Design of an Anthromorphic Upper Extremity Exoskeleton

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Dedicated to my beloved late grandfather Abdul Wasey, my beloved parents.

TH-4 FORM

It is certified that the Thesis work titled "Design of an Anthromorphic Upper Extremity Exoskeleton", is carried out by **Faizan Ahmed** under the supervision of **Dr. Yasar Ayaz**, at National University of Sciences and Technology (NUST), Islamabad. It is fully adequate, in scope and in quality, as a thesis for the degree of Masters in Robotics and Intelligent Machine Engineering.

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DECLARATION

It is declared that the work entitled "Design of an Anthromorphic Upper Extremity Exoskeleton" presented in this thesis is an original piece of my own work, except where otherwise acknowledged in text and references. This work has not been submitted in any form for another degree or diploma at any university or other institution for tertiary education and shall not be submitted by me in future for obtaining any degree from this or any other university or institution.

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ABSTRACT

Stroke and paralysis are the third-most prevalent causes of death and most common cause of disability on a global scale. Although, no large-scale epidemiological studies have been conducted to determine the number of stroke/paralysis patients in Pakistan, it is estimated that there are hundreds of thousands of new cases reported each year [1]. Despite the need for introduction of advanced rehabilitation, very little research in this particular field has been done in Pakistan.

The development of robotic exoskeleton systems can be deemed as one of the most active research areas in contemporary robotics research, due to the vast applicability and necessity for such systems in various industrial and rehabilitative applications. However, majority of the existing exoskeleton systems have been developed with military-level design and applications in mind. Nevertheless, the usage and application of exoskeletons can be considered boundless in nature, ranging from handling of radioactive waste as well as lifting heavy machinery and objects within industrial applications to usage in rehabilitative purposes towards assisting elderly individuals and patients suffering from muscular atrophy that affects different parts of their bodies. The development and control of exoskeleton is of prime importance, specifically due to the close proximity to human beings and the potential for exoskeletons to physically harm other individuals, provided proper care and precautions are not taken in its design, operation and handling. While, at the same time, wearers' comfort, responsiveness, controllability, flexibility, ergonomics and other practical considerations should also be duly addressed during the development and prototyping stages. [2]

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LIST OF ABBREVIATIONS

sEMG	Surface Electromyo graphy
FES	Functional Electrical simulation
CAD	Computer Aided Design
DOF	Degree of Freedom

CHAPTER 1

INTRODUCTION

1.1. Motivation and Introduction

The functional movement such as walking, extending and other actions by the Upper and Lower extremity limbs are the principle motions of living humans today. Due to poor physical and muscular abilities, Aged human beings are ached with many forms of locomotive handicaps such as strokes, paralysis, hemiplegic cases and spinal cord damage [1]. In today's everyday life, there are numerous reasons from which humans are deprived of their functional movements such as geriatric disorders, trauma, strokes and spinal cord damage.

Stroke is the well-known cause of disability and leading to the fifth most prevalent death cause in US. There are no proper published studies related to stroke occurrence in Pakistan. The estimated annual rate of stroke patients in Pakistan is 250/100,000, which leads to an estimate of 350,000 new cases per annum [2]. Most of these cases lead to disabilities and partial paralysis of the patient’s body, which if not treated properly or in time can lead to permanent paralysis. Despite having such a huge number of new cases every year the rehabilitation techniques used in Pakistan are still quite outdated.

If the human body were to be looked upon as a mechanical device, then its complexity marks on such a high level that every other human being would have a different disability. For such disabilities, Rehabilitation therapies stand as the prime solution. Generally, these treatments lean on the dysfunctional motions, which are setup by the means of manipulative physical therapy strategies [1]. Sadly, there are some group of patients that are not able to regain all functions of their bodies. Additional aid of exoskeletons or prosthesis have the ability to support and help in the recovery of the lossy function. Physiotherapy and Functional Electrical simulation (FES) are vastly used techniques for the healing of paralysis and states of lost movement but they have limitations.

Exoskeleton or mobile orthosis is a wearable external device that amplifies the performance of motions. Artificial aid and rehabilitation has lately in recent times have become readily available. Since artificial aid and rehabilitation is preferred, the inventions in commercial robotics and orthosis are readily available and extensively required to aid and speed up the rehabilitation and therapy of patients.

As explained earlier The Robotic exoskeleton is a wearable external device with actuation on specific joints to induce movements in otherwise paralyzed joints. Orthosis is a device that supports and assist people who have paralyzed or weak limbs. While prosthesis is a device that replaces and acts as same as the missing limbs. However, the exoskeletons and assisted devices have designed and developed to improve the losing function of the upper or lower extremity [1]. A robotic exoskeleton is not just a device to use for helping in physical therapic procedures. It can also be used as an assistive device to amplify human joints, or cause less fatigue to limbs in repetitive tasks. Another use of an exoskeleton system is for haptic interactions in virtual reality systems.

1.2. Objectives of Research

Followings are four main objectives of the research carried out in this thesis.

- Design and development of a wearable upper extremity exoskeleton.
- Development of an EMG based motor controller for exoskeleton.
- Analysis of different physiotherapy procedures.
- Development of an automated physiotherapy routine.

1.3. Contribution of Thesis

Followings are three major contributions of thesis.

- Conducted research is for welfare purposes of society by using emerging technology to serve the community. This thesis is part of project, which will provide a cheap solution rehabilitation of stroke and paralysis patients as well as providing a power augmentation and fatigue reducing exoskeleton system that could be used in many civilian and military applications, where it can improve efficiency of repetitive and heavy load bearing tasks.

1.4. Thesis Organization

Chapter 1 is an introductory chapter of thesis and includes the motivation of research, objectives of research, contributions of thesis and brief introduction to overall work carried out in the thesis. In motivation, analysis of local and global number of stroke and paralysis cases and use of emerging technologies for the rehabilitation of those patients.

Chapter 2 is related to the literature study regarding previous exoskeleton and active orthosis systems. In general it includes the anatomy of upper extremity, available exoskeleton systems and methods used to provide control to those exoskeleton systems. As well as review of publication done in this regard and related projects.

Chapter 3 is about the research methodology followed to achieve the task in this dissertation. In general it includes the problem of statement, methodological approach to cover the overall problem and research design for the work carried out in this research. Overall research methods are described in the form of block diagrams.

Chapter 4 includes the fabrication of a prototype Upper Extremity exoskeleton and a EMG based motor controller. Fabrication of a prototype Upper Extremity exoskeleton include CAD modeling, and manufactured hardware implementation. EMG motor controller include development of an EMG based motor controller.

Chapter 5 is about the results and analysis of the prototype exoskeleton. That includes mechanical stress analysis of individual parts of the design, cost analysis the whole system, DH parameters of the robot and kinematics/inverse kinematics of the robot. For EMG controller, test results include muscle readings from different muscle points.

Chapter 6 includes the overall conclusion of thesis depending upon the findings, experiments and results from the implementation and results section. It also includes the area and fields in which improvements and research can be done in future.

CHAPTER 2

LITERATURE REVIEW

2.1. Upper Extremity Anatomy

Before designing a Upper Extremity exoskeleton we should first have to understand and study the Upper limb anatomy of human body. This understanding can better help us determine the safety parameters for our exoskeleton design and make it as anthromorphic as possible. The two major joint of upper limb we are interested in are Shoulder and elbow.

2.1.1. The Shoulder Joint

The shoulder joint which connects upper limb with the body is in nature a ball and socket joint means range means it allows the upper limb to move in 360 degrees.

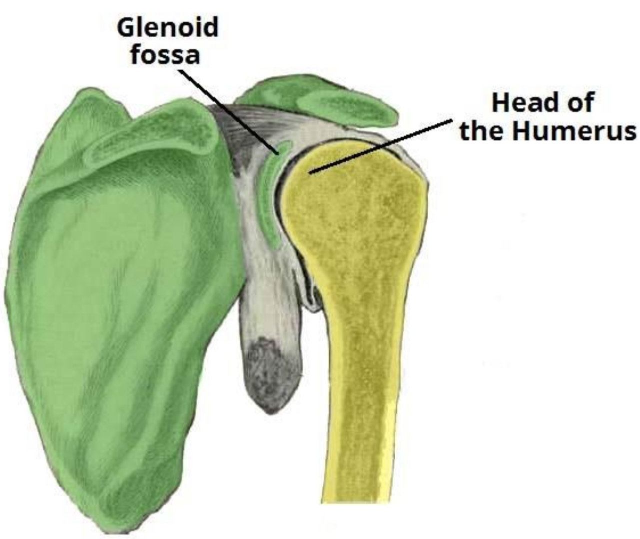

Figure 2.1 Glenohumeral Joint (courtesy teachmeanatomy.info).

The shoulder joint is formed by the head of the humerus with the glenoid cavity of the scapula. (Figure *2.1*) The head of Humer conjoint with a glenoid cavity of the scapula to form this joint hence it known case Glenohumeral joint supported by three types of ligaments glenohumeral ligaments, coracohumeral ligaments and transverse humeral ligaments [3] (Figure *2.2*).

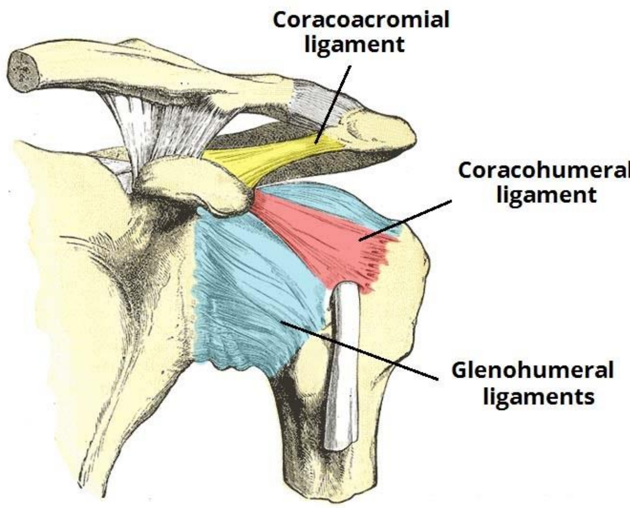

Figure 2.2: Shoulder Ligaments (courtesy teachmeanatomy.info).

The shoulder joint produces 3 groups of movements,

Extension/Flexion

Extension is the movement of upper limb backward in the sagittal plane, it is produced by backside fibers of deltoid, latissimus dorsi and teres major.Flexion is the movement of upper limb forwards in sagittal plane, it is produced by the biceps brachii (both heads), pectoralis major, chest side fibers of deltoid and coracobrachialis [3].

Abduction/Adduction

Abduction is the movement of upperlimb away from the midline in coronal plane. The first 0-15 degrees of abduction is produced by the supraspinatus. The middle fibres of the deltoid are responsible for the next 15-90 degrees. Past 90 degrees, the scapula needs to be rotated to achieve abduction – that is carried out by the trapezius and serratus anterior. Adduction is the movement of upper limb towards midline in coronal plane, it is produced by contraction of pectoralis major, latissimus dorsi and teres major [3].

Rotation

Medial Rotation is the rotation towards the midline, so that the thumb is pointing medially, it is produced by contraction of subscapularis, pectoralis major, latissimus dorsi, teres major and anterior deltoid [3]. Lateral Rotation is the rotation away from the midline, so that the thumb is pointing laterally, it is produced by contraction of the infraspinatus and teres minor.

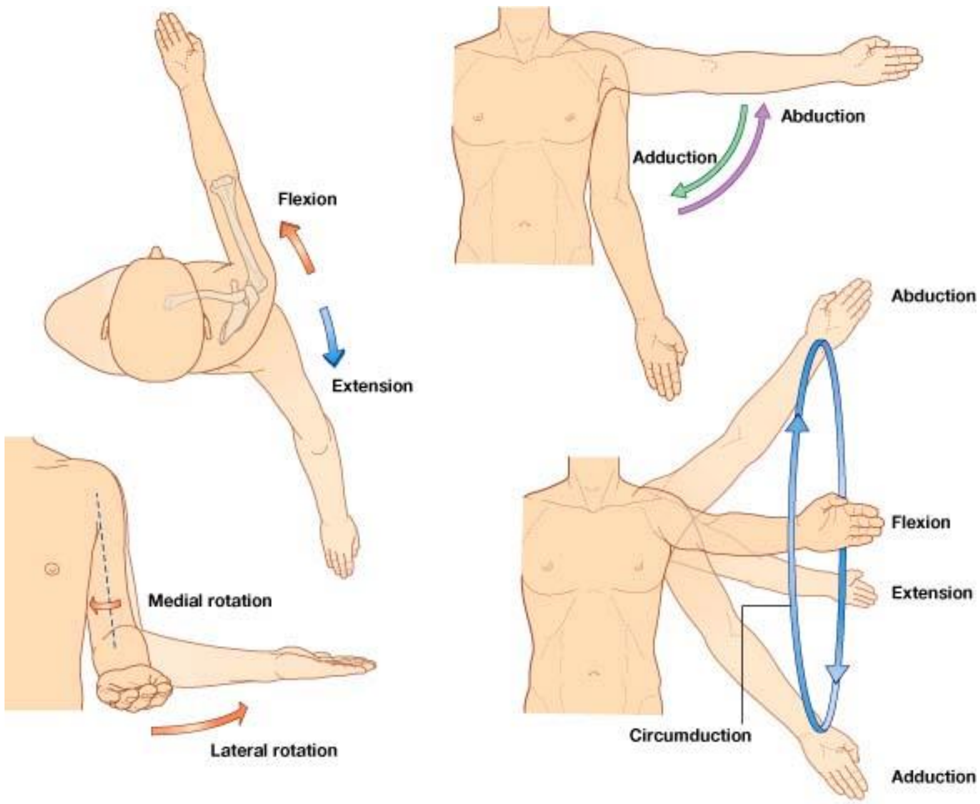

Figure 2.3: Range of Movements Shoulder Joint.

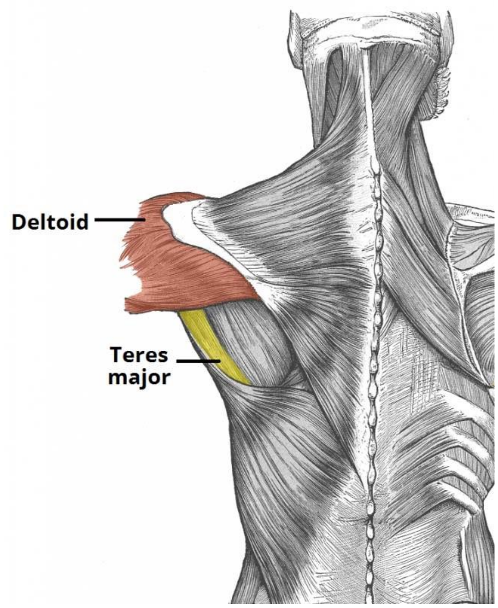

Figure 2.4: Major Shoulder Muscles.

Figure 2.5: Minor Shoulder Muscles.

2.1.2. Elbow Joint

The elbow is the joint connecting the proper arm to the forearm. Structurally, the joint is classed as a synovial joint, and functionally as a hinge joint. Since the forearm consist of two mostly parallel bones i.e. radius and ulna. The joint is formed with two separate articulation of radius and ulna to humerus. Trochlear notch (pulley type) of the ulna to the trochlea of the humerus and head of radius to the capitulum of the humerus [3]. Elbow joint consists of the one set of movement.

