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Powered Wrist Actuator

Defining futures

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ELECTRICAL AND MECHANICAL ENGINEERING
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THESIS REPORT

POWERED WRIST ACTUATOR

Submitted to the Department of Mechatronics Engineering
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ACKNOWLEDGEMENT

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ABSTRACT

The human arm is certainly the most powerful tool a human being has. It is utilized in every task a human performs, from simple tasks like getting up or sitting on a chair to extreme sports like mountain climbing or squash and tennis. The absence of this tool due to any number of reasons can be very disturbing for the amputee and this disability can be mentally and physically torturing. So the modern science is doing its level best to create artificial limbs that can replace the natural arm.

As the human arm consists of three separate joints, namely the wrist, elbow and shoulder joint, the amputation can also be of different types, like above elbow, below elbow or complete arm amputation from the shoulder joint. This requires that separate prosthetic joints should be available that can be easily attached either to the human user or can be attached to each other to form a complete prosthetic arm.

The purpose of this thesis was to create a prosthetic wrist joint that can behave like a human wrist and can be easily carried by a human user. So a 2-DOF powered prosthetic wrist actuator has been proposed that can provide the Abduction/Adduction & Flexion/Extension movements of the human wrist. The basic structure of the actuator is a Ball & Socket joint and the force is transmitted from the DC geared servo motors to the joint through the Bowden cables. The proposed design is capable of providing the required degrees of rotation in both axes i.e. 85° & 90° in flexion extension axis. The size and weight of the actuator lies within the ranges of an average human being's wrist.

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CHAPTER 1

INTRODUCTION

1 Introduction

1.1 Prosthesis

In medicine, “prosthesis, prosthetic, or prostheticlimb is an artificial device extension that replaces a missing body part”. It is anarea of bio mechatronics, “the science of using mechanicaldevices with human muscle, skeleton, and nervoussystems to assist or enhance motor control lost by trauma, disease, or defect”. Prostheses are typically used to replace parts lost by injury (traumatic) or missing from birth (congenital) or to supplement defective body parts.

1.2 Robotic Prosthesis

For a robotic prosthetic limb to work, it must have numerous components to integrate it into the body's function: Biosensorsdetect signals from the user's nervous or muscular systems. It then relays this information to a controller located inside the device, and processes feedback from the limb and actuator (e.g., position, force) and sends it to the controller. Examples include wires that sense electrical activity on the skin, needle electrodes rooted in muscle or solid-state electrode collections with nerves growing through them.Mechanical sensors process featuresdisturbing the device (e.g., limb position, applied force, load) and relay this information to the biosensor or controller. Examples include force meters and accelerometers.Thecontroller is connected to the user's nerve and muscular systems and the device itself. It sends intention instructions from the user to the actuators of the device and interprets feedback from the mechanical and biosensors to the user. The controller is also responsible for the monitoring and control of the movements of the device.Anactuatorimitates the actions of a muscle in creating force and movement. Examples include a motor that aids or replaces original muscle tissue.

1.3 Types of Upper limb prosthesis

There are different types of upper limb prosthesis.

1.3.1 Transhumeral Prosthesis (Above Elbow)

“Above-elbow prosthesis consists of a single plastic upper arm shell, an elbow joint usually with incorporated locking mechanism, a plastic forearm and a wrist joint to which is attached a terminal device, either a hook or a hand”.

1.3.2 Transradial Prosthesis (Below Elbow)

"Below elbow prosthesis consists of forearm, wrist joint and terminal device".

1.4 Scope of Investigation

The purpose of this thesis was to create a prosthetic wrist joint that can behave like a human wrist and can be easily carried by a human user. So a 2-DOF powered prosthetic wrist actuator has been proposed that can provide the Abduction/Adduction & Flexion/Extension movements of the human wrist. The basic structure of the actuator is a Ball & Socket joint and the force is transmitted from the DC geared servo motors to the joint through the Bowden cables. The proposed design is capable of providing the required degrees of rotation in both axes i.e. 85° & 90° in flexion extension axis. The size and weight of the actuator lies within the ranges of an average human being's wrist.

1.5 Review of Thesis Contents

The thesis is organized as follows:

Chapter 2 examines the human wrist joint in detail; its structure and movements.

Chapter 3describes some previous work done on the same topic by other researchers in the form a literature review.

Chapter 4 provides the details of the proposed wrist actuator, its structure, force transmission and the resulting movements.

CHAPTER 2

HUMAN WRIST JOINT

2 The Human Wrist

2.1 Wrist Structure

The wrist joint is placed between the hand and the forearm bones and is made up of a group of eight small bones which occur in two rows with articulations on one side with the radius and ulna and on the other side with the metacarpals. The metacarpals, the long bones in the palm of the hand, run from the further row of carpal bones down to the knuckles where they join the fingers.

