DESIGN OF A WORKING MODEL OF AN UPPER LIMB PROSTHESIS: WRIST MECHANISM

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ABSTRACT OF THE THESIS

Design of a working model of an upper limb prosthesis: Wrist Mechanism

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This thesis demonstrates a new design for an upper limb prosthetic wrist that gives 3 independent degrees of freedom (DOFs) through individual mechanisms. A human wrist has 3 degrees of freedom i.e. Flexion-Extension, Radial- Ulnar deviation and Pronation-Supination. The upper limb prostheses that are currently available in the market generally provide 1 (usually Pronation- Supination) or at most 2 degrees of freedom, which is not sufficient for daily life. For this thesis, a new wrist having all the 3 DOFs was designed in the SolidWorks software, a prototype was 3D printed and a basic analysis of the mechanical properties of the model through SolidWorks simulation was carried out. The prototype mechanisms were then connected to servo motors, with potentiometers as their inputs, that were programmed through an arduino and were tested to see if they work as expected. Faithful recreation of the wrist motions was achieved and the range of motion (ROM) of this prosthesis was similar to the ROM of an actual human wrist.

This thesis also looks at the other prostheses that are available in the market or are under development and their limitations are discussed. The goal of this thesis is to present a design of an upper limb prosthesis which addresses some of the limitations

while also encouraging further research and development in this field and will hopefully result in more people with amputations choosing to use prosthetics in their daily lives.

Keywords: Upper-limb prosthesis, Wrist mechanism, Flexion-Extension, Radial deviation, Ulnar deviation,Pronation-Supination, 3 independent degrees of freedom(DOF), FSR, myoelectric prosthesis, Upper-limb amputation, servo control.

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Chapter 1

Introduction

A prosthesis is defined as an artificial body part, to replace a limb which may be lost by the subject through an accident, congenital disorders or infections. Prosthetic rehabilitation is a huge task that involves both psychological and physical training that takes time and a huge team of health-care experts, not to mention the immense determination on the part of the subject. Anything to streamline this rehabilitation process is always encouraged and sought out for.

A prosthetic design which is light weight, easy to use and replicates human hand motions as faithfully as possible is of vital importance in the rehabilitation process. This will help the subject to focus on overcoming the psychological barriers rather than worry about the learning curve that comes with a nonintuitive design.

1.1 Motivation

The motivation for this thesis is to design a functioning upper limb prosthesis which mimics actual human movements but at the same time, is also simple, lightweight, easy to use and maintain. This thesis will focus on the designing of the wrist mechanisms of the prosthesis. Currently majority of the prostheses available in the market can perform only one of the following motions at a time:

- Flexion - Extension of the wrist
- Radial - Ulnar deviation of the wrist(Also called abduction and adduction of the wrist respectively)
- Pronation - Supination of the wrist

In this thesis, a wrist prosthesis which allows all these motions to be performed simultaneously has been designed and a working model has been 3D printed. The goal is to make this design freely available for people to use and improve on so that a cheaper and a more functional prosthesis can be developed and can help as many people as possible.

1.2 Types of prostheses

An individual who has suffered an upper limb amputation who wants to get back to work which is labor intensive and someone who feels separated from the society due to cosmetic concerns and wants to get back into the social circles and mingle in parties and conferences will have different expectations from the prosthesis. The basic needs could be categorized into three groups as follows:

- Daily activities prostheses
- Recreational prostheses
- Cosmetic prostheses

Daily activities prostheses

Anyone who has recently lost a limb expects their prosthesis to look and feel like the limb that they lost. They expect to perform most if not all their day to day activities at the same level as before the amputation. This leads to very high expectations.Even a good robust design of the prosthesis might not meet their expectations in such cases. So the subject needs to be fully educated in the capabilities and limitations of a prosthesis.

There are four main types of daily activities prostheses:

- body powered prosthesis
- externally powered prosthesis
- adaptive devices
- hybrid devices

Body powered prosthesis

Body powered prostheses or standard prostheses work by using cables to transmit the movement of the body to the prosthesis mechanism and control it. Moving the body in a certain way will pull on the cable and cause it to open, close, rotate or bend. For a new subject, this prosthesis is not what they expect. With the metal hook, the harnesses and the overall construction, it looks nothing like the limb that has been lost. Yet the standard body powered prosthesis is often the preferred choice of prescription for the new subject for many reasons. First, it is significantly cheaper in comparison to an externally powered prosthesis or a custom cosmetic prosthesis. The other reason is the great therapeutic value offered by the operation of the standard prosthesis to the new subject, even though the functional benefits are not great during the initial stages of the training. Learning to use the prosthesis improves the joint range of motion, it desensitizes the tissue, and shapes the stump for optimal prosthetic use. It is, therefore, important that this is pointed out to the new subject.

Externally powered prosthesis

The externally powered prosthesis is a sophisticated prosthesis that contains microprocessors and servo motors which enables greater pinch and grip force along with greater precision, which is not attainable with the standard body powered prosthesis. Myoelectric control is used to actuate electric motor-driven hands, wrists, elbows, etc. Electrodes are embedded in the prosthesis which are in contact with the skin to detect movements in the residual limb caused by voluntary muscle action. This electrical signal activates an electric motor which leads to a certain action (eg, terminal device actuation, wrist rotation, elbow flexion). This prosthesis cannot help in texture detection. For subjects with above-elbow amputations, having control of the terminal device at any position is a significant benefit. Therefore, the functionality of the prosthesis is hugely improved. High level amputation subjects such as those with shoulder disarticulation are good candidates for externally controlled prostheses, since they do not always have the physical capabilities required for a cable operated prosthesis.

Adaptive devices

Generally subjects require different types of prostheses for different functions or settings. For example, one might find a standard prosthesis more useful at work especially if it is a labor intensive job. In social settings though, he or she might prefer a myoelectric prosthesis with a glove. Adaptive devices generally are custom built for particular tasks and functions in mind.

Hybrid devices

In the hybrid devices, body as well as external power is utilized. The most common use of the hybrid configuration is the activation of the elbow joint by body power and the prosthetic hand by myoelectrical means. This system works best when the subject has a good shoulder and a minimum of one quarter of the humeral length. Reduced weight and noise in comparison to electric elbow and elbow locking features to prevent slipping under heavy loads are some of the benefits of this system.

Recreational prostheses

Usually this type of prosthesis is common with upper limb amputations for taking part in sport activities like swimming. The terminal device in this case would be a passive paddle type structure. This prosthesis is designed according to the specific needs of the recreational activity.

Cosmetic prostheses

The objective of this type of prosthesis is to appear as human-like as possible so as to not draw attention from people in a social setting. Most of the time this is done by sacrificing the functionality of the prosthesis. These prostheses are generally of two types. The first one being a passive cosmetic hand and glove which looks human but cannot be actuated in any way. The gloves are manufactured from polyvinylcholoride (PVC), but has low resistance to stains. Stains can easily be absorbed by the glove, making it difficult, even impossible, to clean. Therefore, the average life of a standard PVC cosmetic glove is just a few months. The gloves for myoelectric hands and functional mechanical hands are made from PVC.

The second type is custom designed and fabricated, usually made from silicone, which has excellent resistance to stains. The finished cosmetic prosthesis is custom painted and shaded to look as close to a human hand as possible. This type of prosthesis is very expensive and the number of manufacturers are limited.

1.3 Outline

Chapter 2 describes the previous work done in this field. Chapter 3 discusses the design process and all the components that went into designing the prosthesis. Chapter 4 discusses the actual designs of the mechanisms while also giving a brief look into how the mechanisms work in an actual human hand. Stress and displacement analysis of the model by selecting different materials and the results are discussed in Chapter 5. Finally, the conclusion and future work can be found in Chapter 6.

Chapter 2

Related Work

In this chapter the related work in the field of upper limb prostheses, focusing on the wrist mechanisms, is discussed.

Usually the designs for the prosthetic wrists only have one Degree of Freedom (DOF), usually forearm rotation, be it driven or passive. Multiple-DOF wrists helps in positioning the hand, reduces the need for extra arm motions and in return, makes day to day activities easier. There are a few multi-DOF wrists that are available, either for purchase or in the research phase and this chapter will shed light on some of the popular ones.

2.1 JRRD Two DOF Powered Prosthetic Wrist

This wrist, featured in the Journal of Rehabilitation Research and Development [11] is designed to have two DOFs and has a differential mechanism that combines both wrist flexion - extension and pronation - supination which aims for practical use in the daily life. The design uses two motors to drive the 2 DOFs through the differential mechanism.

The two motors, arranged in parallel, are placed in opposite directions and aligned across the base of the hand. Each drive passes through an intermediate gear on the ends of the wrist to shafts that run below the motors. The motors rotate the opposite ends of a differential, with the central wheel attached to the rest of the prosthesis. When both motors run in opposite directions, the gearing and the differential cause the wrist to rotate about the long axis of the arm, leading to pronation and supination (Figure 2.1 (a)).

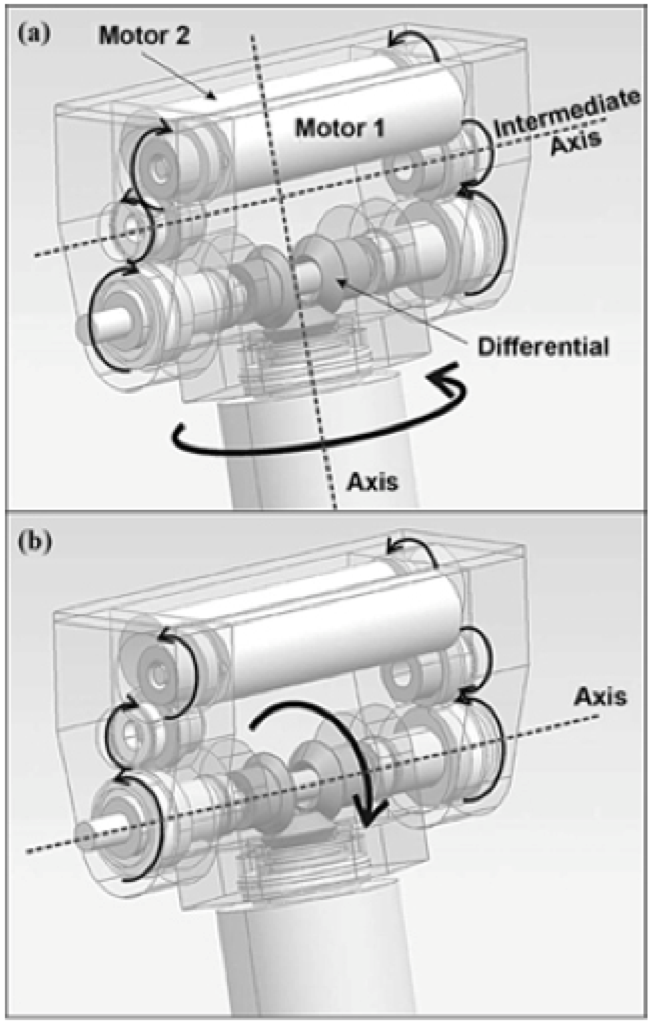

Figure 2.1: **(a)** Pronation and supination: Both motors turn in the same direction so the two gears of differential rotate in opposite directions. **(b)** Flexion and extension: Both motors oppose each other across differential producing the torque for flexion-extension [11].

A second axis, the flexion and extension axis, is along the line of the differential. When the two motors turn in the same direction, the drives oppose each other across the differential. This stops the forearm rotation and creates a torque causing the wrist to flex or extend (Figure 2.1 (b)). If the motors run at different speeds, the output is a combination of the two axes in proportion to the sum (pronation) and the difference (flexion) of the drive speeds. Figure 2.2 shows the initial design of the wrist.

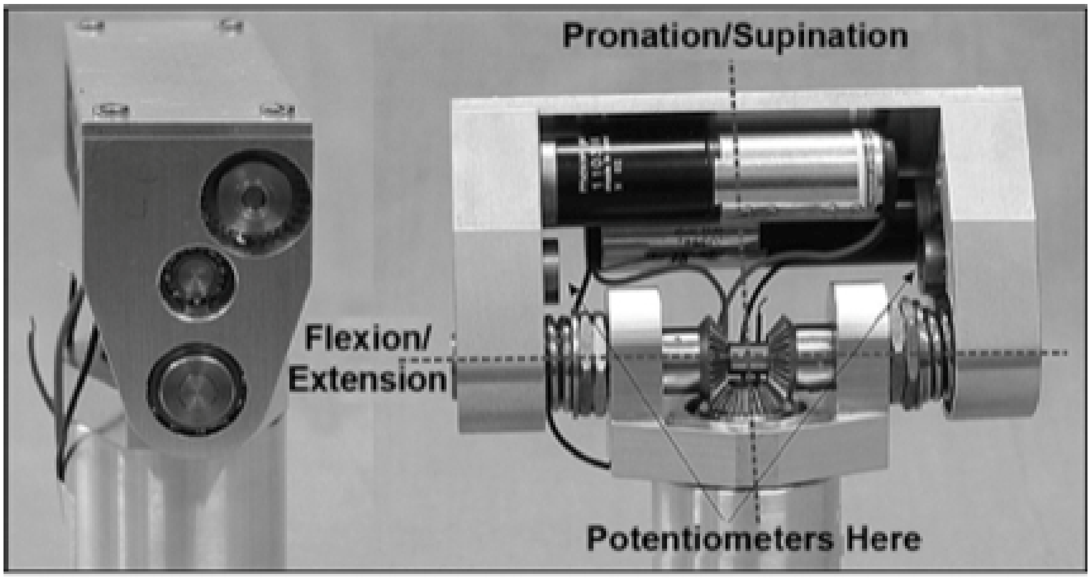

Figure 2.2: Preliminary wrist design with axes and potentiometers to gather joint position data [11]

The wrist is controlled using a micro-controller to drive the two motions. Serial communications through a Controller-Area Network bus is used by the controller to communicate with the rest of the prosthetic arm. A controller node near the wrist can use input signals ranging from switches to myoelectric signals.

The Pros for this design include: 2 DOFs possible at fast enough speeds for practical use. Small size of the wrist.

The Cons include: Not enough torque is produced for general use. The wrist is heavy.

2.2 Two Degrees of Freedom Passive Compliant Prosthetic Wrist with Switchable Stiffness

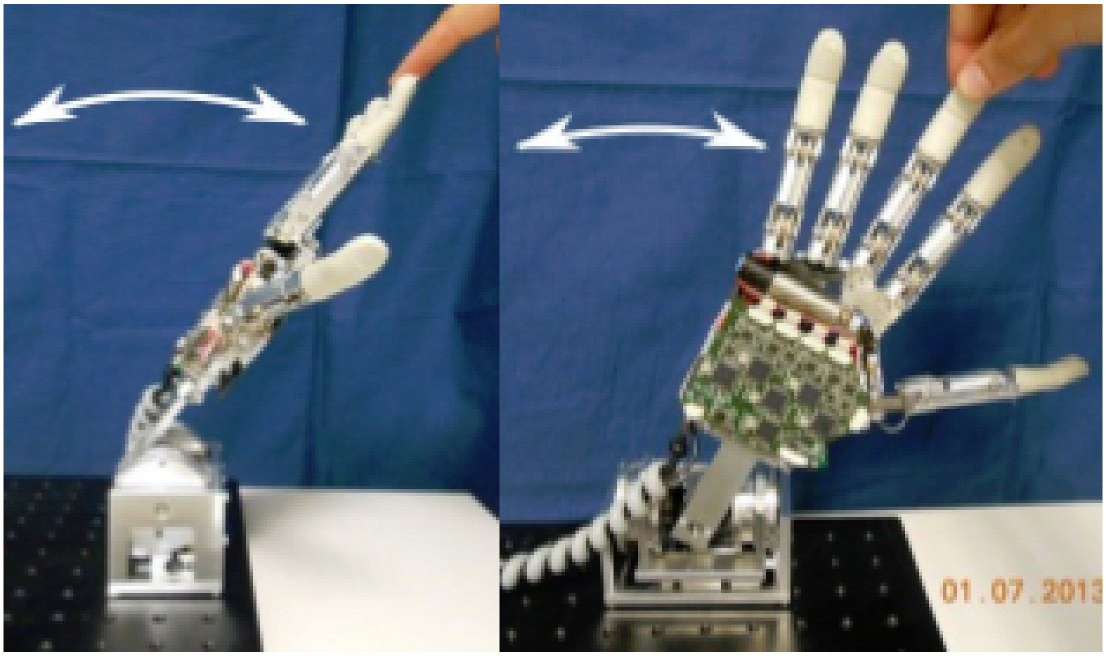

Figure 2.3: 2-DoFs compliant wrist [12]. a) Flexion/extension movement. b) Abduction/adduction movement.