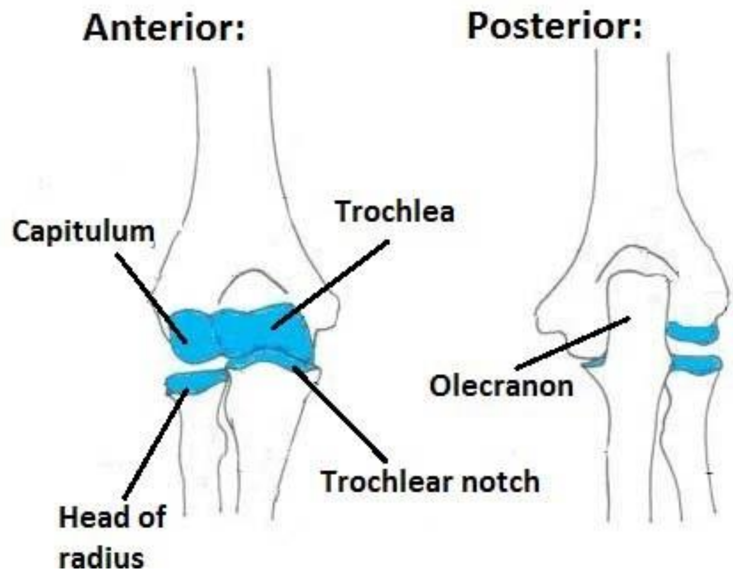

Figure 2.6: Anterior/Posterior View of Elbow Joint.

Flexion/Extension

Flexion or the closing movement of elbow joint (Figure *2.7*) is produced by Brachialis, biceps brachii and brachioradialis (Figure *2.8*). Extension or the opening movement of elbow joint (Figure *2.7*) is produced Triceps brachii and anconeus. (Figure *2.9*).

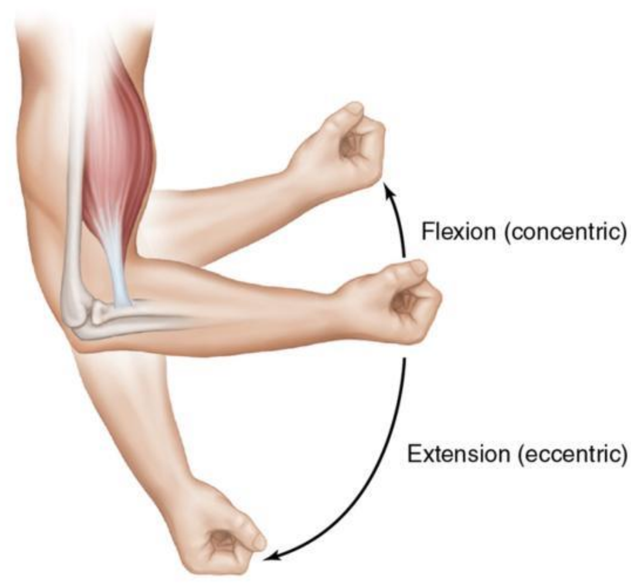

Figure 2.7: Elbow Flexion/Extension.

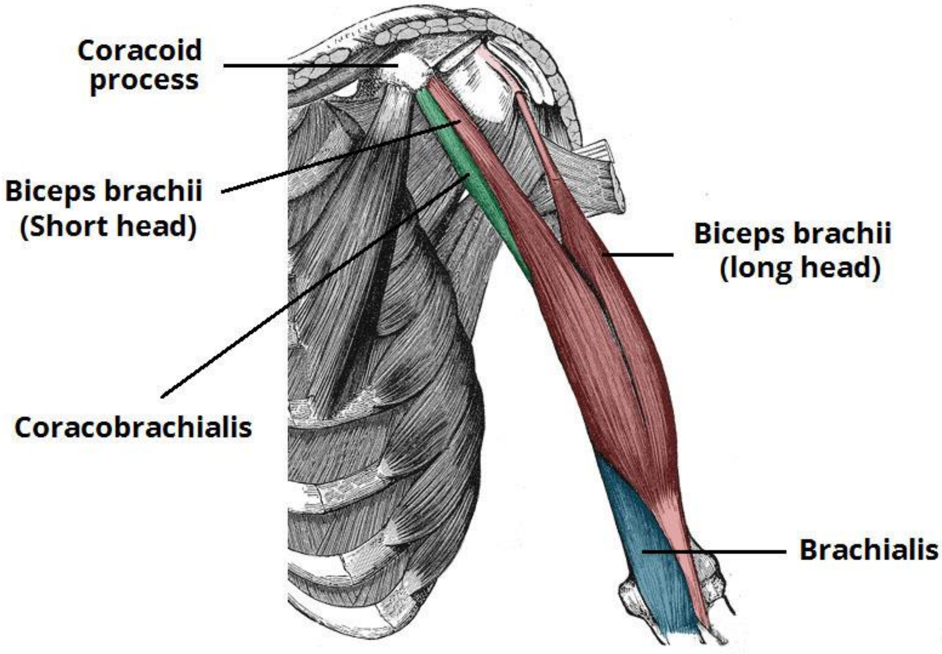

Figure 2.8: Muscles involved in Flexion.

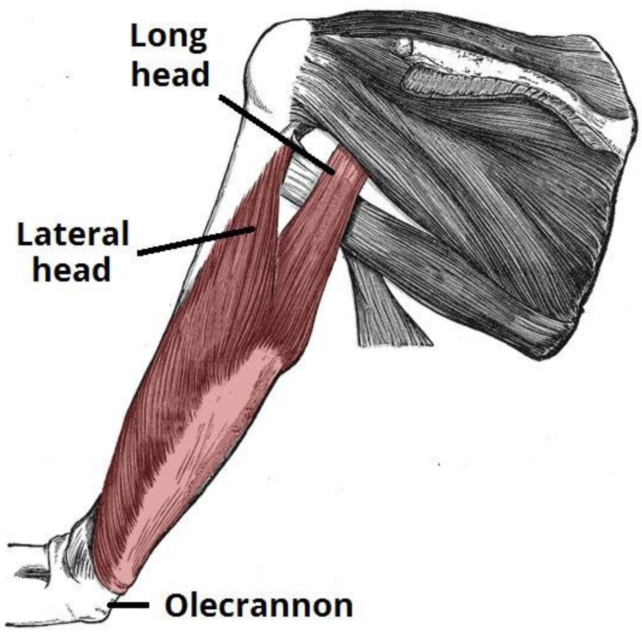

Figure 2.9: Triceps Brachii.

2.2. Related Work

This section includes the review of research articles related to the development of Upper extremity exoskeletons and other rehabilitation procedures. Some of the exoskeleton system developed are listed below.

Miranda et al. of Bio mechatronics Lab, Department of Mechatronics and Mechanical Systems, University of Sao Paulo. Developed a bio inspired wearable exoskeleton for passive therapy exercises targeted at Cerebral Palsy patients. They use a single degree of freedom at the elbow joint. Actuation is done with the help of a DC brushed motor with moved a nut screw mechanism to move the spindle point of a bar whose other end connected to a offset point on the forearm bar (Figure *2.10*). Although the mechanism mimicked the way the actual bicep muscle moves the joint it wasn't fast and efficient. Maximum torque is 45Nm of the design, Maximum Power 40 W, Speed 38º/s, Mass 2,895 kg. It also lacked any symbiotic method to control the joint, just some automated routines were used for therapeutic exercises [3].

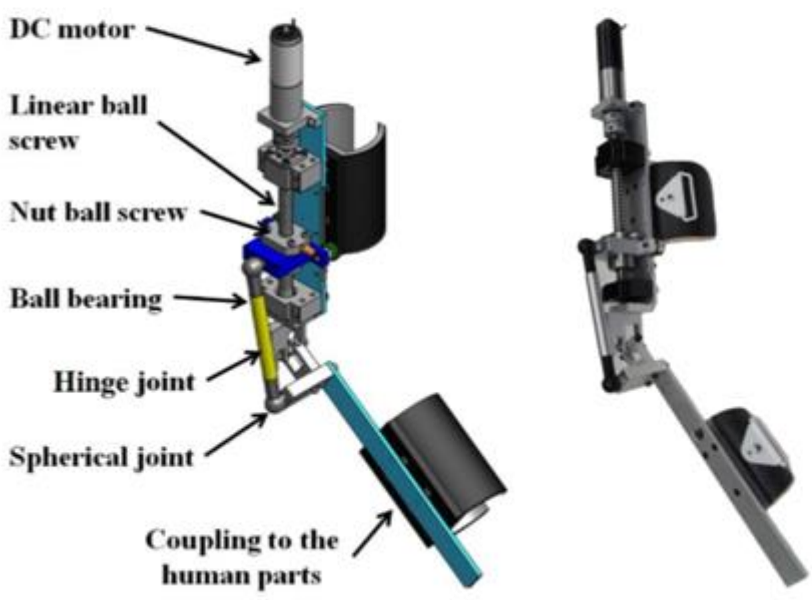

Figure 2.10: (left) 3D model (right) Fabricated Model.

Pransertsakul et al. of Department of Biomedical Engineering, Mahidol University, Thailand, proposed an upper body exoskeleton robotic arm intended to increase the wearer's ability to lift weights. The exoskeleton arm in the following study is focused on the upper extremity, e.g. shoulder and elbow joints. The shoulder and elbow joints in human has 5 degrees-of-freedom movement. Shoulder joint which has 3 degrees of-freedom whereas Elbow joint has 2 degrees-of-freedom movement [5]. Actuation consists of five DC motors and a wire driven system. (Figure *2.11*) EMG based controllers were designed to control motors. The system was heavy and was mounted on a platform [5].

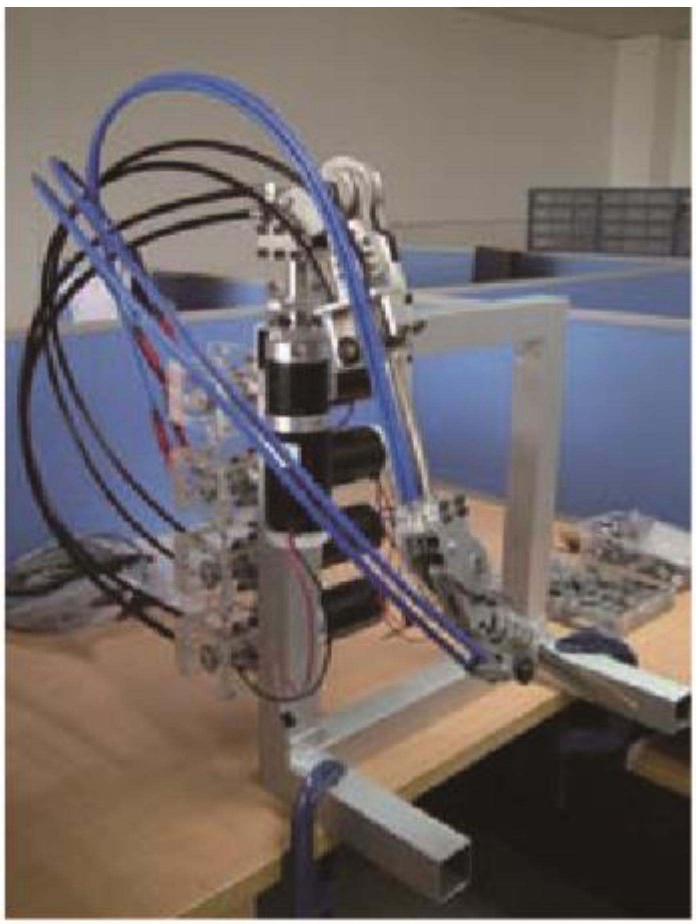

Figure 2.11: The Mahidol University Exoskeleton Arm.

Marcheschi et al. of PERCRO Lab of Scuola Superiore S. Anna, Pisa, Italy (www.percro.org) designed a full body exoskeleton for Italian Ministry of Defense named Body Extender. The main purpose of the exoskeleton was to help soldiers lift heavy loads e.g. loading missiles on an Aircraft or loading rounds on tanks and armored vehicles, which require a lot of difficult labor. System specification are given in

. Most of the actuation is done using frameless high torque DC motors with a ball screw mechanism. Added grippers in both the upper limb to help lifting big and heavy things. *Figure 2.12: Body Extender Worn by a User*Figure *2.12* shows the complete robot worn by a user [6].

Table 2.1: System Specifications of The Percro's Body Extender.

Feature	**Value**
DOF of each robotic arm + gripper	4 + 1
DOF of each robotic leg	6
Rated load capacity of each robotic arm	500 N
Rated grasping force of the gripper	1700 N
Rated angular speed of the robotic joints	60 deg/s
Range of the amplification	3 – 20
Total weight of the robotic device	160Kg

Figure 2.12: Body Extender Worn by a User.

Tsai et al. of National University of Taiwan developed a 9-DOFs exoskeleton for the Physiotherapy and training of upper limb. 3Dofs of shoulder are managed by 6 DOF part, since the robot was seat mounted. The 6 DOF portion managed to align the center of rotation of all 3DOFs of the shoulder joint. For Elbow joint the robot uses only one DOF and 2 DOFs for the wrist joints. The actuators use DC motors of FAULHABER series, which have significant features of light weight and high torque. Total weight of the robot is 23kg. Figure *2.13* shows the 3D model and the actual robot along with its platform.

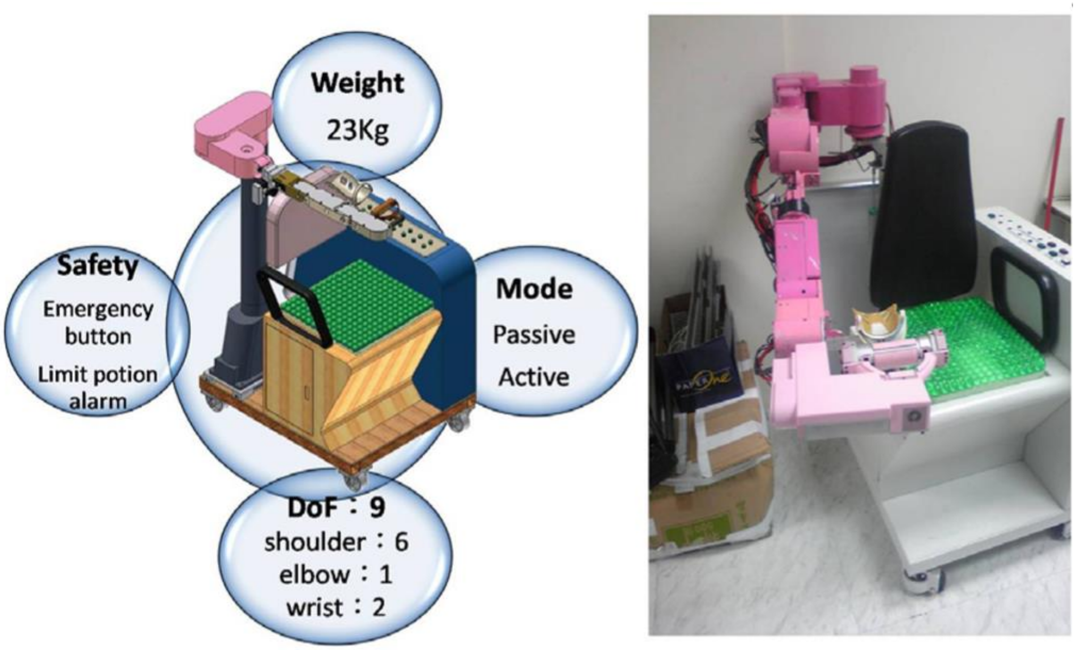

Figure 2.13: (left) 3D Model (right) Rehabilitation Robot.