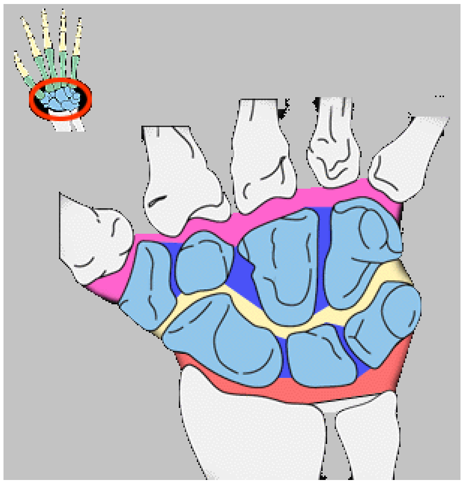

Figure 1: The wrist joint

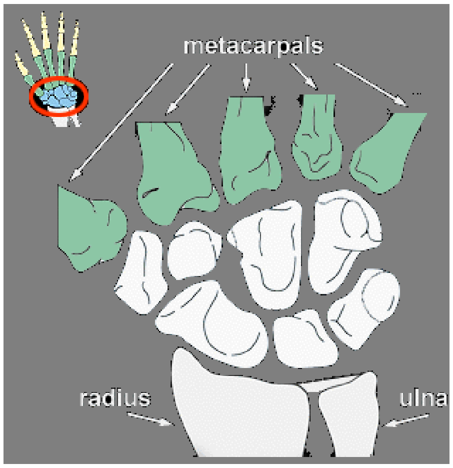

Figure 2: Associated bones

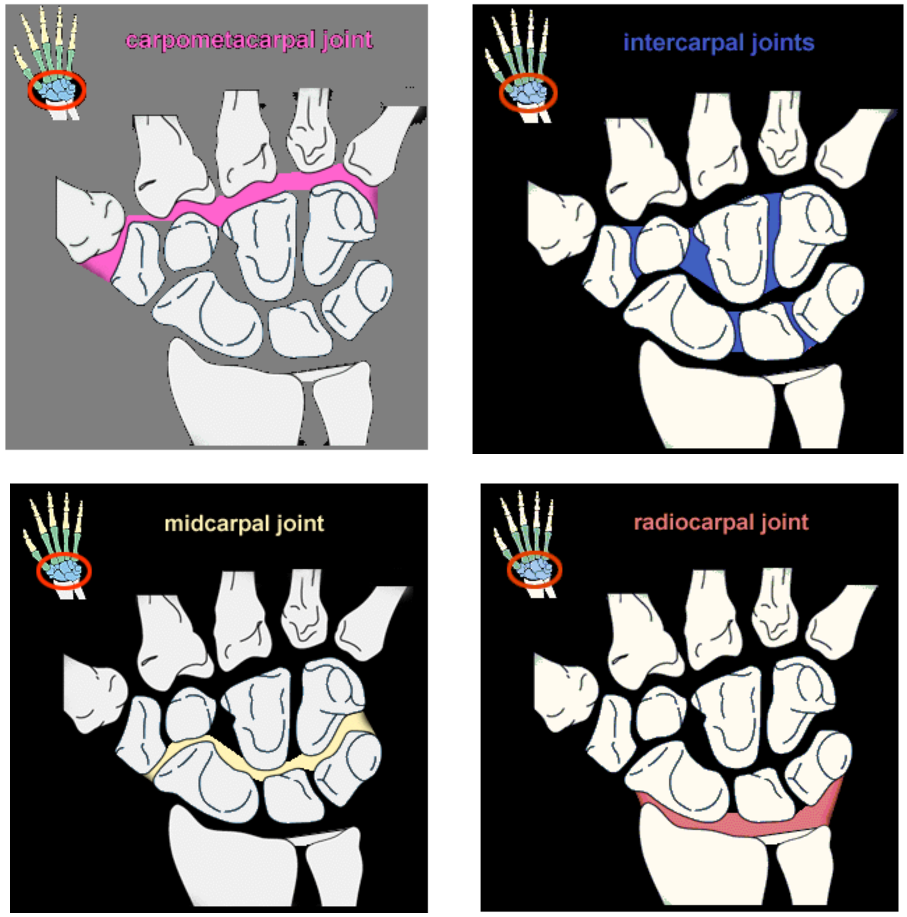

Figure 3: Joints of the wrist

2.2 Wrist Movements

The usual movements associated with the human wrist are the Flexion/Extension, Abduction/Adduction and the Pronation/Supination movements. Among these three motions the first two are produced in the wrist joint itself and the third motion, the Pronosupination motion is actually the motion of the forearm. The human forearm is made up of two bones, the radius and the ulna. Together these two bones provide the Pronosupination motion. So the actual movements of the wrist joint are Flexion/Extension and Abduction/Adduction.

2.2.1 Flexion

It is the bending movement of body parts that decreases the angle between two parts. As for the wrist this motion is the bending of wrist joint that moves the hand closer to the inner side of the forearm. The average flexion movement for human wrist is 85°. This motion is shown in figure 3.

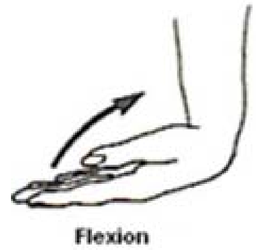

Figure 4: Flexion movement

2.2.2 Extension

This is the straightening movement of body parts that increases the angle between two parts. It is the direct opposite of the flexion movement. As for the wrist this motion is the straightening of the wrist joint that moves the hand closer to the outer side of the forearm. The average extension movement for human wrist is 90°. This motion is shown in figure 5.

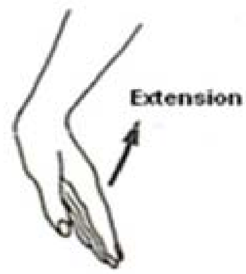

Figure 5: Extension movement

2.2.3 Abduction

It's the motion that pulls a structure or part *away from* the midline of the body. Abduction of the wrist is called *radial deviation*. As for the wrist this movement is the motion of the wrist joint that moves the hand towards the thumb. The average abduction movement of human wrist is 20°. This motion is shown in figure 6.

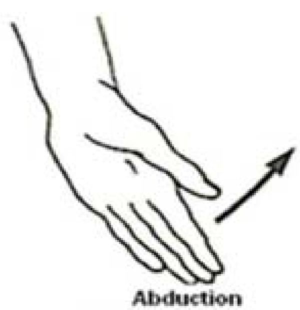

Figure 6: Abduction movement

2.2.4 Adduction

A motion that pulls a structure or part *toward* the midline of the body, or towards the midline of a limb.Adduction of the wrist is called *ulnar deviation*. For the wrist this movement is the motion of the wrist joint that moves the hand away from the thumb. The average adduction movement of the human wrist is 30°-50°. This motion is shown in figure 7.

Figure 7: Adduction movement

2.3 Wrist Muscles

Two dozen muscles cross the wrist and therefore are capable of producing a torque about the wrist joint. These muscles are grouped as flexors and extensors. While all of these muscles are capable of rotating the wrist, movement at the wrist is produced primarily by the “carpi” muscles of the forearm.

2.3.1 Wrist Flexors and Extensors

The wrist flexors are located in the anterior forearm region.

1. Flexor carpi radialis
2. Flexor carpi ulnari
3. Flexor pollicislongus
4. Palmaris longus
5. Flexor digitorumsuperficialis
6. Flexor digitorumprofundus

The wrist extensors are located in the posterior forearm region.

7. extensor carpi radialislongus
8. extensor carpi radialisbrevis
9. extensor carpi ulnaris
10. abductor pollicislongus

11. extensor pollicisbrevis
12. extensor pollicislongus
13. extensor indicis
14. extensor digitorum (a group of 4 muscles)
15. extensor digitiminimi

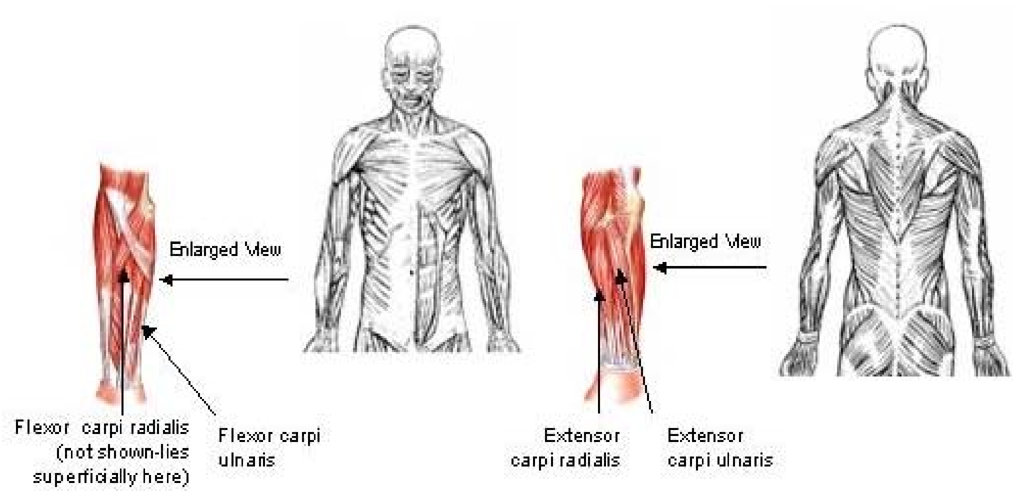

Figure 8: Flexor Extensor Muscles

2.3.2 Muscles movement

"*Flexion of the wrist* is produced by the flexor carpi radialis and flexor carpi ulnaris, with assistance from the flexors of the fingers and thumb, the palmarislongus and the abductor pollicislongus."

"*Extension of the wrist* is produced by the extensor carpi radialislongus, extensor carpi radialisbravis and extensor carpi ulnaris, with assistance from the extensors of the fingers and thumb."

"*Abduction [Radial deviation] of the wrist* is produced by the abductor pollicislongus, flexor carpi radialis, extensor carpi radialislongus and extensor carpi radialisbrevis."

"*Adduction [Ulnar deviation] of the wrist* is produced by simultaneous contraction of the extensor carpi ulnaris and flexor carpi ulnaris".

CHAPTER 3

LITERATURE REVIEW

3 Literature Review

Prosthetics developers have worked a lot on unpowered prosthetic wrist joints but a very few powered prosthetic wrist joints are available. Among the powered wrist joints, majority of the commercially available joints provide only one degree of freedom and that motion is almost in all cases the Pronosupination motion. A few researchers have started working on powered prosthetic wrist joints with more than one degree of freedom from the last six to seven years, so this topic is still in the early stages of its development. As far as the research of the author is concerned, there are no commercially available powered prosthetic wrist joints with more than one degree of freedom.

In the proceeding few pages, the research work of some engineers and scientists is reproduced that was studied by the author during the course of the literature review for this thesis.

3.1 ARTS Wrist

The ARTS wrist is a two DOF wrist actuator. This wrist is actuated by three motors and was designed to collaborate with the hand in reaching, handling and grasping things. The device is cable-driven and it is made of 2 parallel plates attached by a thrust spring. The flexibility of the spring is exploited to implement a compliant surrogate of a universal joint. The movements are achieved by three cables, working as muscles, attached in a circle around the spring and spaced by 120°. The cables are pulled by a motor and the different forces applied make the upper plate curve on different planes in the workspace.

