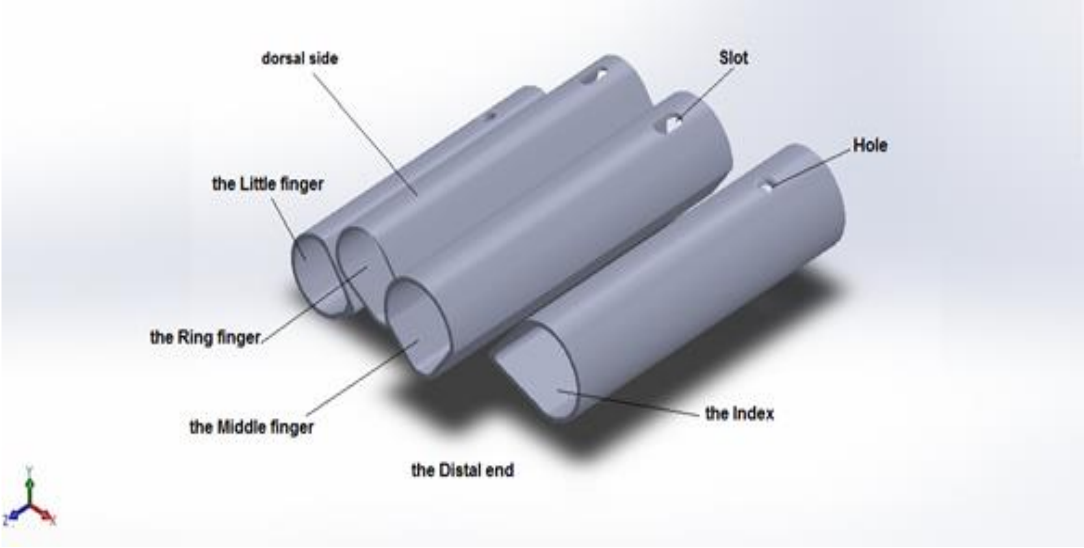


Figure 3.5. The fingers bases three dimensional (3D) model.

3.1.4. The Palm

The palm was designed as a single part with a wider middle and equal dimensions at the ends, its proximal end connected to the wrist joint, and the dorsal surface was flat, with a height extending from the distal end to the middle, as shown in Figure 3.6. This design improved the sliding movement of the two middle fingers. In addition, four stud bolts appear on the surface, representing the attachment points with the fingers' bases, and the lateral side of the palm has a circular cavity that receives the base of the thumb.

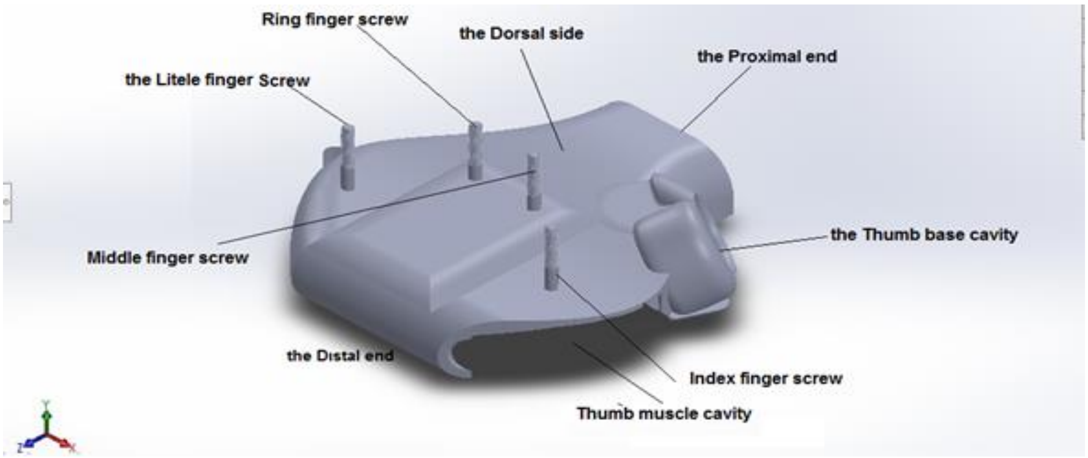


Figure 3.6. The Palm 3D model and its details.

3.1.5. The Wrist

This part was designed to be as two Knuckle-type joints (each joint has a fork with two eyes side and the other side with one eye). The fork of the distal joint merges with the palm, and its one-eye side is combined with the fork of the proximal joint, and its one-eye side is a part of the forearm shaft. The distal joint has a 180-degree range of movement, while the proximal joint has a 90-degree range, with both joints bending in two perpendicular planes (Fig 3.7).

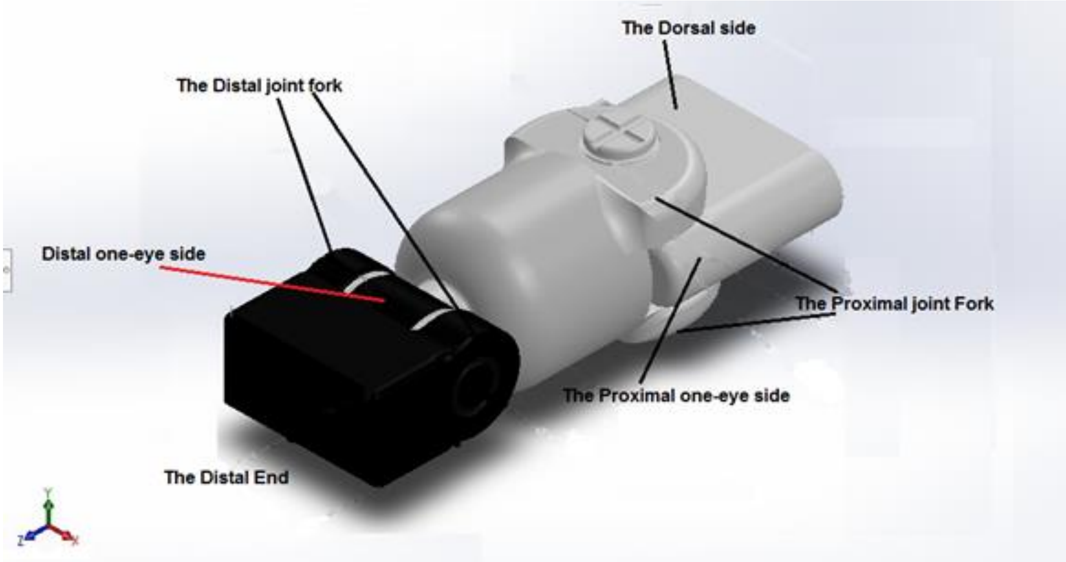


Figure 3.7. The wrist joints 3D model and structure.

3.1.6. The Forearm

The design consisted of a single shaft with a thin distal end representing the one-eye section of the wrist proximal joint. The shaft extended cylindrically, with flats on the sides representing areas for wrist muscle movement. The dorsal side was flat for the sliding platform, and the proximal end was designed with a concave that receives the rotor part (Fig 3.8).

Figure 3.8. The forearm shaft 3D model.

3.1.7. The Sliding Platform

The sliding platform had a cuboid shape fixed on the dorsal side of the shaft and could slide backward (by affecting the wrist extension muscle), and near its distal end, there was the proximal transverse plate, which served as the attachment point for the wrist ligament. At its proximal end was another proximal transverse plate carrying the finger muscles. At the platform's proximal end, there was an attachment point for the wrist extension muscle. This platform's function is to have the fingers flexion muscles, ensuring constant tension in the fingers' tendons during wrist joint movement (Fig 3.9).

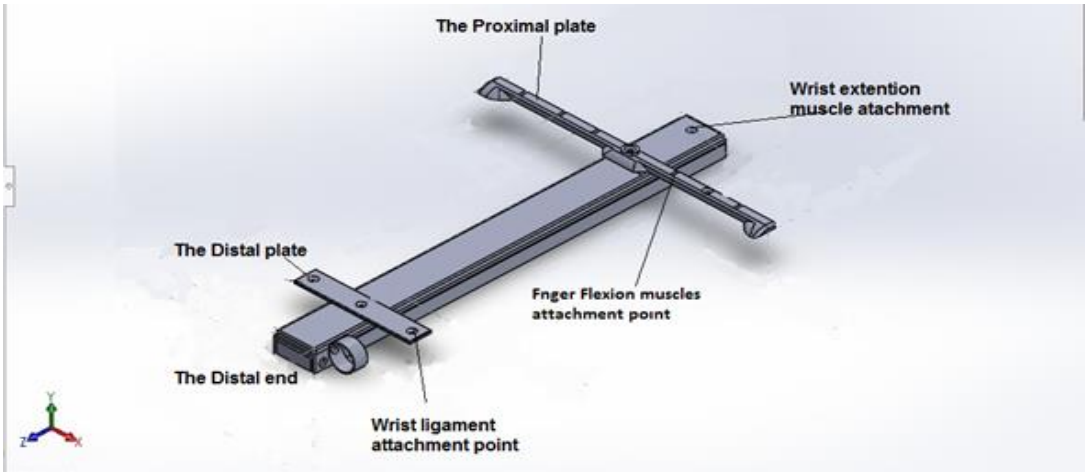


Figure 3.9. The sliding platform 3D model and related parts.

3.1.8. The Rotator

This part was designed with two sections: its distal end was circular and fixed in the shaft's cavity. Its other side had a rotary articulation with the rotator's proximal part, allowing 360-degree rotation. The rotator's proximal part has two holes on its dorsal side to fix the rotation of muscles, and the proximal end contains a knuckle-type joint fork representing the distal section of the elbow joint (Fig 3.10).

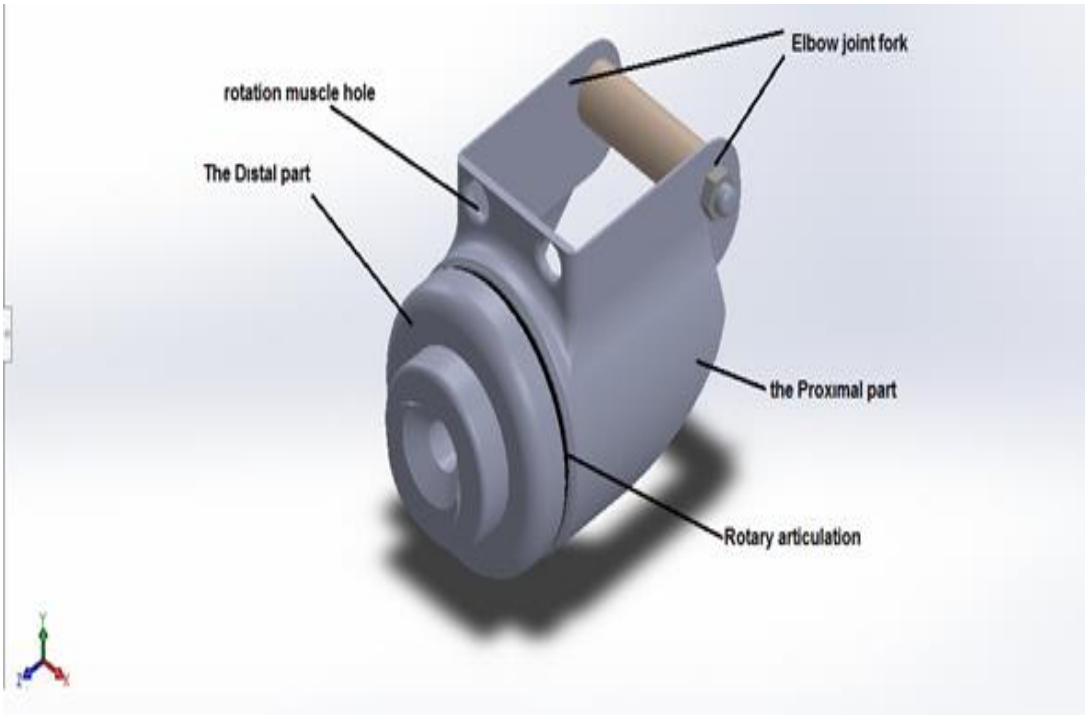


Figure 3.10. The Rotator 3D model.

3.1.9. The Air System

The air system comprises an air pump, valves, and air hoses connecting to the muscles (Fig 3.11).

Each muscle has a single air outlet that serves as a passage for the entry and exit of air. Each muscle's air passage is connected to an air hose, which in turn is connected to a valve - one for each muscle. The valves are also connected to a standard line, with one end connected to the air pump and the other to the discharge valve. The mechanism of action is as follows:

- **Contraction:** The unloading valve is closed, the pump is running, and the muscle valve is open until the required pressure is reached.

- **Relaxation:** The pump is off, and the unloading and muscle valves are open until the muscle is emptied.

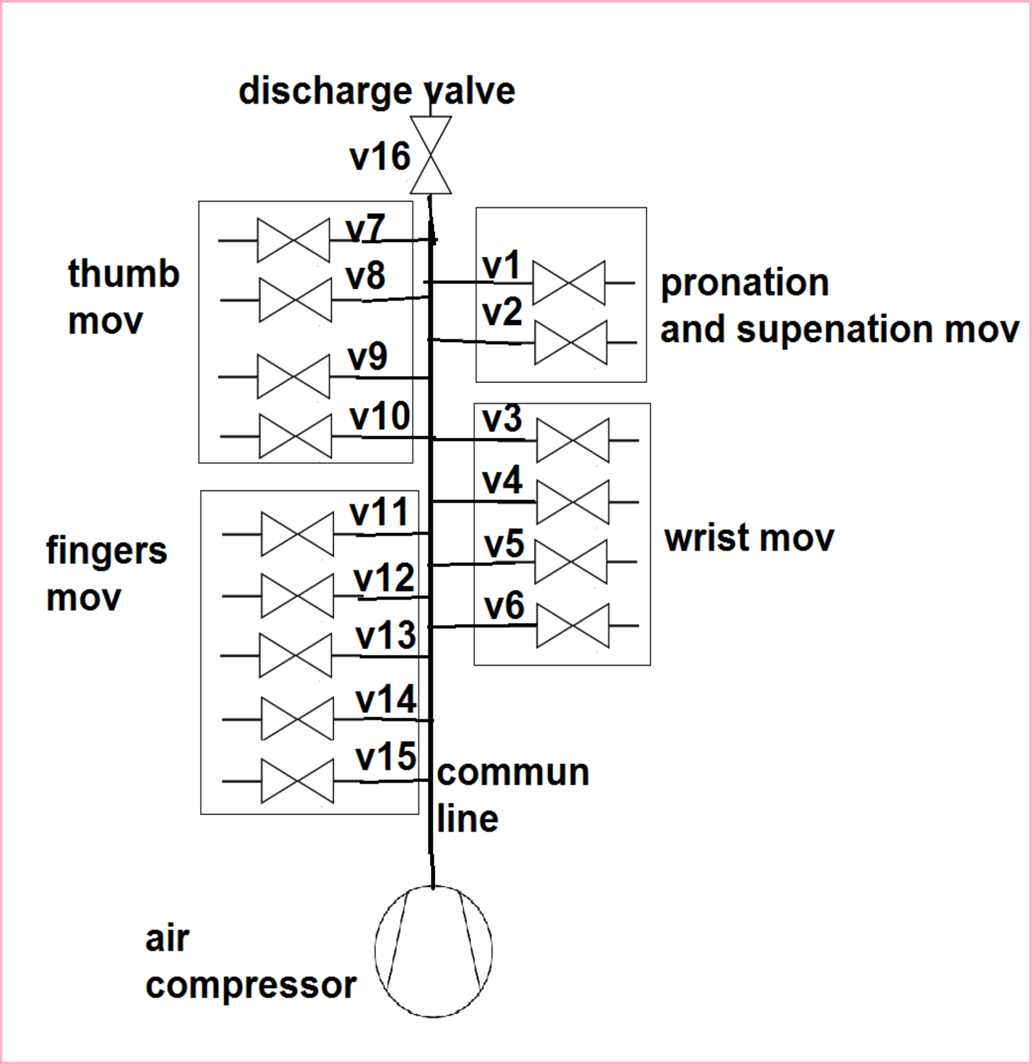


Figure 3.11. Air system diagram.

3.1.10. Electronic Components and Control System

This arm is considered an externally powered prosthesis type. It includes a power source that supplies an electric air pump, usually closed-type electric valves, and control sections with the necessary energy.

Control of the arm depends on managing muscle contraction and relaxation, which is achieved by controlling valves' opening and closing and turning the air pump on and off (Fig 3.12).

The electrical signal reaches the pump and valves through the control buttons for each valve and the pump operating button, allowing synchronization to be applied to move the muscle, as explained in the air system section:

Contraction: The valve control button is closed (conducts the electrical signal), the pump button is closed, and the discharge valve button is open. The pump must work until the muscle contracts to the required amount. Since muscles vary in size, using a timer is impractical. Therefore, a pressure sensor was employed to turn off the pump when the required pressure was reached.

Relaxation: The pump operating button is open, the muscle valve control button is available, and the unloading valve button is closed until the required amount of air is expelled from the muscle.