This wrist is designed to aid subjects in grasping objects [12]. A typical grasp can be divided into three steps: reaching, grasping and holding. In the reaching phase the wrist has a compliant behavior (compliant mode) (Fig. 2.4(a)) so that the palm can be aligned to the object by pushing the hand against something solid like a wall or table (Fig. 2.4(b)). Once aligned, the hand can then grip the object and then the wrist switches to the stiff mode(Fig. 2.4(c)).

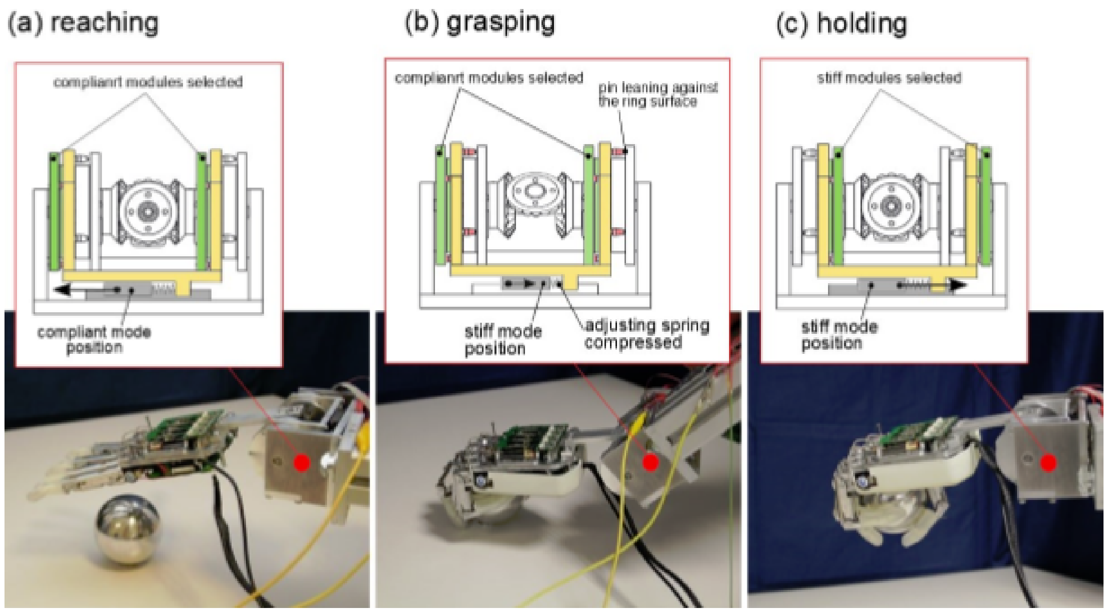

Figure 2.4: A typical grasp sequence using the wrist [12]. (a) Reaching phase: the wrist is in the compliant mode and the compliant modules of the elastic joints are engaged. b) Grasping phase: the hand can be pressed against a constraint (the table) and adjusted for grasping. Then, the selector moves towards the stiff mode position; however as the hand is not in the rest position the pins of the selector are not aligned with the plugholes of the stiff module. Thus the compliant modules are still engaged and the wrist is still compliant. c) Holding phase: when the object is lifted and the wrist goes to the rest position, the wrist becomes stiff due to gravity as the adjusting spring forces the pins into the plug holes of the stiff module.

The wrist works on a bevel gear differential mechanism and two elastic joints (Fig 2.5). Each joint has two compliant modules of different stiffness which engages through a selector to switch the stiffness of the joint and consequently the mechanism. The wrist has a symmetric structure; it comprises of a differential mechanism formed by three bevel gears (90 degrees) in the center connected to the two elastic joints at the sides.

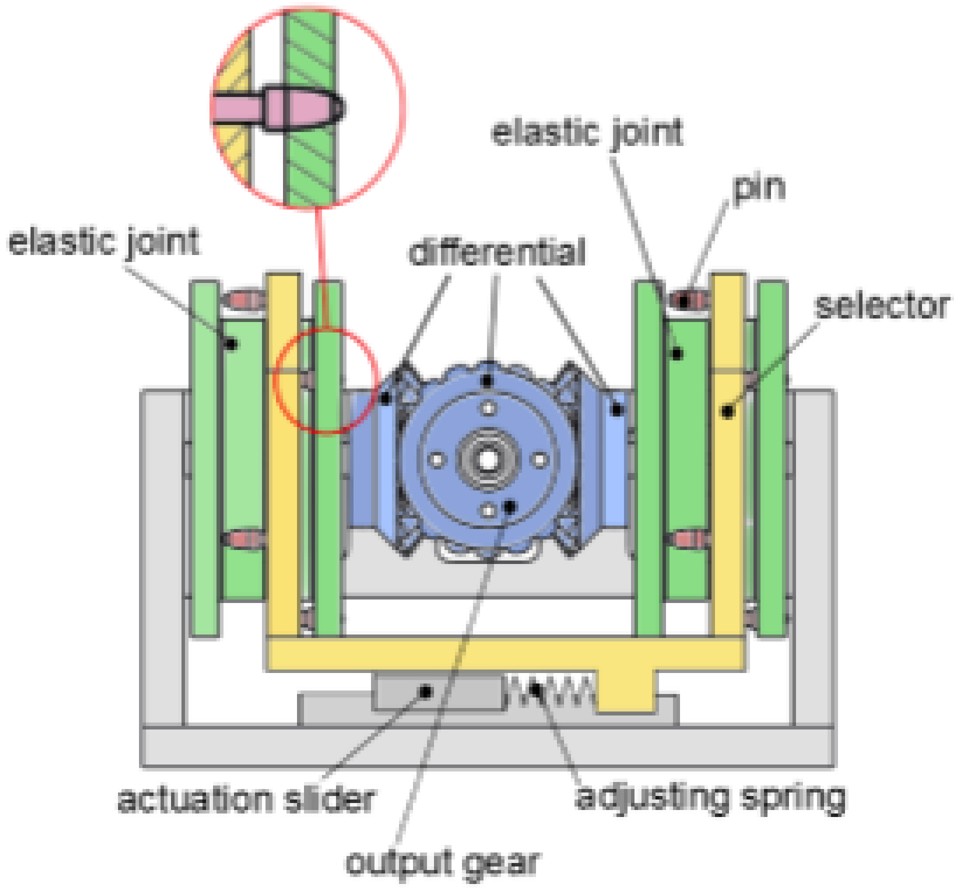

Figure 2.5: Preliminary design of the 2 DoF compliant wrist [12]. The flexion/extension and the adduction/abduction movements are achieved by means of the bevel gear differential mechanism represented in blue. The central gear which is connected to the hand is the output of the system. The lateral gears are the input gears and are connected to the elastic joints (green) at the sides, which are engaged by the selector (yellow) that is actuated by the slider. An adjusting spring is present between the actuation slider and the selector.

The central gear is connected to the prosthetic hand shown in Figure 2.3, the other two gears are connected to the two elastic joints. The differential mechanism allows equal distribution of the rotation of the output during the flexion/extension and abduction/adduction movements. These researchers have also stated that wrist dexterity is more important than finger dexterity for effective day to day functioning of the prosthesis.

The pros of this design are: Two DOFs possible. Two stiffness settings available.

The cons of this design include: Heavy weight of the wrist. Passive and no powered control of the wrist.

2.3 Development of a Bio-Inspired Wrist Prosthesis

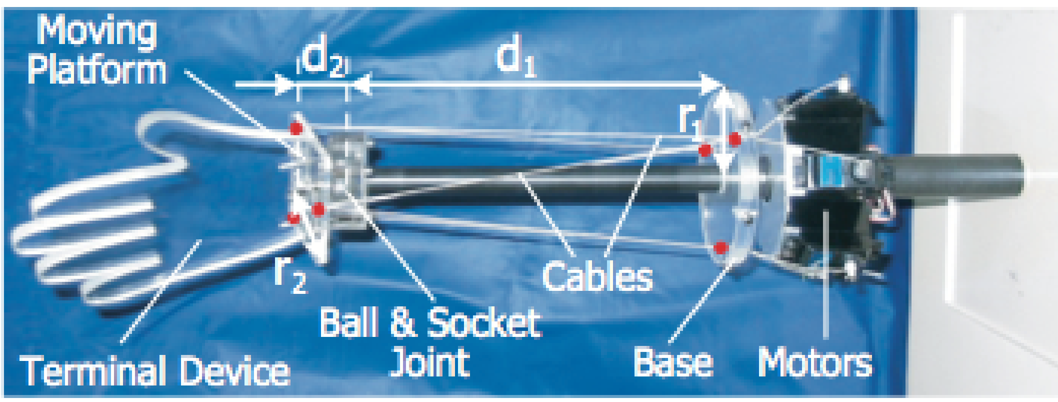

Figure 2.6: Fabricated six-cable Wrist Prosthesis [1] (The 3 cable attachment points (in red) at both the base and the moving platform)

This wrist design (Fig. 2.6), currently under development, will give the subject 3 DOFs while being lightweight and cable operated.It uses a spherical joint with cables and motors for flex/extension and abduction/adduction and a cylindrical joint for pronation/supination thus mimicking the joints in the actual human wrist (Fig. 2.7). [1]

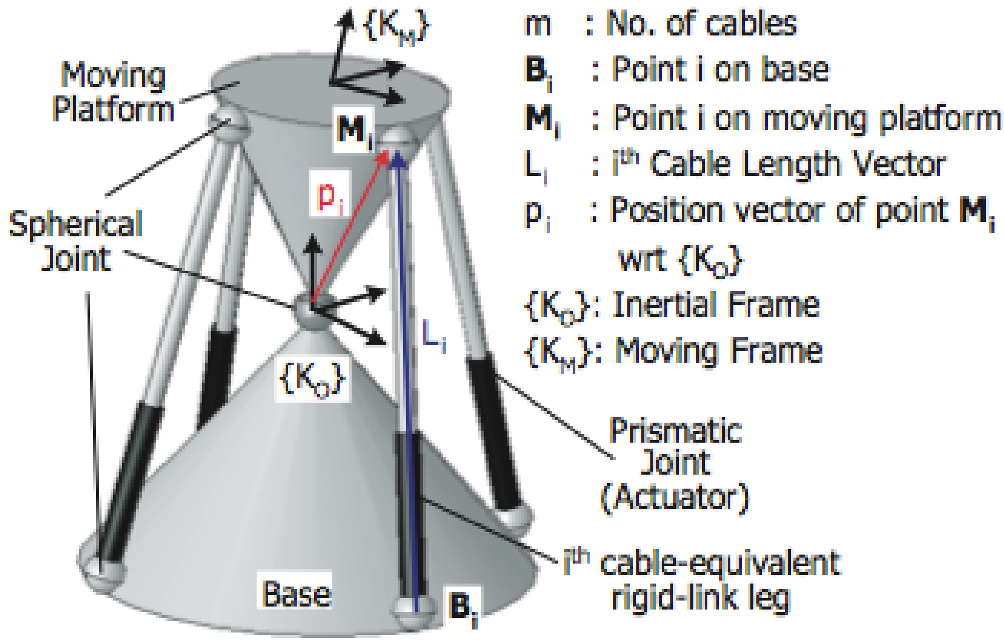

Figure 2.7: Kinematic diagram of the cable-driven wrist prosthesis [1]

The pros of this design are: 3 DOFs available. Lightweight design by using cables. The cons are: Still in prototype phase. Control and stability could be an issue.

2.4 Development of Prosthetic Arm with Pneumatic Prosthetic Hand and Tendon-Driven Wrist

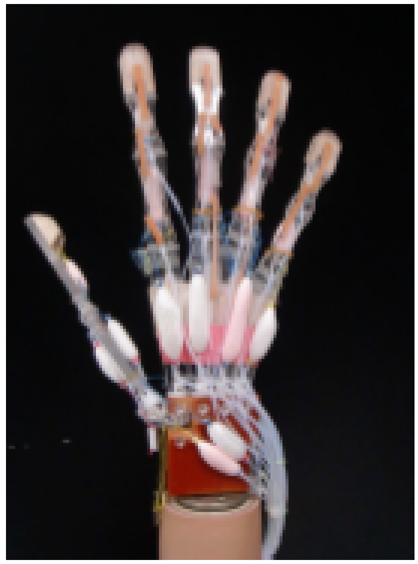

Figure 2.8: Five-Fingered Prosthetic Hand [2]

This design has a five-fingered prosthetic hand (Fig. 2.8) which uses pneumatic actuators and a thin tendon-driven wrist using a wire drive and two small motors [2]. The pneumatic actuator is basically a rubber balloon which can be filled with compressed air through a feeding channel and a net covering the balloon (Fig. 2.9). Expanding the rubber balloon generates force on the surrounding net. The expansion and contraction can be controlled by adjusting the pressure in the balloon.

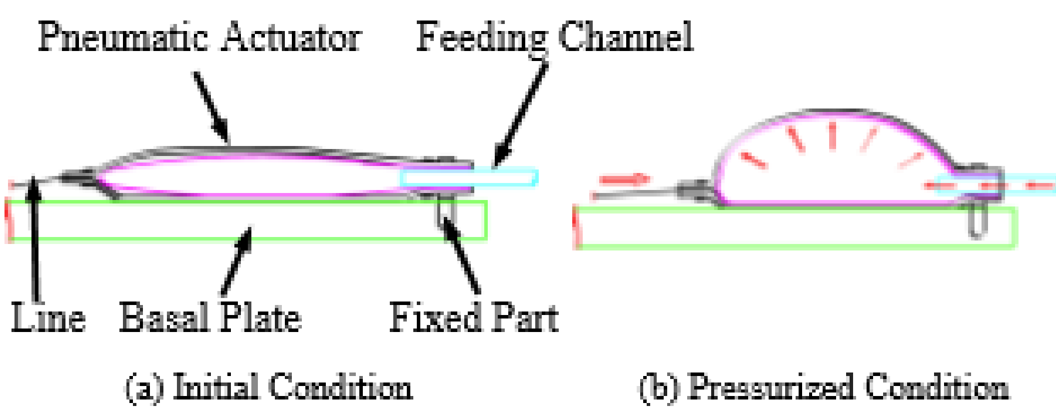

Figure 2.9: Schematic of Pneumatic Actuator [2]

The drive mechanism of pronation and supination is shown in Fig. 2.10. When same voltage is applied to the two motors, the wire is pulled in the same direction, and the pulley is pulled which leads to rotation in the main axis. This is the pronation mechanism. Compared with this, supination is the inverse rotation that occurs when the pulley on the counter side is pulled.

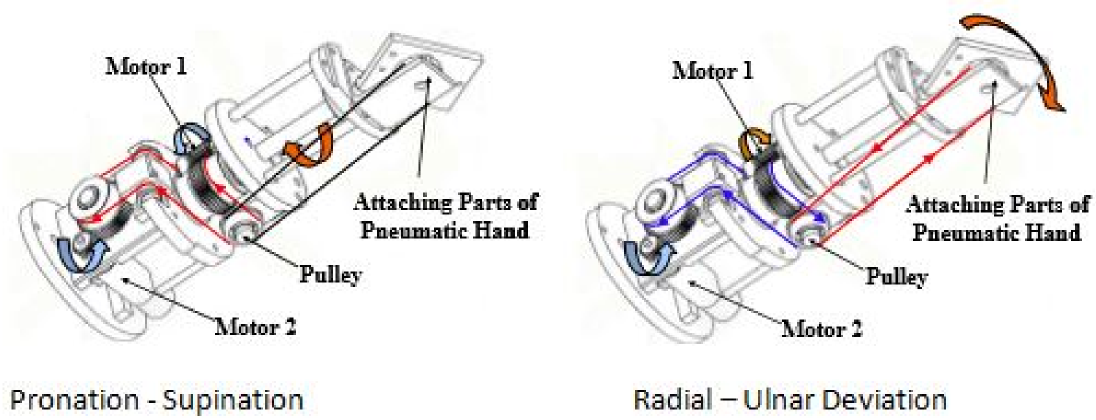

Figure 2.10: Wrist Mechanisms in the tendon driven wrist [2]

For the drive mechanism of radial and ulnar deviations, arbitrary voltage is applied to one motor and a reverse voltage to the other. Unlike pronation and supination, the wire connecting to the attached part of the prosthetic hand is pulled and the part rotates. Radial and ulnar deviations have different rotation direction, but the basic mechanism is the same.

The pros of this design are: 2 DOFs are achieved. The pneumatic finger mechanism is responsive and safe.

The cons of this design are: Air, being a compressible gas, is unreliable to control, and there has been limited success with pneumatic actuation of limbs. Complex design.

2.5 Market ready designs

The products given below are available for sale currently. The mechanisms used in these design have not been made public.

