University of Strathclyde

College of Engineering

Department of Biomedical Engineering

Master of Science Thesis Report

Development of a Prototype of an Active Exoskeleton of Upper Limb

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Abstract

Treatment of partial or full loss of function in upper limb due to spinal cord injuries, diseases, stroke or other health conditions require sophisticated intensive rehabilitation procedures of manipulative physiotherapy. Several mechanical devices and upper limb orthosis were designed to assist or augment upper limb function in some of these conditions.

Active exoskeleton devices are effective technologies that can be used to compensate or assist body functions and provide sensing and support for non-functioned or partially functioned muscles. Moreover, they work as a robotic system to provide attachment framework for enabling patients to perform their daily tasks easily.

This project aims to design and implement a simulated prototype of an active exoskeleton of the upper limb using NI LabVIEW 2014 software with one degree of freedom that represents elbow joint flexing/extension. This was performed using Fuzzy Logic control algorithm to estimate the movement position based on the sEMG signal. The data was recorded from the biceps brachii and triceps muscles of the subject during flexion and extension of elbow joint. The control method was established by extracting two time domain features of EMG which are Integrated EMG (IEMG) and Root Mean Square (RMS) from raw EMG datasets.

The results show that the angle estimation can be performed using the time domain properties of EMG signal based on fuzzy logic system design. Also, the maximum value of the estimated angle was equal to 156 degrees while the actual angle was 170 degrees. Based on that, the estimated value of elbow joint angles was compared with the actual angle using fuzzy logic design in LabVIEW with approximately 70% correlation.

Moreover, the high angle value obtained indicates that more pronounced EMG activity occurred with The RMS of biceps signal being synchronized with the angle of movement. Finally, the angular velocity obtained was positive with elbow flexing and negative with elbow extension.

AKNOWLEDGMENT

I would like to thank my God for giving me the power to go on and work with persistence to achieve my goal. My appreciation goes to my supervisor **Dr. Heba Lakany** for her advice and guidance. Deep thanks goes to **Dr. Bernard Conway** for offering his time and help. Also, I would like to express my gratitude to the staff of the Biomedical Engineering department of the University of Strathclyde namely, **Lijo Varughese Chacko, Hariprashanth Elangovan, Helen Berry and Alejandra Aranceta Garza.**

.My sincere thanks go to **my family** because without their continuous encouragement and support, this dream cannot have come to reality. Also, special thanks go to **Shahd Abubaker**.

Signed: ______Nosiba_______________________________

Dated: _________13/8/2015________________________________

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REPORT ORGANIZATION

Chapter 1 is an introduction that describes the history behind this project along with its aim, motivations and methods. Chapter two discusses. This will be followed by **Chapter 2** which starts with a biological background about the upper limp parts and movement added to Electromyography (EMG) signal generation, influencing factors and analysis techniques. In addition, this chapter will include an overview about exoskeletons concept, classification, technologies, applications, operation modes and challenges. **Chapter 3** deals with the design approach, EMG Signal acquisition and processing added to the experimental procedure and the fuzzy logic control design followed. **Chapter 4** contains the testing and experimental results obtained along with their analysis. **Chapter 5** concludes with the main project outcomes and suggests few ideas for future projects.

1. CHAPTER 1: INTRODUCTION

1.1 Overview

A robotic exoskeleton is a system that is developed to help people with physical impairment, neurological disorders, handicap and those with other motion injuries problems to regain power to perform their daily tasks and vital activities. The term exoskeleton was first introduced to describe the external skeleton of animals' bodies which have the benefits of protection, excretion and support for the animal in different environmental condition (Kwok-Hong April 2014). Humans utilized the rigidity and protection characteristics to build body suits and devices that help healthy people to carry out heavy duty work. Generally, the field of exoskeleton including upper limb has received continues attentions during the recent years in many aspects of life. This is due to its role in giving a wide range of assistance for vulnerable populations to exchange necessary power, muscle training and rehabilitation exercises

However, many challenges face the upper limb exoskeleton devices due to the complexity of shoulder movement and the mechanical design requirements to develop a device that can naturally and safely interact with the patient's joints with proper functionality to carry out the muscle pretended motions through the release of EMG signals that help to analyze, improve and control weak muscles motions. The success of using rehabilitation robots for the recovery of post stroke patients during previous years has been promising which has opened the gate for future developments (Johnson et. al. 1997).

1.2 History

The exoskeleton research in US was introduced in 1965 when General Electric developed HARDIMAN, which weighted 1500 lbs as shown in figure (1). It was the first exoskeleton device designed as whole body robotic systems that has hashydraulic actuators driven using a human operator from the exoskeleton inside system. Hardeman was used for bomb loading of aircrafts to carry underwater structures and space construction. However, the Hardiman project was not very successful where the attempt of using the full exoskeleton caused uncontrolled physical motion (Mosher, 1967).

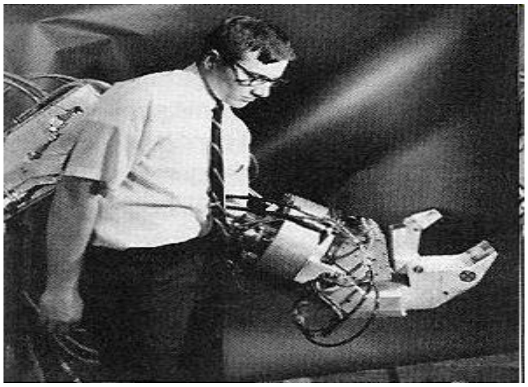


Figure (1) HARDIMAN exoskeleton prototype

Further research during 2001 was conducted by the Defense Advanced Research Project Agencies (DARPA) which was interested in military exoskeleton to increase capabilities of soldiers beyond that of humans. In 2004, DARPA developed a design that helped soldiers to carry extra loads on their back with minimum effort (Bongue 2009).

Several research studied have followed that yielded standard commercial exoskeletons with weight and volume advantages. One example was ARMIN Exoskeleton Robot which was equipped and adapt to suit different patient sizes (Rittenhouse et. al., 2006, pp.1924-1932). Another example was Hybrid Assistive Limb (HAL) powered exoskeletons suits shown in figure (2). It was invented by Japan's Tsukuba University and Cyberdyne robotic company and designed to support and increase the user physical capabilities, especially elderly people and patients with physical disabilities (K. Suzuki, G. Mito, 2006).

Figure (2): Hybrid Assistive Limb (HAL) exoskeleton prototype

1.3 Aim and Objective

The aim of this project is to design and implement a prototype of an active exoskeleton for upper limb with one degree of freedom that represents elbow joint flexing/extension on a simulated platform. The main focus of this study is to simulate the controller of exoskeleton designed. The control system contains the algorithm for decision making process and a motor unit which represents the desired simulated joint that acts as an assistive flexor/extensor.

1.4 Motivation

Our world is facing an increase in the population suffering from physical weakness for different reasons (aging, injuries, different degrees of disable or handicapped). Taking care of such vulnerable groups is a problem facing many communities including developed countries. Robotic technologies may give them some hope by playing an important role in rehabilitation and power assistance as they need assistant to regain their lost strength and give some control to assist the limb motion to carry out minimum daily tasks.

Furthermore, global industry requirements are causing rapid depletion of humans’ energy and safety more than ever before. This has led to technological changes in the approach that industrial options are introduced especially those which are using robots to replace humans. Therefore, Exoskeleton robots have attracted many researchers to make them an important part of the environment. Nowadays, many prototype machines of this invention have been introduced and tested based on the robot classification (Gopura, 2004).