3.1.1 Mechanical Structure

The “ARTS wrist” is made of three parallel plates;the plate on the top is perfectly circular while the other twoare larger and formed as they are the base of the actuator. All the plates are made of aluminum and are 3 mmthick. The plate on top is directly linked to the robotichand. This plate has a 90mm diameter and three sets of three notches spaced by 120°for introducing and housing of the actuation cables. It is shown in figure:

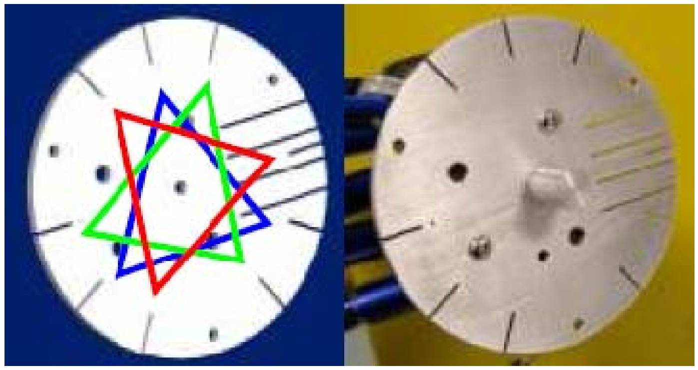

Figure 9: The end effecter plate

Each cable is positioned and fastened corresponding toapex of an equilateral triangle centered in the longitudinalaxis of the device. This means that there are three trianglesand therefore three ways to alter the attachment of the hand tothe wrist. Additionally, the scheme takes benefit from the devicesymmetry: in fact a plane can be uniquely determined bythree non-collinear points. This kinematic solution allowsthe device to execute a wide range of movements by meansof the geometrical arrangement of tendonmovements.In the center of the plate there is a spring tie(cylinder bolted into the plate). The plate has also otherholes for the track of the Bowden cables.

The middle plate has a diameter of 120 mm and isused as base for the actuation units. The motors are arrangedin a circle and spaced by 120° as the matching cables.The last plate is as large as the preceding one and is used asbase of Arts wrist.

Figure 10: The ARTS Wrist

The linking between first and second plate isachieved by the thrust spring (working as flexible joint) andthe three cables heaved by the motors (as tendons). The wristdeveloped in this study has two DOFs: the flexion-extensionand the abduction-adduction; the mixture of these twoprecise movements creates composed alignments, as itoccurs in the human wrist. Furthermore, in case all the cablesapply an identical traction force, the coil spring decreases itslength and the plates get closer but still parallel; so the spring becomes morecompressed and the system stiffness increases.

This has two consequences:

1. The joint developsmore stiffness and the wrist can stand higherloads;
2. The system compliance decreases; this is a drawbackin the event of contact with humans.

3.1.2 Working Principle

As previouslydefined and shown in figure, the device isactuated by three motors (DC motor Faulhaber 1017 006,gearhead 16/1, ratio 14:1). The worm drivemechanism changes the motion from rotational to linear andmakes the system not back-drivable and highly reduced.These high reduction ratio increases the grasping force andit's not back-drivability reduces the power intake, asthe power can be switched off without affecting the stabilityof gripachieved. Moreover the system canbe pretension to a preferred stiffness, and retain this featurewithout controlling each motor constantly.

The pretension of the device is measured with the help of cabletension sensors attached at the end of each cable.The mixture of the different pulling and releasingforces applied by the motors makes the wrist bendcorrectly. This cabledriven actuation is realized by means of Bowden cables.A Bowden cable is "the union of a cable, acting as a tendon,and an elastic, flexible and low-friction iron sheath, acting asthe synovial sheaths of the human body". In assemblystage the coil spring is inserted in itshousing, between first and second plate, and then blocked bytwo clasps. Lastly the cables outgoing from the secondplate (actuation units) are secured to the end-effecter. Thusthe system stiffness can be set by heaving the cables.

Figure 11: Prototype trials of ARTS Wrist: on the right Adduction and on the left Abduction

Figure 12: Prototype trials of ARTS Wrist: on the left Flexion and on the right Extension

3.2 Two degree of freedom powered prosthetic wrist

This is an article from the Journal of rehabilitation research and development that describes a design of a 2-DOF wrist to be used as a prosthetic wrist. The DOF that this wrist provides are the pronation/supination and flexion/extension. The design of this wrist is based around a differential mechanism in which two motors are placed parallel to each other at the place where the palm of the anatomical wrist is situated. The benefit of using two motors is that close to twice the force is available for the two DOFs. The basic requirement for this design was to create a wrist that can provide two independent motions for a transcarpal-type hand. An added advantage of this wrist design that was later seen was that it can easily fit inside the hand volume and users with long residual forearms can also use it.

This wrist design was a part of a larger project sponsored by the European Union, the Totally Modular Prosthetic Arm with High Workability (ToMPAW). The main achievement of this prosthetic arm design was the design of the first modular prosthetic arm. The ToMPAW project was a consortium of engineers from three major prosthetic research projects in Europe which were the Sven Hand, Edinburgh arm and Southampton Hand. ToMPAW project engineers utilized the experience of these three research teams and were able to create a bus-based microcontroller based architecture for a modular prosthetic arm. It was the outcome of the ToMPAW project that a 2-DOF wrist design was created that required very little space and its main feature was the use of a differential mechanism. The basic design of the differential based wrist was developed in the ToMPAW project but it was just a concept at that time and in this research article that design has been further investigated.

3.2.1 Design

The design of this prosthetic wrist is such that two motors have been utilized that are placed parallel to each other but they are oriented in opposite directions. These motors are placed at the same location where the palm of the anatomical wrist is situated. These motors are attached to intermediate gears that are further attached to the two gears of the differential by two shafts. This design provides the pronation/supination and flexion/extension movements.

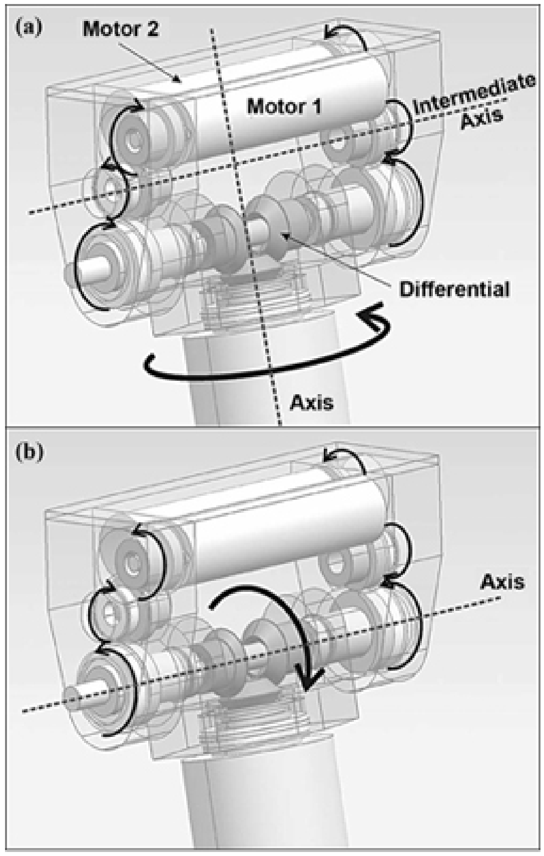

Figure 13: Wrist actions. (a) Pronation and supination (b) Flexion and extension

The pronation/supination motion occurs around the length of the differential and along the intermediate axis as shown in figure the flexion/extension movement is achieved. As the two motors rotate in the same direction and at the same speed we get the flexion/extension movement because as the motors oppose each other across the differential, the forearm rotation is halted and a torque is created around the common shaft. When the motors run at different speeds but in the same direction then we get a combination of the two movements. This concludes that the combined motion as well as the single motion can be achieved by just controlling the speeds of the two motors. Here another major aspect of the differential based design comes to light that both the motors are utilized to produce a combination of the two DOF or a single axis motion. This provides the torque of both the motors to be used which allows us to use smaller motors instead of larger ones. By placing the motors side by side in the palm space, we get a design that requires small space.