OttoBock - Michelangelo Hand

This hand is capable of 2 DOFs: flex/extension and rotation (pro/supination) [3]

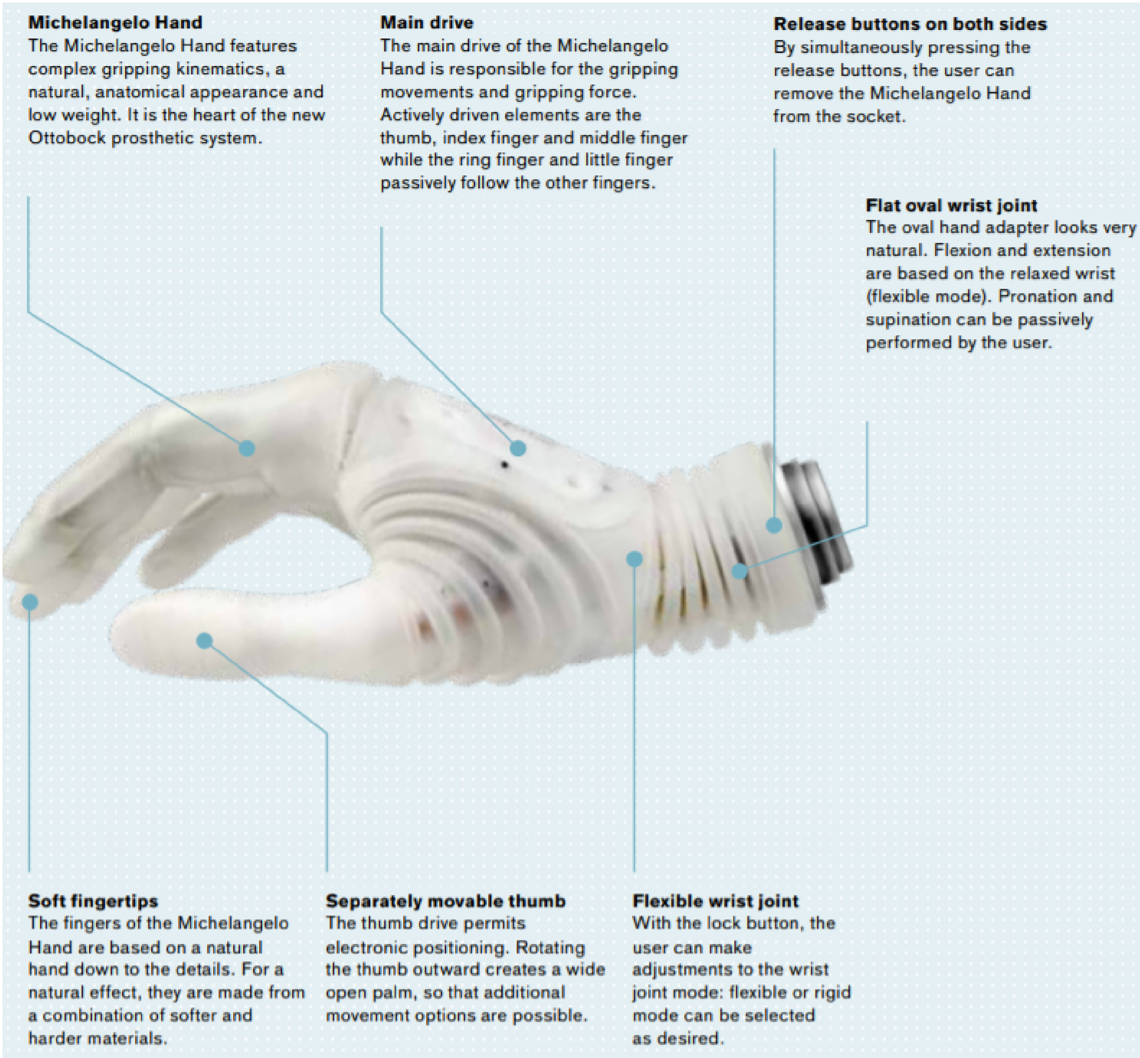

Figure 2.11: Michelangelo Hand [3]

OttoBock - Bebionic Hand

There 3 different variants of the wrist [4]:

Electric Quick Disconnect (EQD): This design allows for the subject to quickly rotate and remove the hand as needed.The pronation/supination is controlled by the subject's other arm.

Figure 2.12: Bebionic Hand [4]

Short Wrist: This design is used for subjects with a long residual limb.The wrist rotates against a constant friction. The pronation/supination is controlled by the subject's other arm.

Multi-flex wrist: This design has passive wrist movement in all directions and the ability to lock in certain positions including the neutral position. This passive wrist movement is done by the sound hand.

Pros: 2 DOFs

Cons: Wrist must be locked in flexion/extension for it to deviate medially or laterally

Wrist Arthroplasty

This design requires a surgery to be implanted in the hand [5]. This just replaces a wrist that no longer works. The components of the wrist arthoplasty are shown in figure 2.13.

Pros: 3 DOFs

Cons: A surgery is required. This can only be done for people with a bad wrist and not for severe amputations.

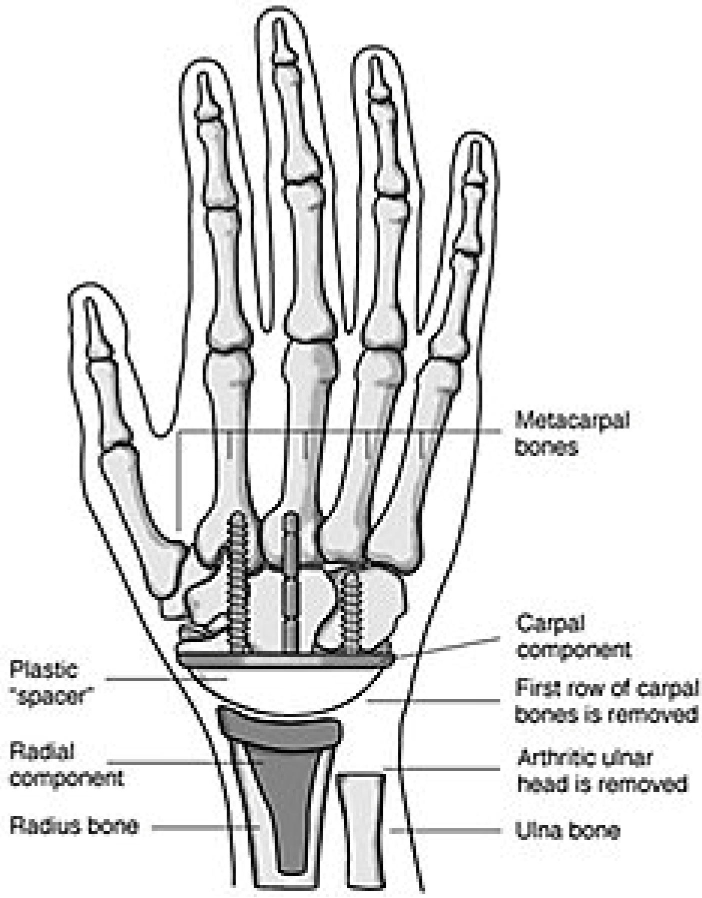

Figure 2.13: Components of Wrist Arthoplasty [5]

To summarize it can be seen that there are a number of designs that are present, or are being worked on. But most of them do not provide simultaneous flex/extension, radial/ulnar deviations and Pronation- Supination. The ones that do are too complex or too expensive or are just very heavy. Almost none of the designs provide the dimensions of the parts, so that it could be replicated or improved upon using cheaper and/or lighter materials.

Chapter 3

Building a Dexterous Prosthesis

In this chapter, a general overview for designing any prosthesis is discussed. This covers the various components, hardware and software, that go into the process, the main topic of focus of this thesis and the thought process involved when undertaking a design project like this. Since prostheses are all custom for the user, the user specifications and requirements must be considered while designing. One of the main requirement that every user has is a fully functional wrist. So it is of vital importance that great thought and effort must be given to designing a wrist that has all the degrees of freedom that an actual wrist has.

3.1 The Design Process

The first step to any design project is the visualization of the entire process from start to finish. A road map will help immensely in taking stock of the work that is to be done, the work that already has been done and will help compartmentalize and prioritize.

The design components are shown in Figure 3.1. This thesis will concentrate on the wrist mechanisms i.e Flexion-Extension, Radial- Ulnar Deviation and Pronation-Supination. The palm with fingers has been designed by the previous team with inspiration from the InMoov hand [13].

Each component will be briefly discussed next.

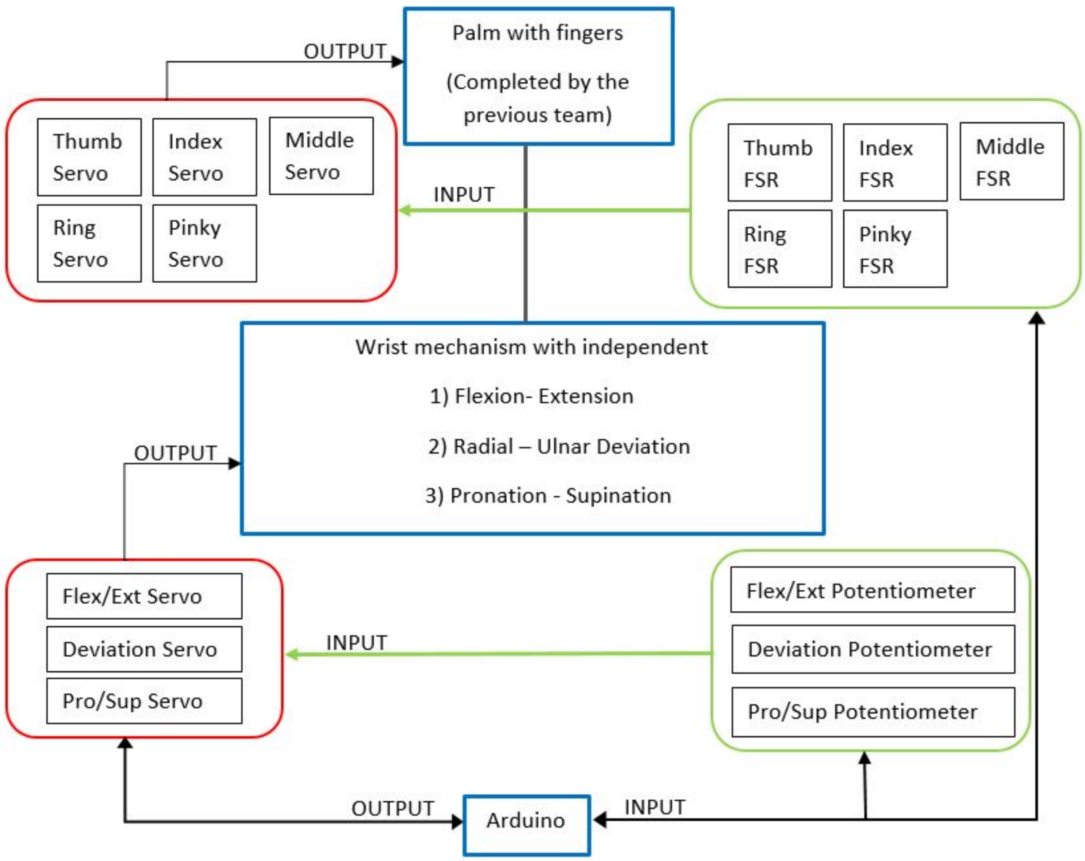

Figure 3.1: Components of the Prosthesis

Figure 3.2 shows the actual 3D printed prototype of the prosthesis with all the components highlighted. Each finger is controlled by a servo which gets the input from a Force Sensitive Resistor (FSR). All the FSRs are arranged on a board and placed in a box for easy operation. The wrist mechanisms are also controlled by servos but take input from potentiometers. All of these inputs and outputs go through the arduino circuit. This entire system is an open loop. There is no feedback from the output to the input.

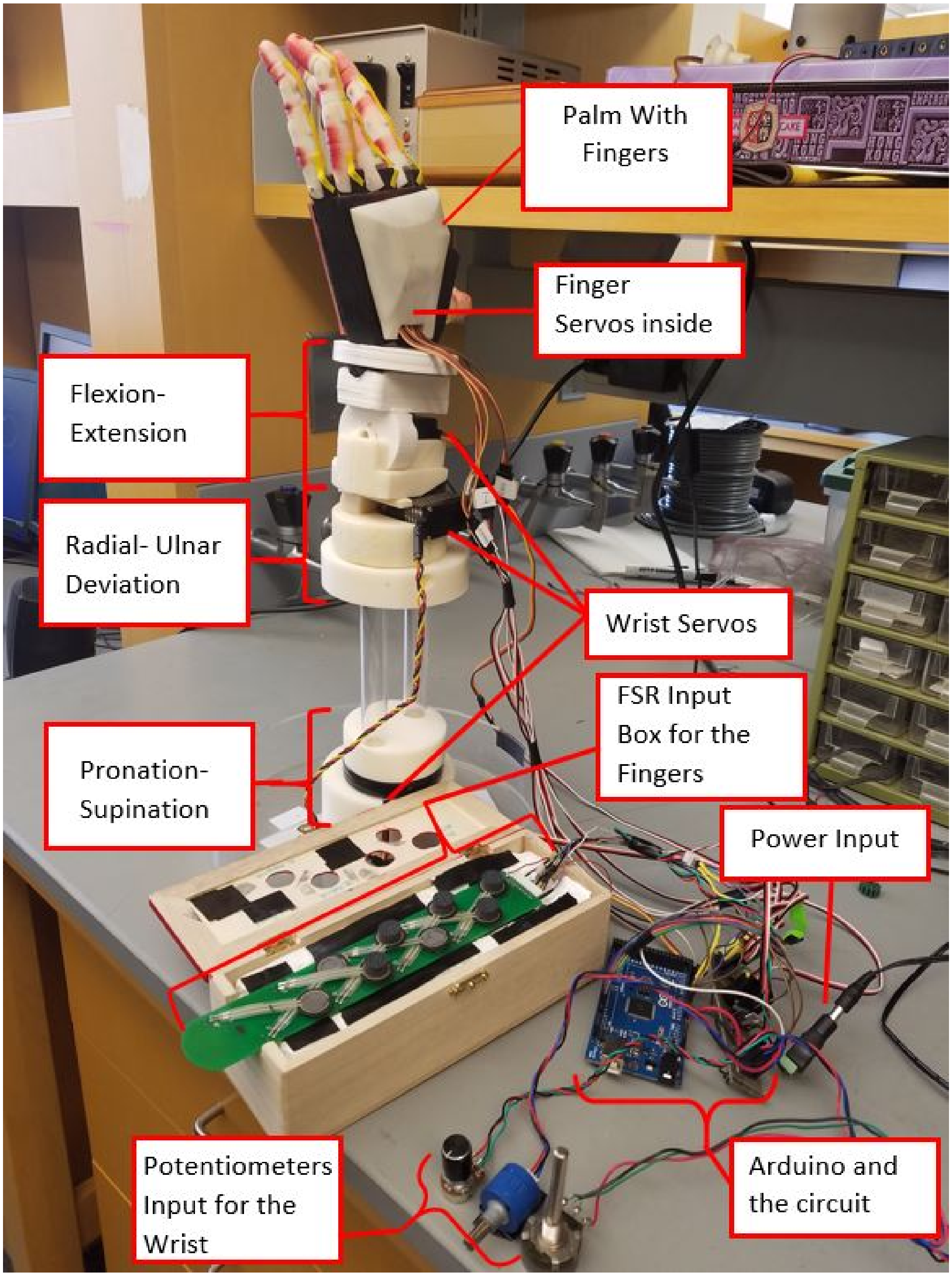

Figure 3.2: Components of the Actual Prosthesis

The prosthesis can be divided into the following parts. This thesis will go into details of the parts in the next chapter:

3.1.1 Palm with five fingers

The hand, distal to the wrist, has been inspired by the InMoov hand [13]. Further development has led to a hand that has fingers which are 3 jointed and can be actuated using wires or strings which act as tendons. Each finger is connected to a servo through the string and thus can be actuated to mimic human fingers which can then grasp or pinch objects. The servos have been placed inside the palm to reduce the thickness of the hand.