Apart from the earlier mentioned 4 reviews, many other exoskeleton designs were reviewed to get the better understanding of the trends and weaknesses in Active orthosis. Table *2.2* shows the summarized form of all the Active orthosis publications reviewed to get the basic understanding of the Exoskeletons and active orthosis.

Table 2.2: Review of Previous Advancements in Active Orthosis.

Research	Application	D.O.Fs	Power Source & Transmission Mechanism	Future Ideas of Amelioration
Miranda [4]	passive therapy exercises	01 Elbow	DC brushed motor	Training of user, increasing level of complexity and comfort, Use of EMG (electromyography)

Prasertsakul [5]	Physiotherapy as well as to support & fulfill the lost functions of the limb.	02 Elbow 03 Shoulder	05 DC motors, pulley system & driving wire system	Maturity of the technology and research regarding controllers and EMG signals.
Body Extender [6]	To enhance human strength in handling heavy materials in unstructured environment.	22DoFs; All actuated; in four anthropomorphic limbs	Electrical motors, gears, pulleys & wire systems.	Improving control tactics to involve joint movement tracking and reducing forces
Tsai [7]	Assistance to rehabilitation patients so that they can perform daily activities later.	06DoFsof Shoulder-complex (additionalDoFsto replicate the motion without conflicts) 01DoFof Elbow & 02DoFfor wrist.	04 force sensors with strain gauges, potentiometer, motor (FAULHABER series) actuators and encoders.	To implement and design a controller preset on therapic exercises.
GARREC [8]	Used for teleoperation (nuclear) and haptics (automotive industry).	02DoFsfor Shoulder, 01-Elbow	The Screw-Cable System, Dc motors, pulleys.	Future work comprises of adjustable segments and optimization of the shoulder.
SUEFUL-7 [9]	In this paper basically exoskeleton has 6 DOF. It is mainly targeted for disabled patients.	6 DOF: 2 DOF of shoulder, 2 DOF of elbow, 2 DOF of wrist	Cable drive, gear and motors.	Bringing internal / external rotation in shoulder. We can even try to balance weight of motors for avoid using wheel chair for weight compensation.

CADEN-7 [10]	(CADEN)-7 were targeted for Physiotherapy of disabled people.	7 DOF : 3 DOF of shoulders, 2DOF of elbow and 2 DOF of elbows	Cable drive, motors.	
Moubarak [11]	Robotic assistance for handicaps and rehabilitative training	4 DOF : 3 DOF of shoulder and 1 DOF of elbow	motors	

CHAPTER 3

RESEARCH METHODOLOGY

This chapter includes the statement of problem, methodological approach and research design in general. Methodology to achieve the task has been explained by use of general block diagrams.

3.1. Problem Statement

The functional movement such as walking, extending and other actions by the Upper and Lower extremity limbs are the principle motions of living humans today. Due to poor physical and muscular abilities, Aged human beings are ached with many forms of locomotive handicaps such as strokes, paralysis, hemiplegic cases and spinal cord damage [1]. In today's everyday life, there are numerous reasons from which humans are deprived of their functional movements such as geriatric disorders, trauma, strokes and spinal cord damage.

Stroke is the well-known cause of disability and leading to the fifth most prevalent death cause in US. There are no proper published studies related to stroke occurrence in Pakistan. The estimated annual rate of stroke patients in Pakistan is 250/100,000, which leads to an estimate of 350,000 new cases per annum [2]. Most of these cases lead to disabilities and partial paralysis of the patient’s body, which if not treated properly or in time can lead to permanent paralysis. Despite having such a huge number of new cases every year the rehabilitation techniques used in Pakistan are still quite outdated.

For such disabilities, Rehabilitation therapies stand as the prime solution. Generally, these treatments lean on the dysfunctional motions, which are setup by the means of manipulative physical therapy strategies [1]. Sadly, there are some group of patients that are not able to regain all functions of their bodies. Additional aid of exoskeletons or prosthesis have the ability to support and help in the recovery of the lossy function. Physiotherapy and Functional Electrical simulation (FES) are vastly used techniques for the healing of paralysis and states of lost movement but they have limitations.

Exoskeleton or mobile orthosis is a wearable external device that amplifies the performance of motions. Since exoskeleton or active orthosis is a wearable device we have to consider many parameters regarding safety. Two main objectives were

1. To make the device as light weight as possible to make it comfortable for wearability.
2. Each DOF should correspond and mimic the relative joint as to avoid stresses on the human body.

3.2. Methodological Approach

This research is based to address the issues of wearability, anthromorphism and modularity of exoskeleton design. To develop a various kinds of actice prosthetics and orthotics (exoskeleton) as well as many other forms of rehabilitation of various kinds of disabilities such as smart wheelchairs, research at RISE robotics lab (NUST), Islamabad, Pakistan is in progress. Methodological approach to develop the wearable modular exoskeleton is to divide the overall project into sub-projects and integrate to get the final product. Methodology adopted to develop the exoskeleton was to build a prototype of aluminum alloy to reduce weight as much as possible as use it as the basis for further enhancements on composite materials.

This dissertation is about the development of an Antromorphic modular and wearable exoskeleton and control it using EMG signals. The prototype was capable of providing assistance on movements of 3 DOFs of shoulder and 1 DOF of elbow controlled via EMG.

3.3. Research Design

The first task was the literature review of the project from the mechanical point of view, meaning thereby that different designs for exoskeleton were reviewed. Various constituents of the policies were studied against the design requirements.

Some of these requirements are as follows:

1. The Exoskeleton should be affordable
2. Non-evasive approach towards human body (Anthromorphic)
3. The light-weight and renewable materials
4. The material strength of the system
5. The anthromorphic control strategy
6. The actuation strategy
7. The HMI (Human Machine Interface) Risk Factor

After literature review, we have found these back-draws of the previously developed exoskeletons: Most of the upper extremity exoskeletons till date are fixed on wheelchair or static structures. Some that provide wearability are supported by lower extremity exoskeletons: like Body Extender from PERCRO Lab of Scuola Superiore S. Anna, Pisa, Italy. Hal full body exoskeleton by Cyberdyne, Japan. But the Anthropomorphic exoskeleton being developed by us is wearable, lightweight and portable. Our goal is to keep its weight less than the normal traveler's bag package. Initially 2 concept designs were created, which were fabricated using Styrofoam to check wearability, center of rotations and link dimensions. Figure *3.1* and Figure *3.2* show the 3D model of the two concepts.

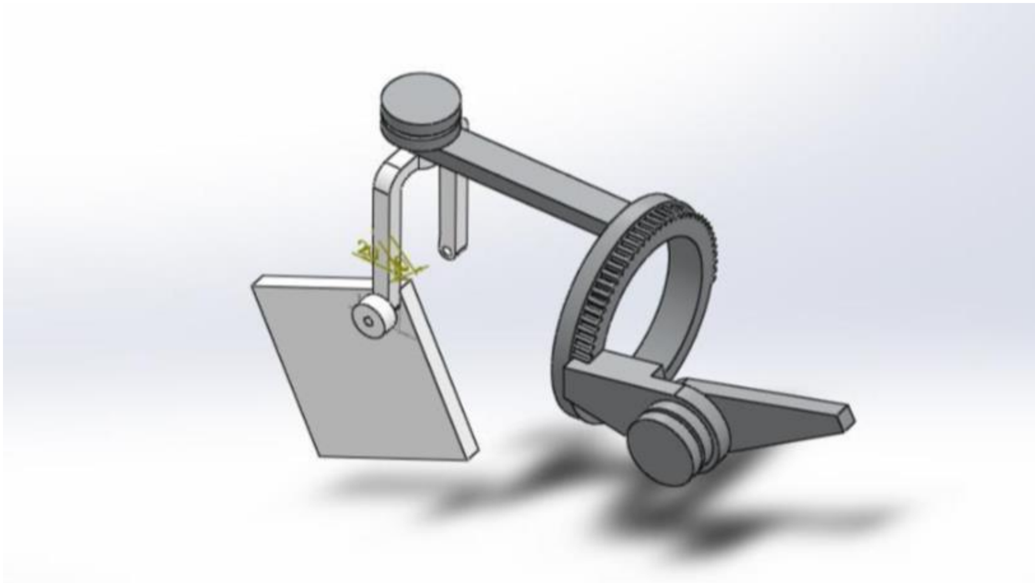

Figure 3.1: Orthosis Concept A.

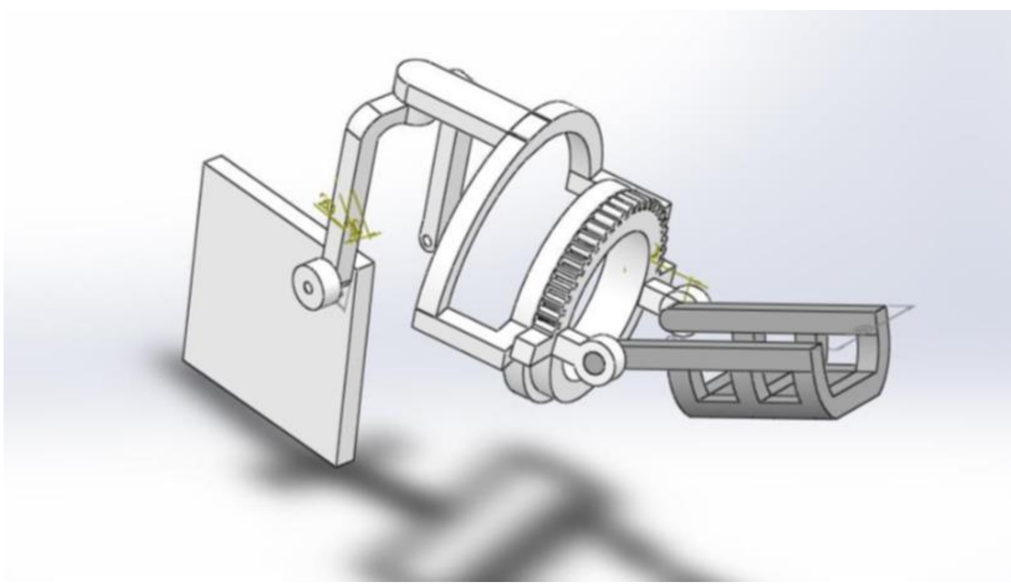

Figure 3.2: Orthosis Concept B.

Concept A was selected as the base of final design. Since Concept A Figure 3.1 is the more simpler to fabricate than the two designs and all its joints can be actuated using Bowden cables.

CHAPTER 4

IMPLEMENTATION

Part I

Modelling and Fabrication of the Exoskeleton

4.1. Designing the Exoskeleton

The main goal of designing the exoskeleton was to make it as simple and precise as possible, so that it can be easily manufactured and fabricated. Plus it was also the requirement that it could be modular so that the Exoskeleton can be modified as per each patient's unique case. For mechanical modelling Solidworks 2012 was used, as it contains a wide variety of standard mechanical parts, such as nuts, bearings etc. one of the unique features of the design is the actuation unit which comprises of Bowden cables and pulleys to keep the weight off the links and joints and make them as light as possible. In the portion below we will discuss the joints and the actuation assembly of the design.

4.1.1. Elbow Joint

The elbow joint of the human body consist of a single degree of freedom. This single degree of freedom can be easily interpreted as a rotational joint. The upward motion of the joint is controlled by contraction of bicep muscle and downward movement by the contraction of triceps muscle as discussed in section 2.1.2. These two movements are translated via a single pulley connected to another pulley via two 1.91mm steel Bowden cables. The secondary pulley is connected to the wormed geared permanent magnet DC motor via nylon gears with the ratio of n1/n2. The use of wormed geared motor gives the advantage of mechanical braking when the motor is depowered as well as lateral mounting. Figure *4.1* shows the 3D model of the elbow joint.

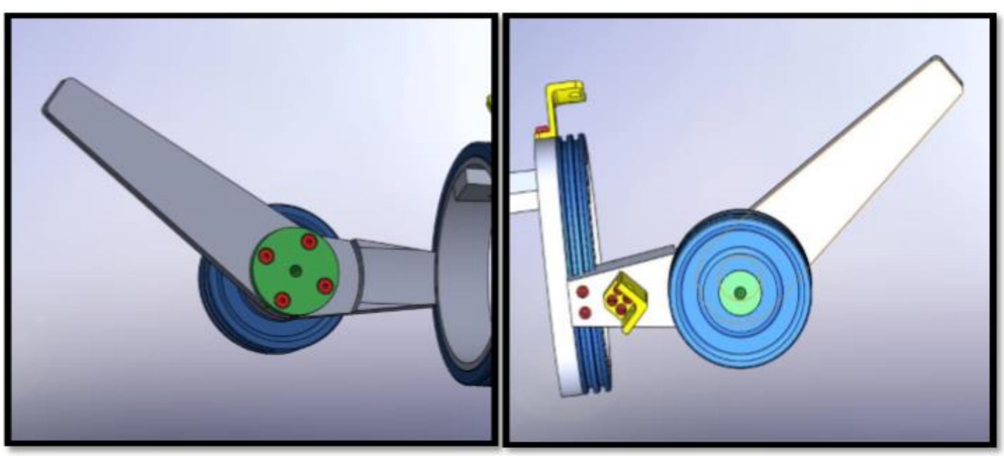

Figure 4.1: 3D Model of the Elbow Joint.

4.1.2. Shoulder Joint

The Shoulder joint of the human body consist of a three degree of freedom. These three degree of freedom joints are all rotational joints in 3 different axes. The upward motion of the arm away from the body is called abduction and is controlled by contraction of mid deltoid muscle and downward movement towards the body is called adduction and is produced by pectoralis major, latissimus dorsi and teres major as discussed in section 2.1.1.2. The upward motion of the arm towards the front of the body is called flexion and is controlled by contraction of biceps brachii (both heads), pectoralis major, chest side fibers of deltoid and coracobrachialis muscles and downward movement towards the back of the body is called extension and is controlled by the contraction of backside fibers of deltoid, latissimus dorsi and teres major as discussed in section 2.1.1.1. The third degree of freedom is shoulder rotation which rotates the arm towards (medial rotation) or away (lateral rotation)from the body and is produced by subscapularis, pectoralis major, latissimus dorsi, teres major and anterior deltoid (medial) and by infraspinatus and teres minor (lateral) as discussed in section 2.1.1.3.