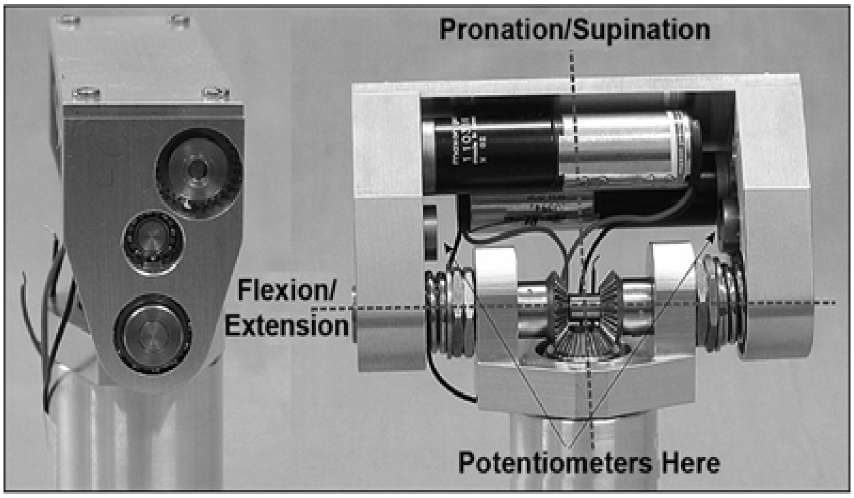

Figure 14: wrist design with axes indicated

3.2.2 Controller

The main requirement for the controller was to provide the desired movement in the flexion/extension and pronation/supination axis. For this purpose the first requirement is to measure the relative motion of these axes which is measured with the help of potentiometers placed at the gears attached to the motors from one side and to the differential on the other. The wrist is based around a differential mechanism that can provide a complete rotation of 360° whereas the human wrist only achieves a maximum rotation of 100° and if this rotation is not limited then the designed wrist will be very obvious which is not required. This requires the controller to limit the movement of the wrist.

The microcontroller that has been used by the researchers in this article is model 18F454, Microchip Technology, Inc; Chandler, Arizona which is capable of controlling two motions at the same time. The microcontroller receives the signals from the potentiometers and uses this information to control the wrist angles. The method of calculating the joint angles is the measurement of the sum and difference of angles.

The communication system that has been used by the controller is the Controller-Area Network bus (CAN-bus). The controlling system that can be employed is to either use a node near the wrist which can use conventional switches or myoelectric signals that will also provide the user with the option of changing the axis that the user wants to move. Another technique can be that the microprocessor takes the inputs from different muscles by using pattern recognition techniques and the processor senses which axis to be controlled and moved. As for the user this control technique closely resembles that of the Sven Hand but the mathematical processes are very different.

The control designed in this article for the prosthetic wrist was required to control two motors and utilize the pattern recognition technique. For this purpose a compact device has also been made that uses smaller motors and gearbox and this device is also controlled in the same manner as the one described earlier.

3.2.3 Results

The differential design of the wrist provides the torque produced by both the motors to be utilized for a single DOF and it is automatically distributed when both DOFs are being utilized. As far as most prostheses are concerned this torque applied by two motors is quite sufficient as most of the prostheses are designed to be used for supporting roles. Another role of the wrist is to position the hand in the arm workspace that requires speed and flexibility than torque. The wrist given in this article covers only 32mm of arm length but only 16mm on the proximal side of the joint axis that makes it a good choice for users with a long residual limb.

3.3 DARPA RP 2009 Arm

Darpa program managers launched Revolutionizing Prosthetics 2009to help soldiers who were returning from combat in Iraq or Afghanistan missing all or part of an arm.This so-called extrinsic hand contains no drive system. Instead, tendon-like filaments extend through the wrist, to be activated by electric motors in a collaborative robot, or cobot. DARPA doesn't provide many details of this robotic prosthetic arm and only some pictures are available that are provided here.

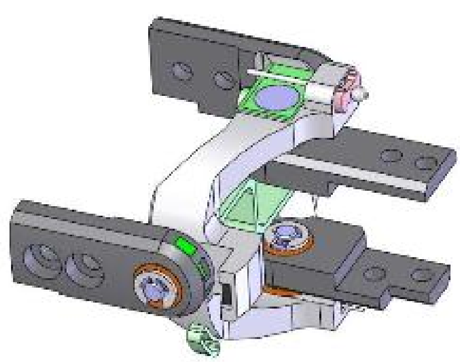

Figure 15: Solid Works CAD model of Wrist

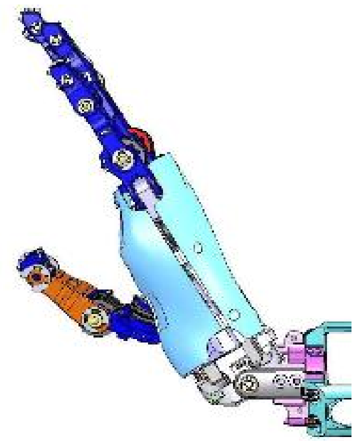

Figure 16: Wrist Extension

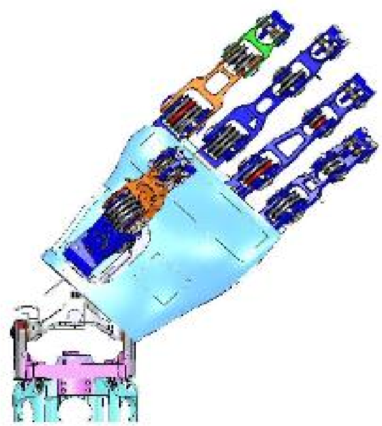

Figure 17: Wrist Adduction

3.4 Otto Bock prosthetic wrists

The German prosthesis development company Otto Bock has developed some commercially available powered prosthetic wrists that only provide one degree of freedom. Some of these wrists are discussed below.

3.4.1 13E205 MyoRotronic

The MyoRotronic prosthetic wrist provides the Pronosupination motion of the wrist and the opening and closing of the prosthetic hand with the help of either one or two 13E200/13E202 MyoBock® Electrodes or the combination of one 13E200/13E202 Electrode and a 9X50/9X52 Linear Transducer.

The wrist can be programmed in five different ways so that it can adapt easily to different patients. Among the five programs, four can provide proportional Pronosupination motion as well as the digital rotation control. The required program can be selected using the 757T13 MyoSelect.

Figure 18: 13E205 MyoRotronic

The Otto Bock system electrical grippers that are equipped with Quick Disconnect Wrsit as well as all types of Otto Bock Electric hands can be used with the MyoRotronic Wrist. Whenever during the operation of the electric wrist rotator or the system electric hand or the system electric gripper the control makes the switch over, a minute vibration occurs in the electric wrist rotator.

3.4.2 MyoWristTranscarpal 10V38

The Otto Bock MyoWristTranscarpal 10V38 provides the user with the flexion/extension movement of the wrist up to 40° that makes the picking and placing and gripping of the objects easier for the patient and the elbow and shoulder joints don't have to provide the compensatory motions. Another advantage of this wrist design is that it allows for the user to see the things he has picked in his hand that makes the prosthesis look more natural. This prosthetic wrist was developed for the Transcarpal hand but when it is used with 9S266 Quick disconnect wrist, the installation height of the system becomes such that it is easy to be interchanged.