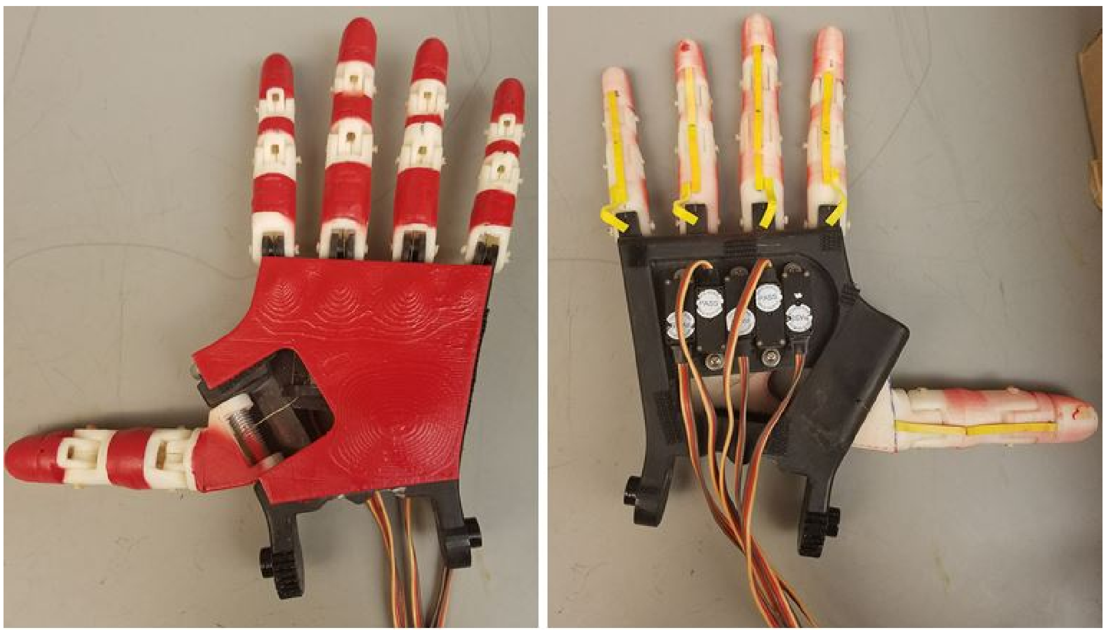

Figure 3.3: Front and Back view of the Palm with Fingers (Left Hand)

3.1.2 Wrist Mechanisms

Next is the wrist mechanism. The aim is to give the subject complete freedom in moving the wrist. This can be achieved by giving the wrist 3 degrees of freedom i.e. Flexion-Extension Radial-Ulnar Deviation and Pronation- Supination. The wrist model designed, which is the focus of this thesis has all 3 of these motions, controlled by individual servos. Actuating them precisely will give the subject full rotational movement just like in an actual human wrist.

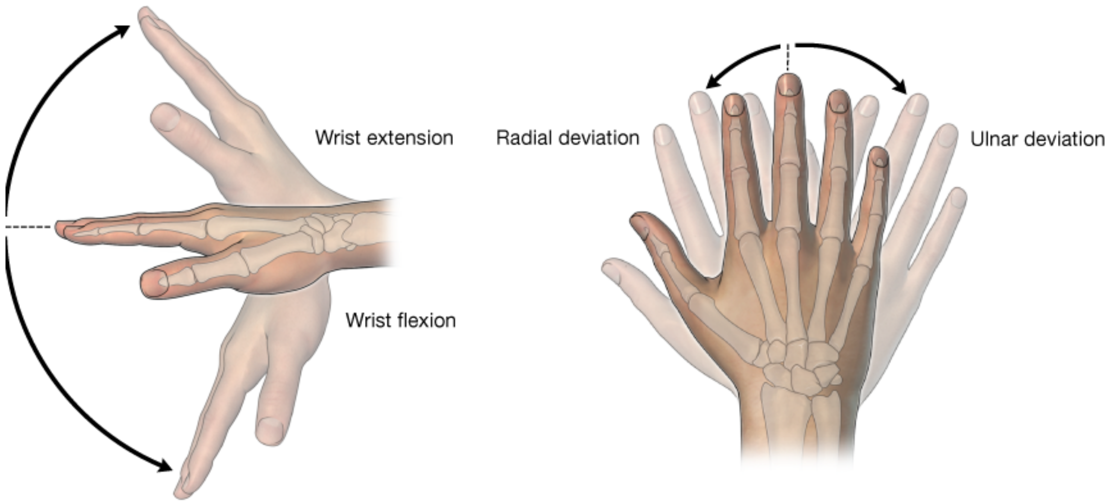

Figure 3.4: Flexion - Extension and Radial - Ulnar Deviation [6]

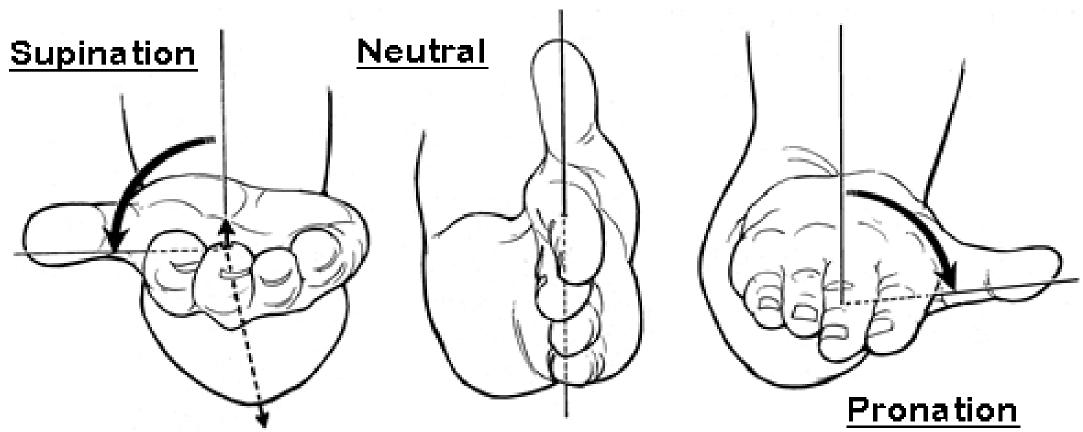

Figure 3.5: Pronation - Supination [7]

3.1.3 Motor Control

All the servo motors that control these mechanisms are then connected to an arduino board through a circuit. The arduino board is the link between the inputs and the outputs. It can be programmed to have the servo spindles rotate to any desired angle and at any specified speed.

3.1.4 The Inputs

The servos can take input from a multiple of sources. For this thesis the wrist mechanisms are controlled by potentiometers and the fingers are controlled by Force Sensitive Resistors(FSR). A FSR is made up of a conductive polymer which changes resistance proportional to any force or pressure applied to it. The servos can be programmed to rotate when the FSRs are pressed.

The wrist servos have potentiometers, used as variable resistors, as inputs. They are particularly useful for the wrist mechanisms as a servo can be programmed to rotate exactly as the dial on the potentiometer is rotated. Precise movement can be achieved by this input. Potentiometers, operating as variable resistors, are used in this thesis for testing purposes. In the future, that is beyond the scope of this thesis, the potentiometers will be replaced by FSRs to enable the servos to be actuated by voluntary muscle movements in the residual limb.

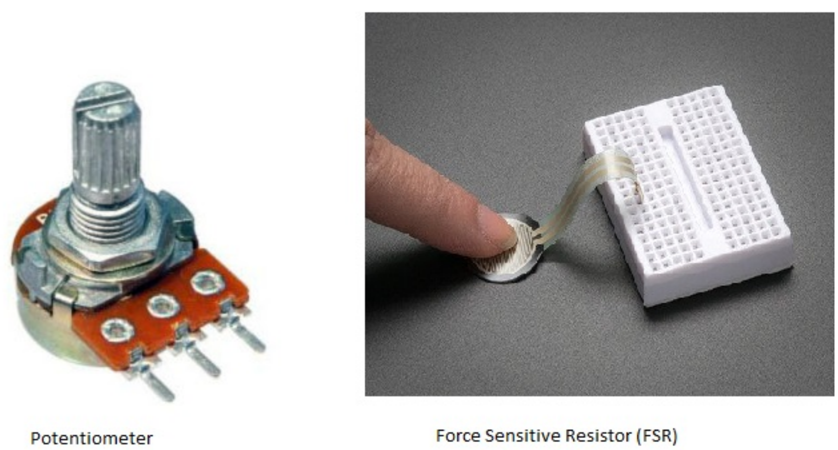

Figure 3.6: The inputs

3.1.5 The Output

The servo motor used for all 3 wrist mechanisms is the HS-M7990TH High Voltage, Mega Torque, Magnetic Encoder Ultra Premium Servo by Hitec. This servo was chosen as it has a good size to torque ratio and for a wrist, torque is everything. The most advanced wrist design is of no use if it does not produce sufficient toque to perform basic daily activities. The servo, though small, is still the limiting factor to the size of the prosthesis. With further developments in the servo technologies smaller, cheaper servos will be produced that will have similar, if not greater torque capacities. The model can then be redesigned for more compactness.

The specifications of the HS-M7990TH Servo [14] are given in table 3.1 below:

Dimensions	1.72" x 0.88"x 1.57" (43.8 x 22.4 x 40mm)
Product Weight	78.2g
Stall Torque (6.0V)	3.53 N-m
Stall Torque (7.4V)	4.31 N-m
No-Load Speed (6.0V)	0.21 sec/60°
No-Load Speed (7.4V)	0.17 sec/60°

Table 3.1: Servo Specifications

3.2 Area of Concentration

For this thesis the area of concentration will be the wrist mechanism with all 3 DOFs along with its motors and the electronics. The focus will be to design a working mechanism while keeping the design as simple as possible to allow for future modifications.

The various components put together to give the final model of the prosthesis is shown in Figure 3.7. The next chapter will concentrate on the individual mechanisms along with the parts involved, with their dimensions.

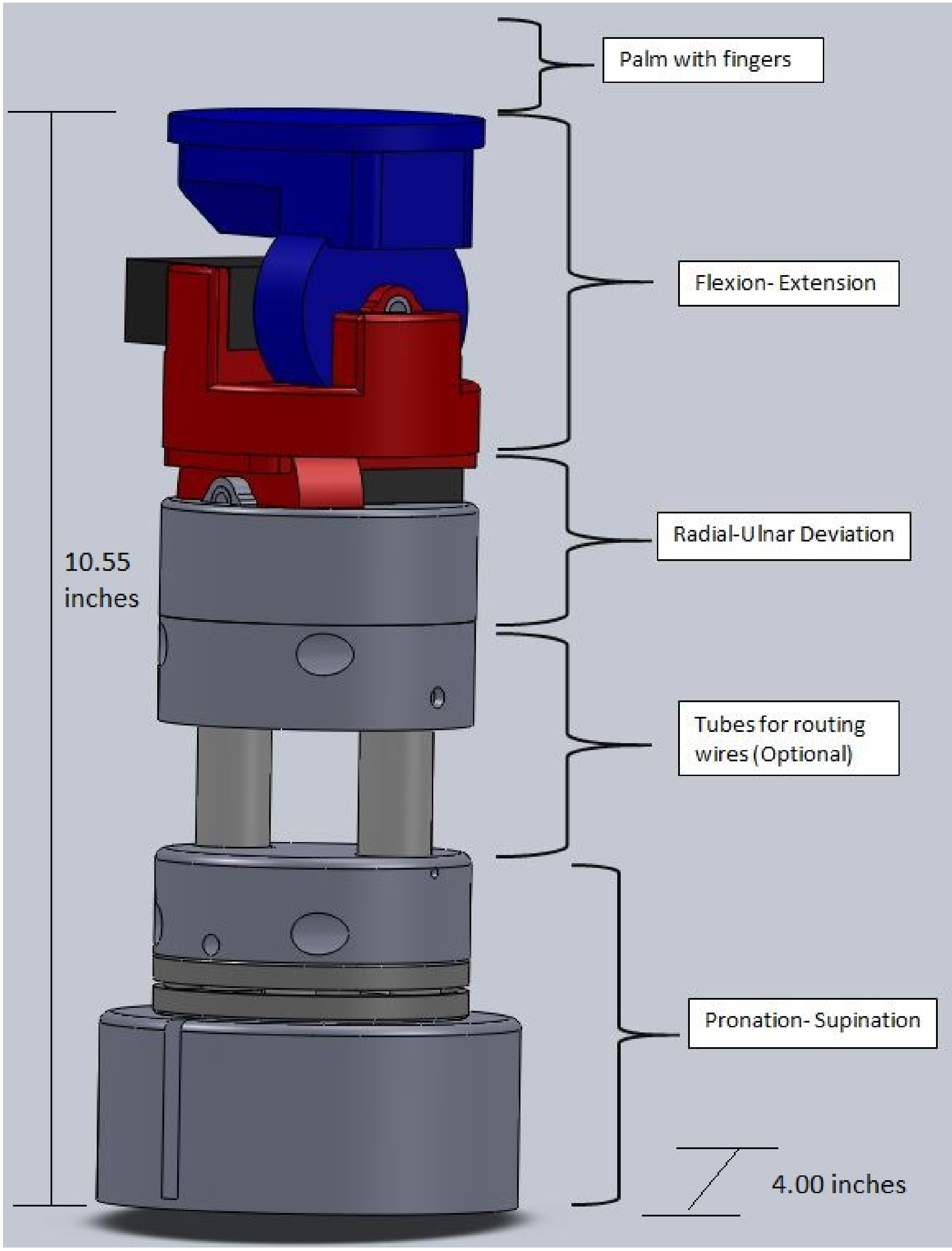

Figure 3.7: Prosthesis design with the mechanisms highlighted

3.3 Equipment

For the successful completion of this prosthetic model and this thesis a number of equipments were used.

The SolidWorks software (Version 2010 and 2016) was used for the 3D modeling and stress analysis of the design. The intuitive functionality of the software continues to improve in every version. Both the 3D modeling and analysis could be done easily with a lower learning curve than some of the other software available in the market.

The model was 3D printed on the Orion Delta Desktop 3D Printer RTP by SeeMeCNC. This printer is cheaper than its competitors but suffers from a few issues. Part warping was a huge issue. As the base of the part starts to cool, it starts warping, ultimately changing the final dimensions of the part. Part dimensions were not consistent and would increase or decrease by a few millimeters.Furthermore, the nozzle diameter is too big, which prevents any parts with intricate designs to be printed properly. Finally, 3D printing is a slow process. Each part had to be divided into smaller parts and then joined later as the longer it takes for a part to print, more does the part warp. Calibration of the machine has to be done manually which takes a lot of time and produces inconsistent results. Anyone wishing to 3D print parts needs to be ready to start over a few times and willing to machine the final part a little to make it suitable for use.

Other equipments used were power tools like the Dremel tool, Milwaukee Power Plus wireless drill and machinist tools to machine the 3D printed part for exact dimensions.

Chapter 4

Design of the Wrist Mechanisms

Table 4.1 at the end of this chapter gives a list of all the parts with their names used to make the model. These parts will be discussed in detail in this chapter.

4.1 The Flexion - Extension Mechanism

This section will concentrate on the flexion and extension of the wrist and how this mechanism can be adapted for a prosthesis.

To understand how to design any mechanism to mimic a body part, it is important to understand how the mechanism works in the human body. The following section gives information about the muscles and bones involved in Flexion - Extension and how they work together to achieve this mechanism.

4.1.1 Human Anatomy: Flexion- Extension

Flexion

According to Gray [9], flexion of the hand is a contribution of 6 muscles acting together.The *flexor carpi radialis* muscle, which crosses diagonally over the anterior portion of the forearm, relies on its main tendon for attachment. The main tendon runs underneath the *flexor retinaculum* across the wrist.The *Palmaris longus* muscle is located along the anterior portion of the forearm. The long and thin tendon,the *palmar aponeurosis*, assists in the process of wrist flexion.

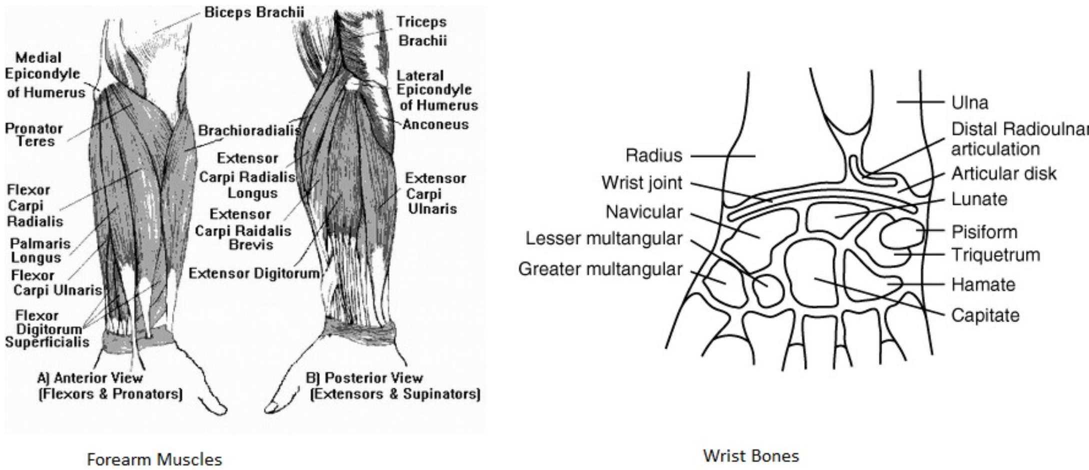

Figure 4.1: Muscles and bones involved in Flexion - Extension [8]

The *flexor carpi ulnaris* muscle is located along the medial anterior portion of the forearm.This muscle helps in flexion and adduction of the wrist.