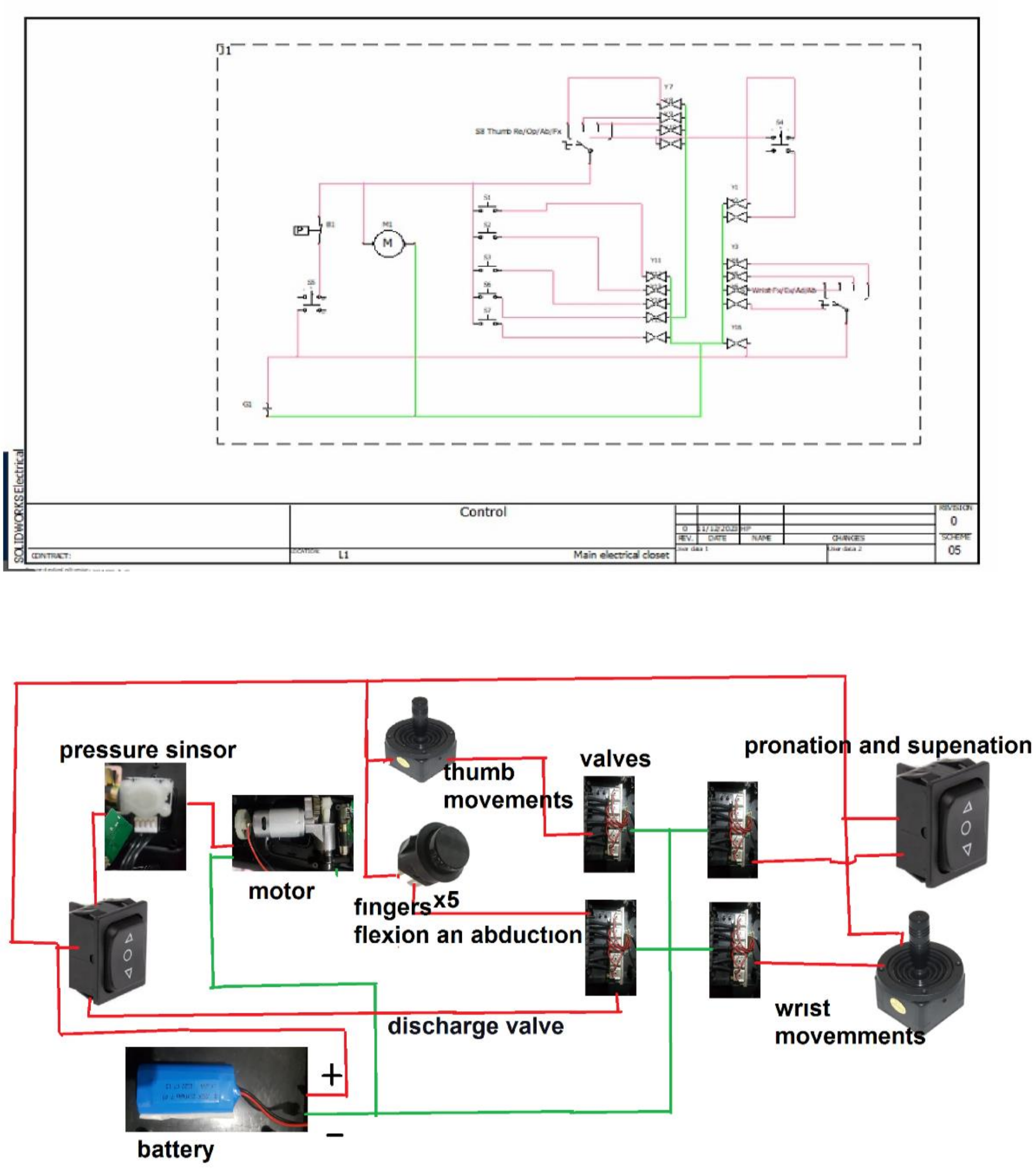


Figure 3.12. The control diagram and electronic components.

3.2. THE MATERIALS AND PARTS MANUFACTURING

3.2.1. The Fingers

The three pieces of the fingers representing the phalanges are silicone, with specific dimensions for each finger (Table 3.1).

As explained in the design section, the **distal phalange** has a semi-circular surface with a flattened shape at its tip that resembles the shape of human fingertips. Its palmar surface at the proximal end is flat, providing more space for holding objects. As for its joint with the proximal phalange (corresponding to the distal joint DIP), it is convex in shape, extending from the sides towards the outside in the middle and inclined from the dorsal side towards the palmar at an angle of 30 degrees with the palmar plane of the hand (the dorsal part is longer than the palmar one).

The middle phalange has a distal end that articulates with the distal phalange in the DIP joint, curving inward from the sides towards the center to accommodate the proximal end of the distal phalange. Its proximal end shares a similar structure to the proximal end of the distal phalange and connects with the proximal phalanx in the IP joint. A rigid plastic tendon canal, 1.5 mm in diameter, traverses the phalange at a depth of 2 mm from the palmar surface. This canal serves as a passage for a flexible tape representing the tendon responsible for bending the fingers, mirroring the tendons in the human hand. Simultaneously, the canal provides support for the phalange.

The proximal phalangeal end articulates with the middle phalange in the IP joint, as in the DIP joint. Like the middle phalange, it contains a canal with the exact specifications and function. In the thumb, this phalanx is cylindrical at its proximal end. It articulates with the palm joint as a ball on the proximal end of the finger that settles in a cavity, similar to Ball and Socket Joints, representing the CMC joint has a hinge joint(see picture). The proximal phalange of the remaining four fingers is fixed inside the fingers' bases.

The finger bases are made from hard plastic and are attached to the dorsal side of the palm by 6 mm stud bolts, enabling the index and pinky finger bases to move within the coordinate plane of the palm and towards the two middle fingers.

Moreover, the bases of the two middle fingers are longer and articulate with the palm over a base (more than 2 mm towards the dorsal side), allowing the bases of the two fingers to return towards the dorsal at an angle not exceeding 4 degrees for the ring finger and 7 degrees for the middle finger. Additionally, the bases of the four fingers have specific shapes; this structure and the previous movements enable the sliding of the fingers' bases over each other, introducing corresponding movement to finger Adduction Abduction in the human hand (Fıg3.13).

Table 3.1. Artificial fingers dimensions.

The finger	Distal end	Middle end	Proximal end	The base
Thumb	33mm	37 mm	70mm	---
İndex	35mm	40mm	37mm	68mm
Middle finger	30mm	40mm	57mm	75mm
Ring finger	33mm	30mm	40mm	75mm
Little finger	27mm	26mm	30mm	60mm

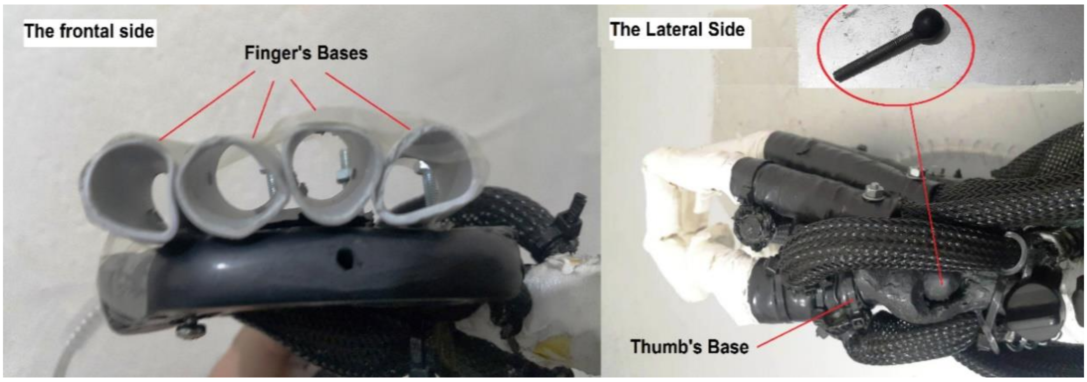


Figure 3.13. The fingers’ bases.

3.2.2. The Palm

Solid plastic has been used as one part with a 17 mm thickness. This model represents the carpal and metacarpus regions, with a proximal end 40 mm wide and connected to the fork of a mechanical joint representing the wrist joint (mechanically classified as a knuckle joint type). This base gradually widens to reach a width of 80 mm in the middle and then decreases in width towards the distal end, which is 40 mm wide.

The palmar surface is primarily flat and contains a groove extending in the middle from the medial to the lateral side, providing space for the opposite muscle of the thumb. Additionally, near the proximal end, there is an increase in thickness on the medial side (helping to confine things towards the fingers). On the lateral side, a spherical cavity receives the proximal end of the thumb.

The dorsal surface is primarily flat, with a 2 mm increase in thickness in the middle and a 30 mm width, representing a platform for the bases of the ring and middle fingers. There are also four 6 mm Stud bolts, illustrating the points that fix the bases of the fingers (Fig 3.14).

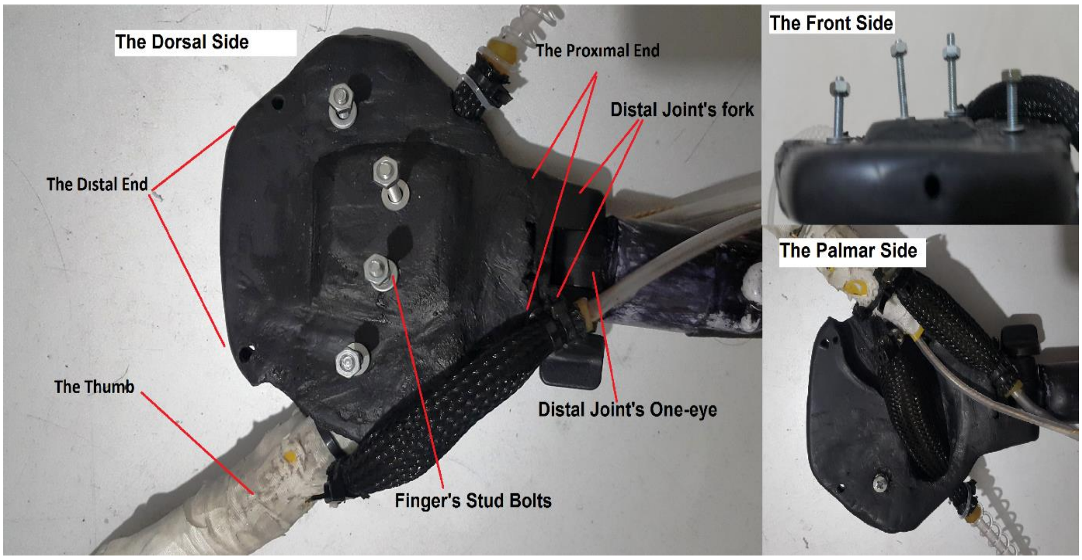


Figure 3.14. The palm.

3.2.3. The Wrist Joint

The wrist is made of two knuckle-type joints made of plastic. The distal joint, at its fork part, is compact with the palm and allows a range of movement of 170 degrees for flexion and extension of the hand.

The fork part of the proximal joint is connected to the distal joint and is on the same straight line but at a perpendicular movement coordinate. It receives the distal end of the forearm shaft, the one-eyed part of the proximal joint made from Teflon. This joint allows limited movement in one direction within a range of 70 degrees, representing the abduction and adduction movement of the hand (Fig 3.15).

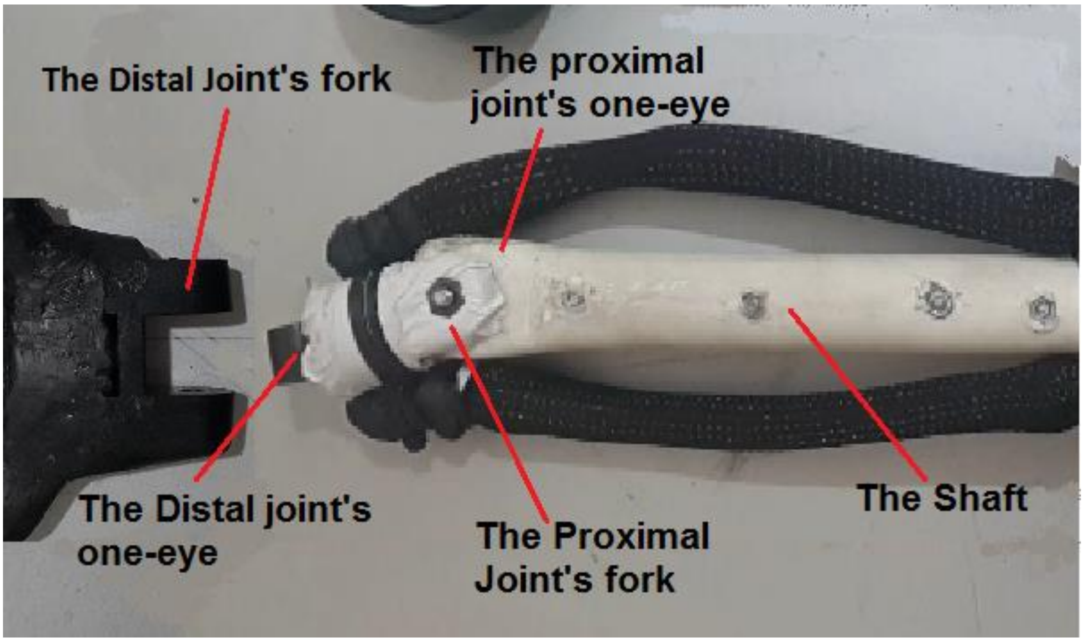


Figure 3.15. The wrist joints.

3.2.4. The Shaft

In this model, as described in the design section, a single cylindrical shape called the forearm shaft has been used instead of the ulna and radius. The shaft is made of Teflon, with a length of 400 mm and a diameter of 22 mm. The distal end of the shaft is thin, representing the one-eye part from the proximal wrist joint, then becomes a cylinder containing flat areas for the sliding platform and the muscles. The proximal end is concave, with a 20 mm hole and a 40 mm depth that receives the rotator part.

3.2.5. The Sliding Platform

The metal platform parts (Fig 3.16) measure (158x13x9) mm and are fixed on the dorsal side, 40mm away from the shaft's distal end. The platform can slide towards the wrist and backward by 42mm and contains a proximal and distal transverse plat.

The distal transverse plate measures (25x8x1.5)mm and is located 25mm from the platform's distal end. It has three attachment points with the wrist ligament using small screws and nuts. This plate has free movement to turn at the same angle as the hand's adduction movement.The proximal transverse plate measures (108x9x8)mm and is 125mm from the platform's distal end. The plate can move within 30 degrees of the platform axes by a particular muscle (tension stabilizing muscle) where the flexor finger muscles are fixed.

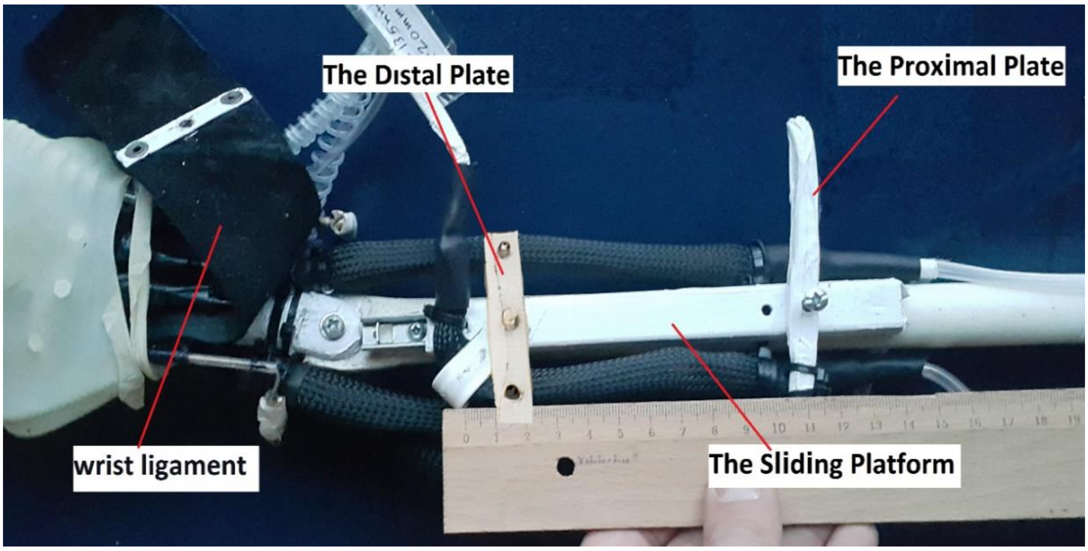


Figure 3.16. The sliding platform

As described earlier, the platform stabilizes the flexor muscles of the fingers, maintaining consistent tension for the muscles' tendons during wrist movements. Without this mechanism, the pinky tendon loses tension during wrist adduction while tension increases at the thumb. Conversely, during wrist abduction. While during wrist extension, all tendon tension decreases, and during flexion, there is high tension in the fingers' tendons, as experimentally observed.