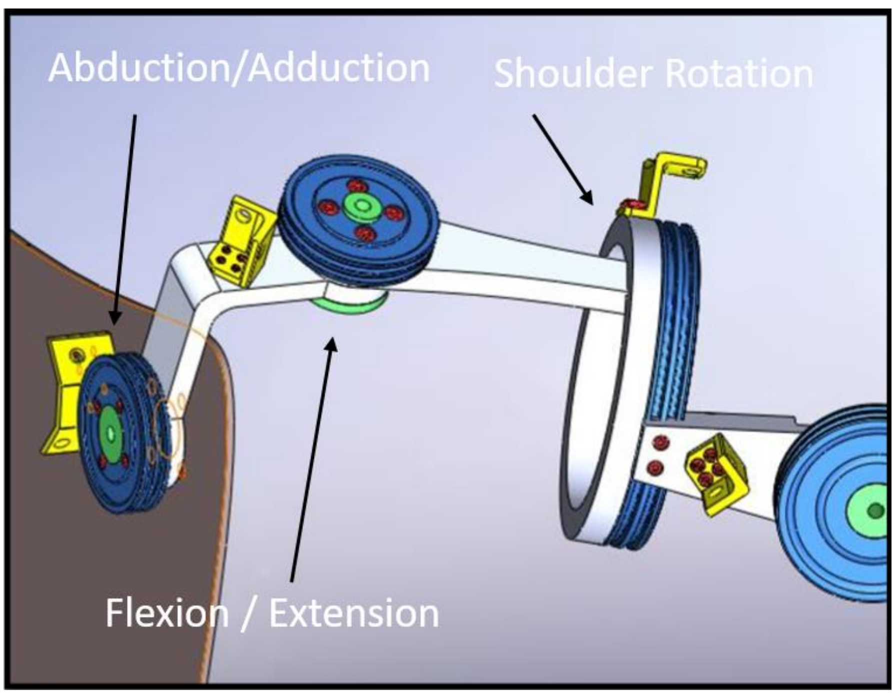

Figure 4.2: 3D model of the Shoulder Joint.

These six movements are translated via three different pulleys connected to the pulleys on the back plate via six 1.91mm steel Bowden cables. The secondary pulleys are connected to the wormed geared permanent magnet DC motors via nylon gears with the ratio of n1/n2. The use of wormed geared motor gives the advantage of mechanical braking when the motor is depowered as well as lateral mounting. Figure *4.2* shows the 3D model of the shoulder joint.

4.1.3. Actuation Assembly

It's a rarity in current upper extremity exoskeletons to use Bowden cable actuated joints. Using Bowden cables allow mounting motors/actuator on back reducing the weight on joints and links thus optimizing power delivery. Lighter then joints lesser force is required to lift/move them. Currently Titan arm provides cable actuation of elbow joint with motor mounted on back. But there shoulder joints are passive. Whereas in our exoskeleton all the joints are active and being powered by electric motors through 1.91mm standard Bowden cables.

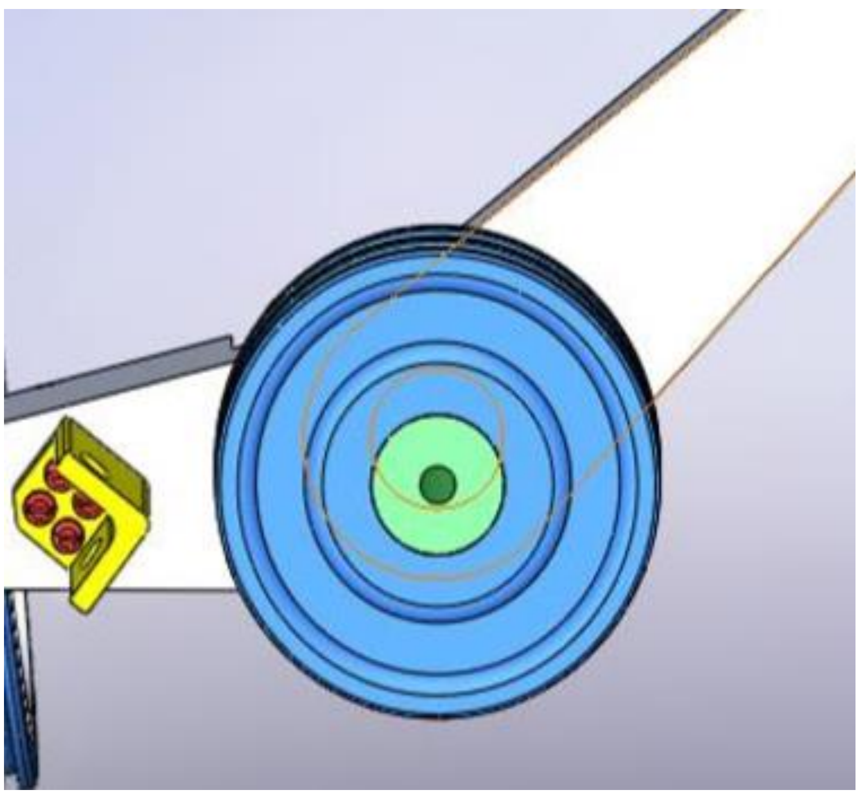

Figure 4.3: Close up of the Pulley on the Elbow Joint.

Every joint has two rotational movements and these two movements are translated via a single pulley connected to another pulley via two 1.91mm steel Bowden cables. The secondary pulley is connected to the wormed geared permanent magnet DC motor via nylon gears with the ratio of 46:14. The use of wormed geared motor gives the advantage of mechanical braking when the motor is depowered as well as lateral mounting. Figure *4.3* shows the close up of the pulley on the elbow joint.

4.1.4. Back Support

The back plate of the exoskeleton provides the base of the robot arm and well as a mounting point for motors and electronics, the back plate is designed with inspiration from a normal backpack that distributes weight evenly on the back. This is turn makes the exoskeleton more comfortable to wear. The back plate can be viewed in Figure *4.4*

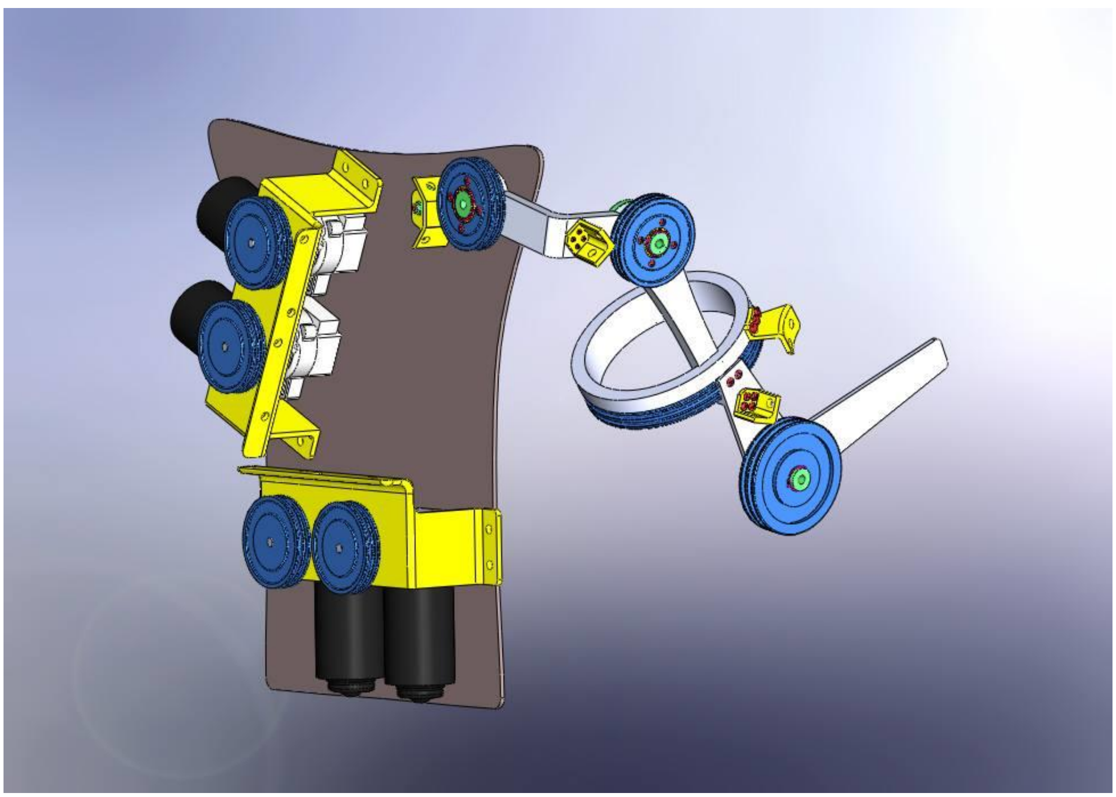

Figure 4.4: Complete 3D Model of the Exoskeleton.

4.2. DH- Table Calculations

The most important part of making a robot arm is calculating its DH – Parameters. Making the DH- table of the robot is the first step towards deriving its kinematics and inverse kinematics equations. Figure *4.5* shows the skeletal model of the robot used to fill the DH parameters of the robot. Table *4.1* shows the DH parameters of the robot.

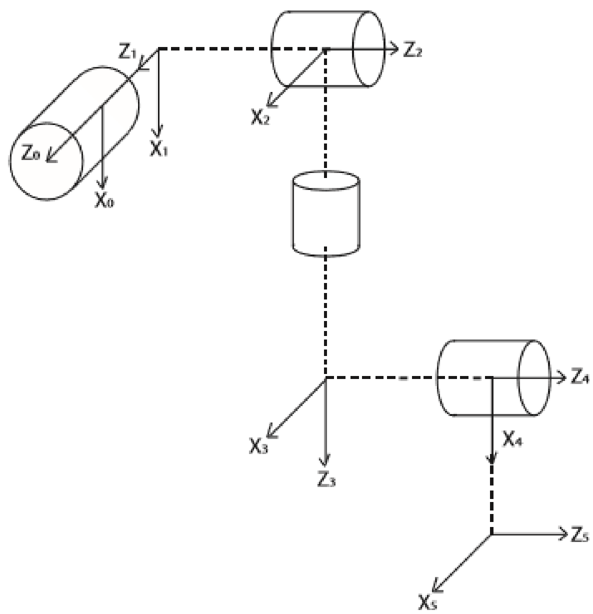

Figure 4.5: DH Parameter Model.

Table 4.1: DH Parameter Table.

Links (i)	a_{i-1}	α_{i-1}	d_i	Θ_i
1	0	0	-L2	Θ_1
2	0	$-\pi/2$	L1 + r	Θ_2
3	0	π	L3 + r	Θ_3
4	0	$\pi/2$	r	Θ_4
5	L5	0	0	0

4.3. Fabrication

During manufacturing of prototype from modified CAD model, most of the parts were machined from solid blocks of Aluminum 1100 alloy. Using CNC machining as well as lathe machine, bending, drilling, milling and threading. Some parts such as the shoulder rotation joint presents cost issue if machined from a solid block and also could produce a large amount of wastage so they were casted using the same allow material then machined as per specifications. We started with cutting the back plate from a 10mm sheet of Aluminum 1100-H12 and mounting the motor and gear assemble brackets on the back plate as shown in Figure *4.6*.

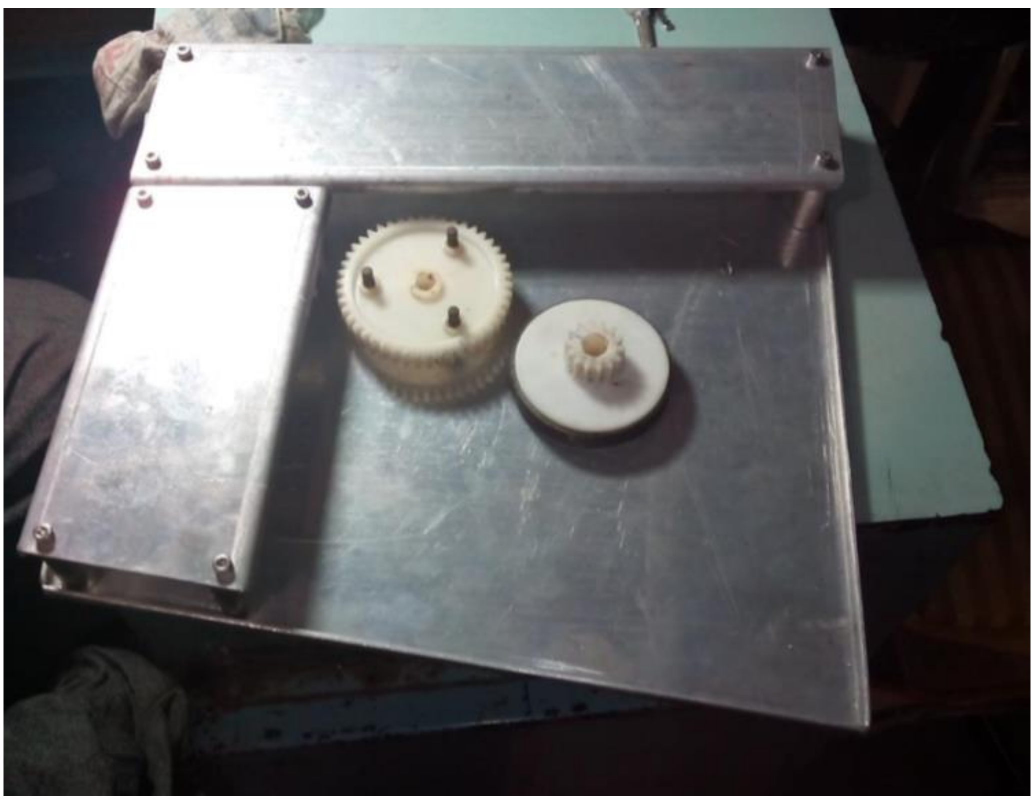

Figure 4.6 : The Backplate with Couple of Gears.

Which followed with the mounting of motor and gear assembly on the brackets as shown in Figure *4.7*.

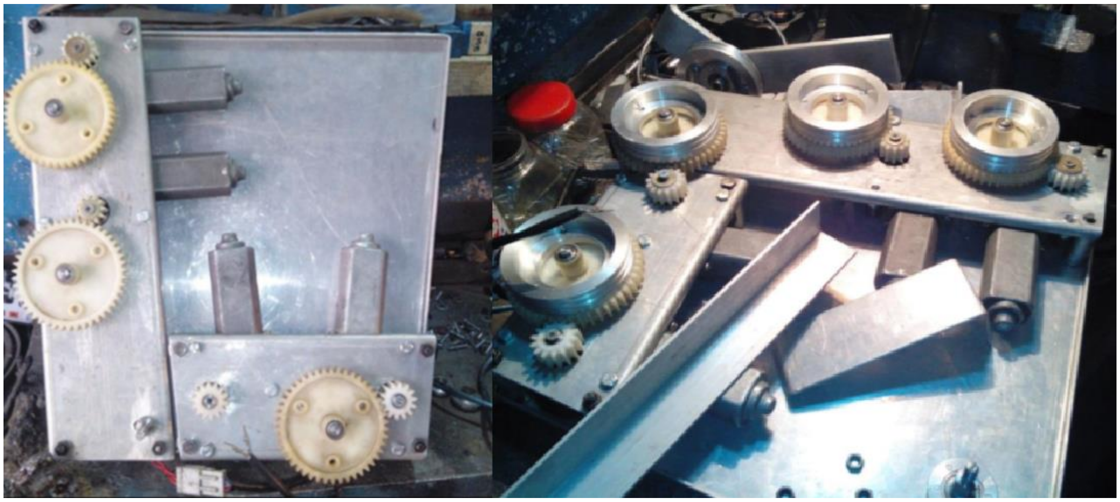

Figure 4.7: Backplate with Motors and Gear/Pulley Assembly Mounted.