Although the upper limb devices have several applications over the past years, this project will focus on the following most common muscular deficiencies:

- **Neuromuscular Disorders**

Neuromuscular Disorders are diseases that result in muscle weakness, muscle cramp, decay, pain and difficulties in breathing and swallowing added to other problems. The causes for these diseases are different ranging from inherited gens to dietary deficiencies to other unknown factors. However, any emerging treatment effort requires injection and in some cases surgery or advanced treatments for some complicated patients in order to meet minimum normal life requirements (Weisberg, Garcia & Strub, 2004, pp.780-787).

- **Stroke**

Stroke is an acute, neurological case caused by an alteration in blood flow to the brain. This alteration could be either a blood deprivation (ischemic stroke) to the brain tissue or a blood spilling (hemorrhagic stroke) onto the brain tissue. According to the American Heart Association, stroke is the leading cause of long term disability in USA. In fact, data shows that 700,000 patient sustain stroke over time (Kelly-Hayes,M et al, 1998, pp.1274-1280).

1.5 Methods

NI LabVIEW 2014 software was used to simulate this system and establish an exoskeleton design that can be controlled and tested by analysing the detected EMG signal to activate a motor and enable the user to move the arm to the desired position. Then, Fuzzy logic control was used to find the relationship between the EMG signal and movement position. The control system is designed and tested using fuzzy logic toolkit of LabVIEW software.

2. CHAPTER 2: LITERATURE REVIEW

In order to maintain a better understanding on the background of this project, a review of the exoskeleton devices need to be conducted in details. In this chapter, the basic physiological background as well as the examples of existing Exoskeleton robots are introduced and classified into various categories. Moreover, classifications of the different design structures for exoskeleton and control methodologies are presented to have the essential knowledge required to decide on a suitable approach to tackle the problem at hand.

2.1 Physiological Background

2.1.2 Upper Limb Components

The word "arm" refers to the body part located between the shoulders to elbow joints as part of the forearm. On the other hand, the upper limb is the body part located between the shoulders to hand and is divided into three segments linked together by three joints which are the shoulder, the elbow and the wrist as shown in figure (3). The three upper limb parts are (Pons, 2008, pp.20-26):

- Arm and Upper Arm: the region between the shoulder and the elbow
- Forearm
- Hand

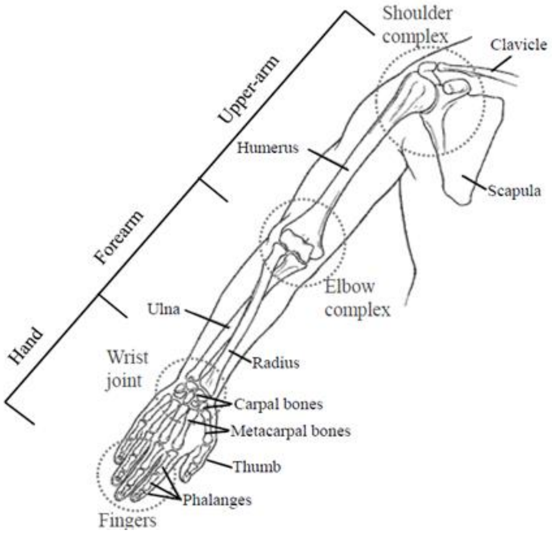


Figure (3): **Human upper-limb components (Gopura, 2004)**

The upper limb consists of muscles, vessels and nerves forming wrist joint, shoulder and elbow complex. It is used to lift and carry the heavy objects with more movement's flexibility (degrees of freedom) and other functions like communication. Therefore, the study of body kinematic associated with the upper limb wearable robots is very critical because there is more active physical interaction between the body and the machine device than in the lower limb myoelectric prosthesis (Li, Liu & Linhong, 2013, pp.1-12).

There are 7 Degrees of Freedom (DOF) in the upper limb divided between the shoulder, elbow and wrist joint where 3 DOF are in shoulder joint, 2 DOF are in elbow joint and 2 DOF in the wrist.

Motions differ based on the degrees of freedom for each joint. The shoulder has abduction/adduction; flexion/ extension, and internal/external rotation movements. While the elbow joint has only flexion/extension motion and the forearm has supination/pronation, the wrist has flexion/extension motion and radial/ulnar deviation.

2.1.2 Upper Limb Movements:

In order to explain the upper limb movement, it is important to classify upper limb muscles that drive that movement, Upper limb muscles include as shown in figure (4):

❖ Arm muscles:

- Antererior group:Biceps brachii; Coracobrachialis and Brachialis
- Posterior group: triceps brachii and anconeus

❖ Shoulder Muscles:

Deltoid; Supraspinatus; Infraspinatus; Teres minor; Teres major and Subscapularis

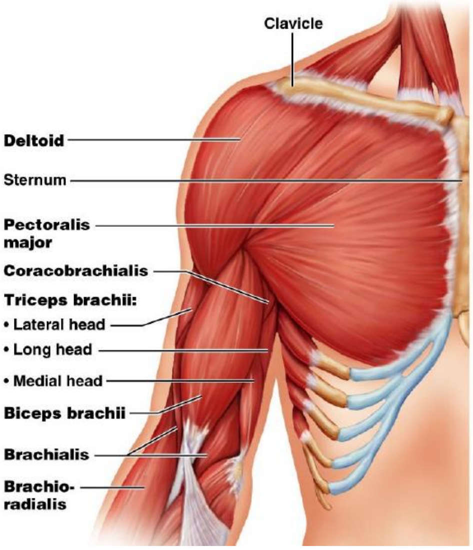


Figure (4): Arm and shoulder main muscles (Pearson, 2006)

Based on that, there are two main types of upper limb movements as shown in figure (5):

1) Extension: where the arm extend through its posterior compartment due to the movement of The triceps brachii muscles with the anconeus being a weak synergist.

2) Flexion: where the arm flex through its anterior compartment due to the movement of the Brachialis muscles followed bybiceps brachii and Brachioradialis muscles.