3.2.6. The Rotator

The rotator is constructed of metal, with Rotary Joints at its distal part connecting to its proximal part. The distal end is fixed to the proximal end of the shaft by a 40mm screw, and the rotator's proximal part features a metal structure resembling the fork of the elbow joint. The rotator's capability to rotate 360 degrees, limited by muscles to reduce step response and achieve a more uniform movement, is the pivot for supination and pronation. This mechanism, involving the entire rotation of the forearm, is used instead of the human hand rotation mechanism to prevent muscles from wrapping around each other and thus losing their ability to contract or relax.

3.2.7. The Muscles Manufacturing

According to its design, the muscle consists of an air chamber and an outer shell. The air chamber is a hollow rubber cylinder with high elasticity that can expand widely due to air pressure and has two ends: a closed-end called the head and an end containing the air passage called the tail. The outer shell is a cylindrical mesh made of non-elastic flexible material, such as nylon, Kepler, or other material that the interconnection between its mesh threads, allowing them to slide over each other. This model, made of a nylon net with 0.2 mm thickness, surrounds the air chamber along its length, without interconnection between them except at the ends (Fıg3.17).

The muscle operates by directing air pressure force in a specific direction to change muscle dimensions, pumping the air and causing the chamber to expand. The mesh pulls the threads towards the outside and the two ends towards the middle. The shortens in the muscle length are directly proportional to the air pressure within the mesh's stretchability limits.

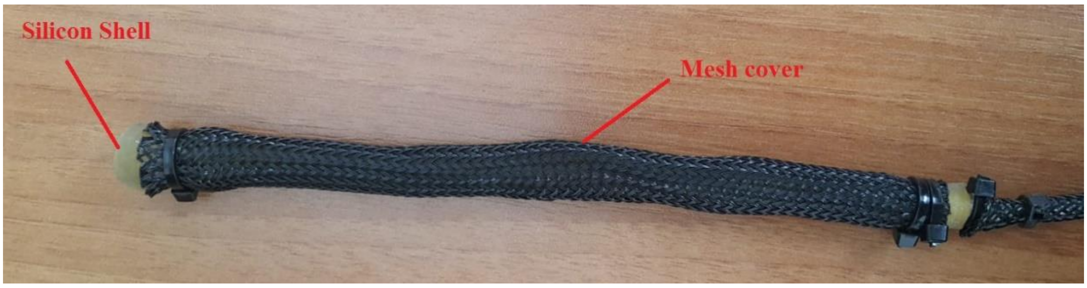


Figure 3.17. The muscle sample.

This arm model consists of 16 muscles of varying sizes. Twelve of these muscles are external and located on the forearm, while the remaining four are internal and situated within the palm. When using the internal or moving muscles, the air hose's size must be considered. Thin and flexible hoses should be utilized as an air passage to ensure greater flexibility and prevent obstruction of the moving part. Each muscle is named based on its specific movement. The muscles included are:

3.2.7.1. Thumb Opposite Muscle

Internal muscle, with a length of 70mm and a radius of 15mm, is located on the palmar side of the hand. It extends from the lateral groove to the medial part in its middle section. The muscle's head is attached to the palmar aspect of the thumb base and advances in the palm groove towards the medial side. The muscle's tail penetrates the lateral edge of the palm, where it is supplied with air measuring 2mm.

This muscle contracts to pull the thumb towards the middle of the palm and its medial side (Fig 3.18).

Figure 3.18. Thumb opposite muscle.

3.2.7.2. Thumb Abduction Muscle

The internal muscle located in the lateral part of the edge between the thumb and the proximal end of the palm has a length of 50 mm. The muscle's head is attached to the border between the dorsal and palmar sides of the thumb base and extends toward the center of the proximal end of the palm. The muscle's tail is fixed at this point and contains the air supply of the muscle with a 2 mm höse (Fıg3.19).

This muscle contracts to raise the thumb, increasing the angle with the coordinate plane of the palm and simultaneously moving the thumb away from the fingers.

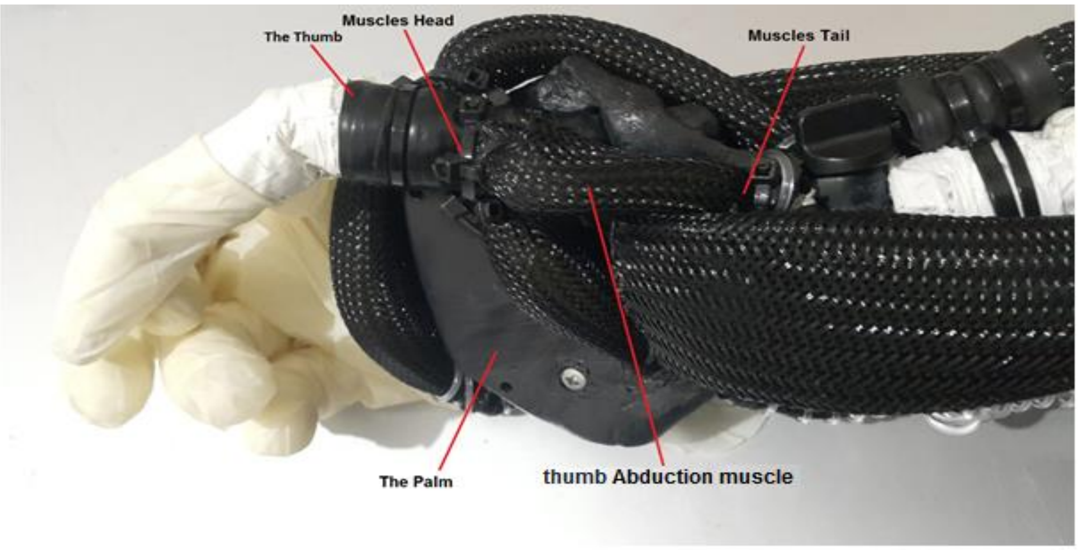


Figure 3.19. Thumb Abduction muscle.

3.2.7.3. Thumb Reposition Muscle

Internal muscle, measuring 95 mm in length, is located dorsally in the lateral region between the thumb and the proximal end of the palm. The head of the muscle attaches perpendicularly to the thumb and is connected to the edge of the dorsolateral side of the thumb base, extending towards the palm end. The tail of the muscle is attached to the dorsal side of the proximal end of the palm, and its air passage is a 2 mm hose. The muscle’s air chamber is made of thinner rubber, allowing it to bend at its head and ensuring that the work of the thumb's opposite muscle is not obstructed.

Contraction of this muscle functions to return the thumb to the coordinate level of the palm and pull it away from the four fingers (Fig 3.20).

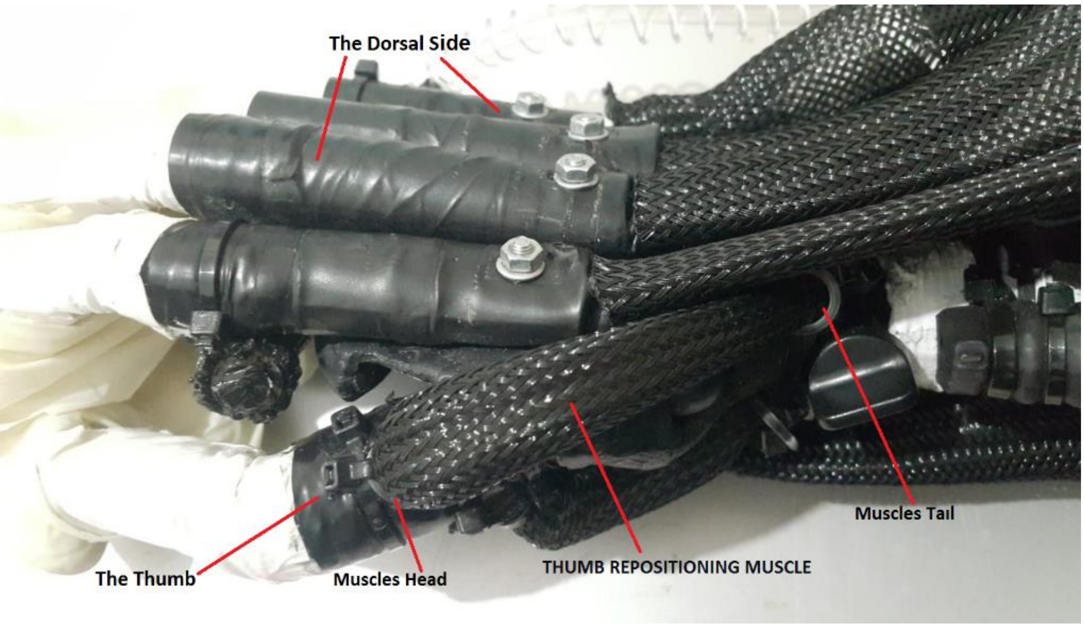


Figure 3.20. Thumb reposition muscle.

3.2.7.4. Fingers Abduction and Adduction Muscle

The internal muscle is located at the distal end of the palm, with a length of 85mm. It extends transversely from the lateral to the medial side of the palm end. İt is attached from its head to the lateral side of the base of the index finger and extends below the middle and ring fingers . Its tail is attached to the palm of the little finger's base, and the muscle has a 2mm air passage on the medial side of the hand.

When contracted, this muscle pulls the index and little fingers towards the other fingers, and the bulging in its middle raises the middle and ring fingers, providing space for the fingers to slide under them. This muscle brings the fingers closer together when flexed, making it easier to pick up small objects. Additionally, muscle contraction helps to tighten the grip while turning the fingers by reducing the space inside the grip (Fig 3.21).

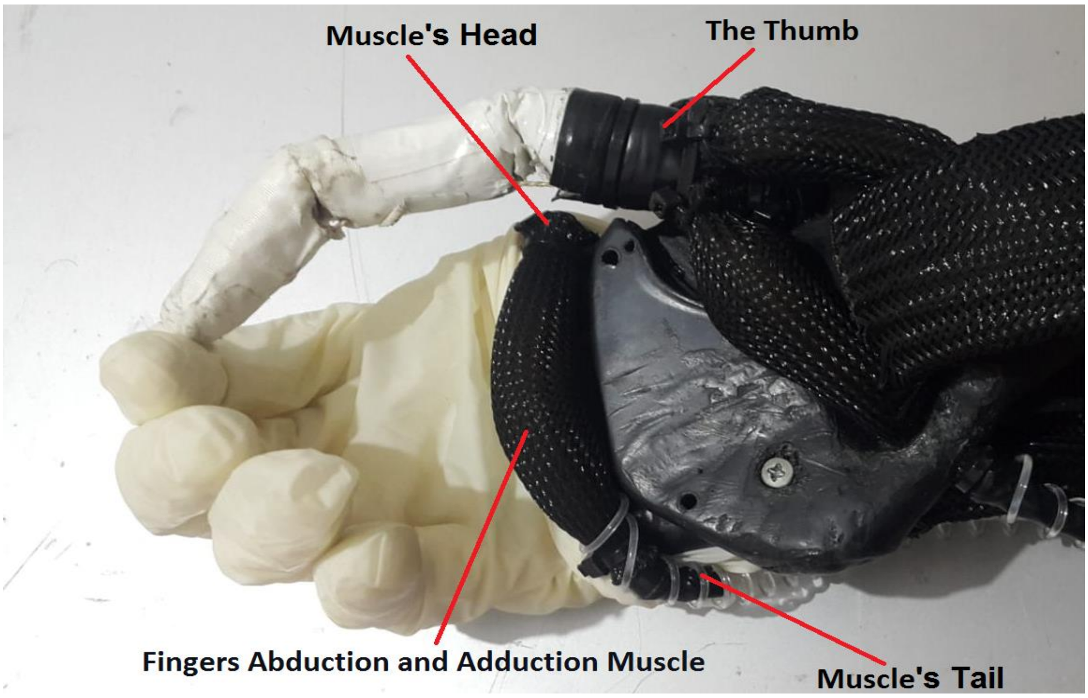


Figure 3.21. Fingers abduction and adduction muscle.

3.2.7.5. Wrist Adduction Muscle

This external muscle is 170 mm long, and its head attaches laterally to the medial side of the wrist's proximal joint. It extends on the medial side of the forearm is fixed at its tail to the forearm shaft at a point 155mm from its distal end. The air passage is a 4mm hose.

Contraction of this muscle pulls the proximal joint towards the medial side, resulting in the adduction movement of the human hand (Fig 3.22).

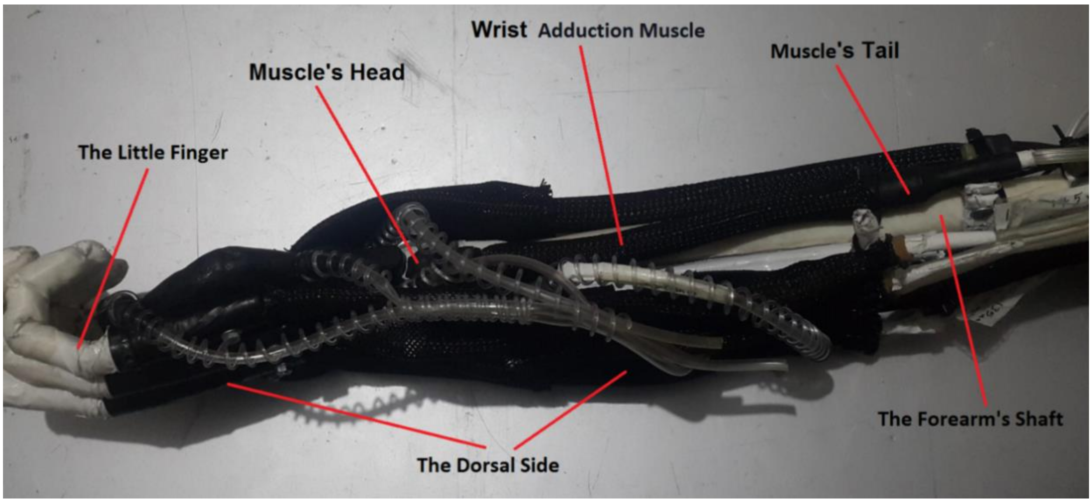


Figure 3.22. Wrist adductor muscle.

3.2.7.6. Wrist Abduction Muscle

This external muscle is 185mm long, attaching from the head to the lateral aspect of the wrist's proximal joint and running laterally along the forearm's shaft. The muscle tail attaches to the shaft 160mm from its distal end and contains a 4 mm air passage (Fig3.23).

This muscle opposes the hand adduction muscle, pulling the hand inside

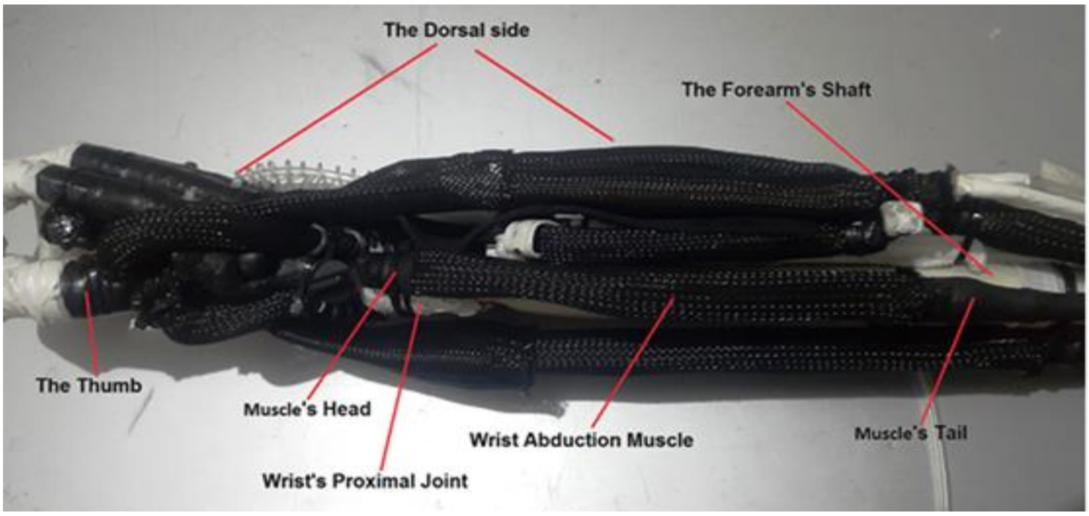


Figure 3.23. Wrist abductor muscle.

3.2.7.7. Wrist Flexor Muscle

This external muscle is 205 mm in length and connected by what appears to be a tendon made of elastic nylon material. This tendon is attached to the palmar side at the proximal end of the palm, extending across the wrist joints to connect to the muscle’s head 5mm from the distal end of the shaft. This tendon provides the necessary flexibility for wrist movements. The muscle extends on the palmar side of the shaft, and the muscle’s tail has a 4 mm hose air passage and is fixed at a distance of 210 mm from the distal end of the shaft (Fig 3.24).

The muscle contraction causes the wrist distal joint to bend towards the shaft palmary due to pulling the hand towards the palmar side of the forearm.