Under these three muscles, the broad muscle, *flexor digitorum superficialis* runs just beneath the surface. This muscle runs along the humerus, the ulna, and the radius. Deeper than the digital flexor muscle rests the *flexor digitorum profundus.* Both of these muscles are responsible for flexion of the wrist as well as 2 fingers.

Extension

The posterior region of the forearm has the muscles responsible for extension of the hand. The long and tapered extensor muscle named *carpi radialis longus* lies medially to the *brachioradialis* muscle. This muscle is mainly responsible for extension and abduction at the wrist joint.

The *extensor carpi radialis brevis* can be located medially to the *carpi radialis longus* . This muscle is responsible for nearly identical functions as the *carpi radialis longus* muscle. The main difference between these two muscles is their points of origination.

In the most medial position the *extensor carpi ulnaris* can be found. It mainly adducts and extends the joints by running along the base of the fifth metacarpal bone.

The bones play a significant role in flexion and extension (Fig 4.1). The greater and lesser *multangulars* on the radial side and the *hamate* on the ulnar side slide forward and backward on the *navicular* and *triangular* respectively. In the cup-shaped cavity of the *navicular* and *lunate*, the head of the *capitate* and the superior surface of the *hamate* rotate. Flexion is freer than extension at this joint. [15]

4.1.2 The Designing of the Flexion- Extension Mechanism

The designing of this mechanism was carried with simplicity being the goal. The design would have to be easy to understand and replicate, simple enough to take it apart and assemble back quickly and would have to be modular with the fewest parts possible.

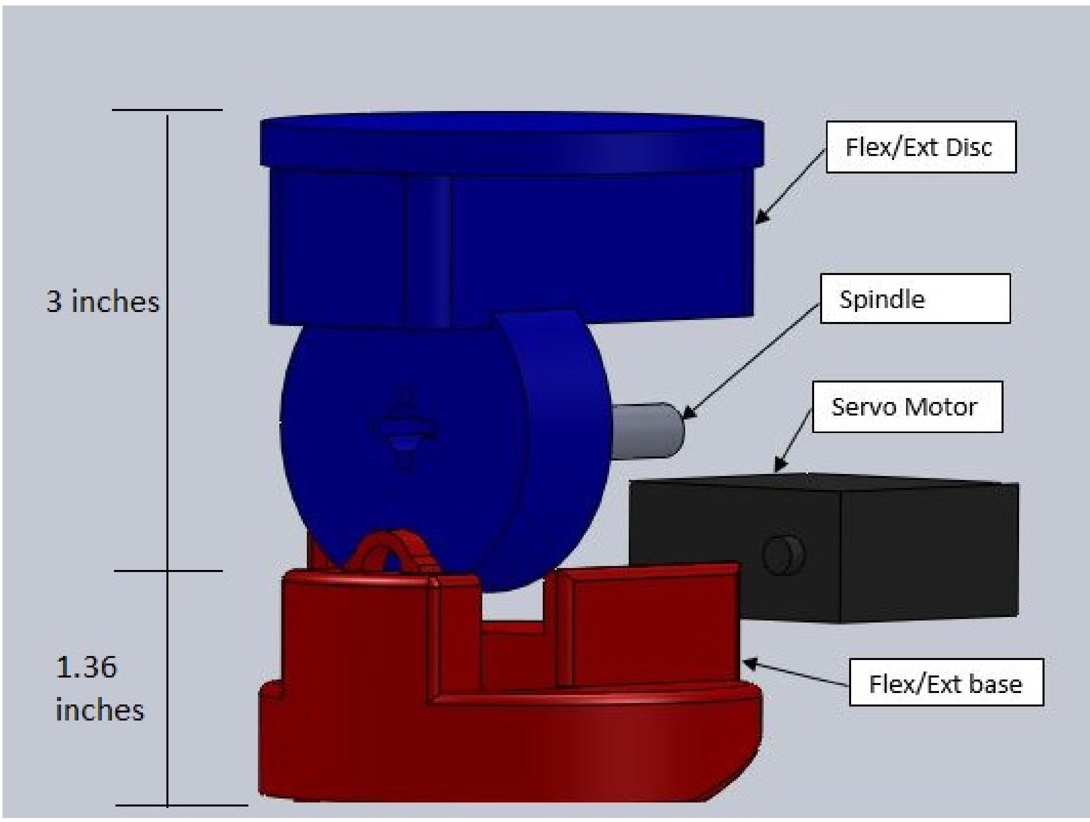

Figure 4.2: Parts for the Flexion - Extension mechanism

Figure 4.2 shows the different parts for the Flexion - Extension mechanism of the prosthesis. The Flex/Ext base has a groove in it in which the Flex/Ext disc fits and rotates. A silicone based lubricant is applied to ensure a smooth motion. The base also houses the servo motor which connects to the disc through a spindle. The spindle goes through the disc and rests in the circular groove on the base. The palm with fingers sits on the top platform of the disc.

The spindle has rectangular extensions on the circumference which fits into the disc through a similarly designed hole and locks the spindle with the disc. The design can be modified to provide a firmer lock which distributes the stresses evenly. This current design is selected for easy 3D printing.

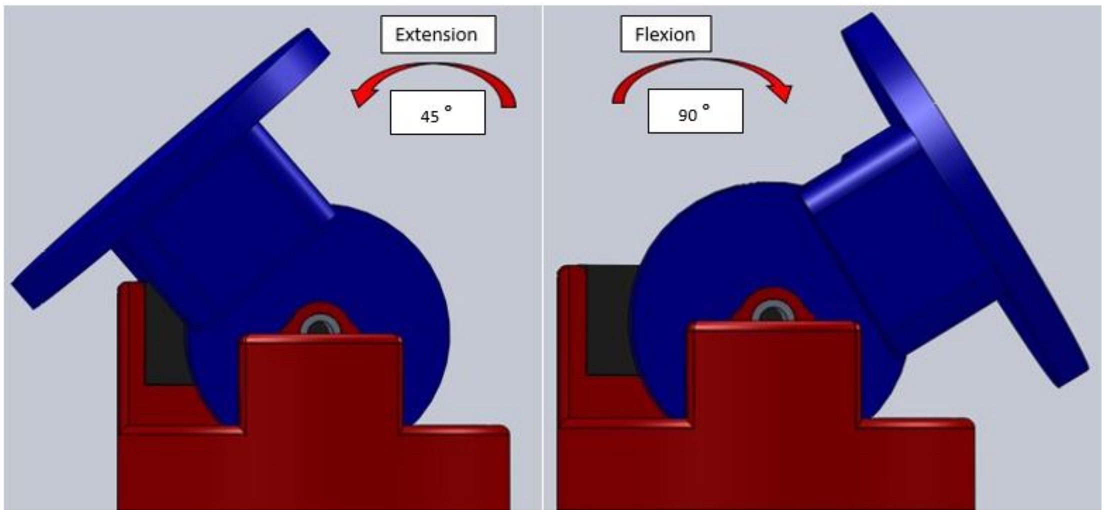

Figure 4.3: Flexion - Extension mechanism in action

When the servo rotates, the spindle and the connected disc rotates with it in either direction, mimicking the flexion and extension motion. The extension side of the base is designed such that the range of motion (ROM) is limited than that of flexion as the angle of extension is lower than the flexion angle in the human wrist. Rubber bumpers can be added to limit the wrist ROM further based on the preferences of the subjects (Fig 4.3).

The parts with their dimensions are given below:

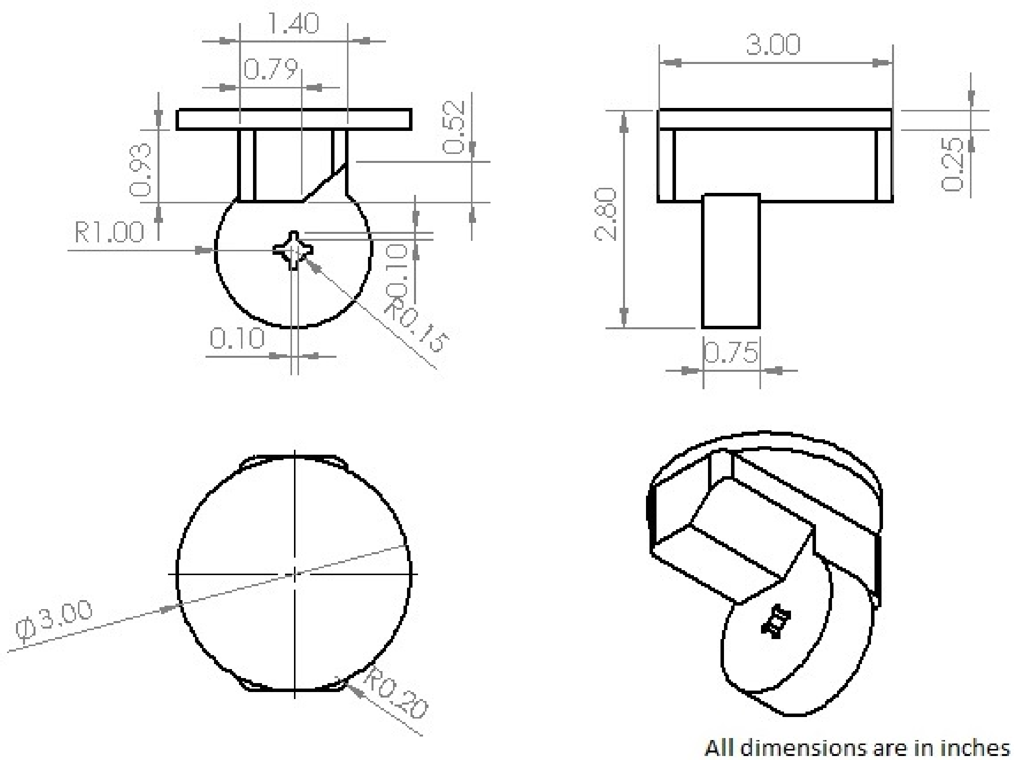

Figure 4.4: Dimensions of the Flex/Ext Disc

The Flex/Ext Disc (Figure 4.4) is the most distal part of the prosthesis, excluding the palm with the fingers which will be attached to the circular base on top of this part. The spindle goes through the center hole of the disc and locks it so that the disc can only rotate when the spindle rotates.

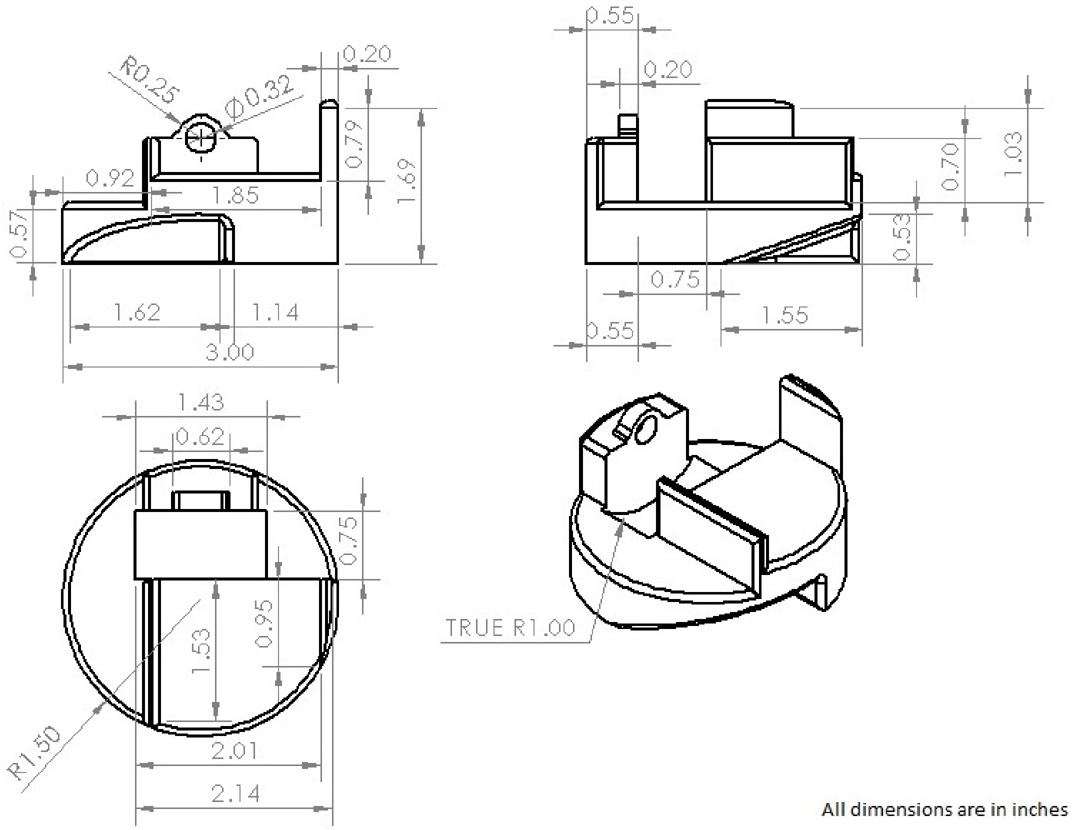

Figure 4.5: Dimensions of the Flex/Ext Base

The Flex/Ext base (Fig 4.5) has a circular groove for the disc to fit in and freely. The groove limits the disc to rotate in only one plane. The base has a seat for housing the servo motor which connect to the disc via a spindle and helps in limiting the disc movement to the plane of rotation.

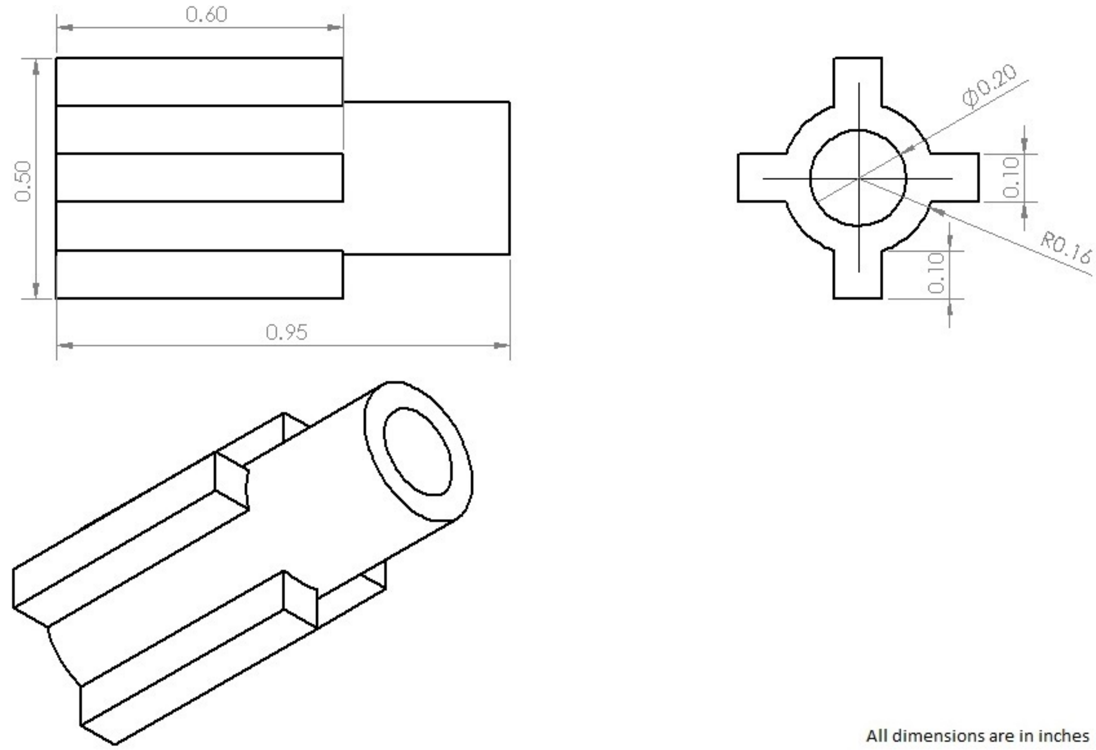

Figure 4.6: Dimensions of the Spindle

The spindle design (Fig 4.6) is the most modifiable amongst all the parts. It can be changed depending on the servo spindle. The threads inside the circumference of the spindle can be made to match the threads on the servo spindle for a snug fit. The spindle can also be glued or screwed to the servo spindle as the main forces acting on it will be perpendicular to its length and not parallel to it. The rectangular design along the circumference of the spindle can also be changed to increase the surface of contact with the disc for enhanced locking.