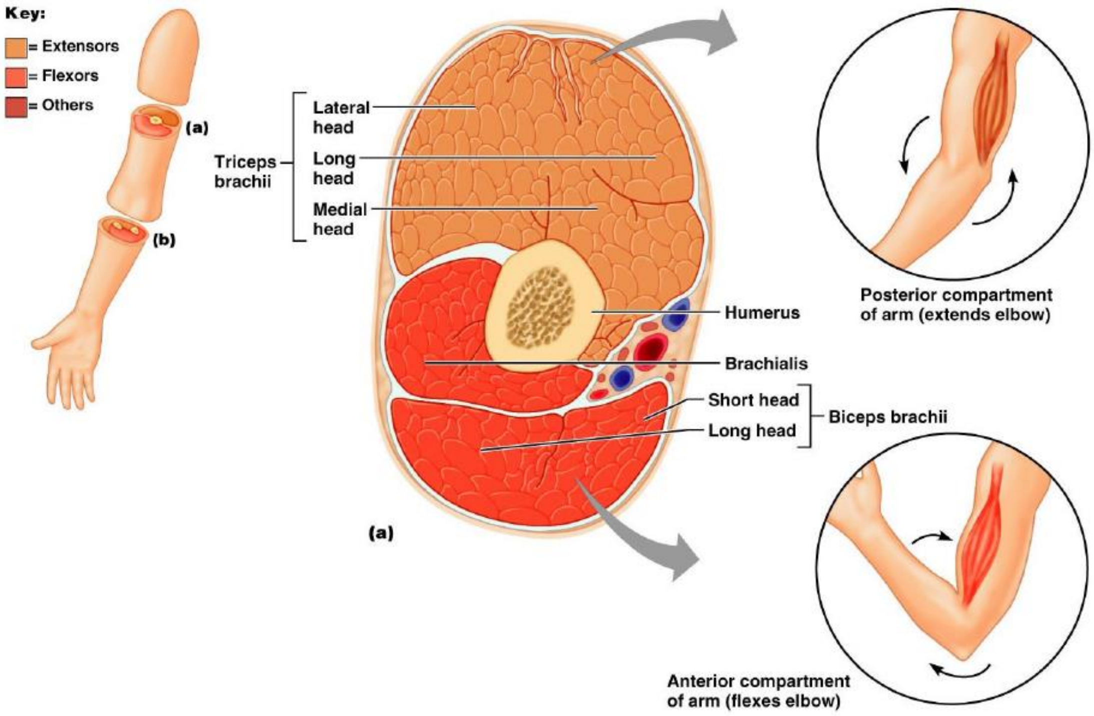


Figure (5): Extension and Flexion of upper limb (Pearson, 2006)

2.2 Electromyography (EMG)

EMG is experimental techniques concerned with the development, recording, diagnosis and analysis of myoelectric signals formed by physiological variation in the state of muscle fiber membranes (Konrad, 2005), see figure (6).

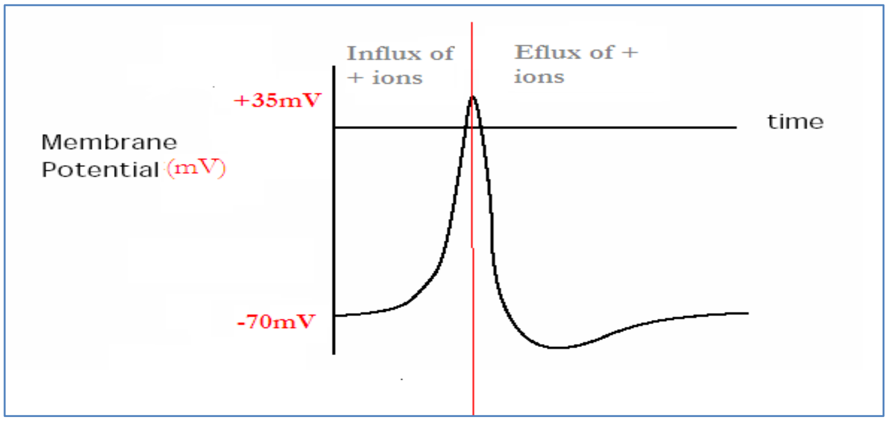


Figure (6): Neutron action potential over time (the resting potential membrane (-7o mV) and the excited is (+35 mV) (Zandt, 2009)

Motor neurons transmit the electrical signal and are responsible for muscle contraction. EMG translate signal into graphs, sounds or numerical value. The device used in this process is called electrode which is either (surface electrode) placed on the skin to measure speed and strength of signal between two or more points or (needle electrode) which needs to be inserted using needles by experienced personnel to aid in showing the patient's nerve or muscle dysfunction.

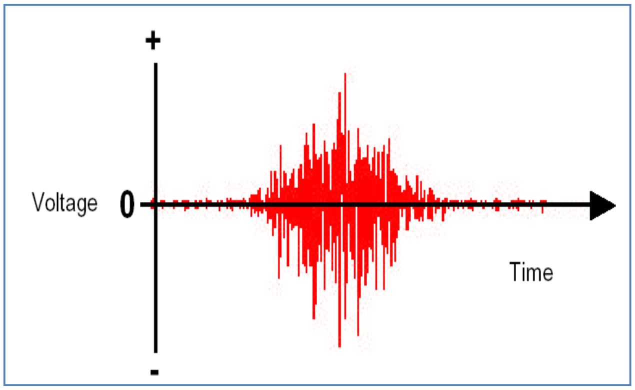


Figure (7): EMG signals (Zandt, 2009)

EMG Signal has the following benefits:

- It is a reliable muscle performance measurement
- it could be used in the assessment of patients before and after surgery
- It could be considered as a continuous data source for tre
- It is an effective measure for patient muscle training durin

2.2.1 EMG signal Generation

The muscle consists of muscle fascicles which contain muscle fibers (muscle cell). Originated in the brain, electrical stimulus travels down through motor neuron to activate the target muscle fiber. The acetylcholine is released from the terminal end as a result of neuron relative polarity differences. Neurotransmitter acts due to reversal action or change in cell polarity and chemical messenger release. The muscle fiber becomes excited and contract due to neuro stimulation; electrochemical change in muscle or Protein of muscle movement (Zandt, 2009), see figure (9).

Understanding the basics of EMG signals is important in understanding the biological signals generation in muscles. The motor system should be coped with a great external and internal constraints demands including force regulation for powerful and accurate motions.

Muscles activates depend on the motor unit concept and the central motor system. In fact, the central nervous system is hierarchically organized in a way that the motor nervous programming takes place in the motor area, premotor cortex, and other cortex related areas. These areas' inputs will converge to the main motor cortex and inhabit the primary motor cortex neurons. On the other hand, the primary motor cortex' outputs have a great influence on spinal cord and brain stem motoneurons. The link existing between alpha (a)-motoneurons and corticospinal tract provides a direct control of muscle activity. Figure (8) indicates the motor unit (MU) which contain motoneuron in the corresponding muscle fibers. In fact, the motoneuron is considered as the final point of all reflex and descending inputs summation. The total membrane current is induced by the group of synaptic innervation sites and that is what determines the motor unit firing which represent the muscle activity (Stegeman, 2004).

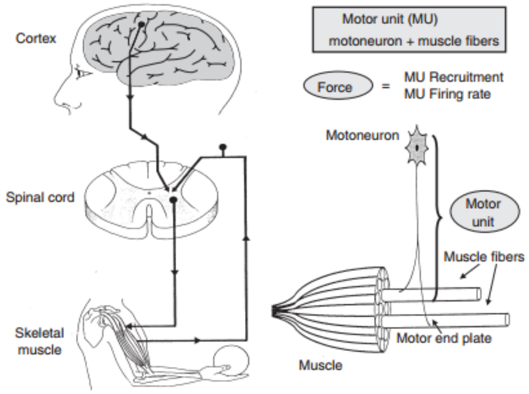


Figure (8): Basic Motor control mechanism (Stegeman, 2004)

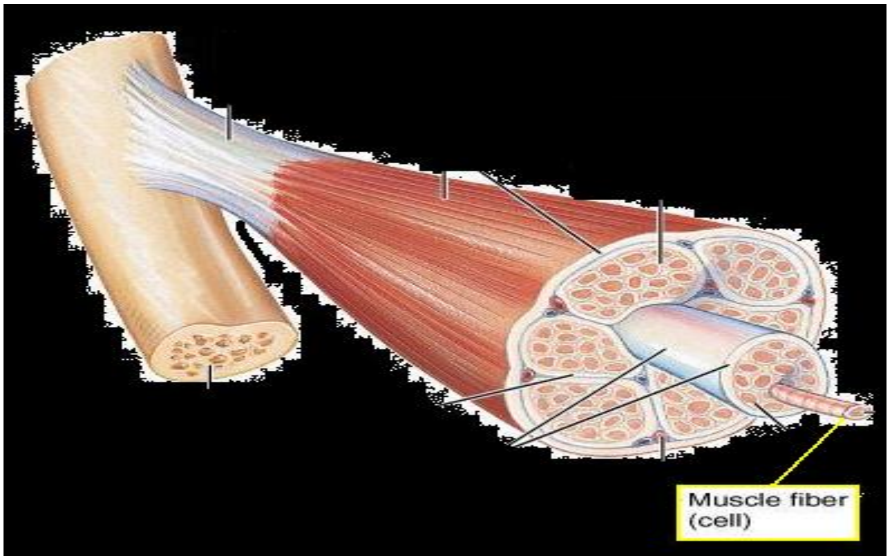


Figure (9): Muscles fibers of cells (Zandt, 2009)

2.2.2 EMG Influencing Factors:

The following external factors affect the shape and characteristics of EMG through its pathway from the muscle membrane up to the electrode are: (Konrad, 2005)

1) Tissues characteristics

Body electrical conductivity is affected by tissue type in term of thickness, physiological changes and temperature. This may cause difficulties in comparing signal from person to anther or even within the same person.