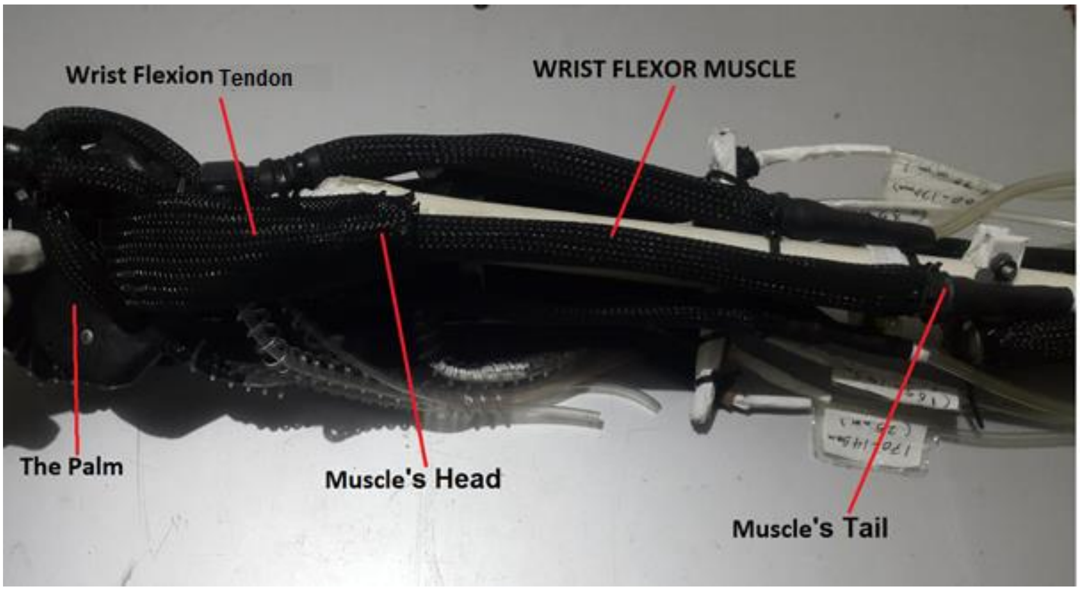


Figure 3.24. Wrist flexor muscle.

3.2.7.8. Wrist Extensor Muscle

This is a muscle with a 160 mm length in the beginning; the sliding platform is attached to the dorsal side of the hand, precisely at the bases of the four fingers, by a flexible strip of nylon material that extends across the wrist joint area to be attached to the distal transverse plate of the sliding platform (Fig 3.25).

The head of this muscle is attached to the proximal end of the sliding platform, and the muscle extends to the end of the forearm to fix it on the forearm shaft, 60 mm from the axis of rotation.

The contraction of this muscle works to pull the platform by 45 mm, which removes the hand from the dorsal side towards the forearm, and thus, the extended movement of the hand can be achieved.

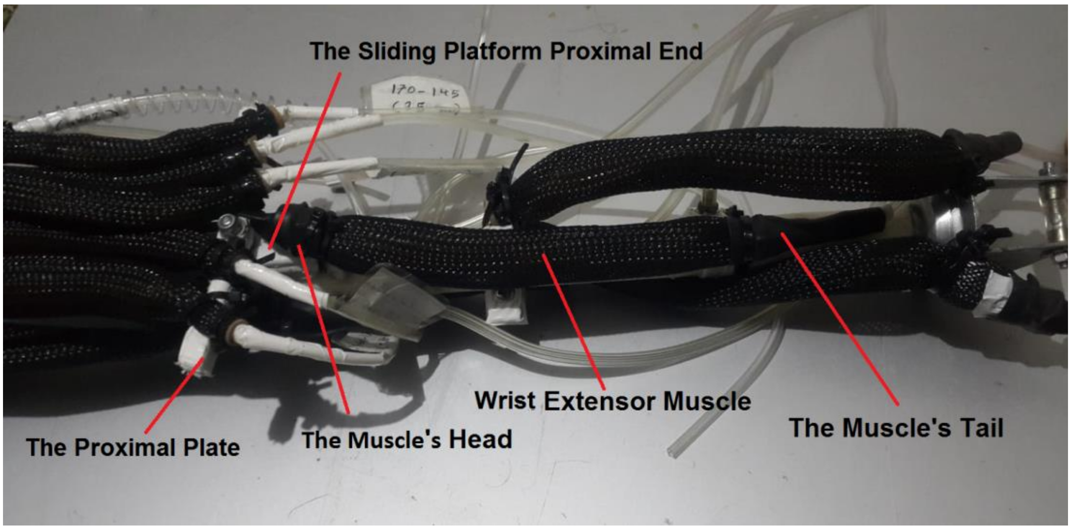


Figure 3.25. Wrist extensor muscle.

3.2.7.9. Fingers Flexors and Extensors

***Extensors*:** The internal joints in the fingers resulting from the meeting of the tips of the phalanges and the interconnection between these phalanges have been done using rubber with a thickness of 2 mm and a width similar to the width of the phalange's ends in each finger. This rubber was fixed on the dorsal side of the phalanges' ends using glue. It was wrapped with a Kepler material and, in the same way, for the corresponding end of the next phalange, maintaining a slight tension in this rubber that works to pull the dorsal side of the phalanx towards the back, thus mimicking the finger's extension. This mechanism ensures that the joints flex sequentially proximal, distal, and distal when pulling the tendon. It is essential for wrapping the finger around objects, as it is difficult to hold objects tightly, and the distal joint is bent before the proximal. This technique reduced the need for muscles for extension, and the interconnection flexibility yielded a more remarkable ability to adapt the fingers to hold objects than if joints with rigid material were used.

Finger tendons: A 2mm wide nylon strip was used in each finger to mimic the function of the finger tendon in the hand. The exception is the thumb, which uses a cylindrical nylon strip with a 0.4mm diameter to maintain movement flexibility. The strip is attached to the distal phalange palmary. It runs through the tendon canal of each finger before crossing over the wrist dorsally to stick the head of the corresponding finger flexor muscle.

Flexor Muscles**:** One muscle for stabilizing tendon tension and five muscles for flexing the fingers have been employed. These muscles have different lengths, with their heads at least positioned 6 mm away from the forearm's proximal end (to keep them away from the joint and not hinder wrist movement flexibility, especially during their contraction). The muscles' tails are fixed on the dorsal side of the sliding platform’s proximal transverse plate in the following order: index, middle finger, thumb, ring finger, and the little finger. This arrangement minimizes the impact of muscle contraction on the wrist joint, directing the force of each muscle to the corresponding finger through ligament linkage. Additionally, each muscle has a 2mm hose for air passage (Fig 3.26).

The tension stabilizing muscle, located on the lateral side of the platform, is linked at its head with the proximal transverse plate and extends distally to be fixed at its tail on the dorsal side of the platform end with a 2mm hose as an air passage. This muscle contracts simultaneously with the hand adduction muscle, enabling the plate (the base of the flexor muscles) to turn at the same angle as the hand adduction movement, thus maintaining constant tension in the muscle tendon.

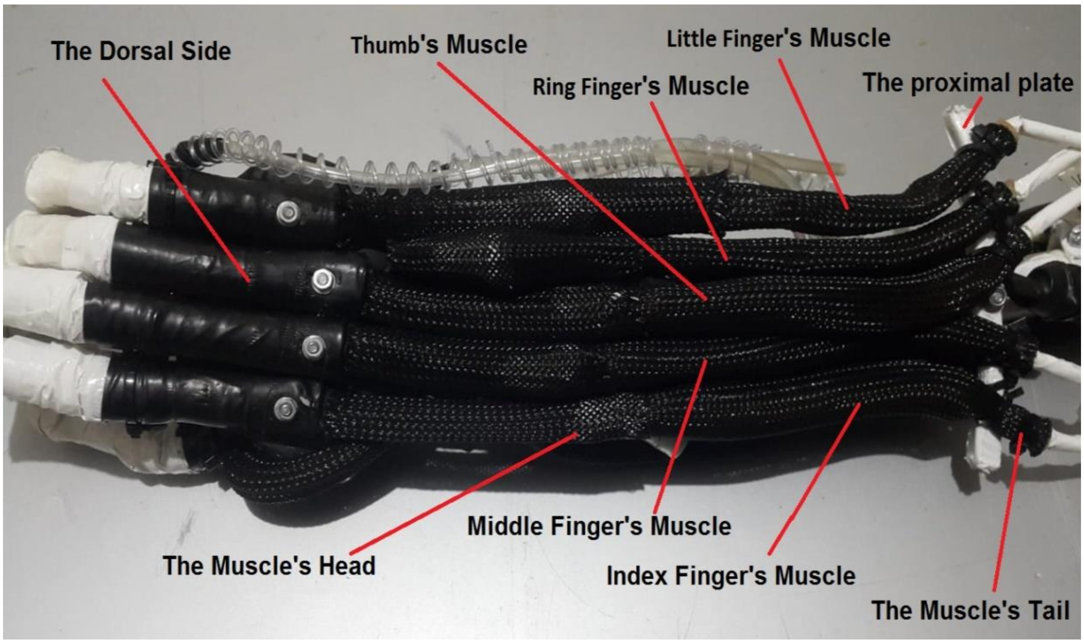


Figure 3.26. Fingers flexor muscles.

3.2.7.10. Rotation Muscles

Two muscles with a radius of 20 mm and a length of 185 mm are situated at the proximal end of the forearm. Each muscle is connected to the palmar side of the shaft and extends on one side, wrapping around to connect to the dorsal side holes of the rotary part from the muscle's tail, and it has a 4mm air passage hose. Contraction of the lateral muscle pulls the palmar part of the shaft, rotating the shaft and causing pronation. Contraction of the medial muscle pulls the palmar side towards its upper side, returning the hand to its position and causing supination.

3.2.8. The Air System of Muscle

The arm comprised 16 muscles that enabled 15 movements under 3 bar air pressure. The parts of the pneumatic system mainly include:

Valves: This part was metallic and robust enough for the high air pressure. Each muscle had its control valve (except for the tension stabilizing and wrist Abductor muscles, which share one valve). There was also a discharge valve, where 16 valves were exploited for muscle movement control. These valves are divided into four groups that share a familiar air passage with the air pump from their supplying port.

Air compressor: This electric motor-operated single-cylinder pump can pump 20 liters of air per minute at a maximum pressure of 10 bar. It is also mounted on a platform with rubber supports to minimize vibration and sound during operation. (Fig3.27).

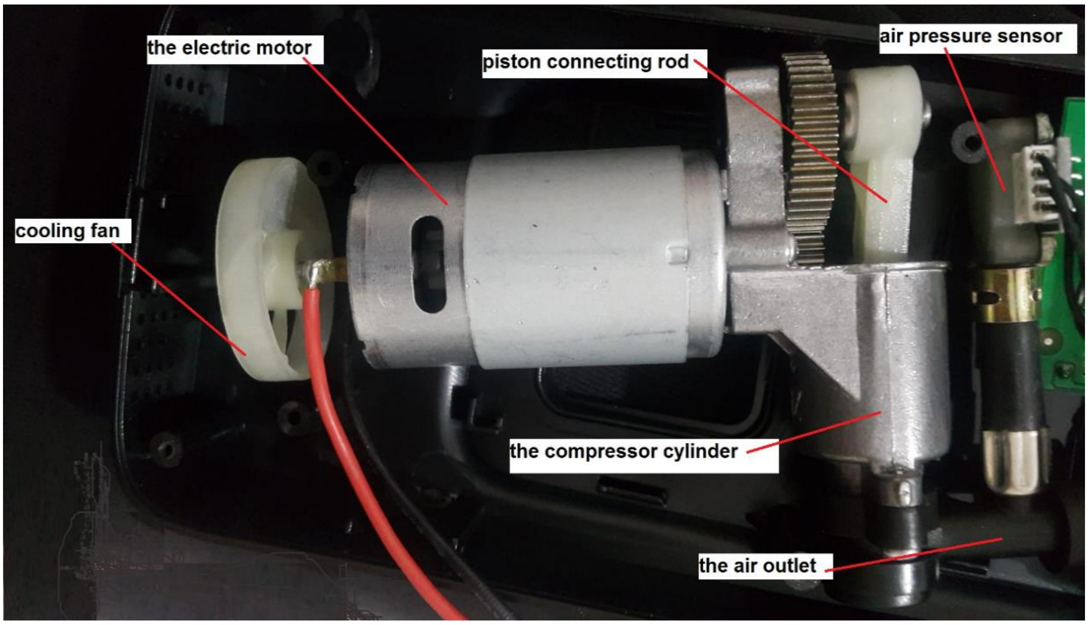


Figure 3.27. Air compressor.

Hoses: They were silicone, connected to the control valves, and extended in a bundled form with straps to attach to the user's arm and click to the muscles. It is important to note that these hoses are longitudinally ribbed with a 5 mm diameter. However, the ones connected to the hand muscles become narrower and more flexible, essential to maintaining hand movement flexibility (Fig 3.29). All the air system components were placed in a plastic box (260x220x80 mm).

3.2.9. Electronic Components and Control System

As the design section explains, the electrical circuit comprises a power source, an electric motor for pump operation, valves, and a control circuit.

The power source is a 2000 mAh rechargeable battery with a 7.4 voltage and two ports. One port powers the air pump motor, which runs on direct current, and the other supplies energy to the valves and control circuit. The valves are usually closed, with a 2-ohm internal resistance, and operate at 5 volts.

The Control Stick was used to make control more accessible and to prevent conflicting commands for opposite movements. The thumb has a control stick to execute its four movements, and the wrist muscles share a control stick.

The Buttons are five single-type bush buttons for bending and adducting the four fingers and a double-type button for operating the pump and opening the discharge valve (fig 3.28).

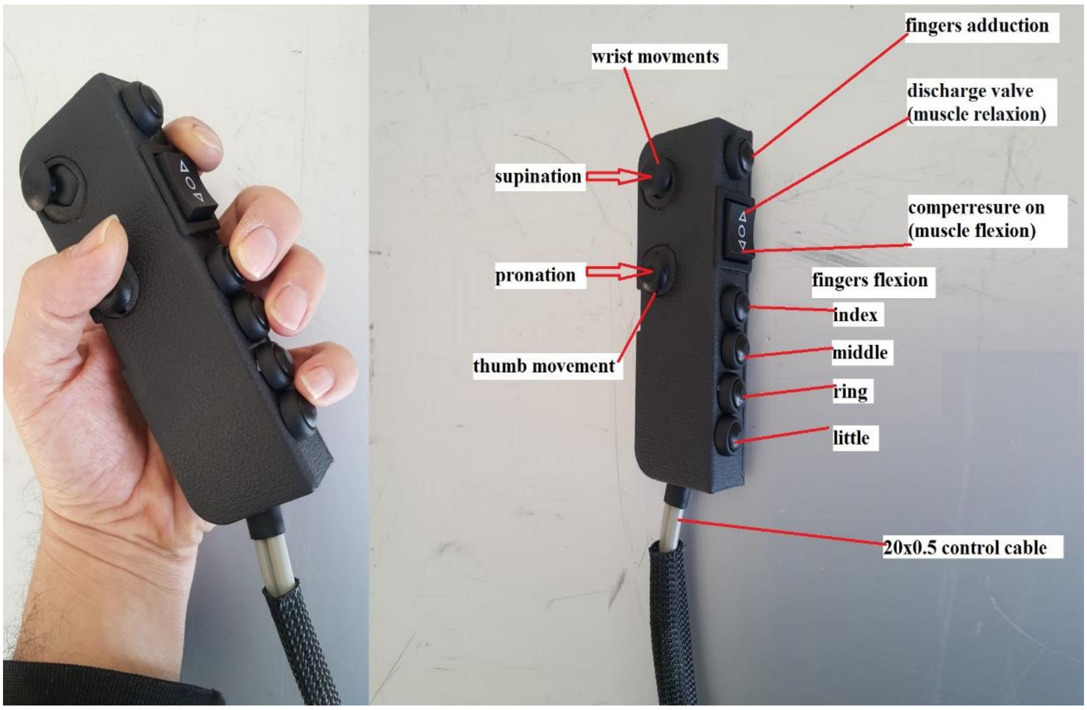


Figure 3.28. The control joystick.

The pump shut-off circuit deactivates when the finger is lifted from the start button. Additionally, an automatic shut-off circuit protects the muscles from excessive pressure, which is facilitated by a pressure sensor adjustable through an electronic circuit, and it has been set at 3 bar. The sensor interrupts the electrical signal, halting the air pump when the necessary pressure is reached. Additionally, a display screen shows the air pressure value (Fig 3.29).