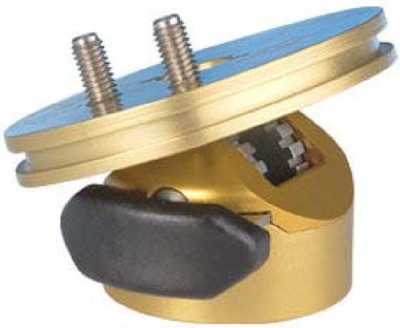

Figure 19: MyoWristTranscarpal 10V38

CHAPTER 4

Powered Wrist Actuator

4 Powered Wrist Actuator

The prosthetic powered wrist actuator that is designed in this thesis has been intended to produce the Flexion/Extension and Abduction/Adduction movements of the human wrist. The pronosupination motion of the forearm is not included in the design. The main requirements for the design are as following:

- To produce 2-DOF Flexion/Extension and Abduction/ Adduction motion
- To produce the required degrees of rotation in all the axis as produced by the human wrist
- To maintain the weight of the wrist actuator up to the average weight of the human forearm.
- To maintain the size of the wrist actuator up to the average size of the human forearm.
- The actuator should be able to produce at least the average torque produced by the human wrist.
- To contain the price of the actuator to such a level that it can be easily purchased by common people.

The powered wrist actuators that are commercially available or that are in the research phase usually employ a switch based control system or a Myoelectric control system. The actuator designed here can be controlled by both of the above mentioned techniques. In this thesis, only the mechanical structure and the transmission design of the actuator have been designed and the integration with any existing control system or a new system has not been considered.

The proceeding pages will thoroughly explain the mechanical and transmission design of the proposed wrist actuator.

4.1 Mechanical Structure

The basic structure of the proposed wrist actuator is a modified Ball & Socket joint with a frame attached at the base that carries the two DC geared motors. The wrist joint is designed to produce 2-DOF and both of these motions are to be produced at the same point as in the human wrist. The human wrist is made of a condyloid joint that can produce the Flexion/Extension, Abduction/Adduction and the circumduction movements on a single point and fixes the three possible translations.This joint is very similar in motion to the Ball & Socket joint in the human shoulder. The mechanical equivalent of the condyloid or Ball & Socket joint is commonly known as simply the ball joint. These joints are also able to produce the three rotations and also fix the three translations associated with the three dimensional world.

Figure 20: Ball & Socket Joint with three rotationsindicated

Considering the properties of the ball & socket joint, it is selected as the joint to be used for the powered wrist actuator proposed in this thesis. The next point to check is whether the ball & socket joint can provide the required degrees of rotation in the Flexion/Extension axis or not. The degrees of rotation that the human wrist provides in the Flexion/Extension axis are 85° and 90° respectively and the commercially available joints only provide up to 15°-20° of rotation.So a modification has been done in the design of a normal ball & socket joint. In the normal ball joint the socket covers approximately 70% of the ball's surface area. This covering is necessary for unpowered ball joints so that when a force is applied the ball doesn't come out of the socket but this also reduces the degrees of rotation of the joint. So a modification has been done in the design of a normal ball joint such that the surface contact of the socket to the ball has been reduced to 25-30%. This low surface contact allows the socket to rotate up to 90° on the ball of the joint. The socket also has four eye rings that are placed at 90° to each other so that the Bowden cables are attached to the socket to deliver the force generated by the DC geared motors. Another set of four eye rings are also placed on the shaft that attaches the ball of the joint to the elbow joint. The Pro-E models of the modified socket and ball of the ball joint have been shown on the next page.

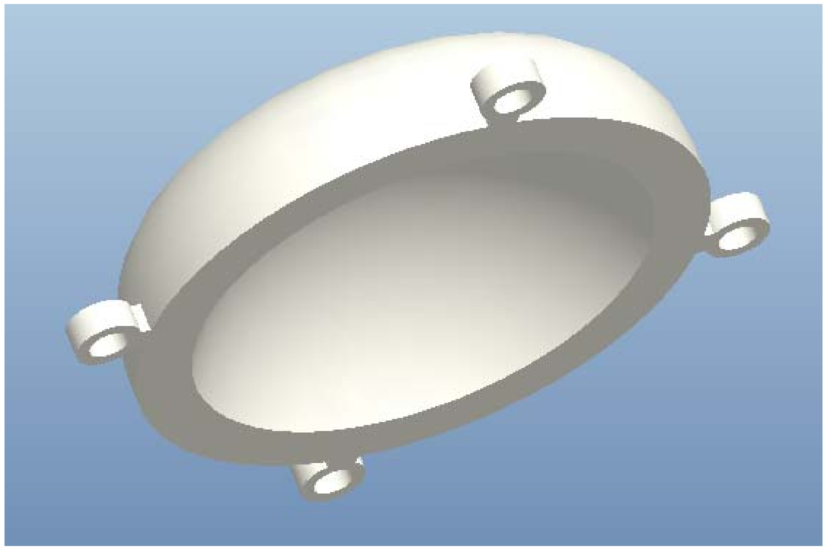

Figure 21: The modified socket

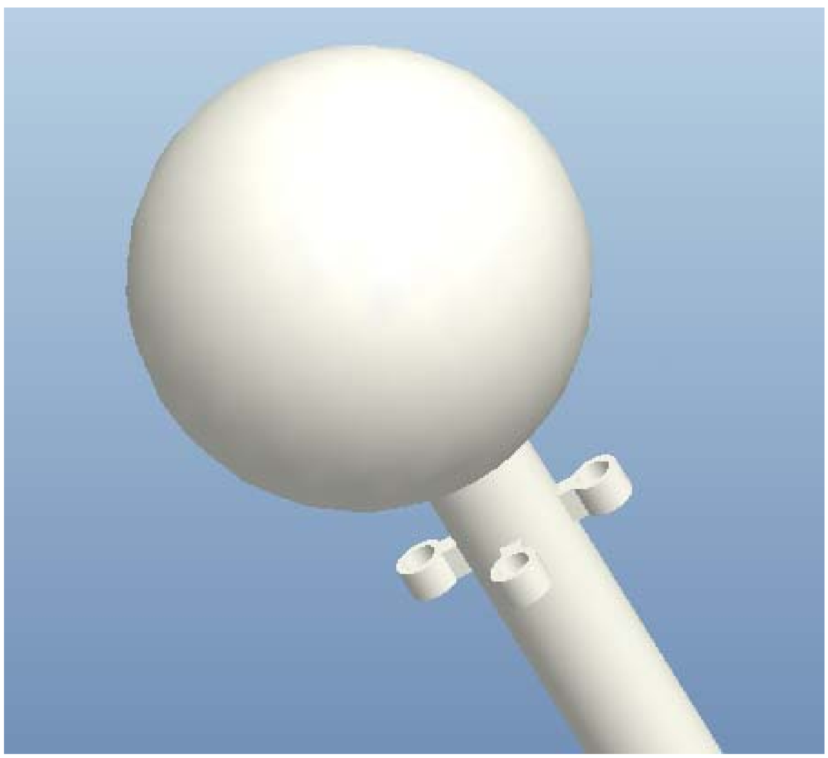

Figure 22: Ball of the Ball & Socket joint

The complete assembly of the modified ball joint with the attached Bowden cables is shown below.