4.2 The Radial - Ulnar Deviation Mechanism

This section will concentrate on the radial and ulnar deviation of the wrist and how this mechanism can be adapted for a prosthesis.

The following section will discuss how the muscles and bones work together to achieve Radial- Ulnar deviation in the actual human hand.

4.2.1 Human Anatomy: Radial - Ulnar Deviation

Radial Deviation

Radial deviation, also called abduction, is the motion of the hand bending towards the radius. *Flexor Carpi Radialis*, a long muscle, originates from the *humerus* and attaches to the base of the digits.This muscle helps in radial deviation at the wrist along with the *extensor carpi radialis brevis* muscle (Fig 4.1).

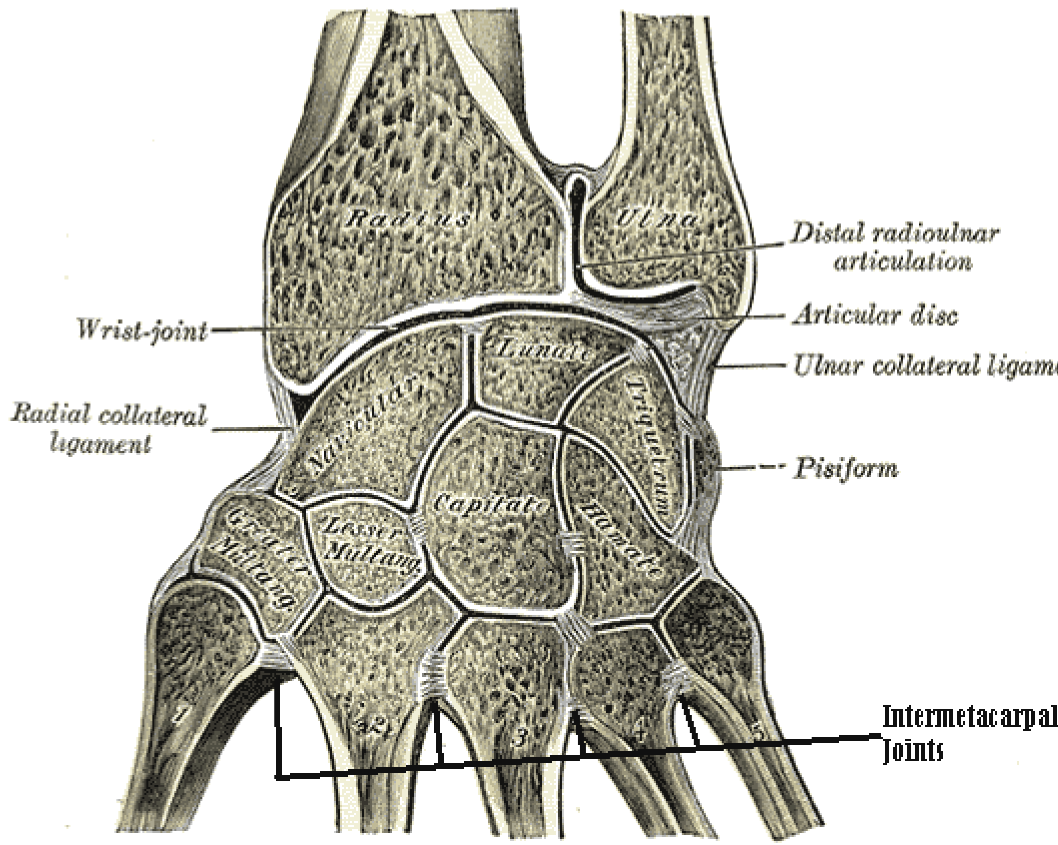

Figure 4.7: Bones involved in Radial - Ulnar Deviation [9]

Ulnar Deviation

Ulnar Deviation or adduction of the hand is considerably greater than abduction due to the more proximal site of *ulnar styloid* process and it occurs mostly at the radiocarpal joint; while at the midcarpal joint the abduction from the neutral position occurs.*Flexor Carpi Ulnaris*, a long muscle, originates from the *humerus* and ulna and attaches to one of the carpal bones in the wrist. This muscle helps in the ulnar deviation at the wrist along with the *extensor carpi ulnaris* muscle.

The bones involved in the Radial- Ulnar deviation are given in Fig 4.7. The adduction/abduction movements occur around an AP axis perpendicular to the axis of the 3rd metacarpal bone if extended through the distal radius. In abduction much of the proximal articular surface of the *scaphoid* becomes subcapsular beneath the radial collateral ligament and forms a smooth, convex, palpable prominence in the floor of the anatomical snuff box 1. The *capitate* rotates around an AP axis while its head passes medially and the *hamate* conforms to this and the distance between the *lunate* and the apex of the *hamate* is increased. During abduction the *scaphoid* rotates around a transverse axis; to articulate with the radius, the proximal articular surface moves away from the capsule. The proximal and distal carpal rows are bridged by the *scaphoid* providing a functional couple between the two. [16]

4.2.2 Designing of the Radial- Ulnar Deviation Mechanism

The mechanism for radial and ulnar deviation is the same as the one for flexion- extension. The main difference is that the angle of movement is restricted as compared to the former, just as in an actual human hand.

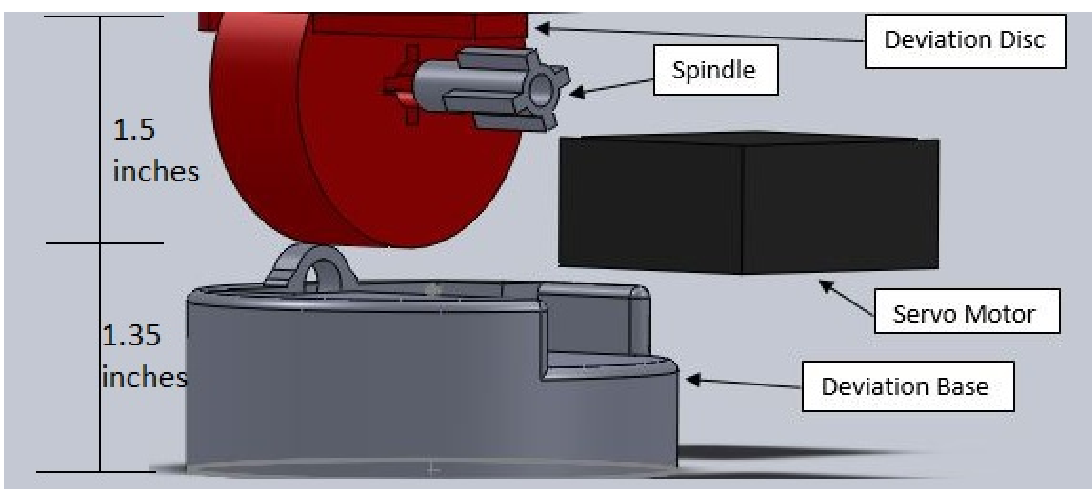

Figure 4.8: Parts for the radial - ulnar deviation mechanism

Figure 4.8 shows the parts involved in the mechanism. The deviation disc is connected to the flexion base at the top. The disc sits in the groove of the deviation base and is free to rotate in it. A silicone based lubricant is applied to ensure a smooth motion. The servo motor sits in the base and is connected to the disc via the spindle. The spindle is the same as the one used in the previous mechanism.The servo motor is programmed to rotate in specific directions and for specific angles thus mimicking radial- ulnar deviation (Fig 4.9).

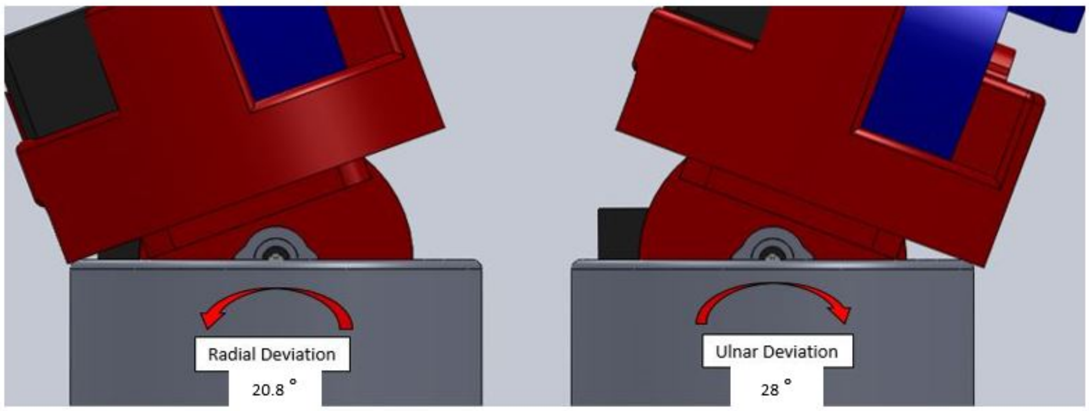

Figure 4.9: Radial - Ulnar deviation mechanism in action

The parts with their dimensions are given below:

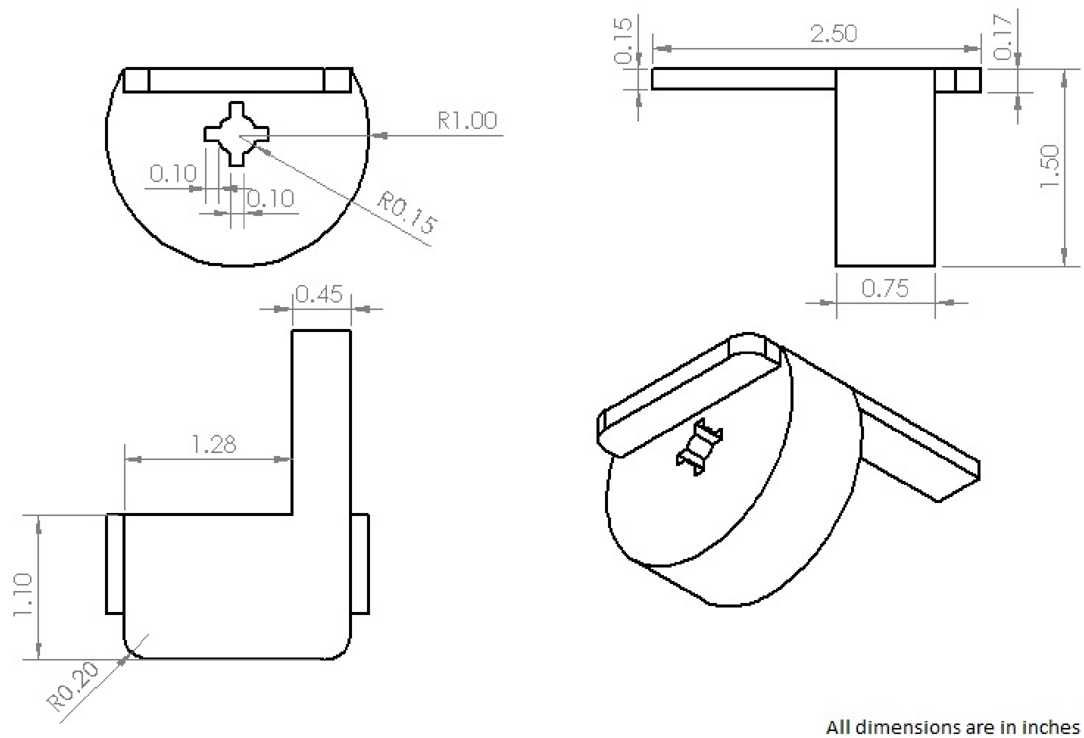

Figure 4.10: Dimensions of the Deviation Disc

The Deviation Disc (Fig 4.10) is similar to the Flex/Ext Disc with the exception of the top platform. There is no need for a circular platform as this disc will be directly connected to the Flex/Ext Base on top. The disc has an L shaped structure on top to help distribute the weight coming from the distal end of the hand i.e. the Flex/Ext mechanism and the Palm with fingers.

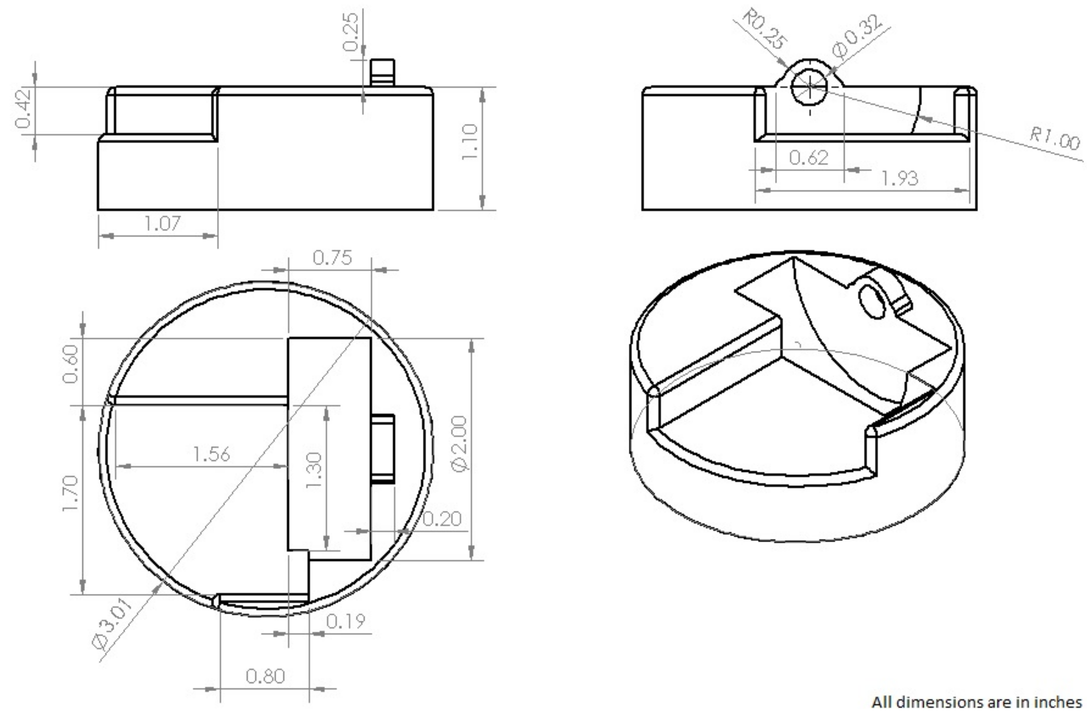

Figure 4.11: Dimensions of the Deviation Base

The Deviation Base (Fig 4.11) has a groove similar to the Flex/Ext Base but is much deeper as the Range of Motion (ROM) for the deviations is much more limited than that of Flexion- Extension. The Base has a seat for the servo motor as well.

The spindle for deviation has the same design as the one for the Flex/Ext mechanism (Fig 4.6) and can also be modified for better stress distribution and a better locking design. The spindle is the smallest part in this entire prosthesis, making the prosthesis easy to assemble and disassemble for maintenance and suitable for children by reducing the choking hazards and easy replacement of parts.

4.3 The Pronation - Supination Mechanism

The third DOF is the ability to rotate the hand which is called pronation and supination. The mechanism for this motion has been designed at a very basic level and will be developed further in the future as it has to be attached to the sleeve with possible elbow mechanism integrated in it as well.

The following section shows the muscles and bones responsible for pronation and supination and how this mechanism is achieved in an actual human hand.

4.3.1 Human Anatomy: Pronation and Supination

Pronation

Two muscles in the forearm, as seen in Figure 4.12, the *pronator teres* and *pronator quadratus*, are responsible in achieving pronation by pulling the radius bone of the forearm. The radius is specially designed to rotate at the elbow and wrist joints around the other forearm bone, the ulna. During pronation, end of the radius rotates around the ulna from the lateral side to the medial side of the wrist.