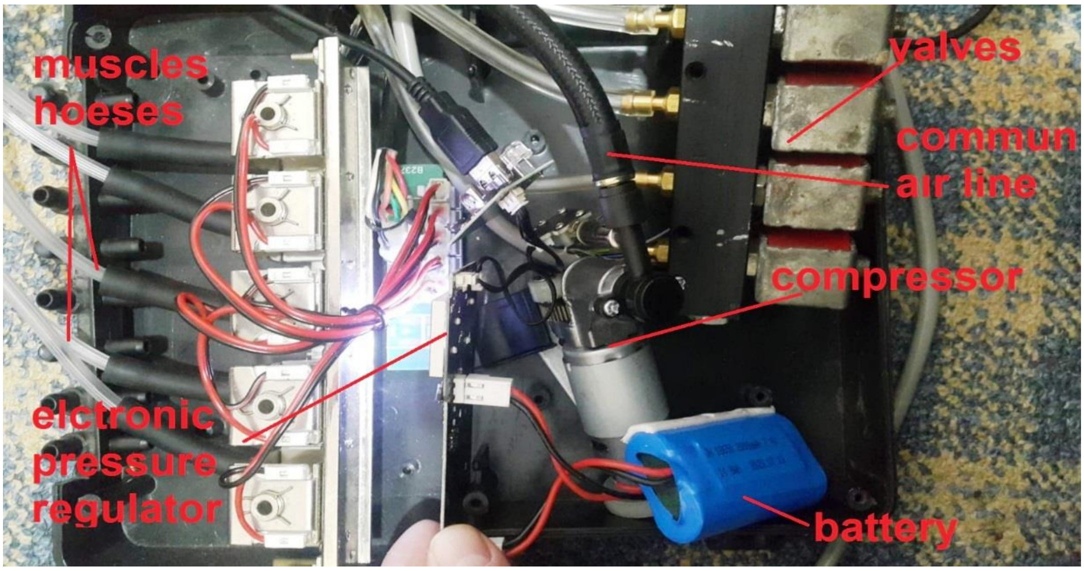


Figure 3.29. The air system.

CHAPTER 4

RESULT AND DISCUSSION

4.1. PNEUMATIC MUSCLE SELECTION:

In muscle design, various parameters, such as shortening and expansion rate, were considered based on testing and observation. In this study, we designed and fabricated three different muscles and examined their performance. For all the tests, we exploited the exact size of the silicon shell (outer diameter of 8.5mm and wall thickness of 2mm).

4.1.1. Length Changing Test

We tested the three types under the same pressure (3 bar), where the length change is an essential function in artificial muscles (Fig 4.1). It should be noted that the muscles were not under any load in this test.

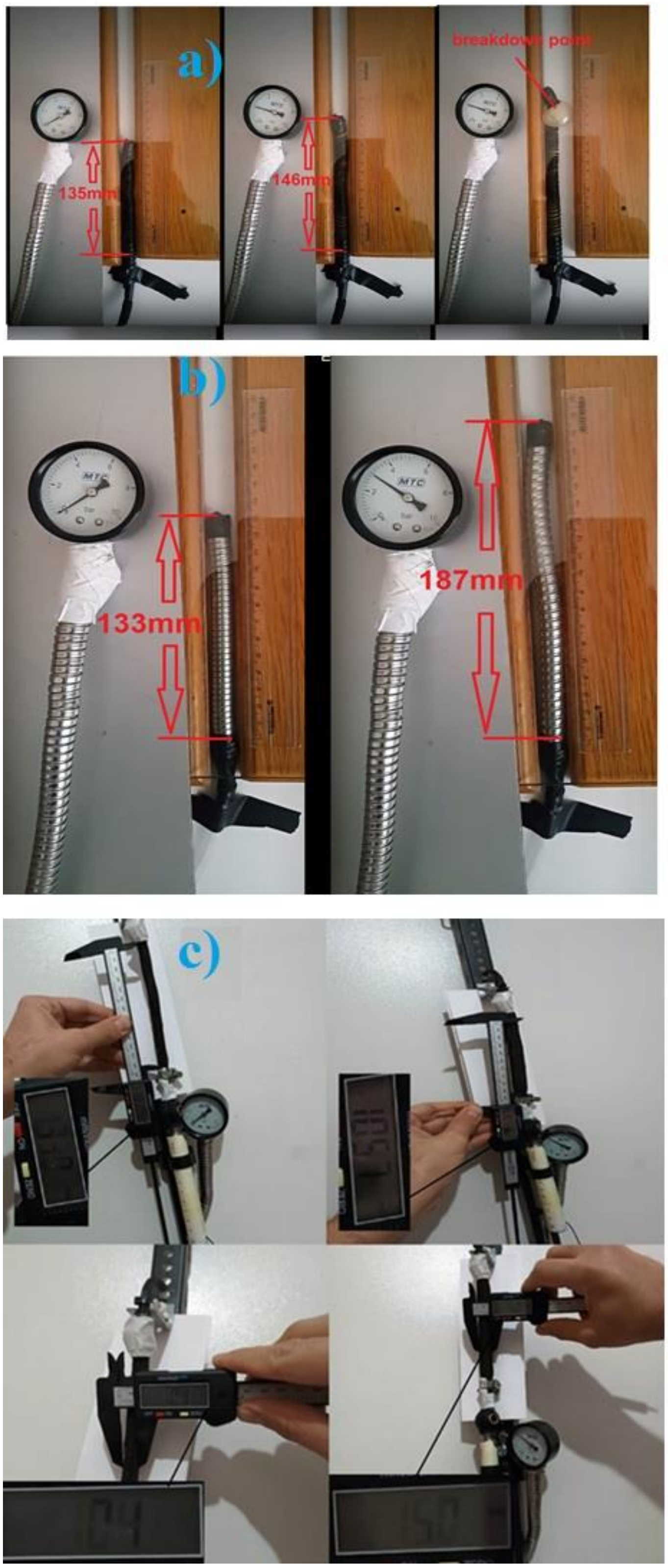


Figure 4.1. Muscle with different covers: a) nylon spiral, b) metallic spiral, and c) polyester mesh cover.

As shown in Fig 4.1, all three types of muscles showed length change under air pressure. The muscles with spiral cover showed lengthening whereas the muscles model with polyester cover expired shortening. This test showed us the muscles with spiral covers were not suitable for mimicking human muscle contractions. Moreover, they needed a guide to yield length change. Furthermore, they needed a guide to deliver length change. Also, the model with a nylon cover was damaged after the air pressure passed 2 bars. Therefore, it can be concluded from this test results that the model with a mesh cover can be selected for a prosthetic hand in which the movement can be achieved with muscle contractions. We continued testing the muscle with a mesh cover to understand its potential application for the prosthetic hand.

4.1.2. Mass Pulling Test

In human muscles, one parameter that determines their job-doing ability is the magnitude of muscle force application. Therefore, we tested the selected muscle to handle a mass under 3 bars of air pressure (Fig 4.2).

Figure 4.2. Mass pulling test.

As seen in Fig 4.2, the muscle produced a force that can keep 5305 gr of mass. Als0, fig 4.3 shows the muscle mass pulling magnitudes under different pressures. The muscle started to respond and produced mass-pulling signs after a pressure of 0.7 bar. This phenomenon indicates that the muscle needs a minimum pressure to be inflated enough to touch with the cover layer mesh.

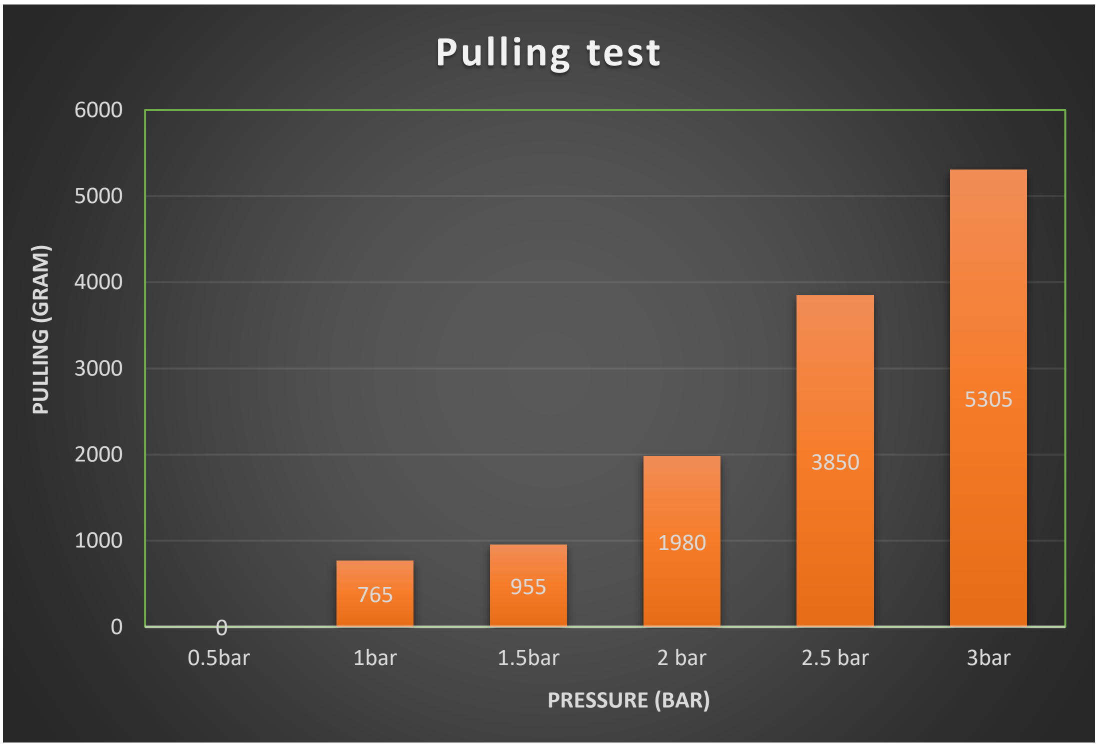


Figure 4.3. Pulling ability test results.

The muscles started to pull the mass after the pressure reached 1 bar. Therefore, the movement threshold can be considered 1 bar for the forearm (Fig 4.3).

4.1.3. Mass Lifting Test

In the human body, the movement of limbs is mainly controlled by the muscle length change when applying an exact magnitude of load. So, we probed the muscle contraction during different mass lifting (fig 4.4).

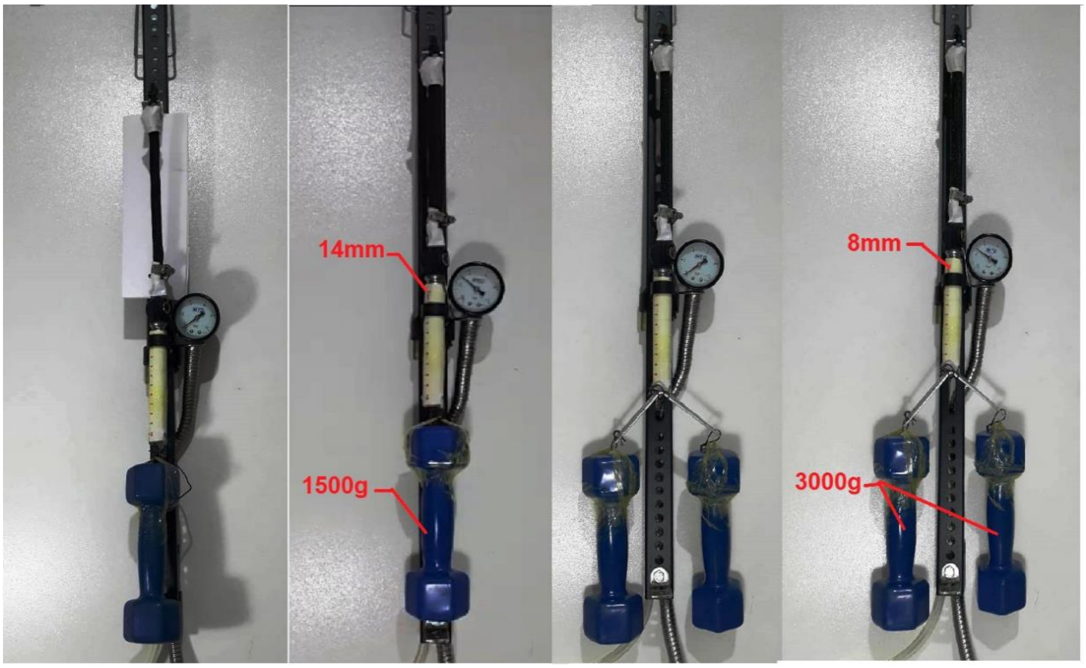


Figure 4.4. Lifting test.

As expected, an increasing mass limited the contractions of the muscles. Also, we need to understand the effect of pressure on muscle contractions. We tested the muscle for two different magnitudes of mass under air pressure from 1 to 3 bars (Fig 4.5). The contractions of the muscles started after the presser reached 1.5 bar.

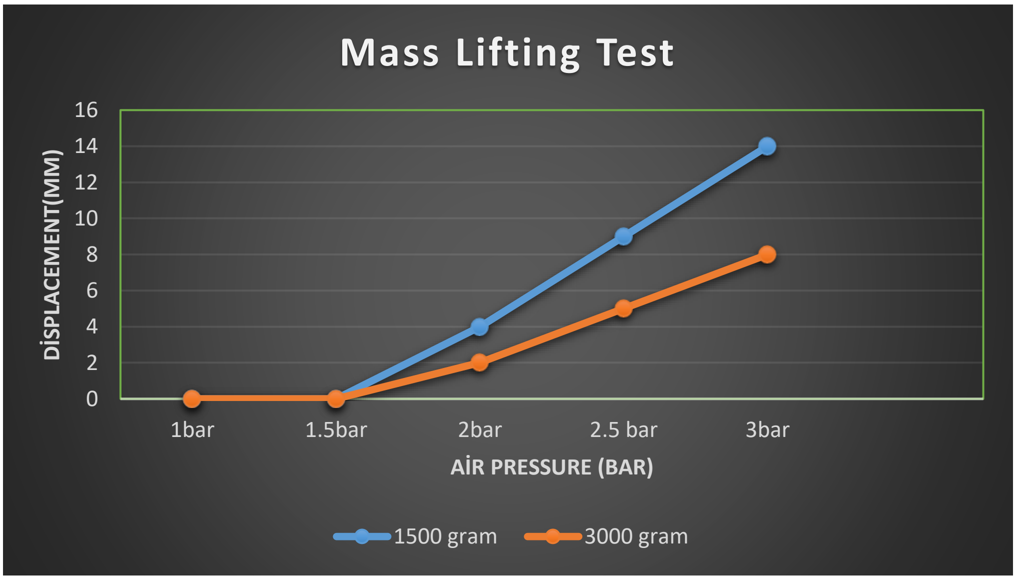


Figure 4.5. Lifting test results for different pressures.

4.1.4. Time Response Test

Figure 4.6. Muscle’s time response test.

In human movement, reflection time is essential for appropriately responding to environmental stimulation produced by the brain to the muscle system. Therefore, in this section, the muscle speed was determined (Fig 4.6).

The Table 4.1 illustrates the muscle speed and contraction magnitudes under different pressures.

Table 4.1. Muscle speed and contraction magnitudes under different pressures.

pressure(bar)	Pulling (gr)	mass lifting displacement (mm) for 1500 gr	mass lifting displacement (mm) for 3000 gr	Time response (s)
0.5	0000	0	0	0.49
1	765	0	0	0.59
1.5	955	0	0	0.63
2	1980	4	2	1.09
2.5	3850	9	5	1.57
3	5305	14	8	2.21

4.2. THE BIOMECHANICS OF THE ARM MOVEMENTS

In this study, we tested 15 different movements of the prosthetic hand.

4.2.1. Wrist Abduction

The wrist muscles are usually relaxed, causing the proximal wrist joint to be at a 10-degree angle with the arm axis. However, the joint angle is reduced to zero when the abduction muscles contract from 180 to 170 mm at 3-bar pressure. This slight movement plays a crucial role in stabilizing the wrist when carrying objects and performing other arm movements (Fig 4.7).

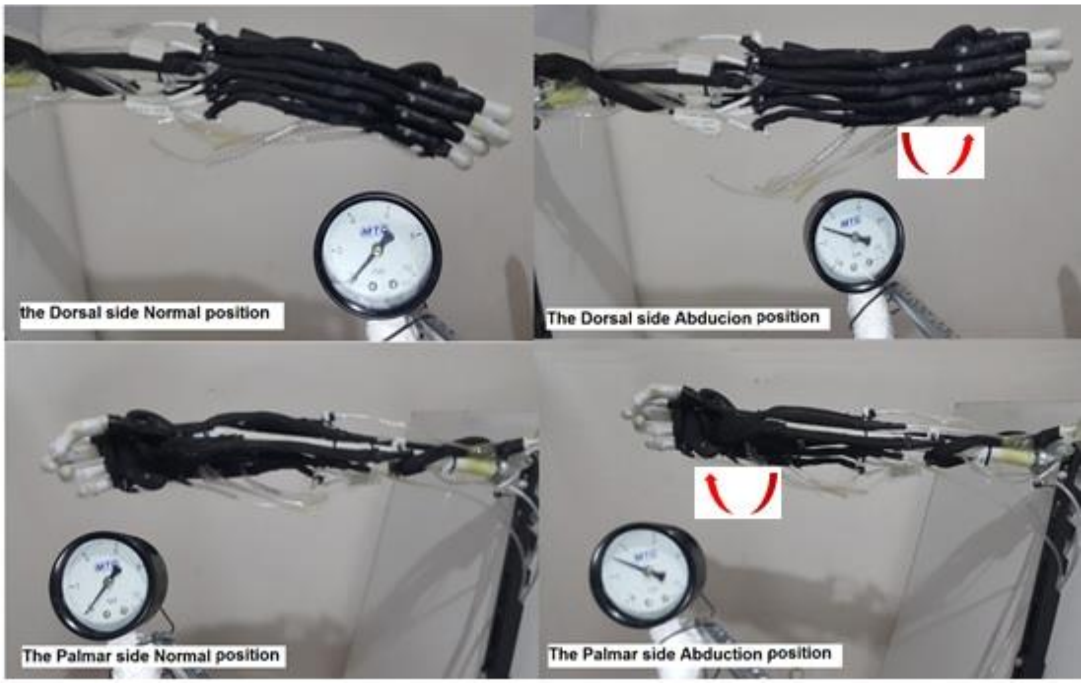


Figure 4.7. Wrist abduction movement.