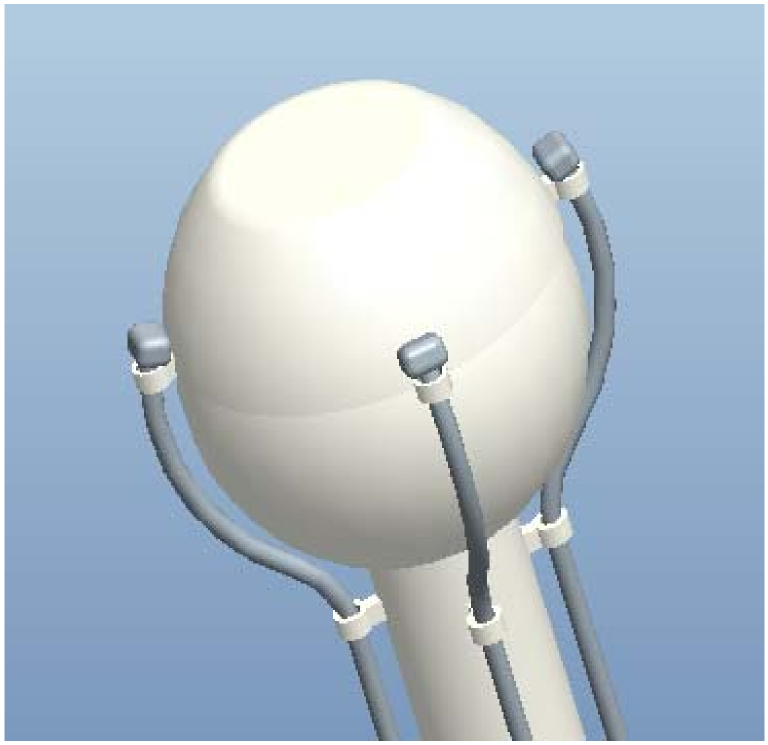

Figure 23: Ball & Socket joint

Another requirement of the model was that the motors needed to be placed at the forearm. For this purpose a frame is designed just below the ball joint that contains the DC geared motors and the pulleys for the application of force and attachment of the Bowden cables. The frame along with the ball joint is shown on the next page.

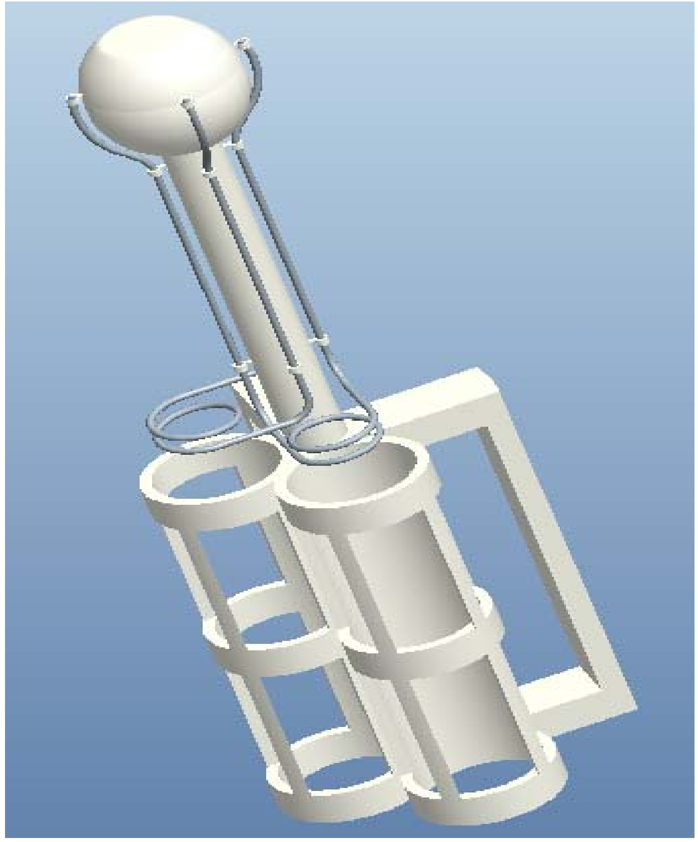

Figure 24: Complete prosthetic wrist with motor frame

The size of wrist actuator is also a consideration in the design because if the size is greater than the average size of the wrist of an adult human being it will become difficult for the user not only physically but mentally as well. For this purpose salient data of the forearm and wrist has been collected and is shown in the table below.

Table 1: Characteristics of right human forearm

Forearm Characteristics	Average
Forearm Circumference	28.48(cm)
Wrist Circumference	17.15(cm)
Wrist Breadth	6.02(cm)
Forearm Weight	1113.2(gm)

The above data suggests that the maximum diameter of the ball & socket joint should be equal to or less than 6cm. So the diameter of the ball is set at 4cm and that of the socket at 5cm.

4.1.1 Material Selection

The selection of the material is also very important for three reasons. One is that the weight of the actuator needs to be well within the average weight of the human forearm. The other reason is that the friction plays a very important role in the ball & socket joint as the socket slides over the ball and if the friction between them is higher, then the force applied by the motors will be consumed in overcoming it rather than being used for the movement of the hand. Higher friction between the parts will also increase the wear and tear of the joint. The third reason for material selection is that the actuator needs to be able to with stand the wear and tear common to prosthetic actuators. For this reason the selected material should be hard enough.

Some of the common materials for the production of the ball & socket joint are steel, brass, bronze and PTFE. Some times for an application where lighter weight is required and the forces on the joint are not high; aluminum is also used but its continuous use makes it sticky and it loses its good low friction properties. Steel, brass and bronze have a high resistance to wear and tear and with proper polishing and greasing provide a very low friction coefficient but there main drawback is the weight. These materials have a high density that makes them heavy and a ball joint made from them can result in a wrist actuator that is heavier than the average human forearm.

For the purpose of selection of a suitable material salient data of the plausible materials is shown in the tables below.

Table 2: Mechanical Properties of plausible materials

Material	Hardness (BN)	Density (g/m^3)
Aluminum	22-40	2.71
Austenitic Steels	192-210	7.88
Commercial Bronze	60-125	8.5
Aluminum Brass	70-175	8.6
PTFE	15	2.0-2.29

Table 3: Coefficient of friction of plausible materials

Material 1	Material 2	Coefficient of Static Friction		Coefficient of Dynamic Friction	
		Static	Lubricated	Static	Lubricated
Aluminum	Aluminum	1.05	-	1.4	-
Mild Steel	Aluminum	0.61	-	0.47	-
Mild Steel	Mild Steel	0.74	-	0.57	0.09
Mild Steel	Cast iron	-	0.183	0.23	0.133
Hard Steel	Hard steel	0.78	0.11-0.23	0.42	0.03-0.19
Mild Steel	Brass	0.51	-	0.44	-
Cast iron	Bronze	-	-	0.22	0.077
Steel	PTFE	0.04	-	-	0.04
PTFE	PTFE	0.04	-	-	0.04

The data shown above suggests that PTFE should be the material of choice as it is lighter in weight and has the lowest coefficient of friction. The only drawback of PTFE is that its hardness number is lower than the metals but it compensates the hardness again by its low friction coefficient as the lower friction will ensure lower forces being applied in the ball joint and so less chances of wear and tear.

PTFE is the abbreviation of Polytetrafloroethylene. It is a fluorocarbon-based polymer. The common commercial name of PTFE is Teflon®. The Teflon® brand of the PTFE is only produced by DuPont. Several other manufacturers make their own brands of PTFE which can often be used as substitute material. This fluoroplastic family offers plastics with high chemical resistance, low and high temperature capability, resistance to weathering, low friction, electrical and thermal insulation, and "slipperiness".

4.2 Transmission design of the actuator

The movement of the human wrist is performed by the muscles present in the forearm and for every movement more than one muscle is utilized. The reason behind this is that the human muscle can only provide the retraction force and cannot apply the extension force. Because of the unidirectional movement of the muscles, they have to be arranged in a parallel manner so that they work in such a way when one muscle retracts the other extends and vice versa. This type of muscle arrangement also makes the system redundant. The arrangements of the muscles of the upper body of a human being are shown below.

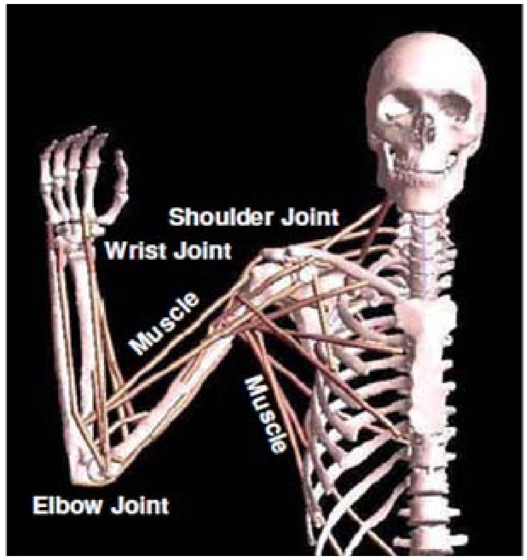

Figure 25: Human arm's muscle drive scheme

The technique utilized for the transmission of motor torque to the ball joint of the wrist actuator closely resembles that of the human arm’s force transmission approach which has been called by some researchers as the “solution in nature approach”. The transmission technique of the proposed wrist actuator utilizes Bowden cables. These cables are flexible just like thehuman muscles and also provide a unidirectional force transmission. The cables have been attached in a parallel manner and one cable is used for flexion/extension movement and another is used for abduction/adduction movement. The cables are attached in a manner that its one end is attached to an eye ring of the socket and from there it goes to the motor where it is wound around a pulley and then is attached to the other eye ring directly opposite the first one on the socket. Similarly the other cable is attached to the other two eye rings of the socket.