2) Physiological cross talk

Local electrode used sometimes detects a significant EMG signal from neighbor muscle but interference may occur especially when the electrode is located on the upper truck, shoulder muscle.

3) Changes in geometry between muscle belly and electrode site

Attention is needed when the electrode is placed on the user body as the EMG signal is affected by the distance between the signal origin and the detection site.

4) External noise

During EMG assessment, very noisy electrical environment should be considered to prohibit the incorrect or misleading signal reading.

5) Electrode and amplifiers

During preparation of patient for EMG analysis, special care should be taken to maintain the quality of the electrodes used and the internal amplifier noise, see figures (10) and (11).

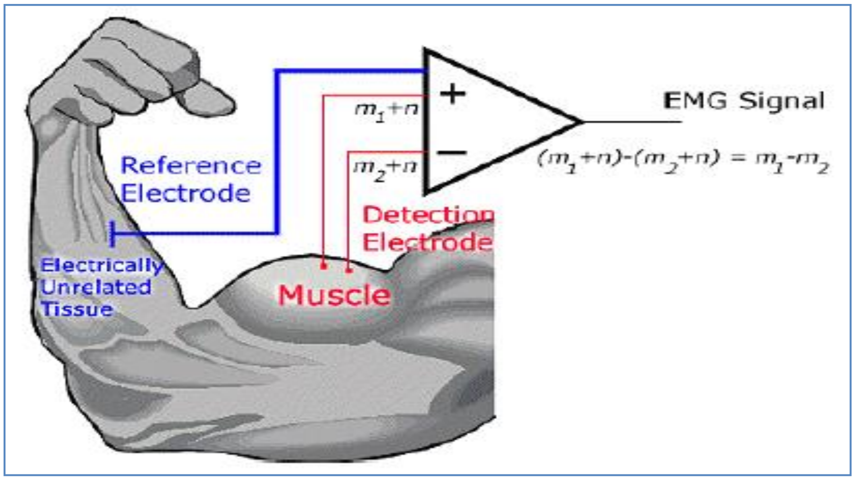


Figure (10): A schematic of the differential amplifier configuration. The EMG signal is represented by 'm' and the noise signals by 'n' (De Luca, 2002)

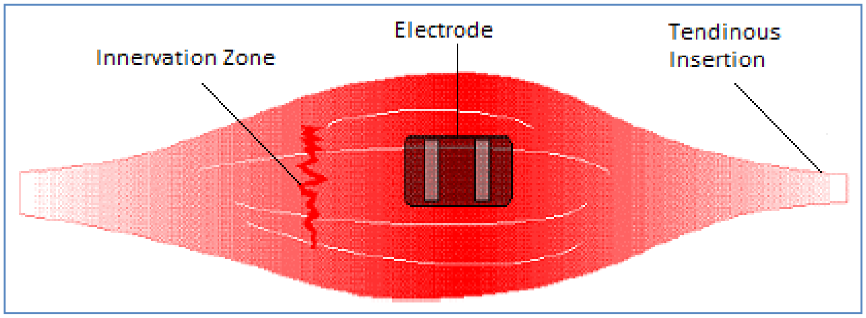


Figure (11): The ideal position of the electrode (two detecting surfaces) is between the innervation zone (or motor unit) and the tendinous insertion (or belly of the muscle)

2.2.3 EMG Analysis Techniques:

Neural Network

EMG signal of muscle activity remain sometimes unpredictable as one source of muscle activity information, so network method was applied to improve EMG analysis. The neural network can be used as good indicator to help physician in detecting of muscular disorder (Nebras et. al., 2008). It used as one of the tool that can give idea about the signal power and motion task, pretended by handicapped person. The network used to predict the muscle activity from signal data avoiding the mathematical method. It results in calculation of joint torque from the EMG signal, leading to estimation of joint moment motion. (Kelly et. al., 1990, pp.221-230).

Fuzzy approach

The application of fuzzy approach to EMG signal depends on the fact the fuzzy logic is based on uncertainty rules to predict the human intention to perform certain motion. Fuzzy logic can be used to detect the EMG signal onset and classify the user intention for the multi-function controller (Zimmermann 1991). In the study by (Kiguchi et al 2004), it was shown that fuzzy logic could be used to tackle uncertainly during arm movement using the range (0-1). O for hand open-closed motion while 1 indicates the forearm pronation- supination motion. The advantages include (Reaz, et. al.. 2006, pp.11-35):

- It can deal with nonlinear system
- It relatively simple and suitable for real time application
- It has characteristic of controlling complex system
- Modification of each membership can be easily done on line

The disadvantages include:-

- It is difficult to generalize because depend on written rules
- Any further changes need alteration in base rules
- It needs an expert to deal with some logical rules

More details about fuzzy logic features and parameters will be detailed in chapter 3.

Hybrid Fuzzy –Neural approach

Electromyography (EMG) is widely used to show the human intended movement, diagnose neurological diseases help in human machine interference. Hybrid Fuzzy –Neural is used as a combination of neural network technology and the fuzzy logic principle to give learning and self-organization ability for exoskeleton muscle activity control approaches (Konrad, 2005). Aiming to improve the effectiveness, efficiency, and accuracy of EMG analysis, control of angle position is based on EMG signal, and wrist force during elbow motion. They consider that the wrist force is more reliable when the little use of muscle is involve, while EMG is more reliable if more muscle activity is practice (Khezri M, Jahed M,2007).

Particle Swarm Optimization (SVM)

The use of SVM approach in exoskeleton field, for classification of EMG have positive impact as this approach gives higher classification accuracy and lower sensitivity. It improve the EMG output by classifing the signal into normal, neurologic,and myopathologic. It shows EMG signal in frequency and it is reported as one of the efficient tool that help in diagnosis of neurological disorder (Subasi, 2013, pp.576-586).

Pulse -Width Modulation (PWM)

This type is used to control the exoskeleton actuator using pulse-width modulation. The signal change from high to low voltage at certain frequency, as the wave length represent the high pulse(duty cycle), which shows the increase in power that is received by the device motor. The program will correct the output by translate the EMG signal into pulse- width to control the motor output power (Weir & Ajiboye 2003, pp.1678-1681).

2.3 Exoskeletons

2.3.1 Concept

Before getting into deep levels of this project, it is important to review the Exoskeleton robotics devices concepts and history and then address the upper robotic exoskeletons specifically and mention the main expected challenges to come up with the key design that consists of the major key technologies and considerations of upper exoskeletons.