4.2.2. Wrist Adduction

The movement involves bending the proximal joint in the wrist to bring the side of the little finger horizontally towards the arm shaft by contracting the adductor muscle. It was experimentally found that with a pressure of 3 bar, the muscle contracts from 180 mm to 150 mm, resulting in the hand position at an angle of 34.6 degrees with the axis of the arm. See the figure below (Fig 4.8).

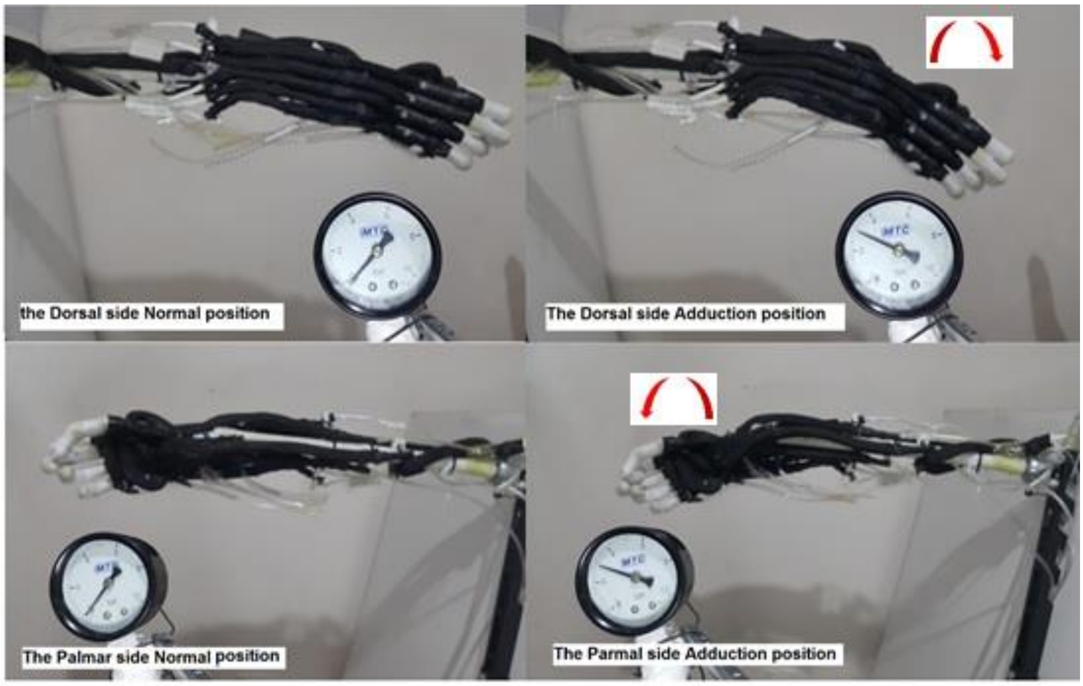


Figure 4.8. Wrist adduction movement.

4.2.3. Wrist Flexion

The hand bends downwards at the wrist joint, produced by wrist flexor muscle contracting and shortening from 205 mm to 170 mm. This results in the hand being at a 39-degree angle with the arm axis (Fig 4.9).

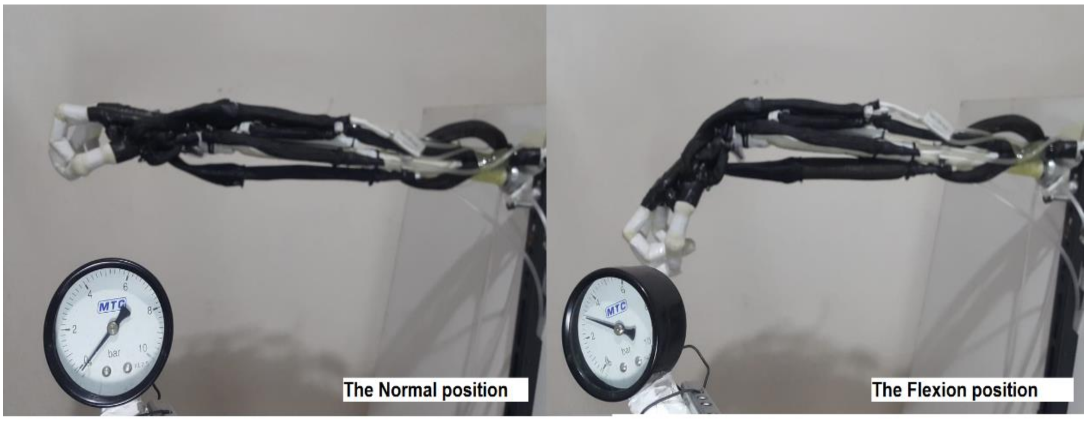


Figure 4.9. Wrist flexion movement.

4.2.4. Wrist Extension

The distal joint in the wrist is bent upward during wrist extension, which is the opposite movement of wrist flexion. This movement is achieved by the contraction of the wrist extension muscle, causing a change in length from 160 mm to 138 mm and positioning the hand at an 18-degree angle with the axis of the arm (dorsal side) under a pressure of 3 bar (Fig 4.10).

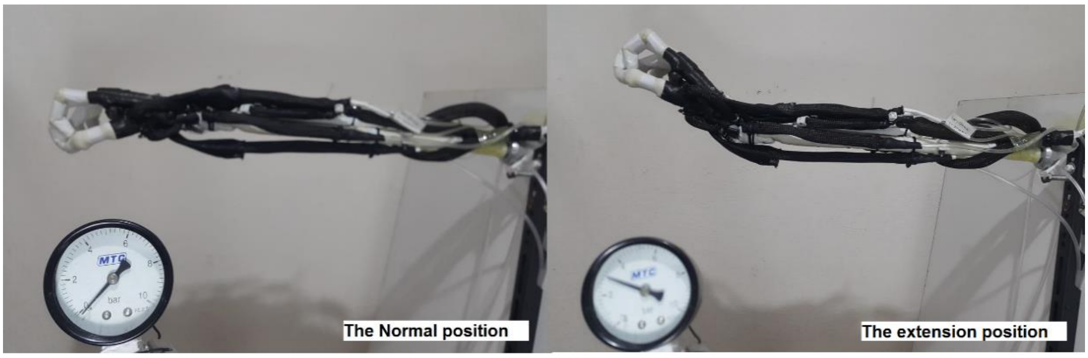


Figure 4.10. Wrist extension movement.

4.2.5. Fingers Flexion

The interphalangeal joints are responsible for finger flexion, with each finger possessing a unique muscle and contraction ratio (refer to table). These muscles are situated in the dorsal part of the arm, causing the wrist to move when contracted. Therefore, wrist stabilization is crucial for concentrating muscle force to bend the fingers.

The wrist can be stabilized by contracting the muscles to achieve the desired position. In various wrist positions, a constant tension force is exerted on the fingers' tendons by adjusting the muscle stabilization base's position (sliding platform movement) and angle (transverse plate angle) with the aid of the tension stabilization muscle, which works in conjunction with the wrist adduction muscle. Please refer to the image for further clarification (Fig 4.11).

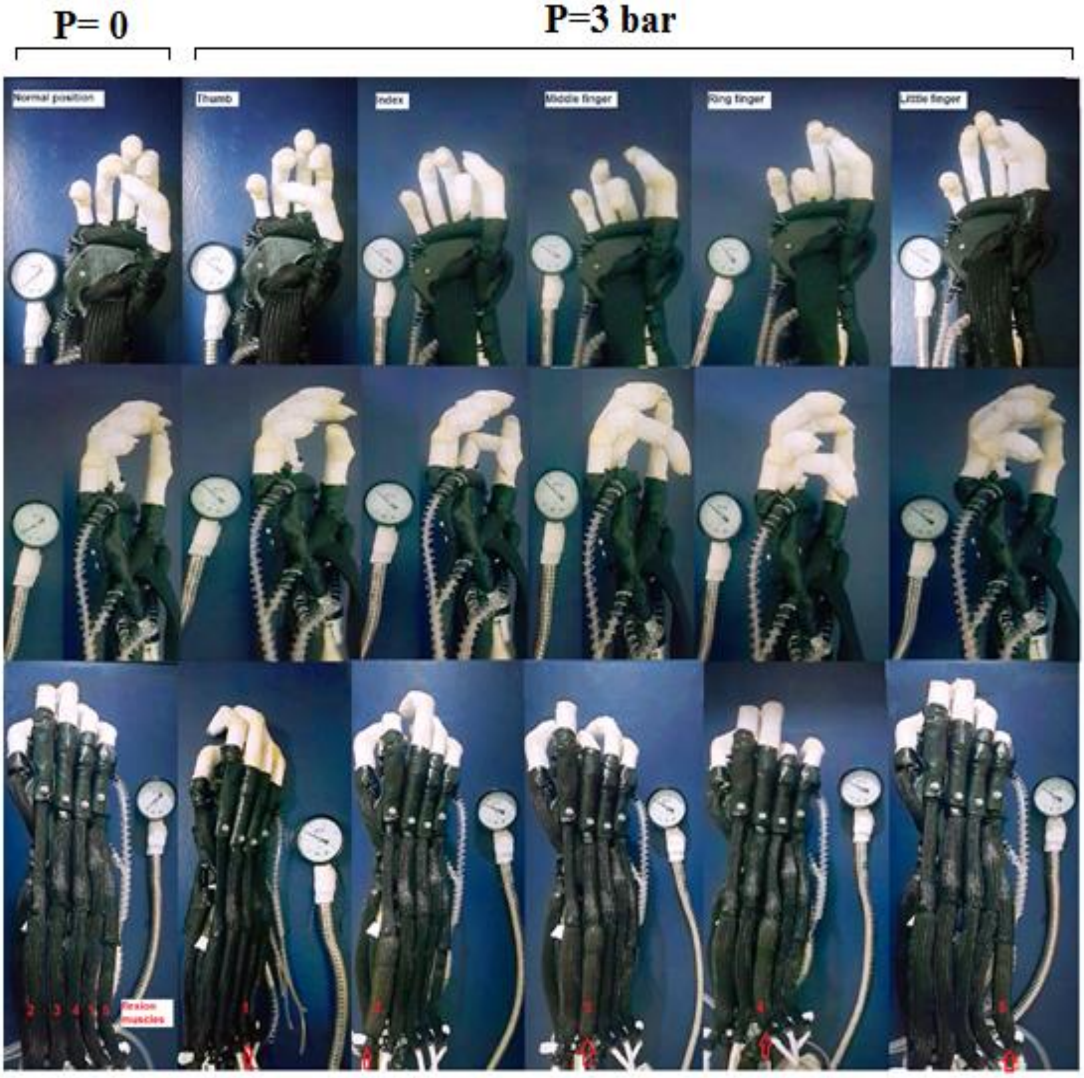


Figure 4.11. Fingers flexion movement and their related muscles.

Table 4.2 illustrates the muscle length change during finger flexion movement.

Table 4-2 Fingers’ flexion muscles length change.

The finger’s muscle	The normal length	Flexion length	Length change ratio
Thumb	175mm	145mm	17.14%
Index	160mm	130mm	18.75%
Middle finger	170mm	135mm	20.58%
Ring finger	168mm	140mm	16.66%
Little finger	170mm	145mm	14.71%

4.2.6. Abduction and Adduction of the Four Fingers

In the normal state,the distance between the base of the index finger and the little finger is 80mm.When the fingers adduction muscle contracts, the distance is reduced to 50 mm, resulting in an approximate reduction of 30 mm, and the middle and ring finger bases rise by 3 mm, causing the finger bases to slide toward each other. This action may help pick up objects and expand the muscles during contraction to reduce the internal space of the fingers during flexion, providing a tighter grip (Fig 4.12).

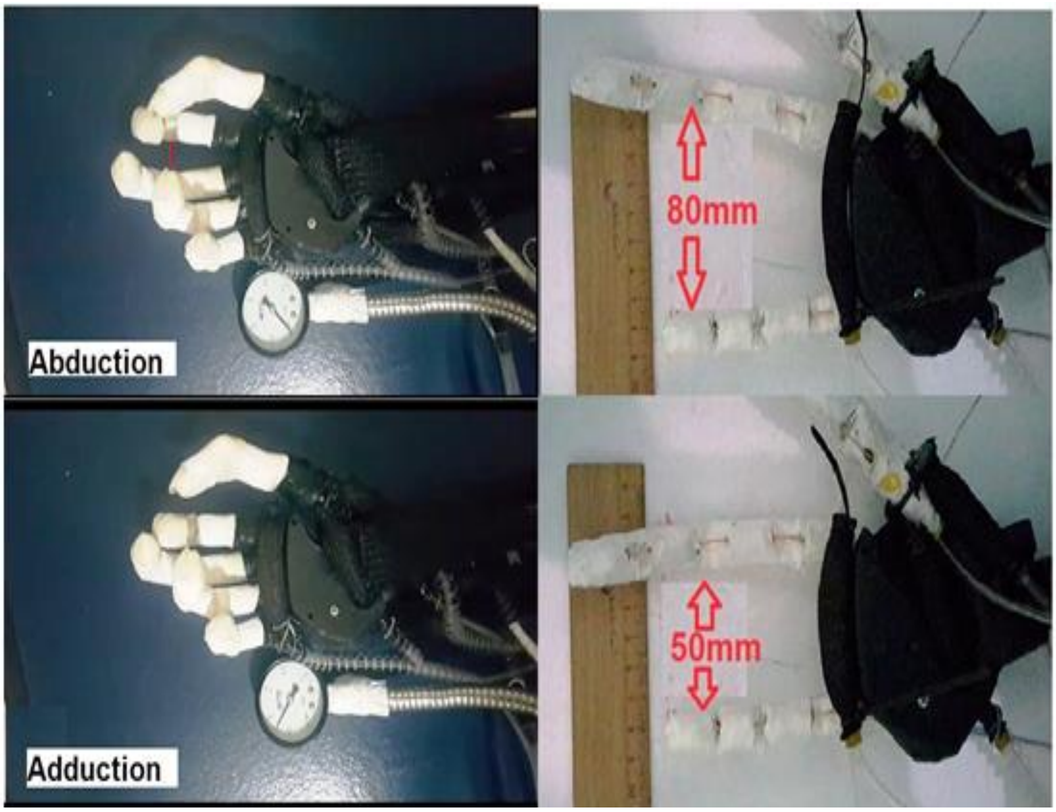


Figure 4.12. Fingers abduction and adduction.

4.2.7. Thumb Movements

In addition to the flexion movement, the thumb has three muscles connected to its base that enable three additional movements:

4.2.7.1. Thumb Opposition

This movment pulls the thumb toward the inner and medial side of the palm by contracting its opposing muscle, from 70 mm to 63 mm, at a pressure of 3 bar. This movement brings the thumb closer to the fingers, crucial for enhancing grip when holding objects (Fig 4.13).

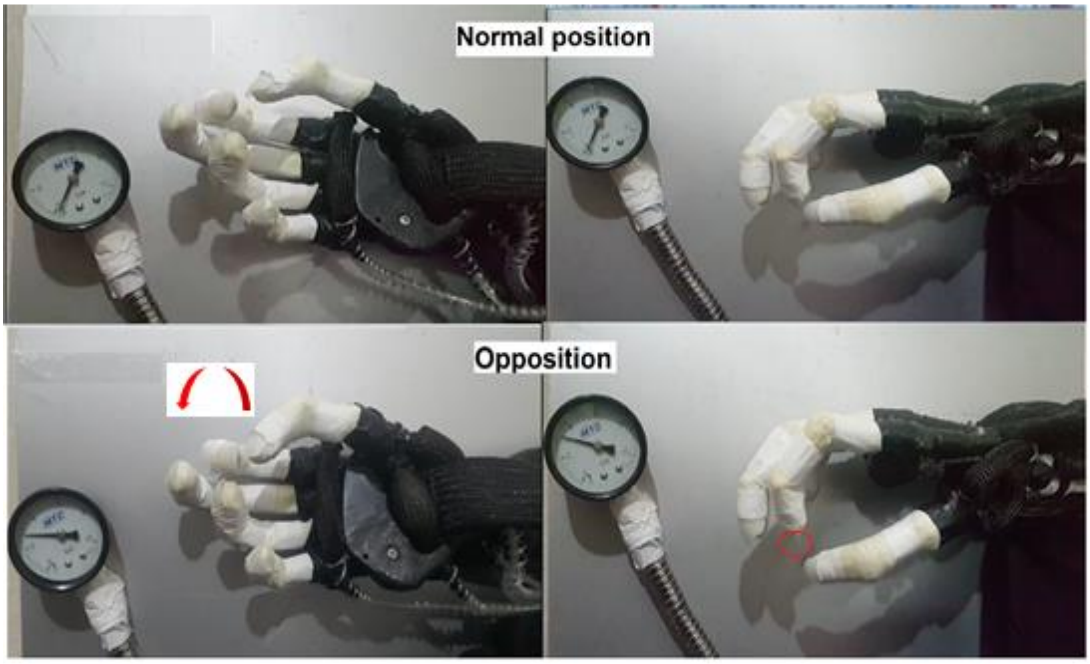


Figure 4.13. Thumb opposition movement.