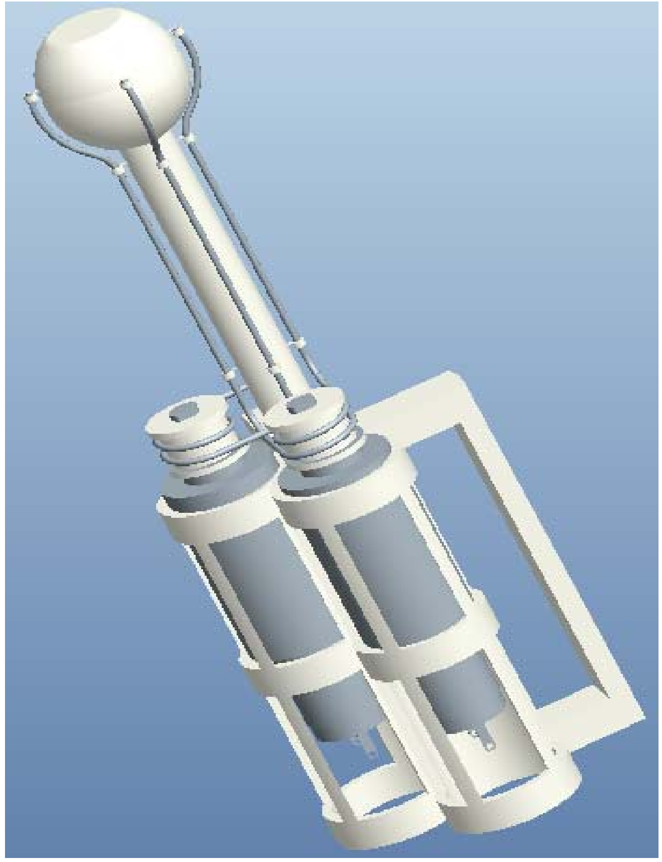

Figure 26: Pro-E model of the transmission

A major issue in designing a transmission using the flexible Bowden cables is to find the optimal number of cables and the optimal number of cable attachment points. This has been done by using two classical theorems in convex analysis that can be employed because of the cable's unilateral properties.

Caratheodory Theorem: If a set $X = \{v1, v2, \ldots, vk\}$ positively spans _n, then $k \geq n + 1$.

Steinitz Theorem: If $S \subset$ _n, and $q \in$ int(co S), then there exists $X = \{v1, v2, \ldots, vk\} \subset S$ such that $q \subset$ int(co X) and $k \leq 2n$.

The Caratheodory theorem gives the lower bound of the number of driving cable attachments required for positive cable tension in a parallel driven mechanism and with *n*-DOF's it is *n+1*. The Steinitz theorem gives the upper bound on the minimal number of driving cable attachments required to attain positive cable tension and for *n*-DOF's it is 2*n*. Together the two theorems imply that the number of driving cable attachments for a parallel mechanism ranges from $n+1$ to $2n$. So in the design of the transmission of the actuator under consideration the number of DOFs are 2 which give the minimal number of driving cable attachments for positive cable tension to be 3 and the upper bound to be 4. In the design the number of cable attachments has been selected to be 4 so that only two motors are required to run the mechanism. This also allows us to use only two cables for the running of the mechanism.

4.2.1 Bowden Cables

"A Bowden cable is the union of a cable, acting as a tendon, and an elastic, flexible and low friction sheath acting as the synovial sheaths of human body."The linear movement of the inner cable is generally used to transmit a pulling force, although for very light applications over shorter distances (such as the remote shutter release cables on mechanical film cameras) a push may also be used.The construction of the Bowden cable is shown below.

Figure 27: Construction of Bowden cable 1) plastic sheathing 2) outer sheathing made of spring steel wire 3) Teflon guide sleeve 4) spiral wire 5) inner core made of spring steel wire

The selection of the Bowden cable is governed by the tensile strength of the inner core spring steel wire that is also called wire rope.Wire rope is an intricate device made up of anumber of precise moving parts. The moving parts ofwire rope are designed and manufactured to maintaina definite relationship with one another. Thisrelationship ensures that the wire rope has theflexibility and strength crucial to professional and safehoisting operations.Wire rope is composed of three parts: wires,strands, and core. A predetermined numberof wires of the same or different size are fabricated ina uniform arrangement of definite lay to form a strand.The required number of strands is then laid togethersymmetrically around the core to form the wire rope.Tensile strength is the strength necessary towithstand a certain maximum load applied to the rope.It includes a reserve of strength measured in aso-called factor of safety.

The term *safe working load* (SWL) of wire rope isused to define the load which can be applied thatallows the rope to provide efficient service and alsoprolong the life of the rope.The formula for computing the SWL of a wirerope is the diameter of the rope squared, multiplied by8.

D x D x 8 = SWL (in tons)

where D is the diameter of the wire rope.

In the proposed actuator, to calculate the minimum diameter of wire rope that can be used first we have to find the amount of force that the wrist actuator will have to apply. Some data has been gathered on the amount of force an average human being applies from the wrist joint during the routine tasks of picking and placing of the objects. The mean value comes out to be 4Nm. The force is calculated by finding the distance of the point where the load has been applied to the center of the wrist joint.

Torque, τ = Force, F $\times$ Moment arm, r

The force comes out to be 80N if we have a moment arm of 50mm which is the average distance of the center of palm to the wrist center. In tons the value is 0.009. So the minimum diameter of wire rope that can be utilized by remaining in the safety limit is 0.0335inch or 0.8509mm. The wire being used in the designed actuator is 2mm thick so it's SWL is 0.05tons or 445.2N.

4.2.2 Motor Selection

The transmission of the proposed wrist actuator requires two motors to provide the required torque. The two motors are required each for one of the 2-DOF of the actuator. The selection of the motor is governed by some design requirements.

- The first is that the motor should be able to apply the required torque.
- The second is the weight and size so that the two motors can be placed in the forearm and then can be easily lifted by the human user.

- The third requirement is that the motors should be DC motors so that they can be operated by the battery and the need of extra circuitry can be removed.
- The fourth and final requirement is that the price of the motor should be moderate so that the actuator can be affordable to common people.

Considering all of the above requirements a search has been carried out that resulted that a single motor that can fulfill all the requirements is not available and a tradeoff is inevitable. Among the requirements the most important are the first two because if they are not met the design of the actuator will have to be changed. So from the research for the suitable motor, three different motors have been selected. All the three have a planetary gear head that helps in increasing the torque output.As the name implies, a "gear motor" (or "geared motor") is a motor having an attached "gear assembly". The gear assembly (or “gear train”) enables the gear motor to provide greater torque at a lower RPM than the motor alone would be capable of providing. Some specifications of the searched motors are shown in Table. Complete details of the motors are provided in Annex. ‘A’.

TABLE 4: Data of geared motors

	ICH D323-3A	**Faulhaber 2232S012BSL with Gearhead Series30/1S**	**Beetle B231 Part# 0-B231**
Length(mm)	132.5	88	68.15
Diameter(mm)	32	30	21.8
Weight(g)	320	200	100
Rated Torque(Nm)	3.9	4.5	2.62
Rated Speed(rpm)	10	4000	70
Rated Current(A)	0.495	1.10	0.4
Voltage(V)	24	12	12

5 Characteristics of Wrist Actuator

The proposed wrist actuator provides two degrees of freedom and uses the flexible Bowden cables for the transmission of force from two DC geared motors. Some salient characteristics of the proposed wrist actuator are shown in the table.