Exoskeleton is a form of wearable robots oriented and designed around the body shape to provide specific functions where the user is able to control the system in order to enhance strength and provide sensing, assistance, augmentation and attachment framework supporting the function of the body part. The robotic exoskeleton is considered as intelligent man machine orthosis links the human with the machine power. The exoskeleton system consists of artificial joints linked to human and transmits torques to these joints by motors (actuators). Figure (12) gives an overview of the main sections of an exoskeleton.

Researchers have been working and giving efforts in order to implant this intelligence system to robots machine and enhance the human power over several decades. This technology could be applied and integrated successfully with the development of artificial inelegance, electronic Engineering, mechanical Engineering, and biomedical engineering.

Moreover, robotics technology fields; rehabilitation robots; tele-operation robots and virtual reality haptic interaction systems are all integrated to form devices that can rehabilitate and assist physically weak patients.

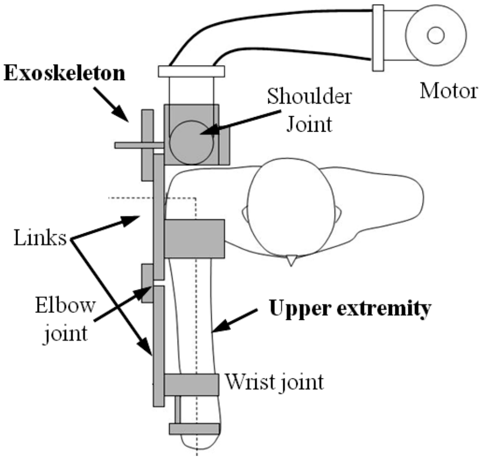


Figure (12): Exoskeleton positioning in the upper limb (Gopura, 2004)

2.3.2 Classifications

Upper-limb exoskeleton robots could be classified into several categories based on their mechanical designs and/or control methods. Typical literature classification categories based on the following factors (Gopura, 2004):

- The applied segment of the upper-limb: where the upper-limb exoskeleton robots could be classified as hand exoskeleton robot, upper-arm exoskeleton robot forearm exoskeleton robot or combined segment exoskeleton robot.

- The Degree of Freedom (DOF): where the upper-limb exoskeleton robots could be further classified according to the number of active or passive actuators by assigning a DOF value like 1DOF, 2DOF and 3DOF.
- The power transmission methods: where the classification is such as gear drive, cable drive, linkage mechanism or other method.

- The applications of the robot: where the Upper-limb exoskeleton robot could classified according to the intended purpose into rehabilitation robots, human amplifiers, assistive robots, haptic interfaces or other usages.

- The control method: where the upper-limb exoskeleton robots are classified based on the used control methods like impedance control, fuzzy-neuro control, force control or other methods.

2.3.3 Technologies

This section introduces several examples of these technologies along with their advantages and disadvantages for upper-limb exoskeleton robots. It is important to note first that the efficiency of any for upper-limb exoskeleton robot depends on actuation and power transmission methods integrated.

Actuation Technologies

Actuation technologies are those based on stimulated systems like electric motors, pneumatic actuators, ultrasonic motor, hydraulic actuators, IC engines, shape memory alloy and static electric actuators. However, not all of these are integral parts of exoskeleton robots due to less torque generation, high weight and large size restrictions. In general, Direct Current (DC) motors added to hydraulic actuators and pneumatic actuators are mostly used in existing exoskeleton robots (Gopura, 2004):

Motor Actuator

This type shown in figure (13) has a gravity compensation advantage for the upper limb exoskeleton that is used for rehabilitation purposes. The structure of the motor is based on a system that has amplify torque through force sensors attached to the user wrist and arm, waiting for the signal to predict the necessary motion. When the control system receives the feedback, it generates the motivation and activation process to the motor to compensate the exoskeleton weight and the user feel no weight when moving arm. Similar device is **WREX** with 4DOF (2 at shoulder 2 at elbow), brushed DC motor is used to actuate the arm link and joints. Some motor actuator design have rigid links, however to prevent the bulk and heavy of the device design, cable transmission is used to decrease the device mass weight. On the hand the advantage of this exoskeleton actuator, is include the shorter time needed for setup, zero force on human arm during moving task, easy control and acceptable accuracy (Moreau R et. al., 2010, pp.4489-4493).

Figure (13): Motor actuator prototype (Moreau R et. al., 2010)

Pneumatic Actuator

Challenges of having a robot with a large DOF and good range of motion and force, is under debate in robot literature. (Bobrow et al 2006, pp. 2687-2693) tried to modify the WREX exoskeleton, by developing a pneumatic actuator and a non- liner force control system. This design help to overcome gravity problem, with maintain no force on user. The pneumatic actuator, has advantage of high power to weight ratio and characteristic of remaining in position, without increase of energy, as the valve is used to control the exoskeleton device, see figure (14). One of the disadvantages of the pneumatic exoskeleton is difficultly in control process; this is why it is not commonly used. Example of this type is **MIME.**

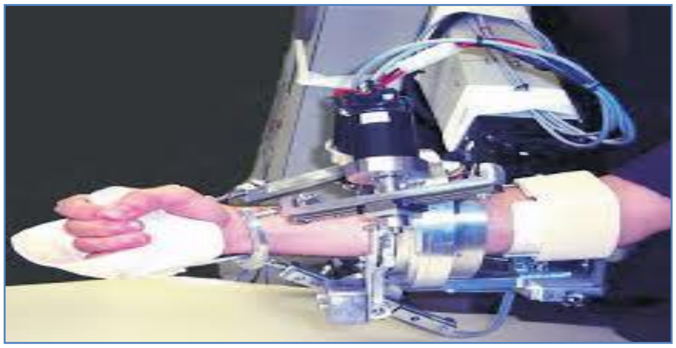


Figure (14): Pneumatic actuator prototype (Bobrow,2006)

Pneumatic Muscle

It is the common actuator used in robotic Skelton designed with a rigid structure. 7 DOF upper skeletons has been developed using a pneumatic muscle, see figure (15). One example for pneumatic muscle upper limb exoskeleton is the **RUPERT.** It have advantage of low in cost, safe ,it have the characteristic to actuate in two direction, as extension/flexion of the arm needs two actuator but unfortunately although it is simple to control, but without an excellent performance (Chang M.K., 2010, pp.13-22).

Figure (15): Pneumatic muscle actuator prototype (Chang M.K., 2010)

Hydraulic Actuator

This type is an elbow exoskeleton actuated by a flexible fluidic Actuator. The exoskeleton design is depend on using hydraulic pump, and it can be fixed on the user wheel chair. Other type cover upper arm with elastic actuator to give stiffness control. The advantage it gives high power outcome (Bretthauer G et.al 2009, pp.167-171), see figure (16).

Figure (16): Hydraulic actuator prototype (Bretthauer G,2009)

Power Transmission Technologies

Power transmission methods of upper-limb exoskeleton robot are those dependent on the actuator. For instance, pneumatic actuators could be additionally used as the actuator with compressed air transmitting the power. Also, hydraulic oil transmits the power in hydraulic actuators and the same thing could be said for electric motor, gear drives and cable (wire) drives. While electric motors can be used as direct drives, they are rarely used in upper limb exoskeleton robots because of the large size of existing motors used to generate needed upper-limb torques. This restriction is less noticed in gear drives and/or cable drives which are commonly used in upper limb exoskeletons application (Gopura, 2004).