After the back plate completed elbow and shoulder parts were machined and assembled. As shown Figure *4.8*.

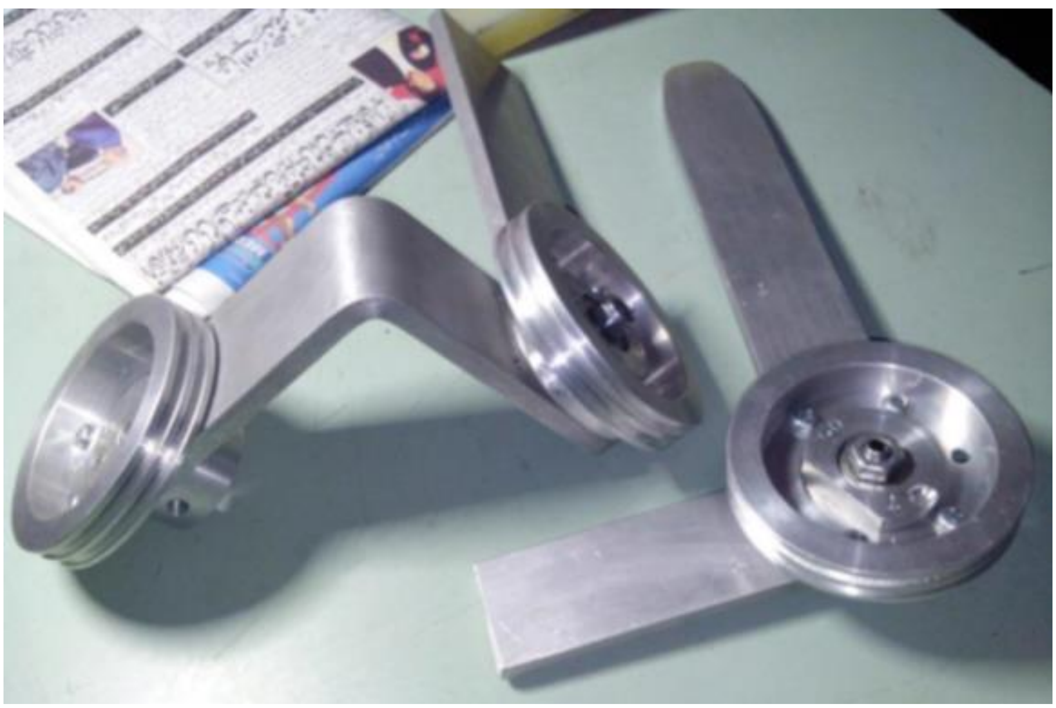

Figure 4.8: Shoulder and Elbow Parts with Pulleys Attached.

Notice that the shoulder and elbow parts in the above Figure 4.8 doesn't contain the shoulder rotation parts. Due to the shape of shoulder rotation joint that part was unsuitable to be machined from a solid piece of aluminum, so it was casted into a crude initial shape and then heat treated to increase the strength of the part. Then the strengthened part was machined to its final shape and attached to the shoulder and elbow part. As shown in Figure *4.9*. The complete assembly of the arm is shown in Figure *4.10*.

Figure 4.9: Shoulder Rotation Part.

Figure 4.10: Complete Assembly of the Arm.

After the arm was assembled it was connected with the back plate and all the joint pulleys were connected with the motor pulleys via 1.91mm steel Bowden cables. The complete assembly is shown in Figure *4.11*.

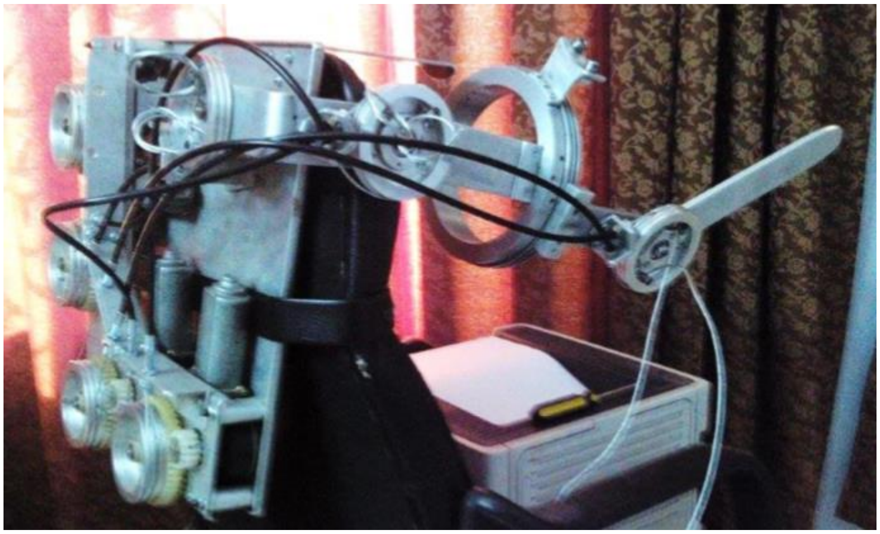

Figure 4.11: Complete Assembly of the Exoskeleton.

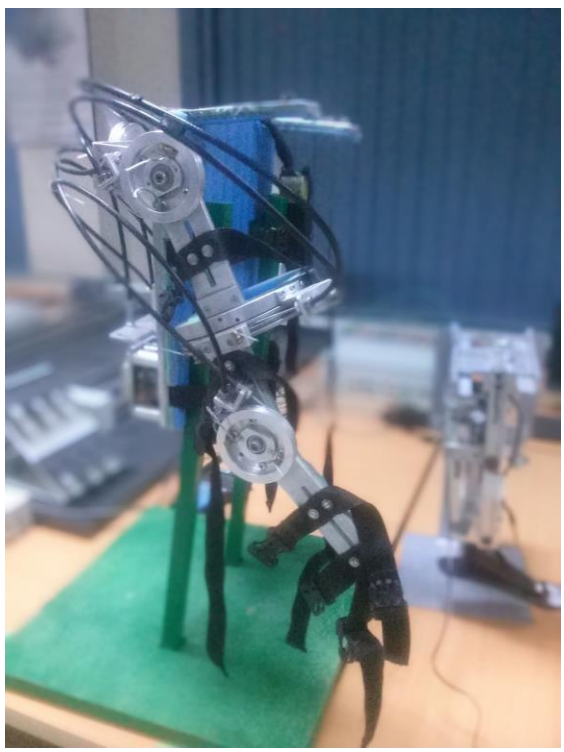

Figure 4.12: Final Form of Exoskeleton.

Later foam base support and nylon straps were pasted on the body contact part of exoskeleton to make it comfortable, secure and more breathable for the user. After the complete assemble the exoskeleton weighed approximately 10Kg with 7Kg distributed on the back, this weight was later reduced by drilling small strips in the arm parts without compromising strength. Figure *4.12* shows the completed exoskeleton on its personalized stand with all foam supports and straps installed.

Part II

EMG motor Controller

4.4. Controller Board

The Control Board is the name assigned to the electronics board featuring the generic modules of the generic board (featuring the microcontroller) and the motor driving electronics board. This board is allowed to be as compact as possible. The reason is that a bulky or cumbersome board would be as impractical as confusing. The small board offers a hidden advantage that as the motors used do not require a high voltage to run, the controllers pins, if buffered can be utilized directly without involving a transistor. This enables ease and flexibility in the design and the board can be made as small as possible. As a matter of fact the board was initially designed with the intention of enabling it to be encased by the actual mechanism so as to make it water and shock proof to some extent.

The microcontroller chosen for control board is Atmega328p based Arduino uno R3. The primary reasons of this selection are.

- Small size 68.8 x 53.4 mm
- High performance low power 8bit AVR Microcontroller Atmega 328.
- 16Mhz clock speed
- Easy to program via standard USB port
- Input voltage range or 7-20V
- Cheap and easily available in local market
- 14 Digital I/O pins (of which 6 provide PWM output)
- 6 Analog input pins (10-bit ADC built-in)

This was coupled with a sEMG sensor board and IRF3205 based dual H-bridge motor driver. The PMDC motors used were salvaged from a car's power windows system which have a peak current of 15A. This particular H-bridge motor controller board was selected for the following reason.

- Small size 10 x 10cm
- Normal current rating 10A

- Peak current rating 30A
- Operating voltage range 3-36 V
- Cheap and can be easily reverse engineered
- Can be operated without adding heatsinks on the MOSFETs as the peak current taken by motor is 15A

4.5. Implementation of Motor Control Using EMG

Surface Electromyography is the field that uses sensors mounted on the residual limb of a person and uses the voluntary muscle signals to control the movement of the prosthesis, such as opening/closing of hand and wrist rotation. Electromyography is an experimental technique concerned with development, recording and analysis of myo-electric signals. This signal is referred to as the electromyographic (EMG) signal. Electromyography uses the electrical activity of the skeletal muscles

There are basically two types of electrodes that are used for acquiring signals from the human body. One is the Surface electrodes while the other one is the pin or needle electrodes. The surface electrodes are stuck on the skin while the needle or pin electrodes are inserted into the body of the patient. But acquiring signals from fine wire sites requires surgical procedure, hence skin surface electrodes are preferred. We are using surface electrodes in our project

Surface electrodes are usually categorized as active electrodes and passive electrodes. Passive electrodes are the more conventional form of electrodes used due to their easy availability and less cost as compared to the active electrodes. The passive electrodes usually consist of a silver disk that sticks to the skin of the patient and measure the electrical activity. A conductive gel is usually used along with the passive electrodes to increase the conductivity hence aiding in sensing. Though for correct measurement, the impedance of the skin should be low. The impedance can also be reduced by abrasion of skin but that procedure is usually avoided. A state of in equilibrium exists between the metal and the skin, it sets up a potential that is measured by the electrodes. Although the potential changes its value based on external factors such as:

- Temperature fluctuations
- Sweat
- Change in concentration of conductive gel
- Relative movement between the skin and the metal

The second type of surface electrodes as mentioned before are the active electrodes. The trend is changing as the passive electrodes are being replaced by the active electrodes. The active electrodes contain a high impedance amplifier within themselves, thus making them more insensitive to the impedance of the skin. This in turn makes them a better quality electrode as compared to the passive electrodes. Moreover, active electrodes are very expensive.

Although modern microelectronics is making it possible to add such amplifiers and filters in the housing of the electrode itself, but the surface electrodes also have some disadvantages such as:

- ➢ One of the main disadvantage is that these electrodes can only be used on the superficial muscles.
- ➢ These cannot be used for small muscles as the “noise or cross talk” from surrounding muscles becomes a concern.

To get a good signal from the subject, there are certain preparations that are important to do on the test subjects skin i.e. removal of hair and drying of surface using rubbing alcohol.

For electronic circuitry two different types of approaches can be used namely DC coupled approach and Ac coupled approach. DC approach is easy to manage but has some drawbacks, which will be discussed later in this chapter. But for this project the DC approach was used although AC approach was also researched.

DC coupled approach was used in the electronics of the low cost circuitry of MYO prosthetic limb. Following are the main points regarding the DC coupled approach used.

- Conventionally used approach
- Uses instrumentation amplifier with DC coupled front end (INA 121)
- Noise removal done by analog filtering

The main drawbacks of DC coupled approach is that the max gain of instrumentation amp is limited due to amplification of input offset voltages of IC and electrodes which can lead to saturation. Hence amplification has to be done in multiple stages, which increases size of circuitry. Raw EMG signal cannot be fed into the ADC due to its bipolar and inconsistent nature. Some signal processing procedures has to be applied in order to make the signal usable for ADC. Linear envelop approach was adopted because:

- Easy to implement.
- Real time value.
- Smooths EMG burst signal to a dc average value.
- Cost effective.

First we attempted to make our own sEMG amplifier using research from Kuang-Wu Institute of Technology. INA118p was used as a primary amplifier then the amplified signal was further amplified in 3 stages using an active high pass filter followed by an active low pass filter then the signal was finally amplified to a microcontroller readable level with the help of an active rectifier. All the active filter circuits used opamp LF351 [12] . Figure *4.13* shows the circuit schematics of the proposed amplifier.

Although the above system worked, it has numerous drawbacks. The circuit was too noisy and costed more than the easily available Advancer Technologies Muscle Sensor v3. Which uses a similar design in a more compact form and variable gain.

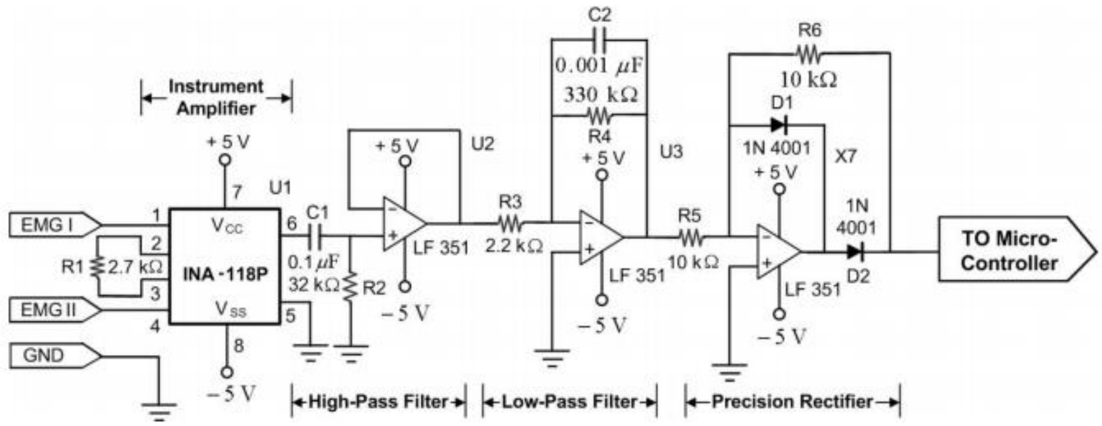

Figure 4.13: Measurement and processing circuit for EMG signals [12].

CHAPTER 5

RESULTS AND ANALYSIS

Before fabrication of the exoskeleton. Some analysis were performed on the 3D model to verify and test its strength and strain levels and boundary conditions. These tests also help in finding weak spots in the design so that they can be rectified before fabrication. These tests insure a good safety factor and prevent any harm or future accidents.

5.1. Mechanical Analysis of Exoskeleton

Designs are meant to be simple and precise that are efficient, meaning that they are easy to manufacture and accomplish their goals with the minimum amount of materials. To design our anthropomorphic exoskeleton we used SolidWorks 2012, because Solidworks 2012 is highly designer-friendly which provide built-in mechanical fastening and bearings, with easily executable commands to develop even complex parts.

By help of it virtual real-world environments can be set up to carry out analysis test on product designs before its fabrication. a wide range of parameters can be analyzed during the design process, such as durability, static and dynamic response, motion, heat transfer and fluid dynamics etc.