TABLE 5: Characteristics of wrist actuator

Characteristics	**Wrist Actuator**	**Human Forearm**
Forearm Circumferance	28.274 (cm)	28.48 (cm)
Wrist Circumferance	14.76 (cm)	17.15 (cm)
Wrist Breadth	4.7 (cm)	6.02 (cm)
Weight	870 (gm)	1113.2 (gm)
Max. Lift Capacity	3.9 (Nm)	4 - 6 (Nm)
Flexion/Extension	85°/90°	85°/90°
Abduction/Adduction	15°/45°	15°/45°

6 Pro-E model of wrist actuator

The complete model of the Bowden cable based powered ball & socket joint wrist actuator with the motors and pulleys attached is shown below.

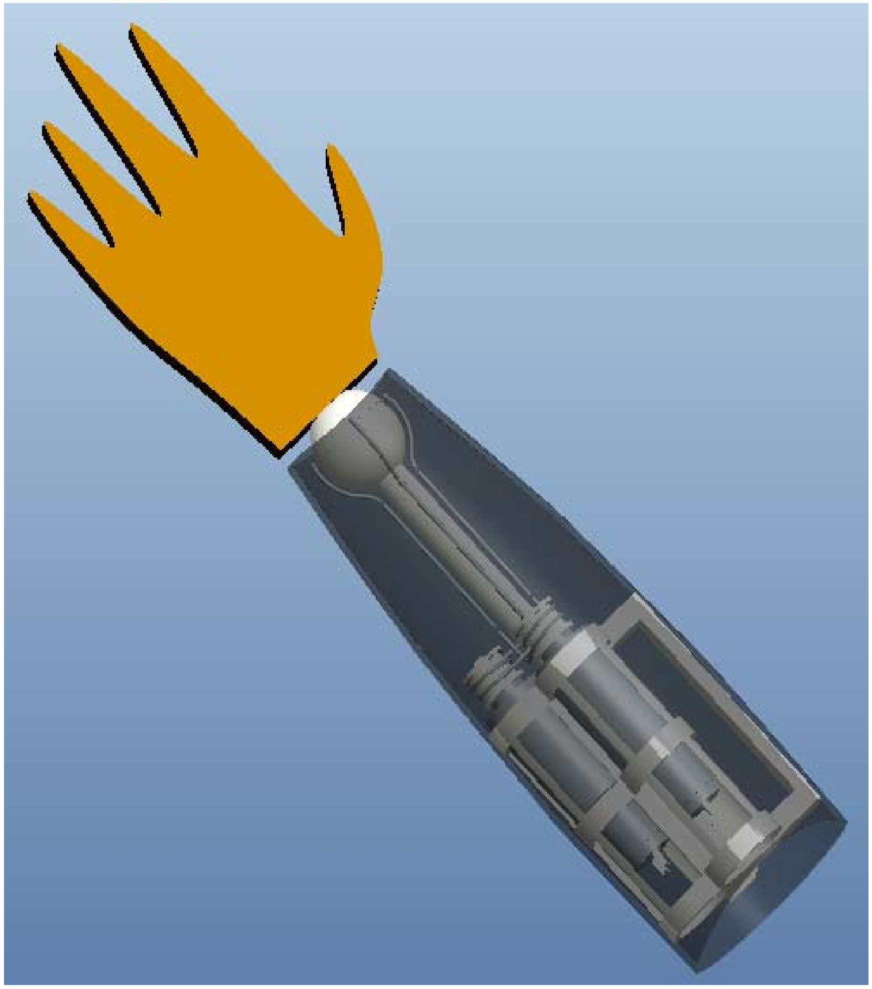

Figure 28: Pro-E model of the wrist actuator with forearm casing.

7 Conclusions

7.1 Review of thesis

The wrist actuator proposed in this paper is a novel design which is light in weight, low in price and is designed specifically to provide the degrees of rotation that the human wrist is able to produce because the previous designs by other researchers were only able to provide the required degrees of rotation in the Abduction/Adduction axis but not for the Flexion/Extension axis. The actuator also meets the requirements for a prosthetic limb and can be developed for practical implementation. This actuator can also be used in rehabilitation exoskeletons.

7.1 Future Work

The control system for the proposed wrist actuator needs to be designed. A number of control system techniques are available and the suitable one can be utilized. The prototype of the mechanical design has to be made so that an analysis of the movements of the actuator can be performed.

Some improvements can also be made as the motor with a higher torque and lower weight should be chosen which will increase the efficiency of the design.

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APPENDIX A

DC geared motors data

Beetle B231 Gearmotor 231:1

Part# 0-B231

	B231 model	
	6V	12V
No load speed	40rpm	70rpm
Amps @ nominal	0.3 A	0.4 A
Stall current	3.0 A	6.8 A
Stall torque	225 oz-in (16,202 g-cm)	370 oz-in (26,643 g-cm)
Gear ratio	231:1	
Weight	3.53 oz (100g)	
Diameter	0.86" (21.8mm)	
Length	2.25" (57.15mm)	
Shaft diameter	4 mm - with flat	
Shaft length	11 mm (0.43")	
Mounting Holes	Four M2 mounting holes on gearbox face	

DC PLANETARY GEAR MOTOR D323-3A（Size 32mm）

APPLICATION

- ATM in Bank,
- Automatic window bind,
- Medical instrument,
- Cosmetology instrument,
- IT Mechanism,
- Security cameras

PICTURES

GEARBOX MOTOR SPECIFICATION

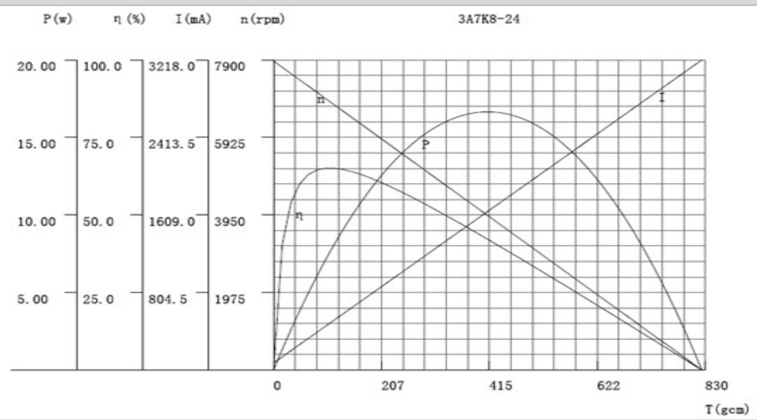
Type	Ratio		1:3.7	1:5	1:16	1:19	1:27	1:51	1:79	1:100	1:139	1:190	1:253	1:305	1:352	1:408	1:516	1:596	1:721	1:1012
D323	Rated torque	kg.cm	0.4	0.5	1.5	1.8	2.5	3.5	6	8	12	14	18	24	28	34	38	45	45	45
	Rated speed	rpm	1600	1300	380	320	220	120	76	59	51	32	24	20	17	15	12	10	8	6
Gearbox	Instantaneous torque	Kg.cm	15		30			45				60								
	Allowable torque	Kg.cm	10		20			30				40								
	Length	mm	28		37.5			47				56.5								
	Backlash	O	0.7		0.8			1				1								
	Weight	g	133		162			190				218								

MOTOR DATA

Frames volt (V)	No road speed (rpm)	Noroad current (mA)	Rated torsion (g.cm)	Raterd speed (rpm)	Raterd current (mA)	Output power (w)	Weight (g)
3A7K8-24V	7800	100	120	6800	495	8.25	102

Note: Product voltage, output shaft size, electrical performance, you can request custom-made!

MOTOR CHARACTERISTICS



Mechanical Dimensions