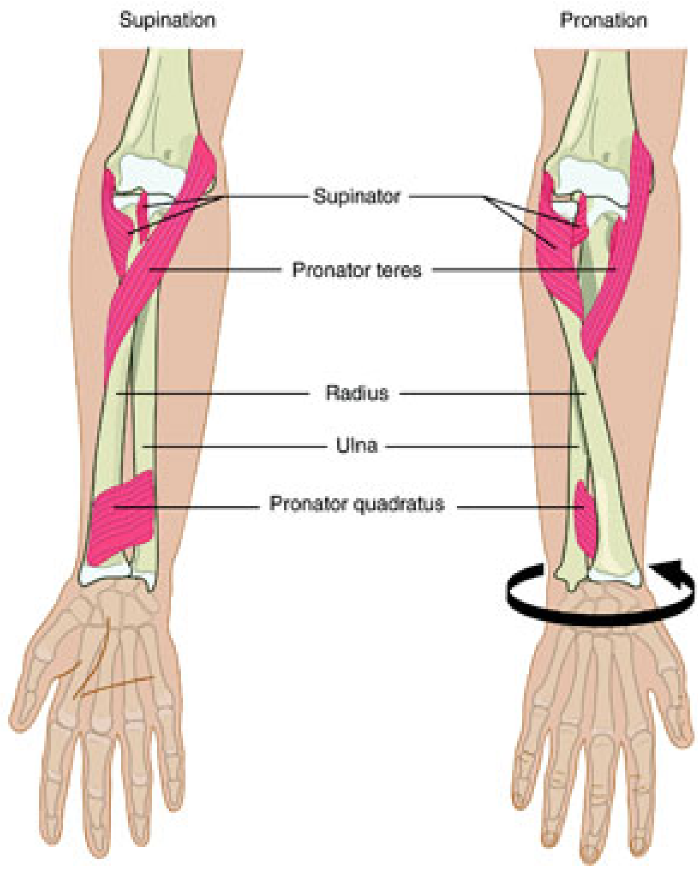

Figure 4.12: Muscles and bones involved in Pronation and Supination [10]

Supination

In the anatomical position, with the arms extended to the sides of the trunk and palms facing forward, the arms are already in the supinated position. The motion of supination rotates the palms anteriorly or superiorly to the face-up position. The forearm supinates when the supinator muscle of the forearm and the *biceps brachii* of the upper arm pulls on the radius. These muscles rotate the radius in the opposite direction of the pronator muscles, moving the distal end of the radius back to its position on the lateral side of the wrist [17].

4.3.2 The Designing of the Pronation- Supination Mechanism

Figure 4.13 gives the parts associated with this mechanism. This simplified version of the mechanism has a plastic turntable with ball bearings in it, which is connected to the servo housing on one end and to the top attachment on the other. When the servo rotates, the top attachment, connected to the servo by the spindle, rotates and the turntable provide a smooth friction less rotation. The spindle connects the servo to the upper attachment, going through the center of the turntable.

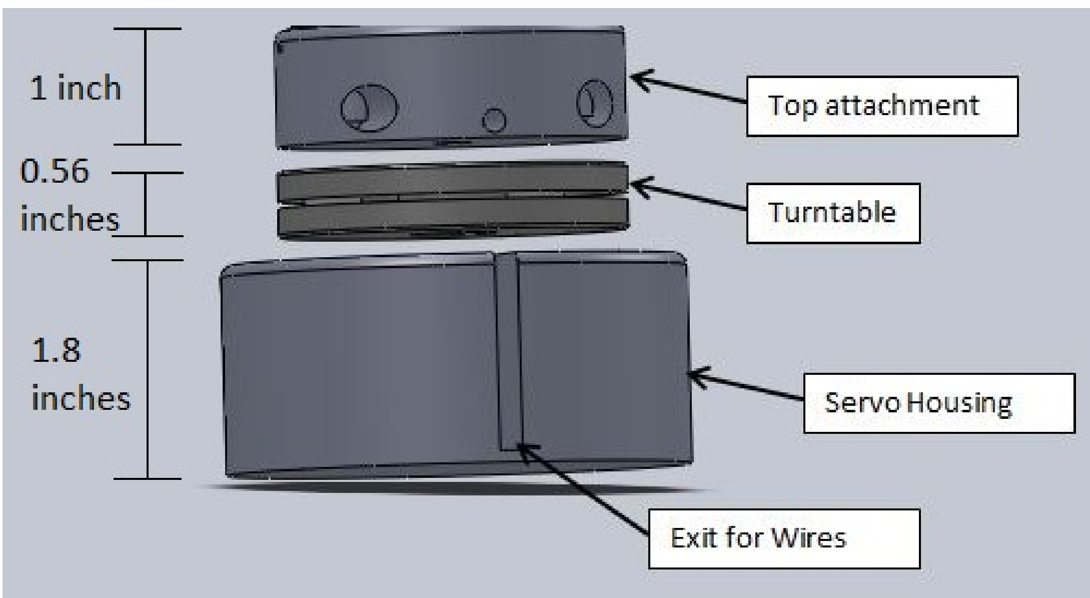

Figure 4.13: Parts of the pronation - supination mechanism

The parts with their dimensions are given below:

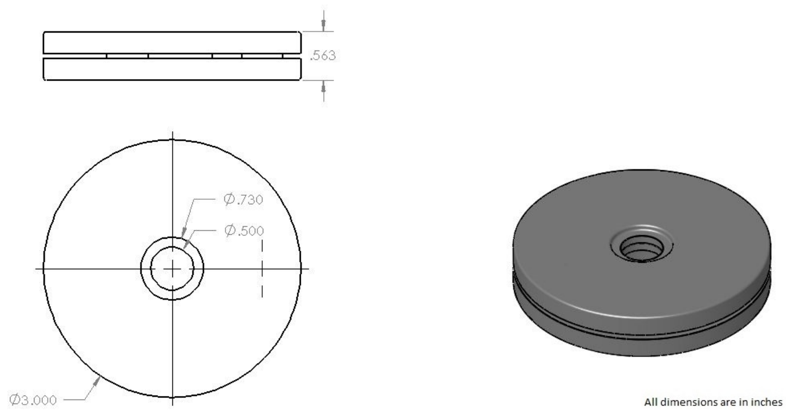

Figure 4.14: Dimensions of the Turntable

Figure 4.14 is a standard plastic turntable widely available in the market. It has two discs separated by ball bearings so that one disc can rotate with respect to the other.

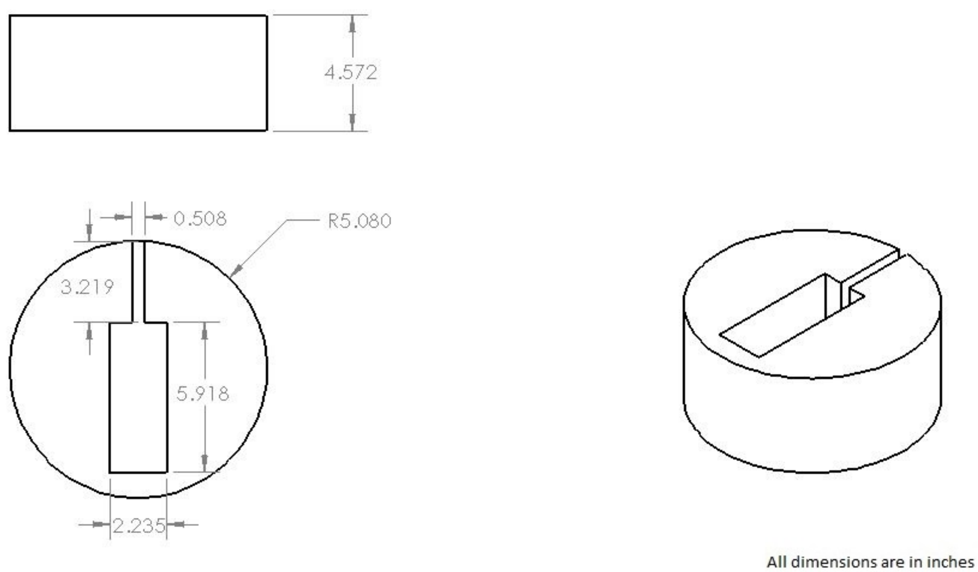

Figure 4.15: Dimensions of the Servo Housing

Figure 4.15 shows the Servo Housing and as the name suggests houses the servo motor while also acting as the base of the entire prosthesis model for the purposes of this thesis. This part will later be modified to accommodate the connector sleeve or even incorporate the elbow joint mechanism in it. That is not within the scope of this thesis. This Servo Housing will be the most proximal part of this prosthesis and will be closest to the residual limb.

4.4 Motor Control

The servos for all the mechanisms and the fingers are programmed through the arduino board. The input to the servos controlling the fingers are Force Sensitive Resistors(FSR). The inputs to the servos for the mechanisms can be a number of things but for this thesis, potentiometers working as variable resistors are selected for the precision they offer. In the future, with the correct positioning and calibration of the FSRs, these servos can too be given an input through the FSRs.

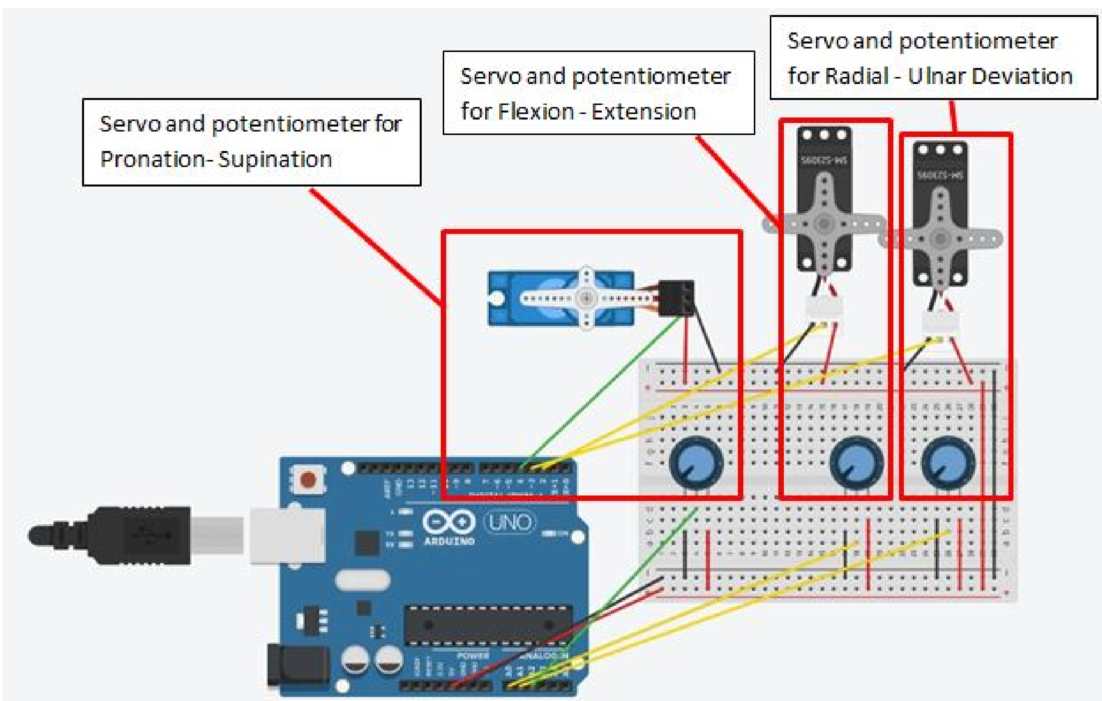

Figure 4.16: Circuit for the Wrist Mechanisms

The arduino program for the circuit above is as follows:

```
#include <Servo.h>

Servo FlexExtServo;
Servo RadUlnDevServo;
Servo ProSupiServo;

int const potPinFlex = A0;  //analog pin for the Flexion-Extension mechanism
int potValFlex;             //stores value of the Flex/Ext potentiometer
int angleFlex = 0;          //stores position of the Flex/Ext servo

int const potPinDev = A1;   //analog pin for the Radial- Ulnar Deviation mechanism
int potValDev;              //stores value of the Deviation potentiometer
int angleDev = 0;           //stores position of the Rad/Ulnar Deviation servo

int const potPinPro = A2;   //analog pin for the Pronation- Supination mechanism
int potValPro;              //stores value of the Pronation- Supination potentiometer
int anglePro = 0;           //stores position of the Pro/Supi servo

void setup() {
  FlexExtServo.attach(2);       //tells board that the Flex/Ext servo is on output pin 2
  RadUlnDevServo.attach(3);     //tells board that the Rad/Ulnar servo is on output pin 3
  ProSupiServo.attach(4);       //tells board that the Pro/Supi servo is on output pin 4
  Serial.begin(9600);
}

// the loop routine runs over and over again forever:
void loop() {
  potValFlex = analogRead(potPinFlex);
  Serial.print("potValFlex: ");
  Serial.print(potValFlex);                       //Displays the Potentiometer value on the Serial Monitor

  angleFlex = map(potValFlex, 0, 1023, 0, 179); //angle is the pot value re-scaled to 0-179 degrees
  Serial.print("angleFlex: ");
  Serial.println(angleFlex);                      //Displays the re-scaled pot value as an angle on the Serial Monitor
 FlexExtServo.write(angleFlex);                   //Tells servo to rotate to the re-scaled pot value
  delay(15);

  potValDev = analogRead(potPinDev);
  Serial.print("potValDev: ");
  Serial.print(potValDev);                        //Displays the Potentiometer value on the Serial Monitor

  angleDev = map(potValDev, 0, 1023, 0, 179);   //angle is the pot value re-scaled to 0-179 degrees
  Serial.print("angleDev: ");
  Serial.println(angleDev);                       //Displays the re-scaled pot value as an angle on the Serial Monitor
  RadUlnDevServo.write(angleDev);                 //Tells servo to rotate to the re-scaled pot value
  delay(15);

  potValPro = analogRead(potPinPro);
  Serial.print("potValPro: ");
  Serial.print(potValPro);                        //Displays the Potentiometer value on the Serial Monitor

  anglePro = map(potValPro, 0, 1023, 0, 179);   //angle is the pot value re-scaled to 0-179 degrees
  Serial.print("anglePro: ");
  Serial.println(anglePro);                       //Displays the re-scaled pot value as an angle on the Serial Monitor
  ProSupiServo.write(anglePro);                   //Tells servo to rotate to the re-scaled pot value
  delay(15);
}
```

Figure 4.17: Arduino program for the Wrist mechanisms

Each mechanism i.e Flexion- Extension, Radial- Ulnar Deviation and Pronation-Supination has a separate servo motor that is being controlled by individual potentiometers. The circuit for the wrist mechanisms can be seen in Figure 4.16. The arduino collects the analog signal produced when the potentiometer dial is rotated. The potentiometer values are scaled to the angles that the servo can rotate. So any change in the dial is reflected by the turn of the servo spindle. Each servo has a different potentiometer so each servo can be controlled independent of the others.

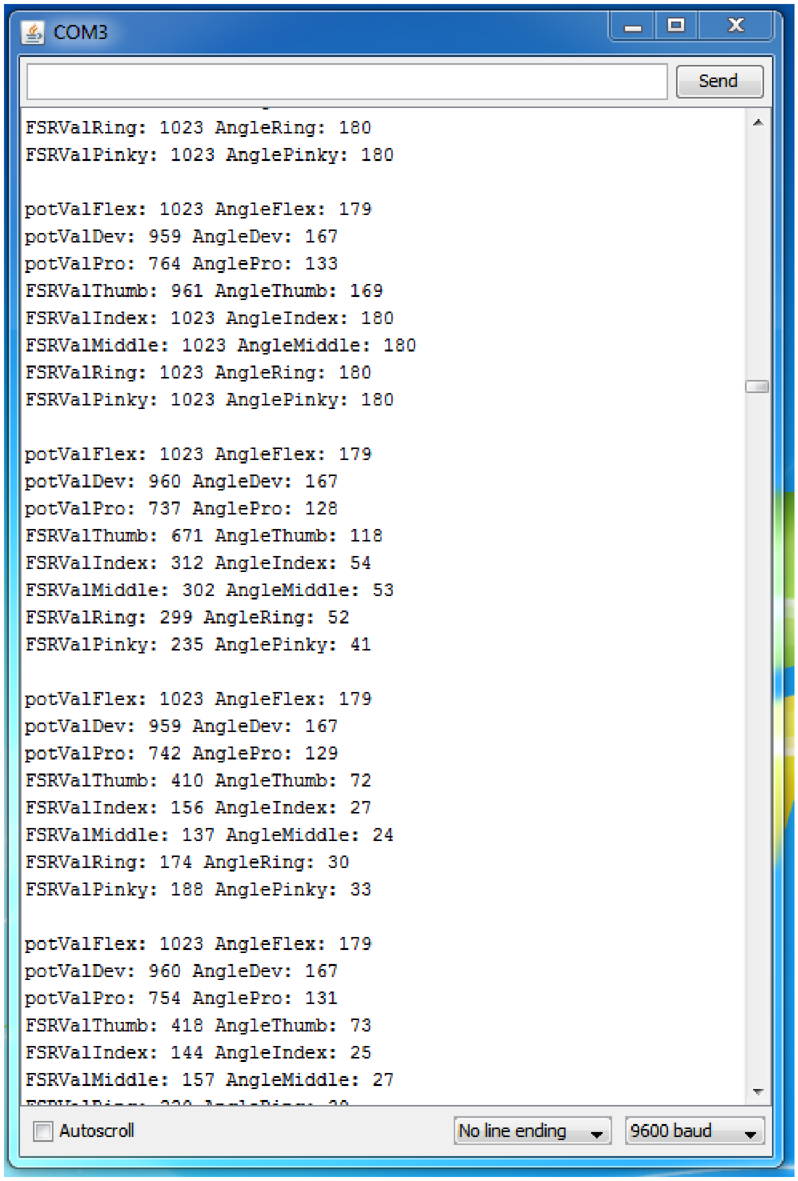

Figure 4.18: Arduino Serial Monitor

When the arduino is connected to a computer, all the input and output values can be seen and analyzed through the Serial monitor in the arduino IDE on the computer in order to fine tune or debug the program. Figure 4.18 shows the Serial Monitor for the arduino code for the entire prosthesis including the fingers. These values are updated in real-time and are very useful when checking how the input is affecting the output. In order to be able to see these values, a few lines must be added to the code as seen in Figure 4.17.