Basically it uses the displacement formulation of the finite element method to calculate component displacements, strains, and stresses under internal and external loads. During analysis part is discretized using tetrahedral (3D) or pyramid for complex part shapes, 30 triangular (2D), beam elements, and solve by direct sparse or iterative solver. SOLIDWORKS Simulation also offers the 2D simplification assumption for plane stress, plane strain, extruded, or axil symmetric options. Analysis carried out for Exoskeleton assembly. Analysis was carried out in SOLIDWORKS Simulation Xpress Analysis Wizard. In Simulation Xpress, we apply loads and fixtures to part, specify its material, analyze the part and view the result. Basically I carried out Von Mises Stress

Criteria. It is basically used to analyze whether our design will withstand a given load condition. If the maximum value of Von Mises stress applied to the material is less than strength of the material, hence part is safe. It works well for most cases, especially when the material is ductile in nature. Some of the assumptions were carried out for analysis feasibility according to SolidWorks software constraints. Assumptions as follows,

- Uniform load will be applied on material.
- Static analysis will be carried out separately on design parts rather than whole assembly.

On whole assembly Von Mises Stress was carried out with the help of two UG students to obtain different results regarding assembly Max stress, displacement and strain limit. Analysis was carried in multiple situations by applying forces in different directions and varying the magnitude of force also. In every case single joint is fixed, force is applied at one end and analysis was carried to obtain different parameters of design.

5.1.1. Analysis for Major Parts of the Assembly

Forearm Beam

Von Mises analysis was carried out on forearm made of aluminum. Hence it shows that yield strength (27,574,200 N/m^2) of material (aluminum) is above the maximum amount of force (15,487,209 N/m^2) applied on it. As you can see in Figure *5.2* FOS is this part is 1.4 according to simulation. Hence forearm beam will be safe for fabrication. Figure *5.1* shows the Von mises analysis of forearm made out of Aluminum 1100.

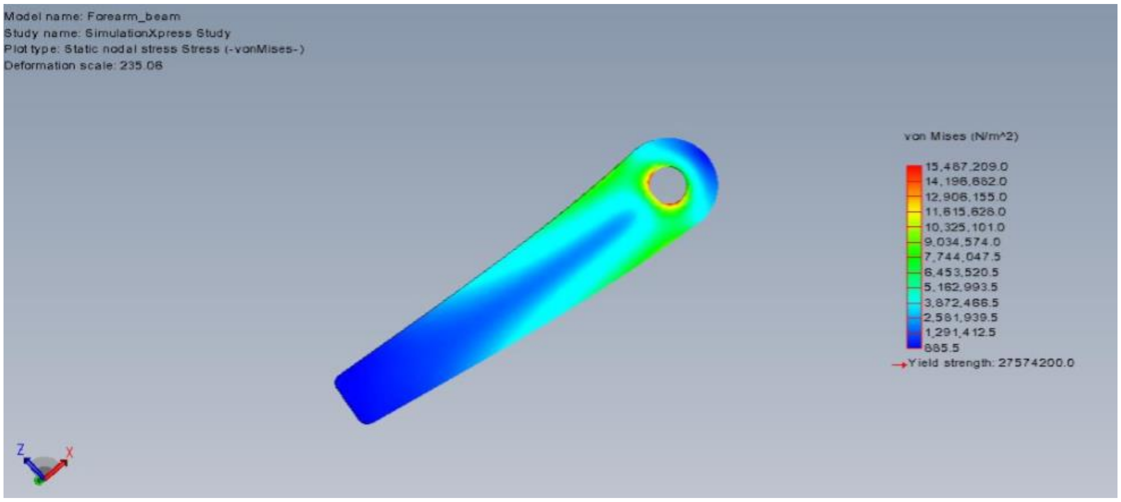

Figure 5.1: Von Mises Analysis of Forearm Beam.

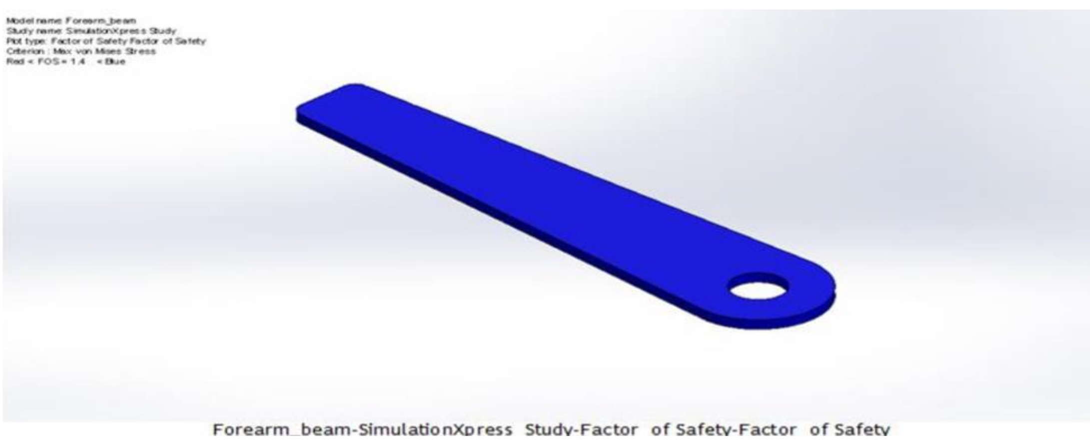

Figure 5.2: FoS of Forearm Beam.

Upper Shoulder Beam

As Von Mises analysis was carried on this part made of aluminum, analysis shows that yield strength (27,574,200 N/m^2) of part is higher than the maximum amount of force (3,149,511.8 N/m^2) applied on it as seen in Figure *5.3*. The factor of safety of this part is 1.2 according to simulation as seen in Figure *5.4*.

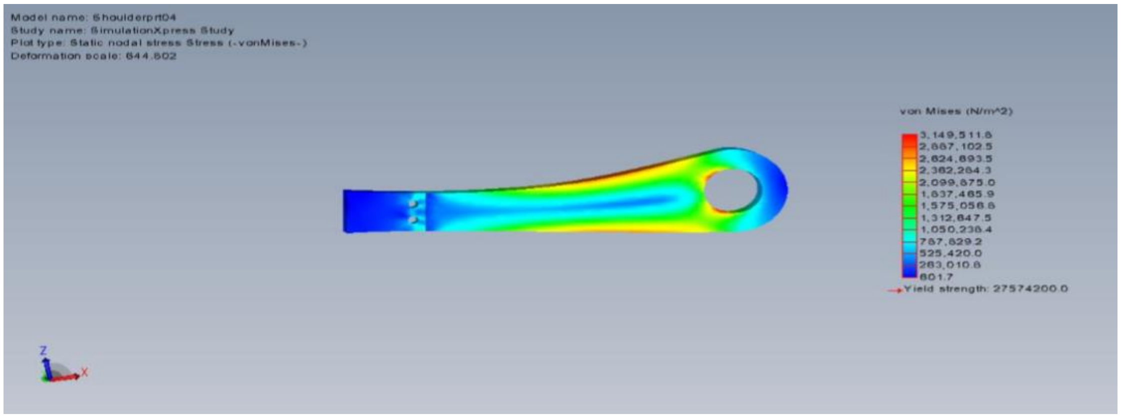

Figure 5.3: Von Mises Analysis of Uper Shoulder Beam.

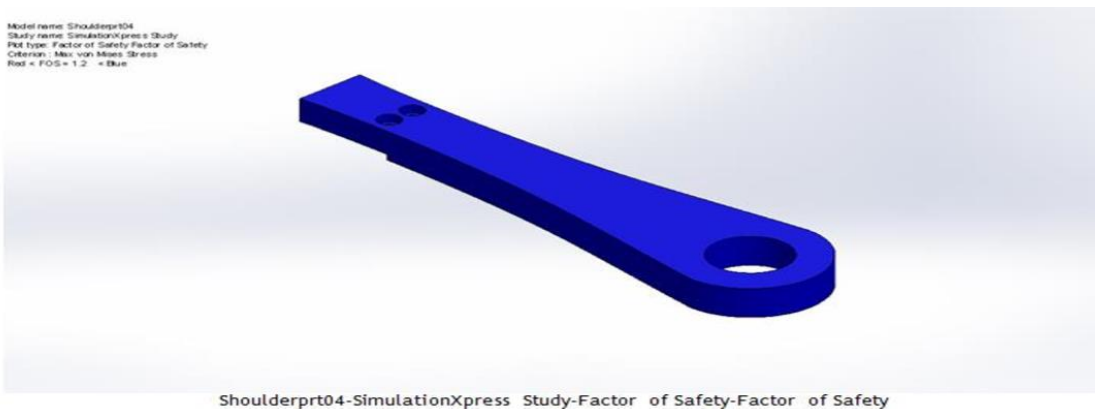

Figure 5.4: FoS of Upper Shoulder Beam.

Over Shoulder Beam

Von Mises analysis was carried on this part made of aluminum. The result of analysis shows the result that yield strength (27,574,200 N/m^2) of this part is higher than max force (24,849,628 N/m^2) applied on it as seen in Figure *5.5*. According to simulation FOS is: 1.2 as seen in Figure *5.6*.

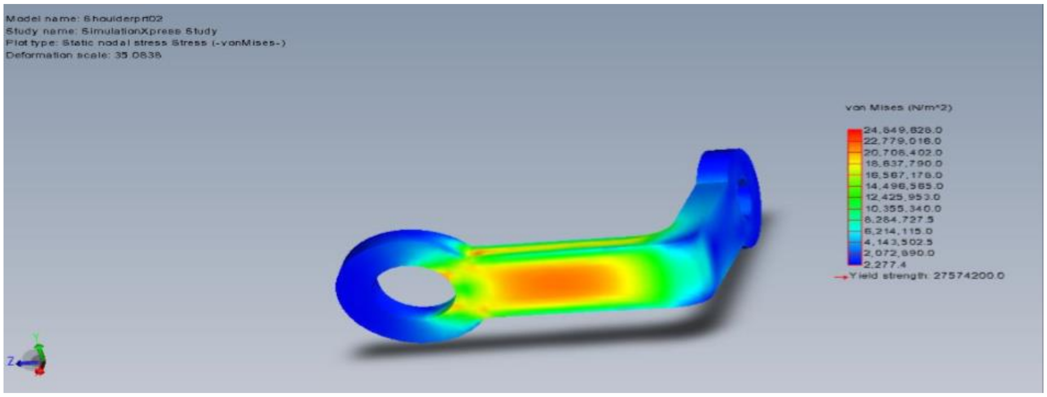

Figure 5.5: Von Mises Analysis of Over Shoulder Beam.

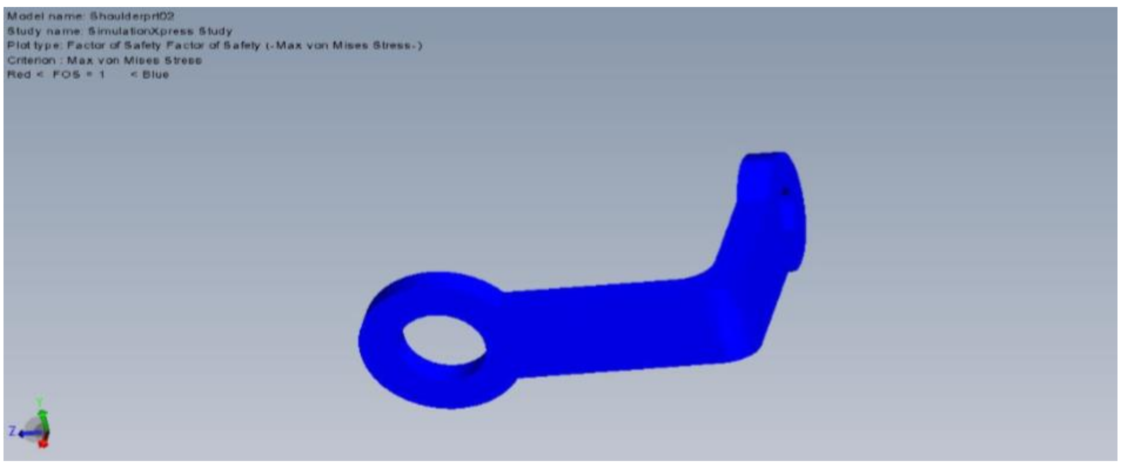

Figure 5.6: FoS of Over Shoulder Beam.

Elbow Beam

Von Mises analysis was carried on this part made of aluminum. The result of analysis shows the result that yield strength (27,574,200 N/m^2) of this part is higher than max force (44,817,380 N/m^2) applied on it. According to simulation FOS is: 0.16. Hence it is not safe for fabrication as it can deform at the red label area shown. That particular area was later thickened to add more strength during fabrication.

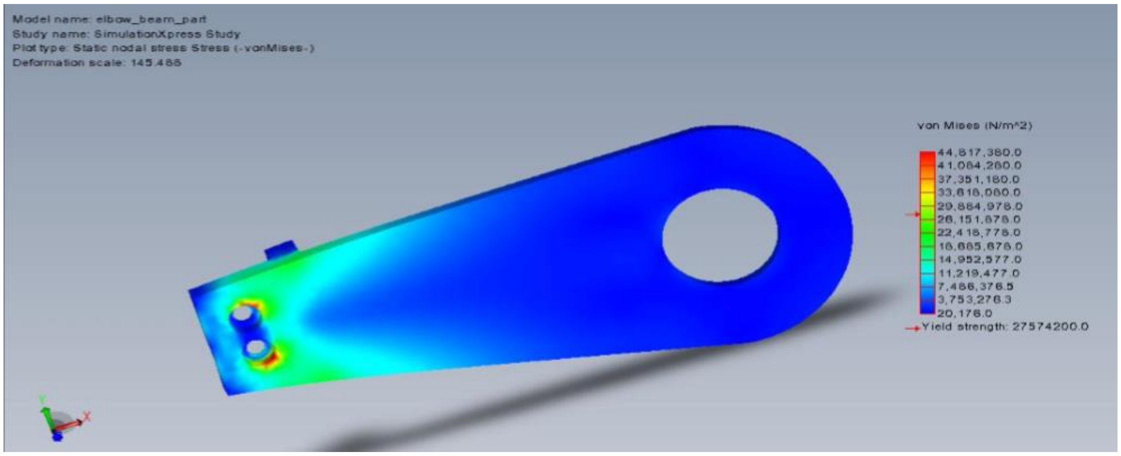

Figure 5.7: Von Mises Analysis of Elbow Beam.

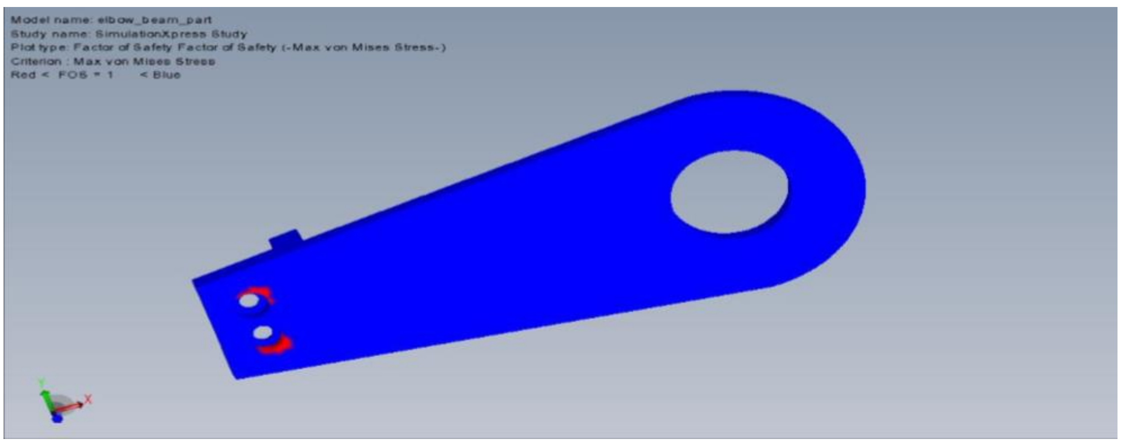

Figure 5.8: FoS of Elbow Beam.