2.3.4 Applications and Operation Modes

The arm support system are continuously developed to maintain a rigid exoskeletal structure that is physically connected to the human user to support the upper arm functions and its application include: (Herder et.al., 2006, pp.591-604):

1) Devices that intended to help individuals with a limited arm function in order to provide suitable assistance during daily life activities (person with neurological diseases, person with muscle weakness, elderly).
2) Devices that are designed to provide support during training as a part of rehabilitation process (person after stroke experience).
3) Devices that help the arm function of healthy persons to carry out different daily tasks, in particular dealing with, heavy and complicated activities; especially among persons with muscle weakness or elderly population.

Exoskeleton devices are used in four fundamental modes of operation (Loureiro et al 2003, pp.35-51):

- Physiotherapy: the patient wears the exoskeleton to help in performing the daily basic tasks or during an active or passive physiotherapy session.

- Assistive Device (human amplifier): during use and interaction with the device, the person feels a scaled down load because the exoskeleton carried most of loads.

- Haptic Device: the force generated when user interact with the device depend on many characteristics including the shape, stiffness, texture.

- Master Device: A real robot (master/slave) is used, where the user benefits from exoskeleton to control for tele-operation. The force is reflected back to the user as a slave robot (Frisoli,et al 2005).

2.3.5 Challenges

The robotic exoskeleton usually transmits the torques from actuator to the human joints through its links. Through the recent years many aspects of development occurred in the robotics industry with coordination of many fields including Mechanical engineering, Biomedical engineering, Electrical engineering and artificial intelligence (Gopura, Kiguchi & Bandara 2011, pp.346-351).

As the exoskeleton affects the human user directly through the physical connection with the normal body joints ,various challenges and issues should be considered during designing process, which include the following:-

- **Mechanical design challenges**

The structure of the upper limb exoskeleton should be well planned and managed to meet the aspiration and satisfaction of patient, user, and the medial and technical communities.
The upper limb exoskeleton require certain requirement (Tan et. al., 1994, pp.353-359)

- Should be light with low mass as heavy exoskeleton will need excessive use of actuator power to reach the gravity balance.
- The design should be comfort during wearing, with easily fitting, adjusting and removal process. It should cause no fatigue to the user even when used for long period e.g. (1- hours).
- It should be design with extensive range of motion.
- The device must have accurate force feedback (the average is around 0.36 N). This help the user feel no force during use session.
- Relatively low complex design ,low energy consumption and low construction cost
- Low and easy maintenance criteria
- The key factor in design is the compensation of gravity to fit the user weak arm and the motion that be afforded.
- Joints torque control in each limb joint should be consider in the design and contrition phases.
- Easy switch on and off
- High speed with control procedures to match different users

❖ Natural control challenges

- Good sensing motion to match the normal human body sensing connection mechanism, this is varying according to different upper limb joint points (0.8 degree at the shoulder and 2.0 degree at the wrist).
- The design and structure materials should be suitable to be used in rigid environment including water, dust, heat, and grease.
- Reliability of device depends on the acceptance of the device operation and feeling of rest when doing normal daily task as one part of natural limb joints.
- Characteristic to easy control and easy stop during emergency

❖ Safety challenges

As the exoskeleton device involve in direct physical contact with human upper limb and body the device must be designed to fulfill the safety condition and patient psychological feeling requirements during treatment sessions (Johnson, G.R. 1997, pp.399-401).

3. CHAPTER 3: METHODOLOGY & DESING

After reviewing the available technologies and options, this chapter tackles the basic design and methodology that were selected and used to approach the target of this project. It discusses the information and steps that were considered to establish the fundamental design of the exoskeleton robot in terms of the software algorithm and control design. This chapter is divided into four parts: design approach, EMG acquisition and processing, experiential procedure and fuzzy logic control design.

3.1 Design approach

This section represents the final design proposed based on the design criteria discussed in section (2.3.3).

After researching the many available actuation and power transmission technologies, a suitable one had to be chosen for this project. Initially, the project is to design an active upper limb exoskeleton. Therefore, an electrically actuated type of exoskeleton is selected.

Power transmission method is directly related to the actuation method. As a result, the motor unit designed in this project is considered to act as an electrical motor that works based on the principle of gear drive to represent the elbow joint.

Control method

Automation and control of exoskeleton devices based on EMG signals has been a major focus of many engineers and researchers. Since EMG signal is complex in nature, the motion classification and detection based on EMG signal is not an easy task. There are different control approaches that can be used to efficiently control an exoskeleton or drive a device based on the EMG signal.
Algorithms for EMG Classification.

There are various control approaches to classify the EMG signals and relate them to different physical parameters and quantities. In this project, fuzzy logic approach is used for controlling the joint based on the EMG signal.

Fuzzy logic is a learning base control approach with an ability to deal with uncertainty, imperfect imprecise, and nonlinear information. This technique is inspired by human brain since its purpose is to make the machine able to make decisions. Therefore, fuzzy logic is used to solve the problem of vagueness of many data collection and represent the desired outcome mathematically. This method is very useful in biomedical project related to signal processing because biomedical signals are not always understandable or repeatable. Moreover, contradictions may occur in biomedical signal and fuzzy logic is suitable method of tolerating the contradictory information. Another good feature of fuzzy logic is that data classification feature extraction, and pattern discovery is possible in fuzzy systems as in neural network (Kiguchi, K. Tanaka, T. & Fukuda, T ,2004).

Degrees of freedom:

As mentioned above, degrees of freedom of an upper limb exoskeleton represent the direction of movement the single passive or active joint can perform. For simplicity, one DOF at elbow joint is selected to represent the flexing and extending movement of elbow joint.

Design fundamental concept:

In general, myoelectric powered devices require EMG signals as an input to the control system and that is why the EMG is a common measurement methodology to extract the muscle activity. Since the main target of this project is to design an exoskeleton system for the upper limb, the flexing/extension movement should be controlled based on the user intension. To achieve this target, the system needs to detect the human user intention of movement by sensing and measuring the EMG signal from the biceps and triceps muscles. After performing the required acquisition and processing of this signal, it will be used to drive and control the motor (joint). After that, other parameters can also be extracted to analyze the EMG signal and make it easier to understand.

3.2 EMG Acquisition and Processing

As mentioned in section(2.1) , human muscles are consisting of a large number of muscle fibers arranged as individual motor units and they are functionally activated by nerves impulses generated by the nervous system and propagated through the nerve fiber length (Artigue & Thomann, 2009, pp.3079-3084).

Therefore, Electromyography (EMG) is an active experimental method related to recording, development, and analysis of muscles myoelectric signals (Merletti & Philip, 2004).

In terms of elbow motion activity, it can be observed that biceps muscles contract while triceps muscles extend during flexion of elbow joint. On the other hand, triceps muscles contract while biceps muscles extend during extension of elbow joint.

Before implementing the EMG signal as an input to the robotic system, it is important to evaluate the EMG signal and its changes during elbow motion. Moreover, as the EMG signal is contaminated with noise and artefacts, signal pre-processing, filtering and amplification need to be carried out to get a noise-free, clean signal that can be controlled with high signal to noise ratio as much as possible. After that, the signal can easily be converted to an amplitude envelope that represents the root mean square (RMS) of the sEMG signal, see figure (17). In fact, the EMG signal is based on various factors, such as the signal amplitude and other time/frequency domain features. The main features which were used in this project are explained in the following section.