Mechanism	Part Name	Description
Flexion-Extension	Flex/Ext Disc	This is the most distal part of the wrist. The Palm with fingers is attached on the top surface.
	Spindle	This connects the servo motor to the disc and has a distinct shape to ensure that the disc rotates with the spindle.
	Flex/Ext Base	This part has a circular groove in which the disc rests and rotates. It also houses the servo motor.
	Servo Motor	This motor is programmed and is given an input to rotate the disc via the spindle to perform the Flex/Ext motion.
Radial - Ulnar Deviation	Deviation Disc	The Flex/Ext base is attached to the top of this part. This part has a circular disc and a through hole for the spindle.
	Spindle	This spindle is identical to the one used in the Flex/Ext mechanism.
	Deviation Base	This part has a circular groove in which the Deviation Disc fits and rotates. It also has a housing for the servo motor.
	Servo Motor	A similar servo motor to the one used for the Flex/Ext mechanism is used.
Pronation - Supination	Top Attachment	The Deviation Base attaches to the top of this part. This also has holes for all the wires to pass through from above through glass tubes.
	Turntable	This is a simple plastic turntable that is connected to parts on both sides and which rotates with the help of ball bearings within it.
	Servo Housing	This part acts as the base of the entire model as well as a housing for the servo motor
	Servo Motor	A similar servo motor to the one used for the Flex/Ext mechanism is used.
	Spindle	This spindle is also identical to the one used in the Flex/Ext mechanism.

Table 4.1: Part List

Chapter 5

Analysis

Basic analysis of this design has been done, primarily to determine the feasibility of the design and the mechanism. A prototype was 3D printed to test this and to demonstrate the mechanisms.

5.1 Finite Element Analysis (FEA)

Using the analysis tools available in the 3D modelling software, SolidWorks 2016, the stress and deformation were calculated for the entire wrist by assigning different materials to the model.

5.1.1 Boundary Conditions

For this analysis, the Base of this model has been fixed. Both the upper and lower spindles are given a no penetration contact with the surrounding Disc. This ensures that during the analysis the Disc does not intersect with the spindle, thus giving an accurate representation of the stresses produced. The lower spindle is also fixed as in the prototype this spindle is connected to the servo. The servo is attached to the fixed Base. The other parts have been given a bonded contact which converts all the different parts into one part as if welded together.

A normal force is applied to calculate how much weight can be carried by the hand safely without causing any significant deformations. Torque analysis was not carried out for this thesis.

5.1.2 Material Selection

We considered 3 materials for this analysis:

- ABS (Acrylonitrile-Butadiene-Styrene): This being the material of the 3D printed prototype.
- Stainless Steel (ferritic): This material is commonly available and has good machinability and has a high yield strength. However, this material is heavy.
- PVC (Polyvinyl chloride): This material is promising for this type of application, being both strong and light weight.

  The properties of the materials and the weights of the wrist when these materials are used are given below:

Name	Density (kg/m^3)	Modulus of elasticity (GPa)	Yield Strength (MPa)	Weight of wrist model (kg)
ABS	1020	1.1 - 2.9	30	0.34
PVC	1300	2.4 - 4.1	40.7	0.47
Stainless Steel (ferritic)	7800	200 - 215	172.33	2.58

Table 5.1: Material Properties

5.1.3 Simulation

In SolidWorks, the model was assigned the ABS material and a normal force of 100 N was applied to the top platform to mimic the hand holding a weight of 10 kg. The model was meshed using the standard settings and the simulation was carried out. The results are given below.

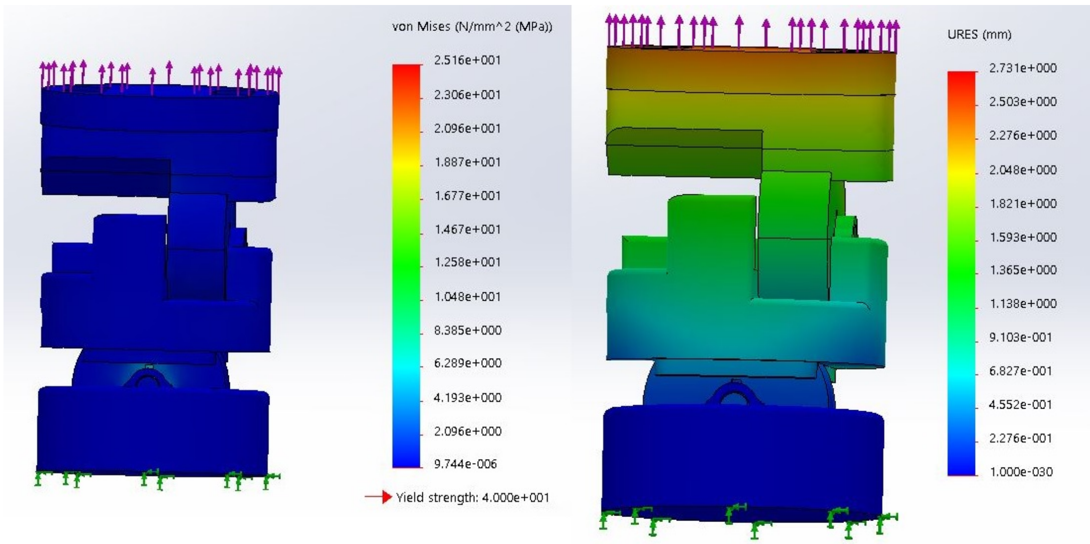

Figure 5.1: Stress and Displacement when ABS is used and a pulling force of 100 N is applied

It can be seen that the ABS model can safely carry 100N or 10kg of weight without causing any significant stresses or deformations. However a similar analysis for the PVC and stainless steel model revealed that they deflect even less when subjected to the same weight.

5.2 Results

The results of the analysis using all three materials are given below:

5.2.1 FEA Results

This section will give the results of the SolidWorks stress and displacement analysis. Table 5.2 gives details of the materials used, the weight applied to the model and the corresponding maximum stress, strain and displacement produced.

Name	Weight applied (Kg)	Maximum Strain	Maximum Stress (MPa)	Maximum Displacement (mm)
ABS	10	0.0012	25.16	2.73
PVC	10	0.0095	25.22	0.24
Stainless Steel(ferritic)	10	0.00012	27.19	0.03

Table 5.2: Analysis Results

Figure 5.2 shows a cross-section of the stress analysis for the ABS model. It also shows the point where maximum stress occurs when a pulling force of 100 N is applied. As seen in the figure, the point of maximum stress occurs in the lower spindle. The spindle is connected to the servo motor which is attached to the Deviation Base which is in turn fixed. The spindle also has a no penetration contact with the Deviation Disc, which is why when any pulling force is applied maximum stress is concentrated at the point shown in the figure.

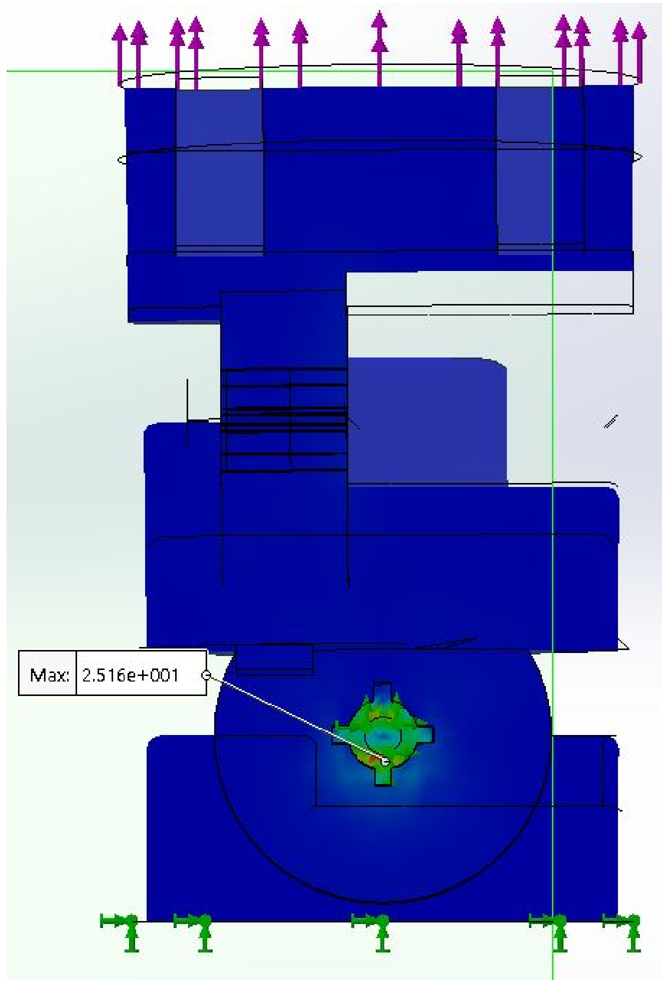

Figure 5.2: Cross-sectional view with point of maximum stress (MPa) under a force of 100 N

The simulations and point of maximum stress for the stainless steel and PVC models are similar but with different values as given in Table 5.2.

Figure 5.3 gives a plot of the weight carried by the prosthesis and the corresponding maximum stress produced by that weight till failure occurs i.e the maximum stress exceeds the yield strength of the material. It can be seen that failure occurs in the ABS model when more than 25kg of weight is applied.

1 MPa= 10^6 N/m^2

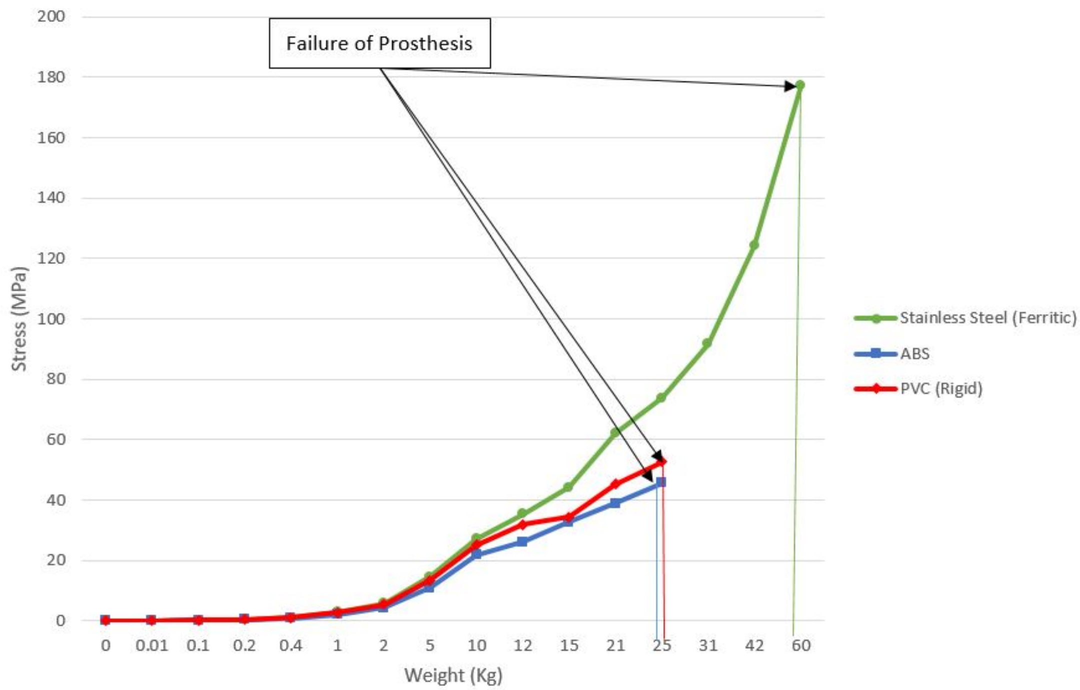

Figure 5.3: Weight vs Maximum Stress

5.2.2 Kinematic Results

The angles of movement(Range of Motion(ROM)) of all the prosthesis mechanisms are compared to the angles of movement of the actual human hand [18] and the values are given below:

Motion	ROM in human hand (Degrees)	ROM in the Prosthesis (Degrees)
Flexion	80	90
Extension	70	45
Ulnar deviation	30	28
Radial deviation	20	20.8
Supination	90	90
Pronation	90	90

Table 5.3: Range of Motion Results

The ROM for the prosthetic mechanisms can be shortened by adding blocks to stop the motion early or by removing material to extend the motion. These are changed based on subject's feedback and preference.

Chapter 6

Conclusion

In conclusion, this thesis shows the mechanisms for the 3 DOFs in a human wrist and how it can be incorporated in an upper limb prosthesis. The aim during designing these mechanisms was to keep it simple, not make it too bulky, and make it easy to use and maintain. The potential materials for the prosthesis were briefly discussed and the corresponding weight capacities, stresses involved and the deformations caused were seen. Sheet metal can also be used to produce this prosthesis in the future, which would be relatively lighter yet still be strong enough for daily use. This current design is by no means the final design. It can be further streamlined and modified to include more functionalities and better aesthetics. This design is a proof of concept of the mechanisms, that can quickly and easily be produced and used.

The goal of designing a wrist prosthesis with 3 independent degrees of freedom i.e Flexion - Extension, Radial - Ulnar deviation and Pronation - Supination, has been achieved in this thesis. As seen earlier no other designs available have all these DOFs working simultaneously without being body controlled as well. From this the hope is that more people are encouraged to develop on this design and make better and cheaper prostheses so that there is no one who will have to choose between using a cumbersome prosthesis and living without a limb.

Future Work

A connector sleeve is under development and is the next step to this prosthesis. The connector sleeve contains sensors that register the user's volitions and also connects the residual limb to the prosthesis. The FSRs are used to register the residual muscle movements as control signals. In other words, they are the inputs to the man-machine interface. These FSRs are embedded throughout the sleeve that will then be fastened to the residual limb while the other end is connected to the prosthesis. Operation of the sleeve is beyond the scope of this thesis, but is described in Craelius, Science, 2002 [19]

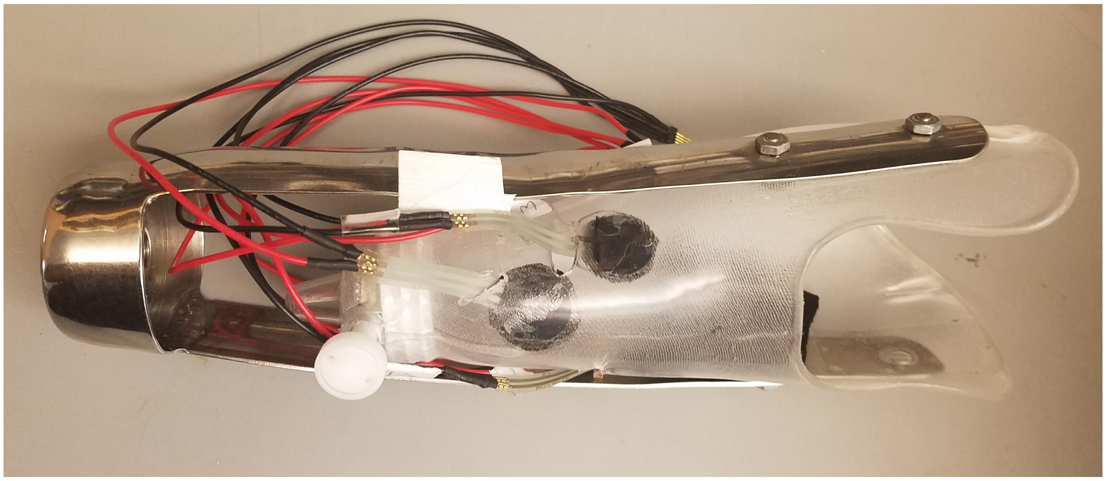

Figure 6.1: The connector sleeve with FSRs embedded along the inner surface(Under development)

In the future, the connector sleeve needs to be designed. This requires mathematical algorithms to decode muscular signals.

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