4.2.7.2. Thumb Repositioning

It involves pulling the base of the thumb towards the dorsal side of the proximal end of the hand, aligning it with the same coordinate plane as the hand. This is achieved by contracting the thumb reposition muscle, reducing its length from 95 mm to 76 mm at 3.4 bar air pressure. This action decreases the distance between the thumb and the palm, enhancing the grip strength. Please refer to the figure for visual aid (Fig 4.14).

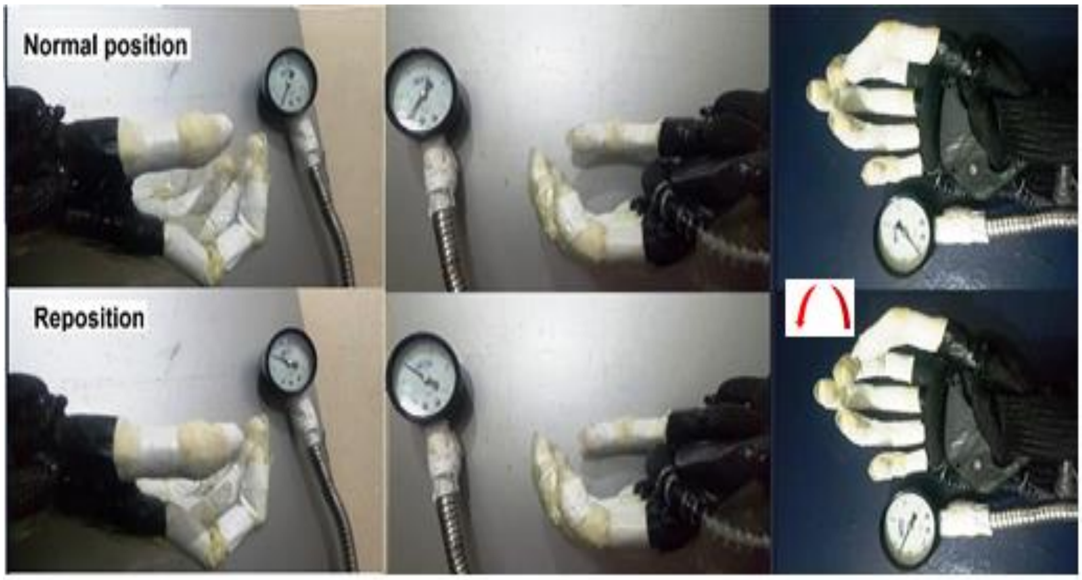


Figure 4.14. Thumb reposition movement

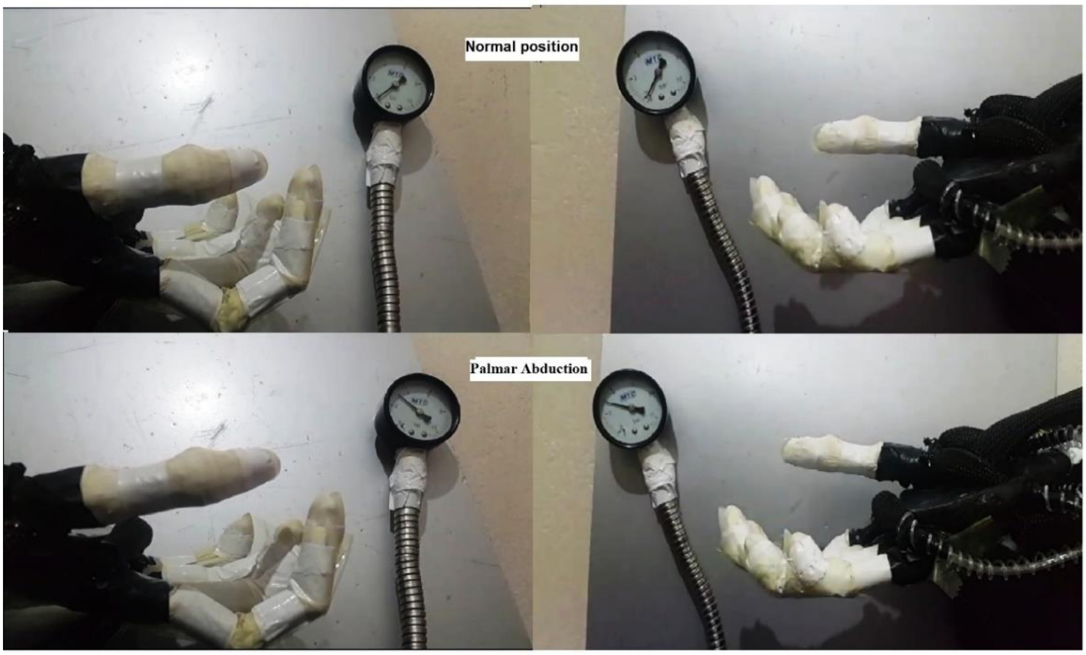


Figure 4.15. Thumb palmar abduction movement.

4.2.7.3. Palmar Abduction

It involves pulling the base of the thumb towards the wrist from its palmar side and moving the thumb away from the index finger. This movement is caused by the contraction of the thumb Abduction muscle, reducing its length from 60 mm to 56 mm at a pressure of 3 bar. This action allows the thumb to create a larger space for picking up objects (Fig 4.15).

4.2.8. Arm Pronation and Supination

The arm undergoes a two-direction rotational movement, with the palm generally positioned at a 58-degree angle to the horizon. During pronation, the pronation muscle contracts from 185 to 155 mm at a pressure of 3 bar, causing the palm to face downwards at a 10-degree angle to the horizon. In contrast, during supination, the supination muscle contracts using the exact mechanism as pronation but in the opposite direction, resulting in the palm rotating upwards to a 140-degree angle with the horizon (Fig 4.16-17).

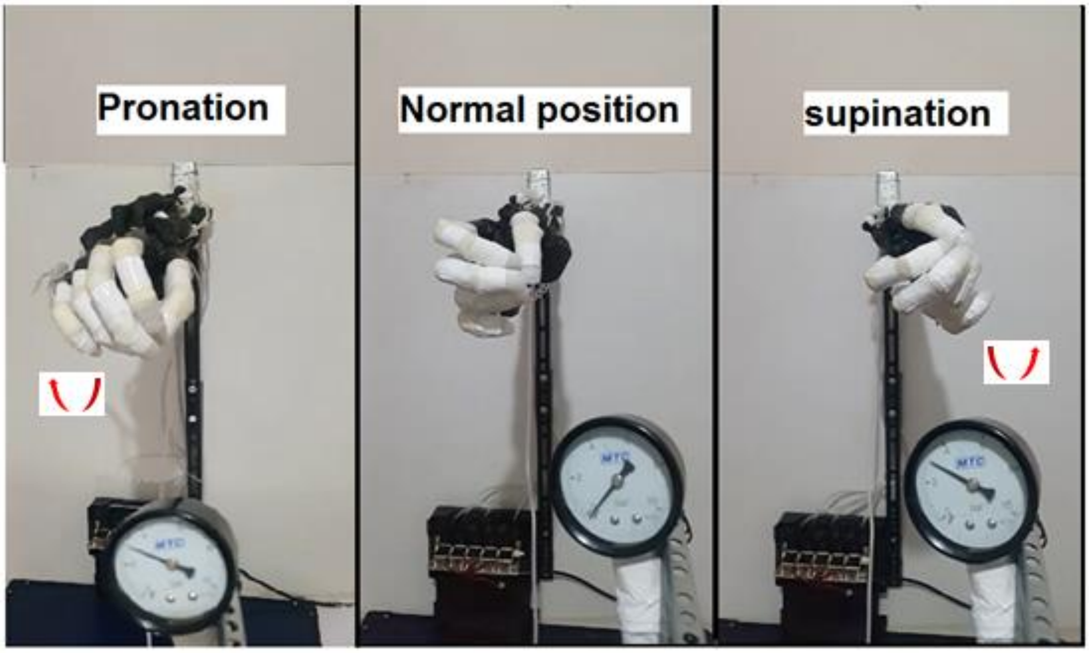


Figure 4.16. Pronation and supination frontal view.

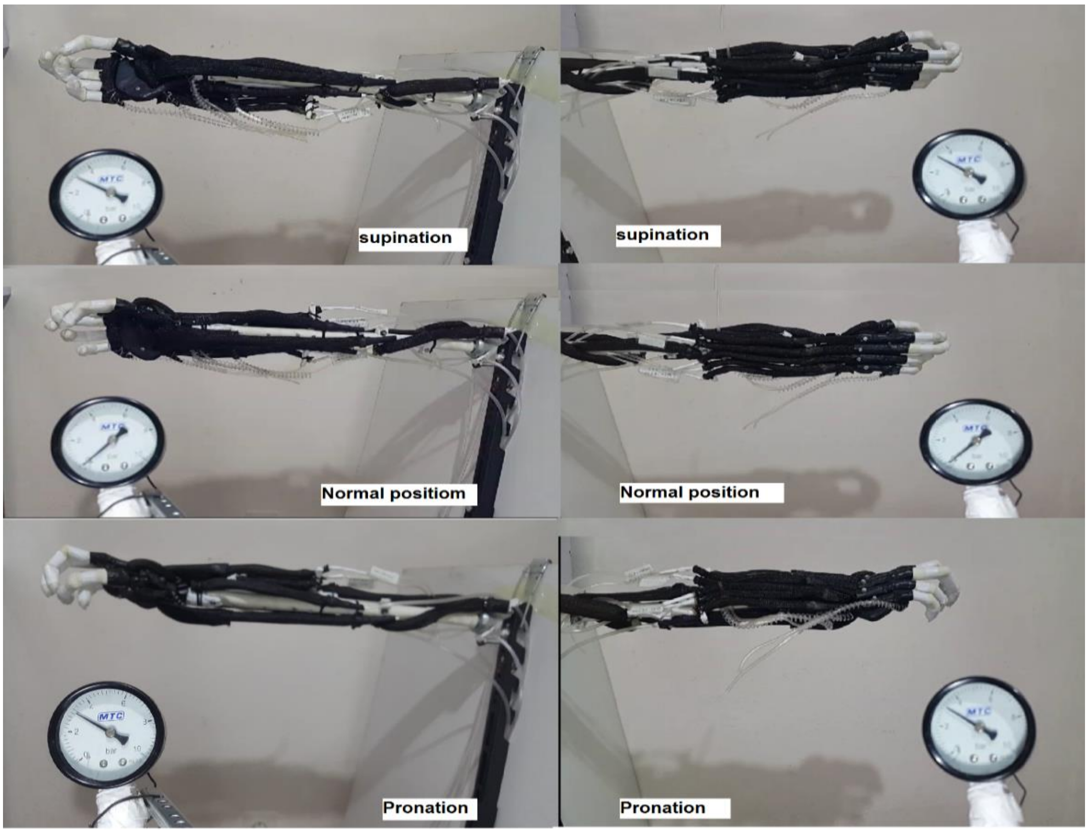


Figure 4.17. Pronation and supination sides view.

4.3. THE GRIP

The human hand, grip involves a combination of delicate and forceful physical movements, with the position of the fingers determined by the size and shape of the object.

In this model, stabilization of the wrist through muscle contraction is necessary for the correct functioning of the finger flexor muscles. Accuracy depends on the user's skill, aided by the model's flexible, adaptive fingers.

The force of the hand, which is controlled by force control, comes from the flexible flexors of the finger, which depends on air regulation by timing valve pressure. In addition, adding the finger adduction and thumb repositioning muscles can reduce the internal volume of the area between the fingers and the palm and thus increase grip strength (full grip). See the figure below.

4.3.1. Grip Shape

The distance between the thumb and index finger at their medial level is 47 mm, and the internal shape of the fist was made using a paper cylinder and a transparent nylon cylinder to illustrate the pressure areas of the fingers and the effect of the auxiliary muscles (full grip (Fig 4.18)).

Figure 4.18. Gripping shape.

4.3.2. Grip Tests

The primary function of the human hand is to pick up and hold objects. We tested the hand's ability to hold objects of different dimensions and shapes, simulating various situations such as:

4.3.2.1. Cylindrical grasp

The preceding passage (4.3.1) simulates grasping a cylindrical object with a 40 mm diameter. A cylinder with a 14 mm diameter was also tested but proved too small for the hand to grip (see Figure 4.19). A range of 20 to 65 mm was determined to suit the hand's model capabilities.

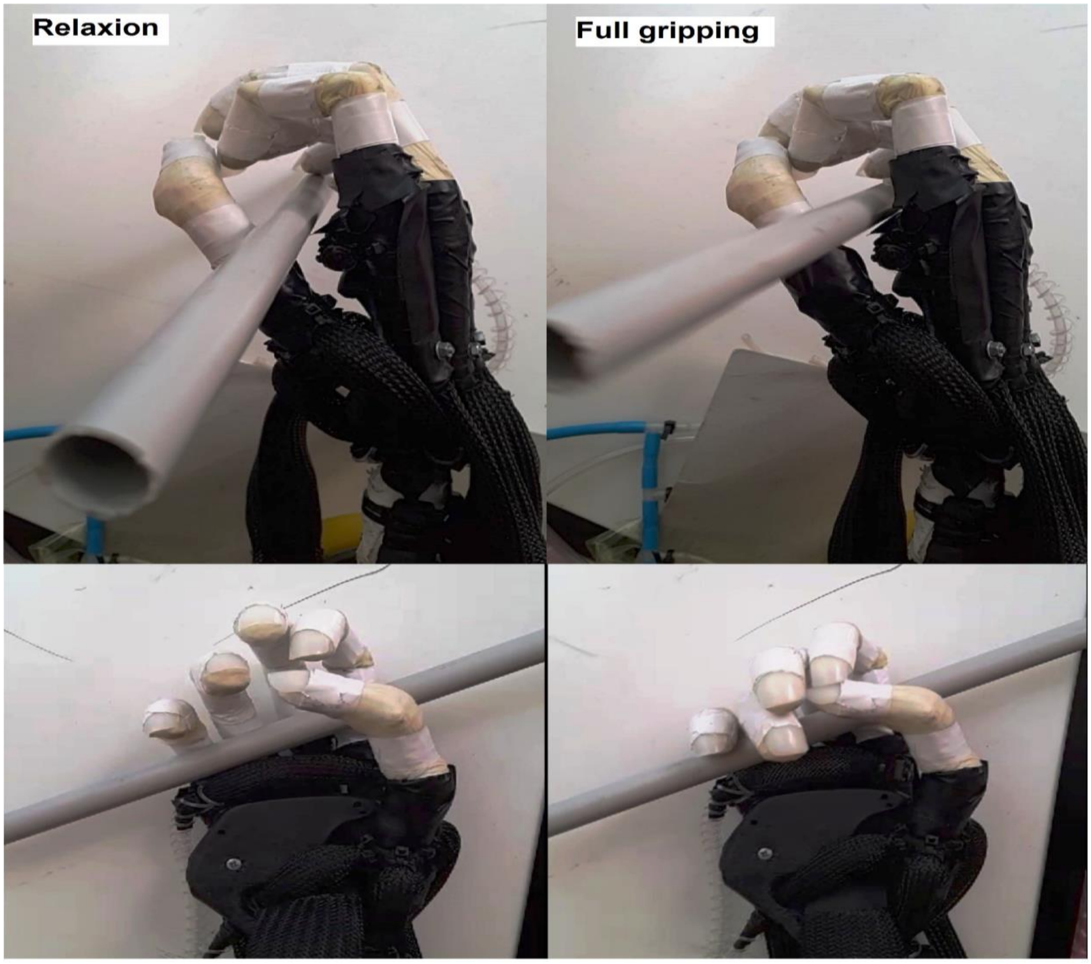


Figure 4.19. Cylindrical grasp.

4.3.2.2. Spherical grasp

In this experiment, two balls were used, one with a diameter of 60mm (blue) and the other with a diameter of 40mm (yellow). The device could grip the blue ball tightly but only loosely held the yellow one. As a result, the grip of this shape ranges between 40 and 80 mm to hold it tightly (Fig 4.20).