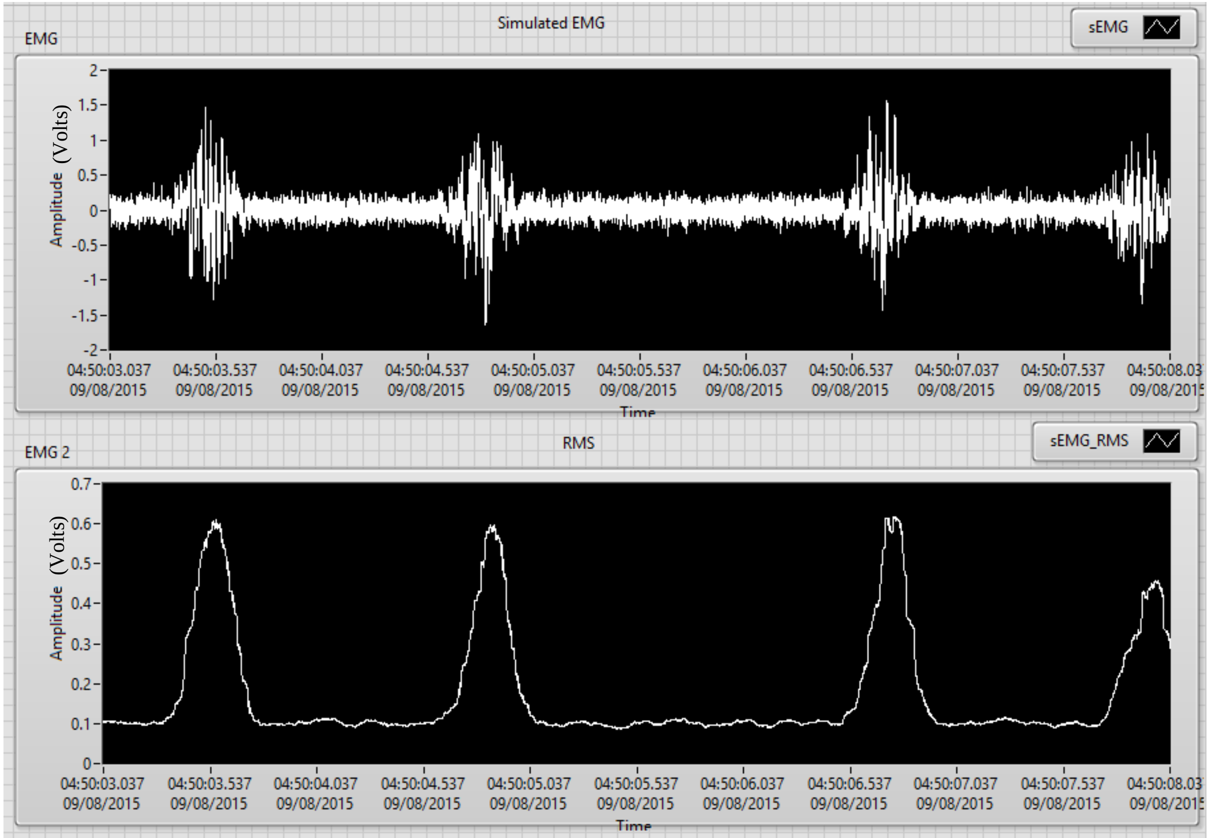


Figure (17): LabVIEW Stimulate EMG processing

EMG features:

Once the SEMG signal has been recorded, it can be processed and analyzed using common EMG data features and approaches like the Root Mean Square (RMS) .These features are in time and frequency domains. The main time domain measurements are Mean Absolute Value (MAV), Root Mean Square (RMS), Integrated of EMG (IEMG), Zero Crossing Rate (ZCR), and waveform length(Raj & Sivamamdan, 2015, pp.2074-2081). They are described as follow:

Root Mean Square Value (RMS)

The Root Mean Square (RMS or rms) of an EMG signal is a statistical measurement of the signal amplitude. This measurement is very useful when the data variants are distributed as positive and negative values like EMG signals [15].The following equation gives the RMS value:

$RMS = \sqrt{\frac{1}{N}\sum_{1}^{N} {x_n}^2}$……. Equation (1)

Where,
N is the number of samples.
Xn is the EMG signal amplitude.

Mean Absolute value (MAV)

The Mean Absolute Value (MAV) is simply defined as the Average Rectified Value (ARV) of the signal. It can be calculated by taking the sEMG absolute value which is moving average of the full-wave rectified EMG signal. In fact, it is a direct way to detect the muscle level of contraction and is a known EMG feature used in various applications of myoelectric control and it is represented by the following equation (Raj & Sivamamdan, 2015, pp.2074-2081).

$MAV = \sqrt{\frac{1}{N}}\sum_{n=1}^{N}|x_n \quad |$……… Equation (2)

Where,
N is the number of samples.
Xn is the EMG signal amplitude.

Integrated EMG (IEMG)

Integrated EMG is simply the summation of all signal amplitude absolute values of the sEMG signal amplitude through the recording time period. In general, this measurement is related to the group of fitting points of the sEMG and is used to detect the activity of the muscle for the purpose of device control. IEMG is expressed mathematically by the following equation (Raj & Sivamamdan, 2015, pp.2074-2081).

$IEMG = \sum_{n=1}^{N}|x_n \quad |$…….. Equation (3)
Where,
N is the number of samples.
Xn is the EMG signal amplitude.

Zero Crossing Rate (ZCR)

Zero-crossing rate is an expression of how many times the signal crosses the abscissas axis. Sometimes, it is considered to be more accurate measurement of detecting muscles activity pulses than other amplitude features of EMG signals. It is referred to the random signal fluctuations and that what makes it a tool to distinguish muscle activities and diagnose any abnormal conditions from the EMG signal. The following equation gives the value of Zero Crossing at a certain sample range (Raj & Sivamamdan, 2015, pp.2074-2081).

$$\mathrm{ZC} = \sum_{k=1}^{N} \mathrm{sign}(x_k * x_{k+1}) \text{and } |x_k * x_{k+1}| \geq \text{threshold} \qquad \text{………… Equation (4)}$$

Extracting the EMG Signal

The EMG signal could be easily extracted and collected but it is difficult to interpret. A clear EMG analysis can provide a good chance of understanding the procedure of muscle force generation to understand how the movements are produced. Therefore, the ability of extracting this information accurately depends on the methods of signal acquisition and processing. EMG can be recorded using invasive electrode (needle electrode) and non-invasive electrode (surface electrode) (Chan-Francis et. al., 2000, pp.305-311).

The surface Electromyography (sEMG) is usually used to analyse the muscular condition during functional activity or at rest. It is acquired by placing electrodes on the surface of the skin after cleaning the skin to measure the electrical activity of muscles and any changes in muscles electric potential to investigate the muscle synergies (Kelly, Philip & Scott, 1990, pp.221-230).

sEMG recording is directly influenced by many factors such as muscle fibre type, nerve fibre conduction, and anatomical structure of muscle fibre, depth of muscle with respect to electrode, skin thickness and body temperature. The major EMG signal extraction procedure has three main steps: signal capturing, signal conditioning, and signal processing. In this study, this process was implemented in LabVIEW software after the signal has been rectified and filtered to remove the unnecessary noise. The following section describes the experiments done to record the EMG signal and obtain the necessary datasets (Chan-Francis et. al., 2000, pp.305-311).

3.3 Experimental Procedure

To obtain the required EMG data, Trigno^{TM} Wireless EMG System was used to record EMG signals from a subject during elbow flexing and extending. The following section discusses the devices used and the procedure of obtaining the signals from the desired muscles.