Gears

Von mises analysis was carried out on both the motor and pulley gears to check for stress strain and displacement of the gears. Figure *5.9*, Figure *5.10* and Figure *5.11* shows the 3 different analysis on Motor gears. Figure *5.12*, Figure *5.13* and Figure *5.14* shows the same 3 tests done on pulley gear.

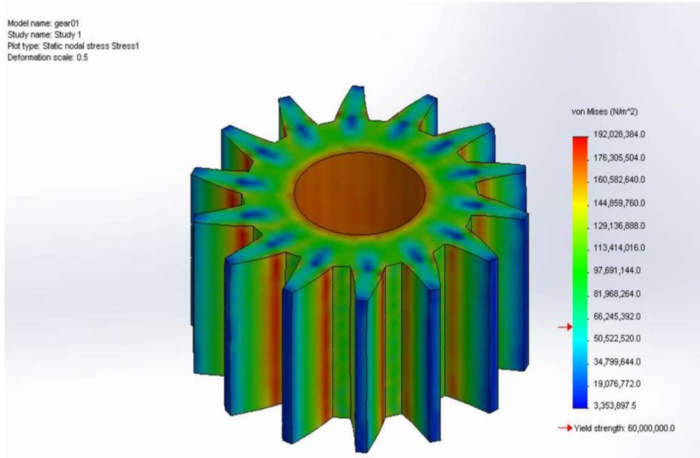

Figure 5.9: Stress Analysis of Motor Gear.

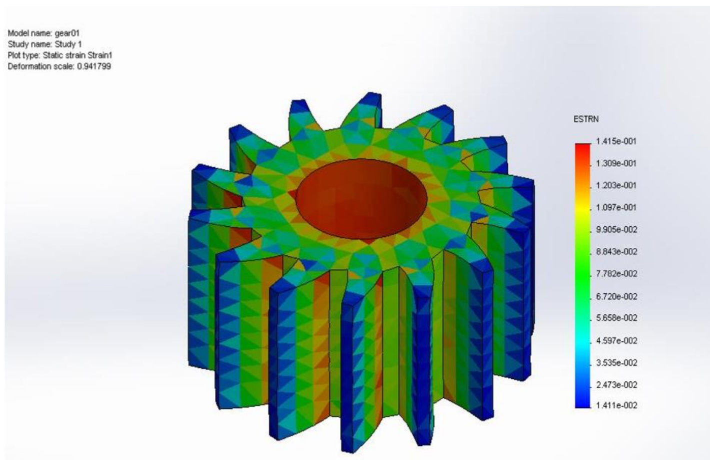

Figure 5.10: Strain Analysis of Motor Gear.

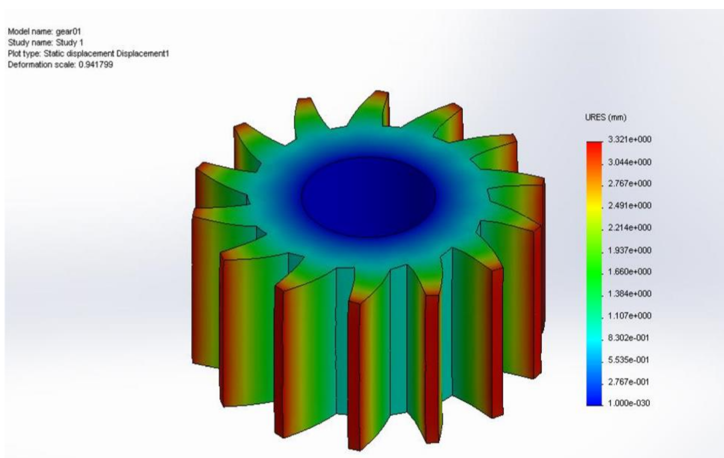

Figure 5.11: Displacement Analysis of Motor Gear.

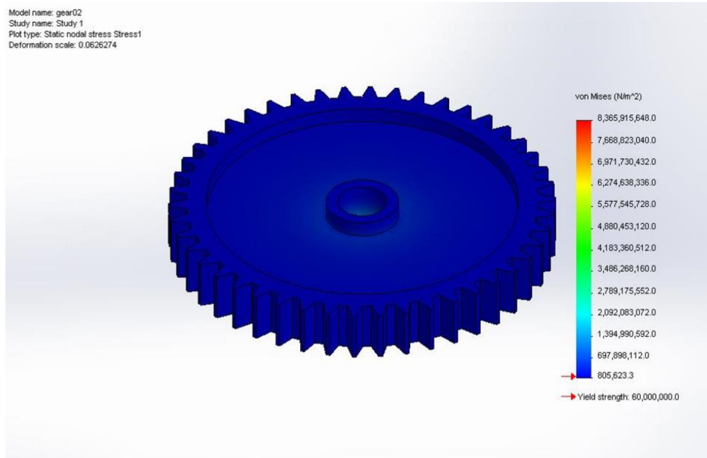

Figure 5.12: Stress Analysis of Pulley Gear.

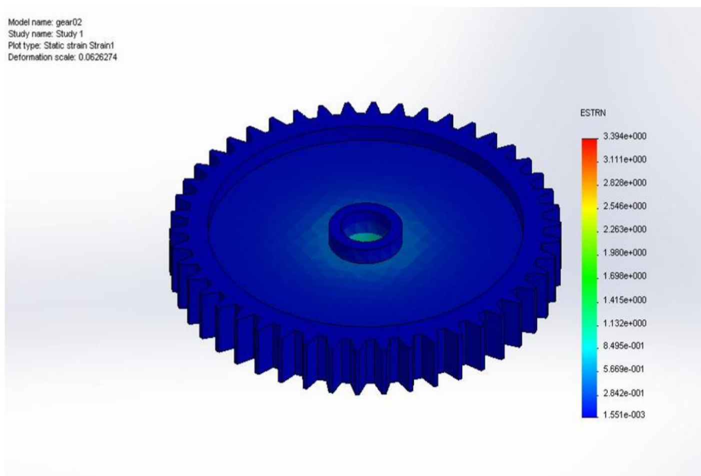

Figure 5.13:Strain Analysis of Pulley Gear.

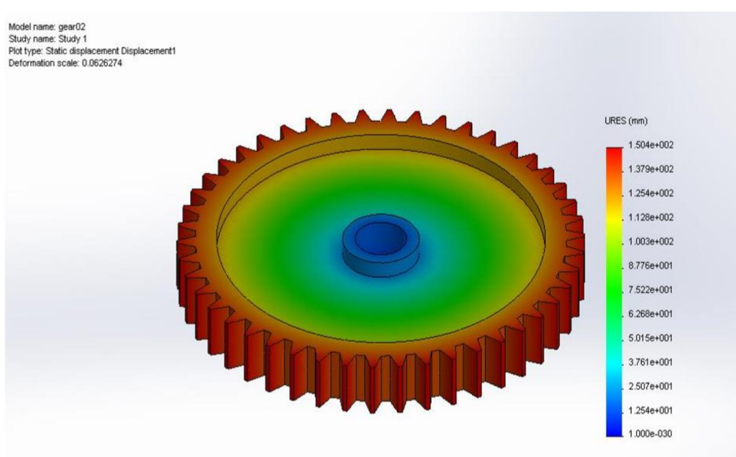

Figure 5.14: Displacement Analysis of Pulley Gear.

5.1.2. Solid Works Analysis for Torques and Resultant Forces

During analysis whole arm was assumed to be fully extended forming 90 degrees to body longitudinal axis and Abduction, adduction case were analyzed. 2Kg of load was applied at the end of forearm beam due to which resultant forces and torques on each beam was analyzed to obtain the amount of torque required for motors.

Resultant Forces and Torques on Forearm

By adding the weight and gravity at the end, we found the following for the forearm part. Figure *5.15* for reference.

- Resultant Moment : 35.8 N-m
- Resultant Force (Fy) : 219N

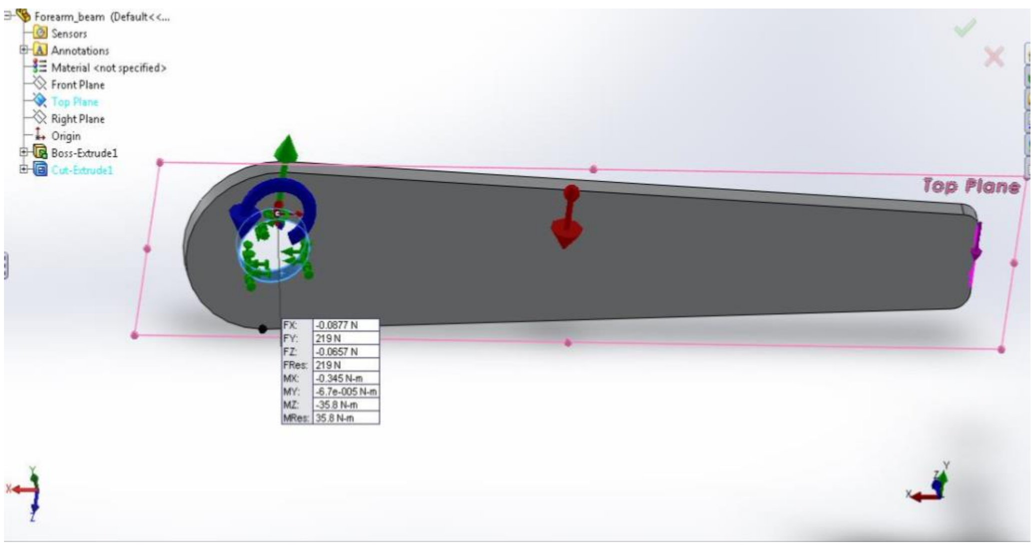

Figure 5.15: Resultant Forces and Torques on Forearm.

Resultant Forces and Torques on Elbow Beam

By adding the weight and gravity at the end, we found the following for the elbow beam part. Figure *5.16* for reference.

- Resultant Moment : 78.4 N-m
- Resultant Force (Fy) : 158N

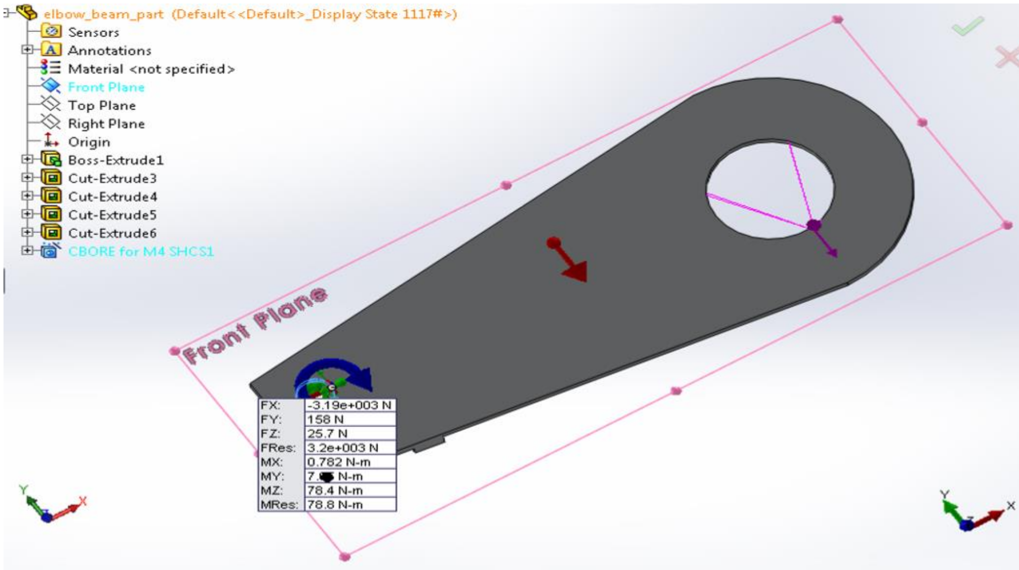

Figure 5.16: Resultant Forces and Torques on Elbow Beam.

Resultant Forces and Torques on Shoulder Beam

By adding the weight and gravity at the end, we found the following for the shoulder beam part. Figure *5.17* for reference.

- Resultant Moment : 106 N-m
- Resultant Force (Fy) : 228N

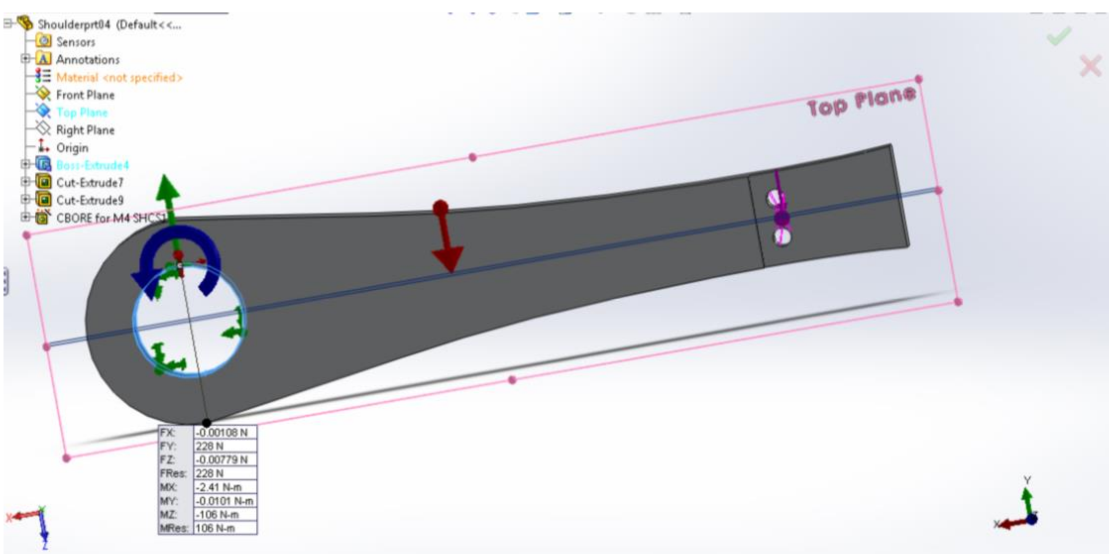

Figure 5.17: Resultant Forces and Torques on Shoulder Beam.

Resultant Forces and Torques on Over Shoulder Beam

By adding the weight and gravity at the end, we found the following for the over shoulder beam part. Figure *5.18* for reference.