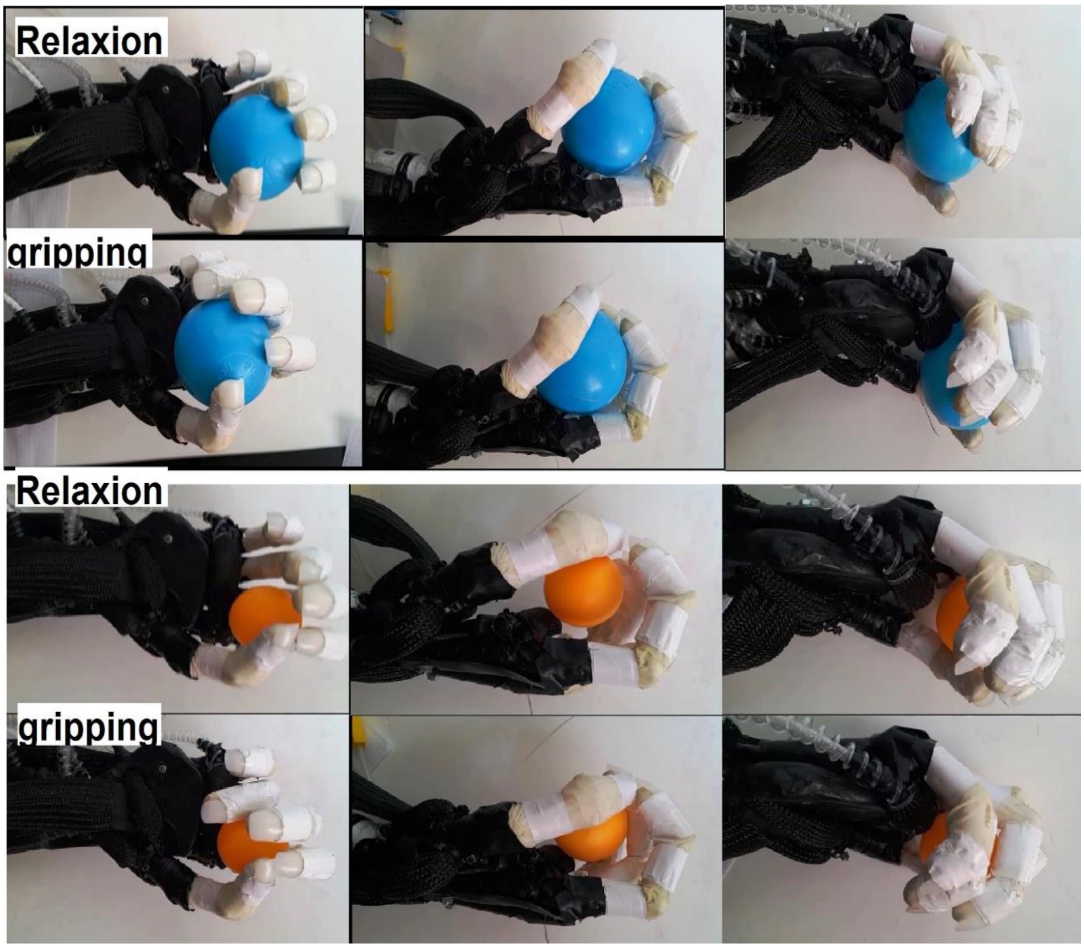


Figure 4.20. Spherical grasp.

4.3.2.3. Pulp pinch

This action occurs when an object is held between the middle and index fingers, supported by the thumb, similar to gripping a pen while the writing. Figure 4.21 shows using a marker pen with a 15 mm diameter. The range for an object with a 14 mm diameter is approximately 20 mm.

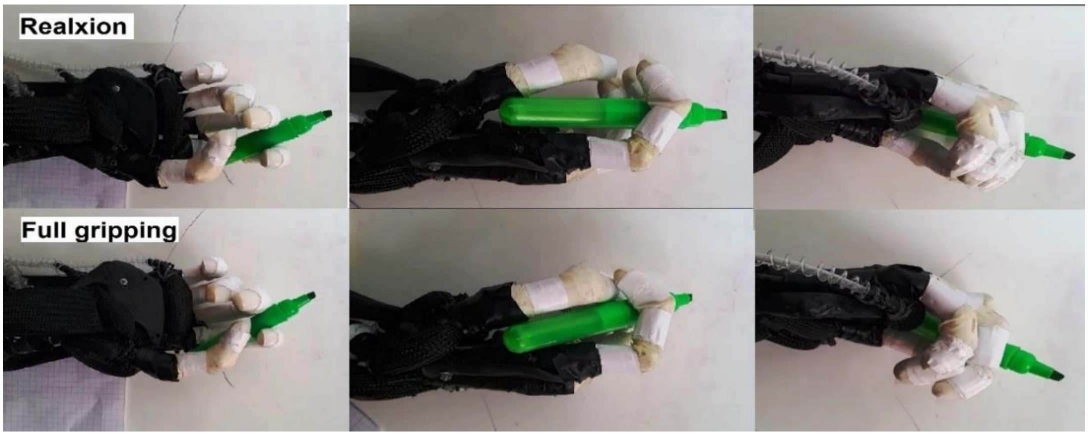


Figure 4.21. Pulp pinch.

4.3.2.4. Side pinch

It occurs when the index and the thumb hold an object, such as a key for opening a door, with the thumb facing the middle phalanx of the index. A card was utilized for the test (Fig4.22), and the range for this situation ranges from 2 mm to 35 mm.

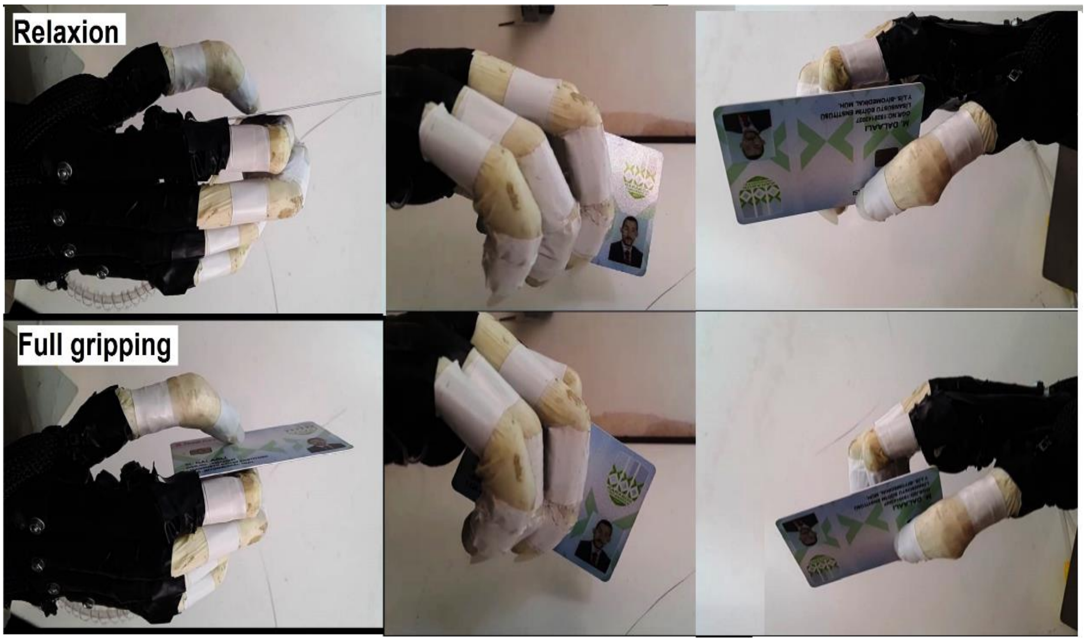


Figure 4.22. Side pinch.

4.3.2.5. Hook

This grip is similar to holding a handbag. A 1500-gram dumbbell was lifted vertically using this technique. It was successful, but this weight represents the maximum safe limit for this model (Fig 4.23).

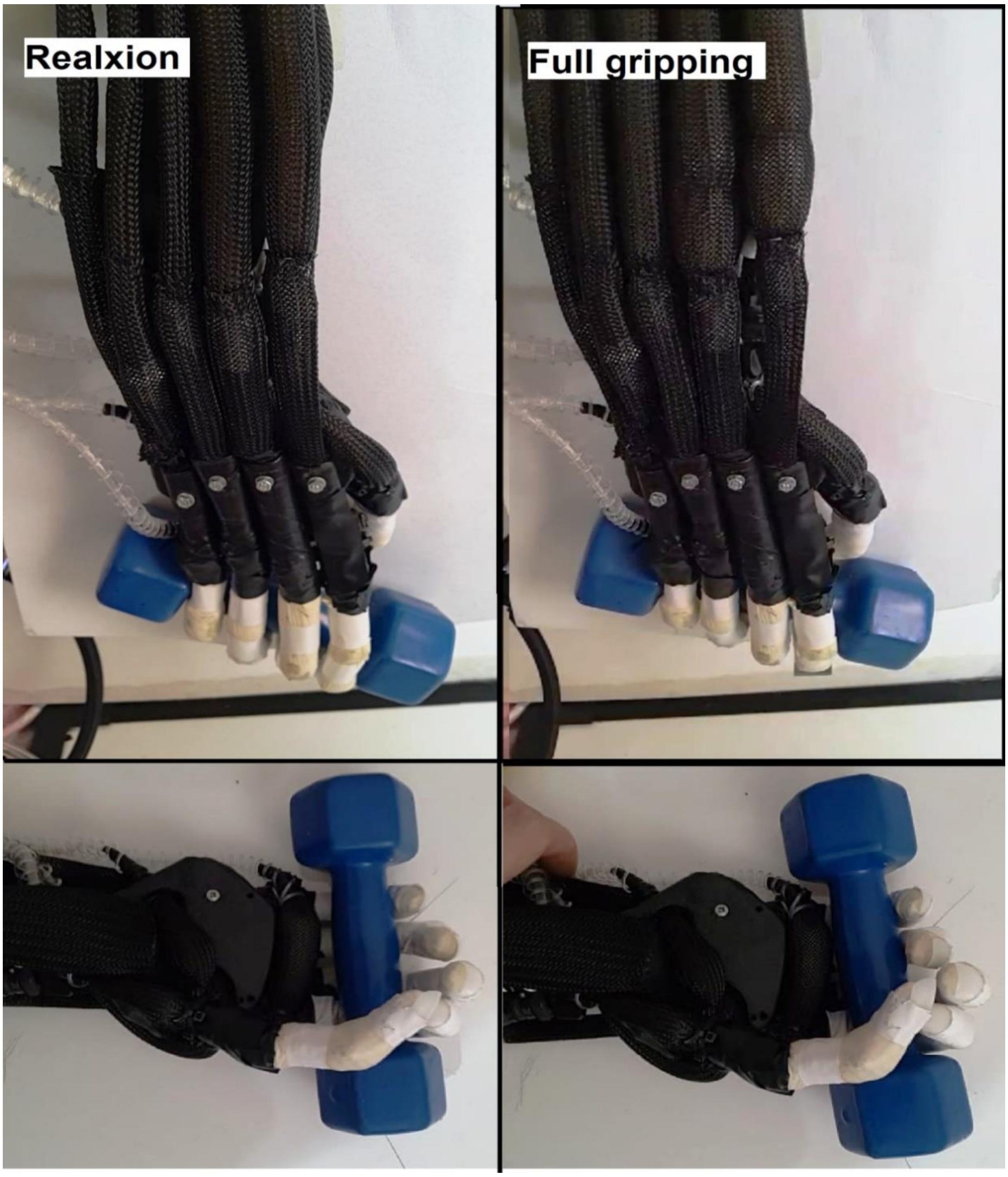


Figure 4.23. Hook gripping.

CHAPTER 5

CONCLUSION

5.1. COMFORT AND WEIGHT

The total mass of the arm designed in this study was about 1 Kg. Its weight is acceptable compared to a similar prosthetic hand on the market. Although some prosthetic hands are lighter than the hand fabricated in this study, their functions are limited to only some main movements or are used for cosmetic purposes.

The main advantage of this prosthetic hand is that it can move 15 different motions using 16 artificial muscles. Also, the hand is easy to fabricate and, consequently, more cost-effective.

5.2. GEOMETRY AND ANATOMICAL SHAPE

This arm was fabricated using right-hand anatomical sizes from the author's hand, with a 1:1.3 scale (Fig5.1). Its shape is also satisfactory and can be covered with a flexible palm to enhance its aesthetics. Furthermore, the shape and texture of the silicone fingers closely resemble that of the human hand.

5.3. STRENGTH

The small muscles could support a maximum mass of around 600 grams without reducing the contraction rate from its actual length when not carrying anything, and the arm could withstand a mass of 1500 grams safely.

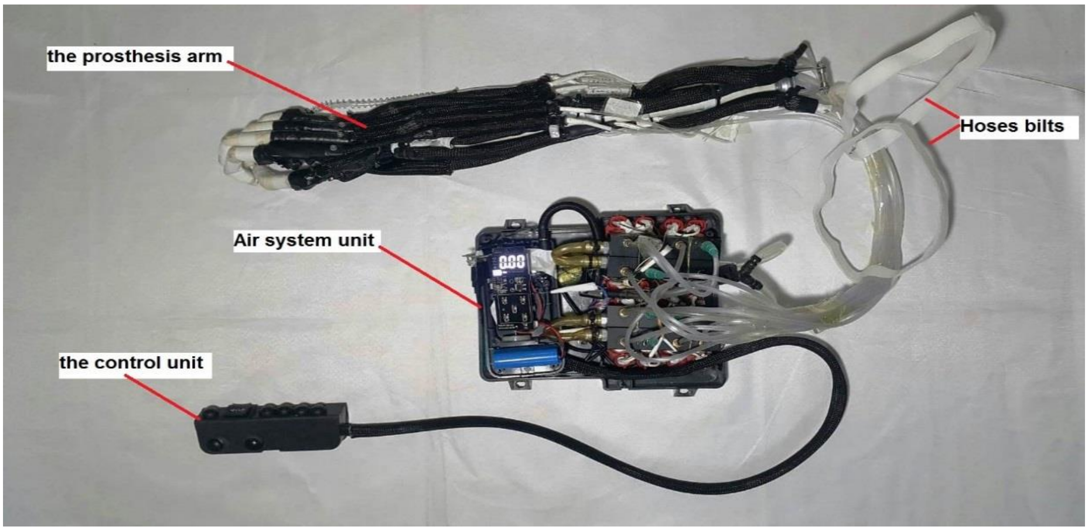


Figure 5.1.The pneumatic arm and its air and control units.

5.4. SUSTAINABILITY

The muscles can withstand pressure or shock and have a long lifetime with no damage to their structure, which can be extended by reducing friction with the casing. The fingers are made of silicone, and the flexible joints are unbreakable but vulnerable to pulling force. The solid parts, such as the rotor and arm, are vital, while the palm and platform may be prone to breakage or direct shocks. It should be noted that the arm is not affected by water, except for the air supply and control circuit. The arm is an externally powered prosthesis type with an air supply and a capacity of 2000 mAh. Additionally, as a plan, the air resulting from muscle relaxation can recharge the air pump battery. It is worth noting that water only affects the air supply and control circuit box, not the entire arm, which can be considered waterproof.

5.5. FLEXIBILITY OF MOVEMENT

As described in the arm biomechanics, 15 movements are executed by contracting 16 muscles in various locations, including movements at the wrist and rotation angles, which is in an acceptable stage, except for the fingers, which have relatively limited movement angles. Enhancing finger movement angles by using longer flexor muscles or adding specific muscles to open the fingers is possible.

5.6. THE COST

Each arm component is constructed using affordable, recyclable, or repairable materials, with a total cost that may surpass $800.

5.7. INTELLIGENT AND TECHNOLOGY

It lacks sensors or electronic devices, except for the control unit, making it devoid of temperature or touch sensors. However, there are plans to integrate these sensors or even electromagnets to aid in picking up keys or small metal objects. The control system can also be enhanced using Electromyography (EMG) systems where the arm is purely conceptual. However, this approach may have a detrimental impact on the cost aspect.

5.8. RESPONSE TIME FOR MOVEMENT

The movement speed is contingent on the muscle's response time, as Table (4.1) indicates. Nevertheless, movements vary based on movement range and muscle position. Research revealed that the completion time ranges between 2 and 4 seconds from the cativatıon of the air pump, although this duration ıs deemed lengthy.

The human hand exhibits rapid responses, yet it can execute tranquil and harmonious movements, potentially enhancing this response by integrating an air reservoir into the system.

Finally, despite the difficult comparison with the human hand and the limitations of this model in some tasks, its movements and functions are acceptable. The fabrication of prosthetic hands in combination with other muscle types could result in a cost-effective prosthetic arm with good quality, especially in terms of speed in future work.

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RESUME

Mohammed Najm Abdullah DALAALI, he started his education journey in Jordan Amman, then graduated first and elementary education from Iraqi Annah School. He completed high school education in the same city, then he started the undergraduate program in 2007 at AL-Anbar University Department of Electrical Engineering and graduated in 2012.

In 2020, he started the master’s degree studyıng in Biomedical Engineering at Karabük Unıversıty.