- Resultant Moment : 12.8 N-m
- Resultant Force (Fy) : 158N

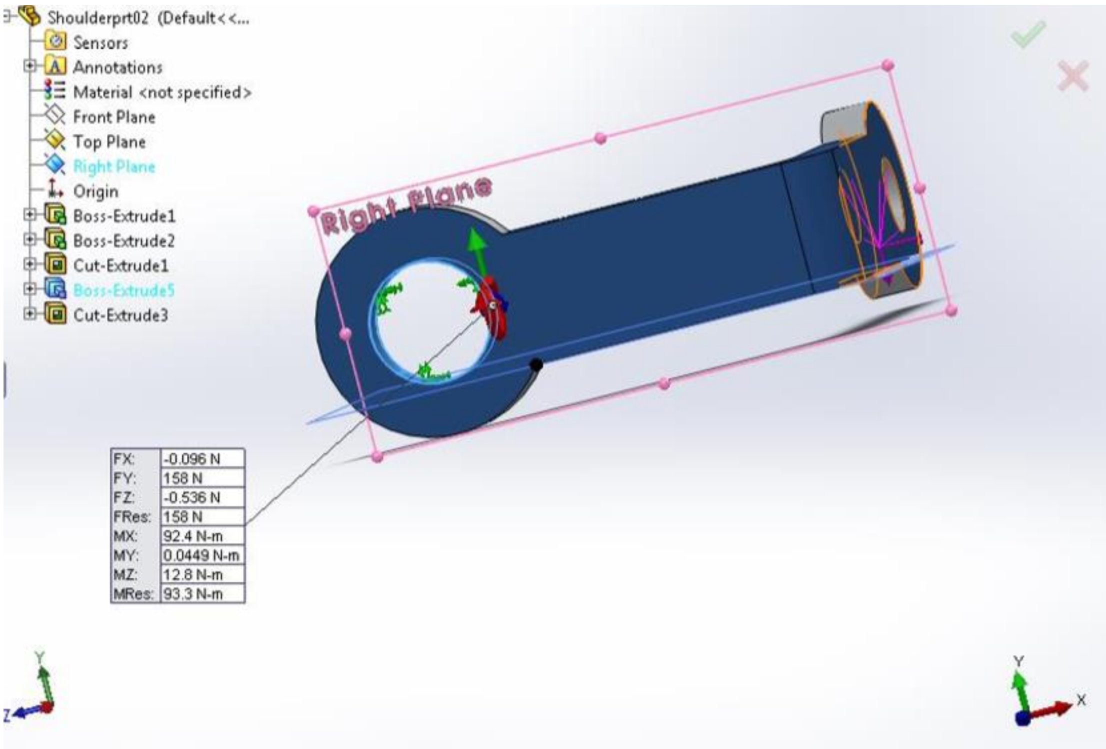

Figure 5.18: Resultant Forces and Torques on Over Shoulder beam.

5.1.3. Full Assembly Analysis

As we had fixed shoulder back plate joint and forces were applied in different configurations, through which design was modified according to our requirements of application. The finalized design was under FOS of 1.2 and ultimate strength was below ultimate stress by help of Von Mises Stress. Figure *5.19* shows the von mises analysis of the full assembly.

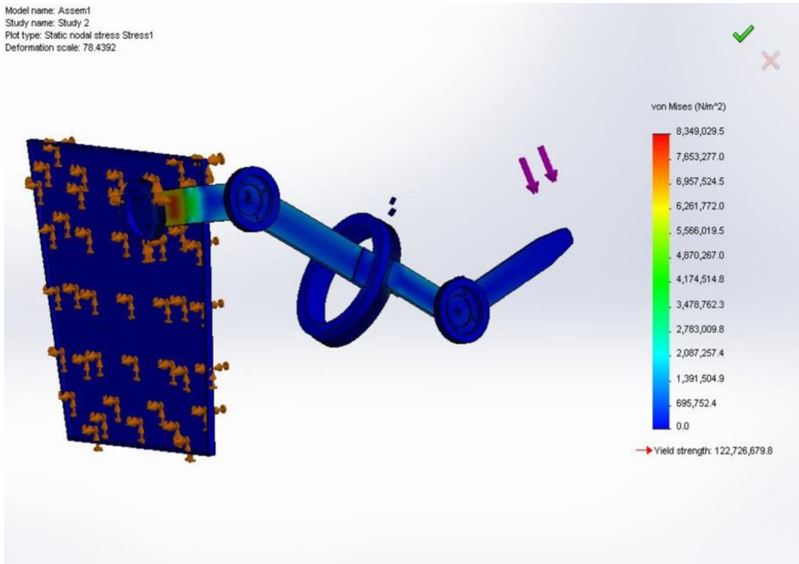

Figure 5.19: Von Mises Analysis of Full Assembly.

The maximum stress does not exceed the yield strength (99 MPa) of the material for the applied loads. However, it is desirable to operate the model below 30N so that the factor of safety remains greater than 1.8 and the displacements does not exceed 6mm. Although when worn the stress and strain constraints are also complimented with the human body. The analysis was done on a simplified model. The real model would include other load bearing components including pulleys and cables which will reduce the maximum stress and allow a greater load to be applied.

5.2. Torque and Motor Testing

5.2.1. Maximum Torque Required

The maximum torque requirement was calculated at the shoulder joint as it is required to lift the whole length of arm.

- Weight of exoskeleton arm and human arm = 4000 grams
- So force exerted by this weight = 4*9.81 = 39.24N
- Maximum distance for maximum torque = 0.4m
- Torque required = 39.24*0.4 = 15.69 Nm

5.2.2. Torque Produced by Motors

The maximum current drawn by motors at full load is 5A at 12V generating a maximum of 120 RPM.

Therefore power generated is

$$P = VI = 12 * 5 = 60W$$

As we know

$$P = (Torque * 2\pi n)/60$$

$$Torque = (P * 60)/2\pi n$$

Were n is the RPM

$$Torque = {}^{60 * 60}/_{2 * 3.14 * 120} = 4.77Nm$$

Adding the final gear ratio of 14/46

$$final\,Torque = 4.77 * \left(\frac{46}{14}\right) = 15.7\ Nm$$

So we can see that the final torque the motor can generate is almost equal to the maximum torque requirement.

5.3. EMG Motor Controller

As mentioned in segment 4.5, initially testing the sEMG amplifier shown is Figure *4.13*. We decided to opt for the Advancer Technology's Muscle Sensor v3™, which cost the same as the board we made and was easily available in the market. The board uses almost the same structure i.e. instrumental Amplifier, followed by an active high pass filter, rectifier and a low pass filter for smoothening the output signal. The power requirement for the board is a dual power supply which can easily be provided by two

9v batteries connected in series. Figure *5.20* show the schematic diagram of Muscle sensor v3.

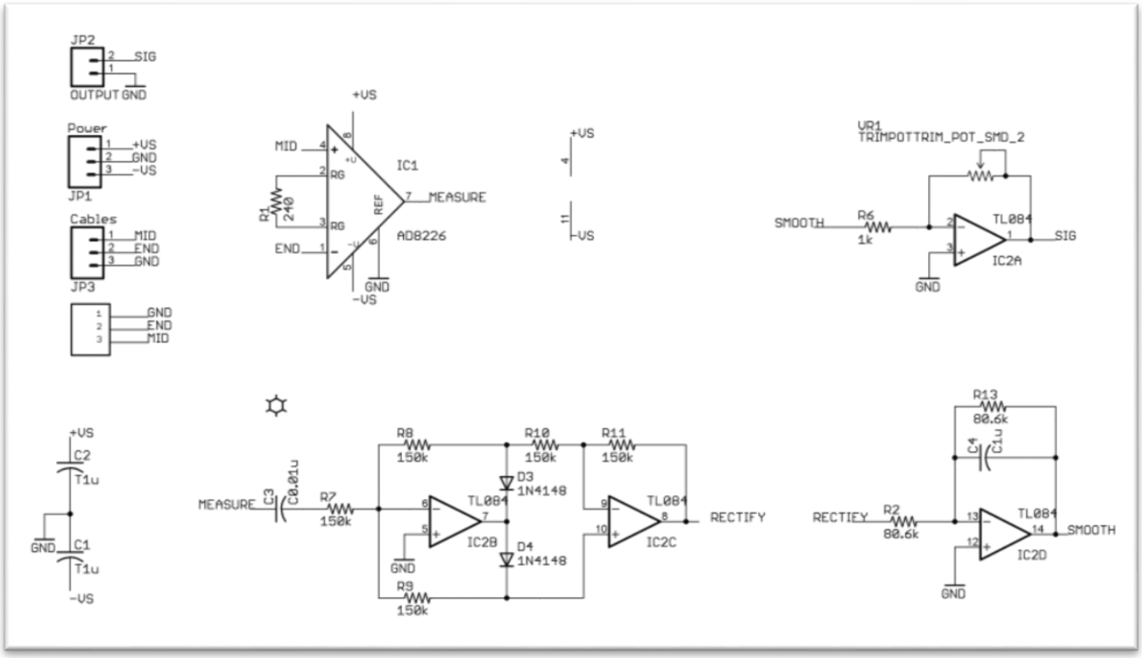

Figure 5.20: Schematic Diagram of Muscle Sensor v3.

Initially we tested the muscle sensor board by connecting its output to an oscilloscope, while giving input from the forearm muscles as they were easier to locate and can be tested by just closing and opening of your fist. Figure *5.21* shows the results of the oscilloscope. In which you can see, it gives a peak of 2V-3V when the muscle is activated and 0.5 to 1 v when muscle is inactive.

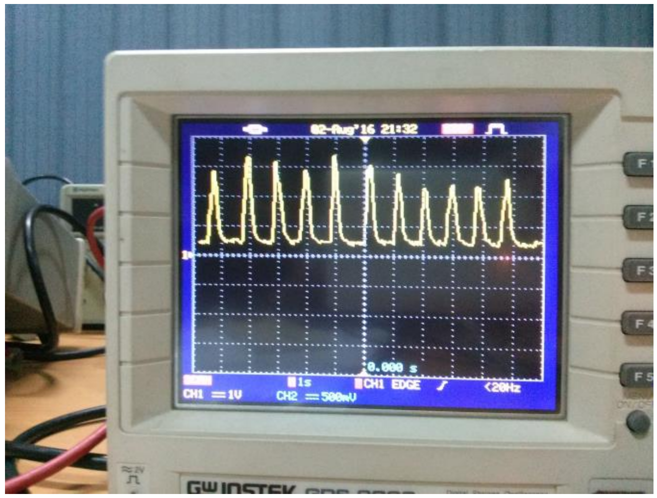

Figure 5.21: Oscilloscope Results of Muscle Sensor v3.

Taking these values in consideration we programed our Arduino to control the motors following the flowchart in Figure *5.22* . We also added limit switches at the end of each joint as a safety precaution to avoid overloading the motors and pulleys mechanism. The exact code can be seen in appendix A.

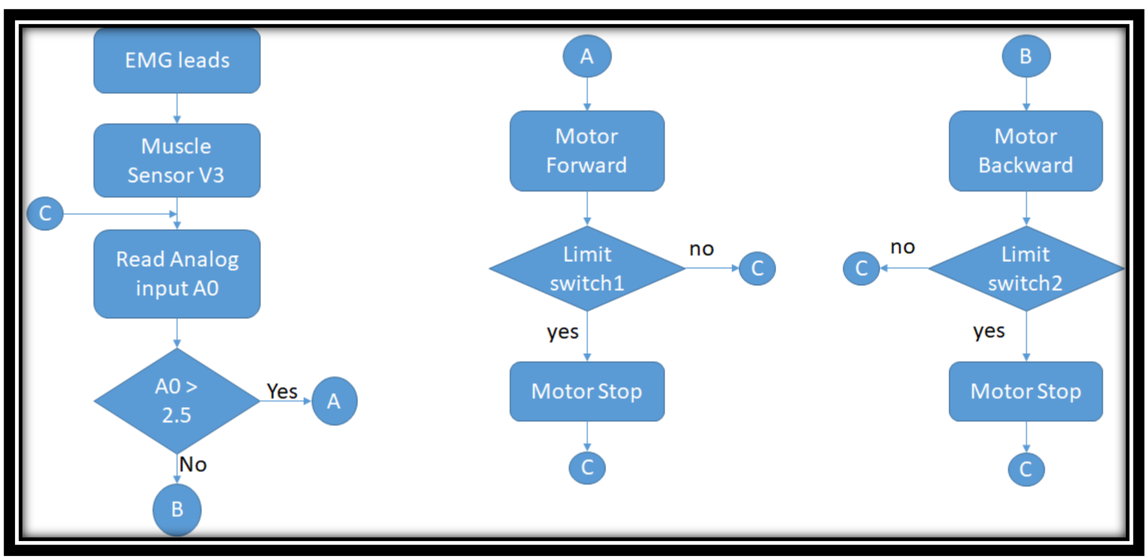

Figure 5.22: Flowchart of Motor Control.

CHAPTER 6

CONCLUSION AND FUTURE RECOMENDATIONS

6.1. Conclusion

Technical Merits:

This project is a direct application of supported actuation, a field that is currently an active frontier for research internationally. The development of this project ensures establishment of research and development and awareness of this particular field in the country.

- The project is a step in building test-benches for upper body exoskeleton systems.
- The algorithms and technologies developed can be applied in other fields of knowledge also, hence making it an ideal test bench for advancement in the technology.
- The students shall also represent their work in international community, thereby promoting NUST as well as Pakistan in international robotics community.
- The R&D effort carried out during the course of this project shall enable students to publish two publications and one journal in the field of robotics.

Industrial Applications:

- In industry, there are numerous applications in which identical autonomous agents are performing same tasks. This field has a tremendous application in all the industries having where individuals are required to carry cargo.
- Our work in stroke and traumatic rehabilitation can lead to development of new industrial opportunities in this field. Currently there is no such body working in Pakistan on it.
- The final product of this project will be a wearable exoskeleton device that can be worn as a back pack and sold commercially to rehabilitation centers.

Other Benefits:

- These assistive exoskeleton devices can make the dream of leading a normal life a reality for elderly and people suffering neuromuscular diseases.
- Disaster management systems, including earthquake rehabilitation systems, firefighter systems etc. can benefit from this devices, which may increase the efficiency of such systems in a radical way.

Global Visibility:

- Pakistan will be having a head-start in the field of hand exoskeleton, bringing country at the upfront of technology.
- Opportunities will be created to work in collaboration with the world's advanced centers of excellence in the field of robotics, a relatively new and thriving area of research
- Pakistan will be competing against the top universities of the world, hence creating opportunities of international exposure to students.
- The economical device will be beneficial not only in Pakistan but also in rest of the world. In USA and EU countries there are numerous cases reported to have loss of motion to the hands.

6.2. Future Recommendations

Followings are potential future plans for the research carried out in this thesis.

- Making the Exoskeleton out of composite materials e.g. Carbon fiber reinforced ABS instead of Aluminum to decrease weight and increase strength.
- Replacing Aluminum with Carbon fiber reinforced ABS can provide the option of 3D printing the exoskeleton and can be modified with each user's preferences.
- Replacing Aluminum with Carbon fiber reinforced ABS can reduce weight by almost 50% making it further comfortable to wear.
- Introducing other control techniques such as EEG and FSRs to increase robustness of control.

- Using Machine learning algorithms to increase robustness of EMG control.
- Using a custom back pack design to cover backplate and making it more comfortable to wear.
- Using more powerful servo motors which can further reduce overall weight and increase power at each joint.

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APPENDIX A