Overview of Trigno^{TM} Wireless EMG System:

Trigno^{TM} Wireless EMG System is a sophisticated device that is designed to extract measure and analyze EMG signal wirelessly with high performance. It is easy to use since it has reliability features and all the sensor are advanced it their structure.

Each sensor contains an internal triaxle accelerometer (ACC) with a 40 m transmission range. It also contains gyroscope (Gyro) and magnetometer (Mag) in X,Y,Z direction as seen in figure (18). The sensors work with a rechargeable battery that can last for up to 7 hours.

This device is designed to be capable of data streaming and interface with EMG software for analysis and acquisition. Another good feature of this device is that it can generate up to 48 accelerometer channels and 16 EMG to capture the muscle activity with a sophisticated acquisition system and additional techniques of measurement. All sensors are equipped with advanced features (Delsys, 2012, pp.10-23).

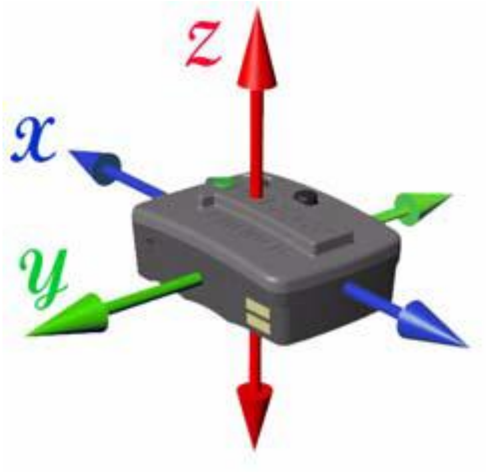


Figure (18): Trigno^{TM} 4-channel Wireless Sensor (Delsys, 2012)

Wireless EMG Sensors operation principles

Trigno™ has innovative sensors for Wireless SEMG synchronous recording. For fast access to sensory data, EMGworks® software can fuse the EMG data and present them on the screen as real time visualized data based on gyroscopic drift for rotational velocity and magnetic distortions for orientation information. Moreover, this data is available to be used in further processing required in various applications. In addition to, it can serve the ability of measuring body positioning information and joint angles from the wireless EMG sensors attached on the muscle of interest. These features allow easy recording on patterns of muscle activities and their corresponding physical motions.

The sensor is designed to retain the system performance specifications, such as low noise, full signal bandwidth, consistency in collecting data protocols and reliable detection. The system sensors apply contacts of 4 silver bar on the skin surface to detect the signal. It is important to point out that the silver bars should be perpendicular to muscle fibers to get a high quality detected signal. For this reason, the top surface of the wireless sensor has an arrow shaped to make it easy to determine the orientation, see figure (19). This arrow must be attached parallel to muscle fibers in the muscle area of interest. Another good feature of this device sensor is that they are easy to be placed and attached to skin surface and directly interface with Delsys Adhesive sensor (Delsys, 2012, pp.10-23).

Figure (19): Trigno™ Wireless Sensor Oriented with Muscle Fiber (Delsys, 2012, pp.16)

Figure (21): Trigno™ Wireless EMG System

Figure (20): EMG Data Recording using Trigno™ wireless sensors

Data collection steps

The sensors were turned on by pressing on the rubber button for one second. Then, the green LED began to flash to indicate that the data are in the streaming status.

First, the range of the subject was measured by goniometer angle ruler and it was reorders as 6 degrees for fully extended position and 132 degrees for fully flexed position. Then, 3 sensor wireless of the system has been activated and attached to the desired muscles with the muscle fiber direction as seen in figure (19). Sensor (9) has been laced on biceps to measure flexing activity; sensor (11) has been placed on triceps to measure the extension activity and sensor (10) was placed on the Brachioradialis muscles to give the angular component, see figure (20). Then, the sensors were turned on by pressing on the rubber button for one second. After that, the green LED begun to flash to indicate that the data are in the streaming status. The sampling frequency was set at 2000 Hz. The subject performed the motion of flexing and extending the elbow joint for three times, each with different speeds performed as slaw, medium then fast speed.

EMGWorks software was used to record the EMG data and pre-set up was done on the software to adjust the features of the recorded signal. The following section shows the recoded signals for the three muscles with their corresponding angular information measured by the sensor Gyroscope (Gyro).

The simulation was performed using a training data set which was previously recorded. The training dataset was recorded using disposable electrodes which were placed on Biceps brachii, Brachioradialis, and Triceps medial muscles. Then, the electrodes were connected to an EMG amplifier with four channels. After that, the amplifier was directly connected to the NEUROLOG system that has many filter blocks for EMG signal processing and conditioning. The Sampling frequency was set as 2000 Hz and a goniometer was used to measure the angle of motion during flexing and extending the elbow joints in five repeated cycles. Angular velocity and acceleration were also obtained. The recorded EMG signal was read by LabVIEW and they are shown with their LabVIEW code in the following figures.

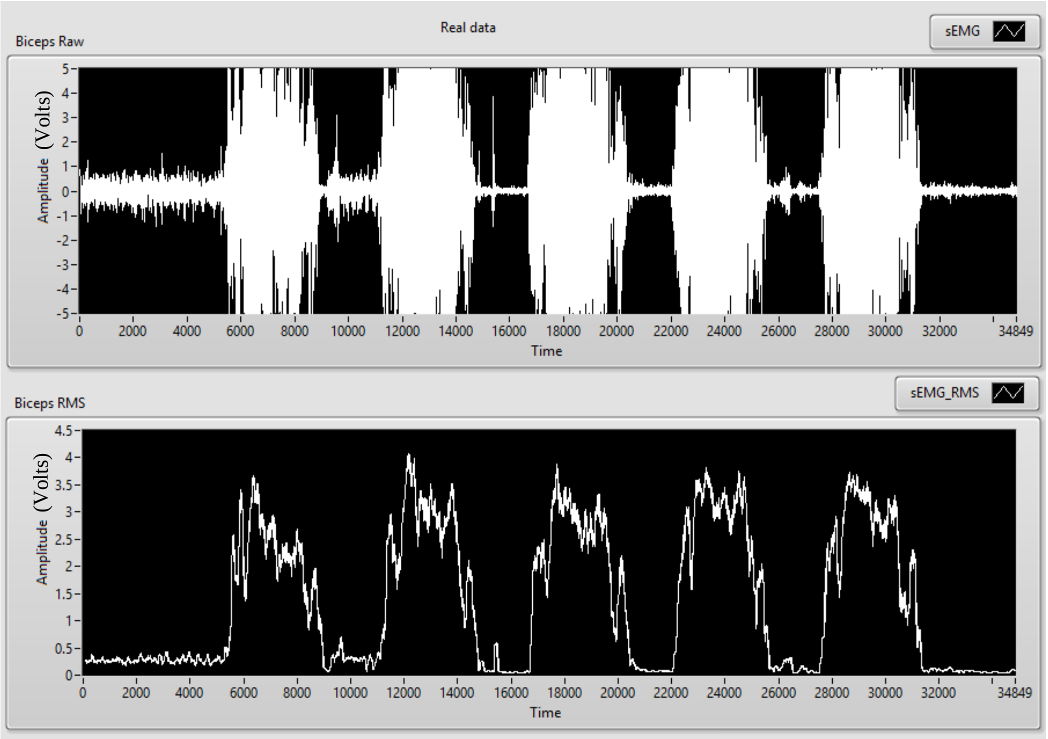


Figure (22): biceps EMG signal and the Corresponding RMS

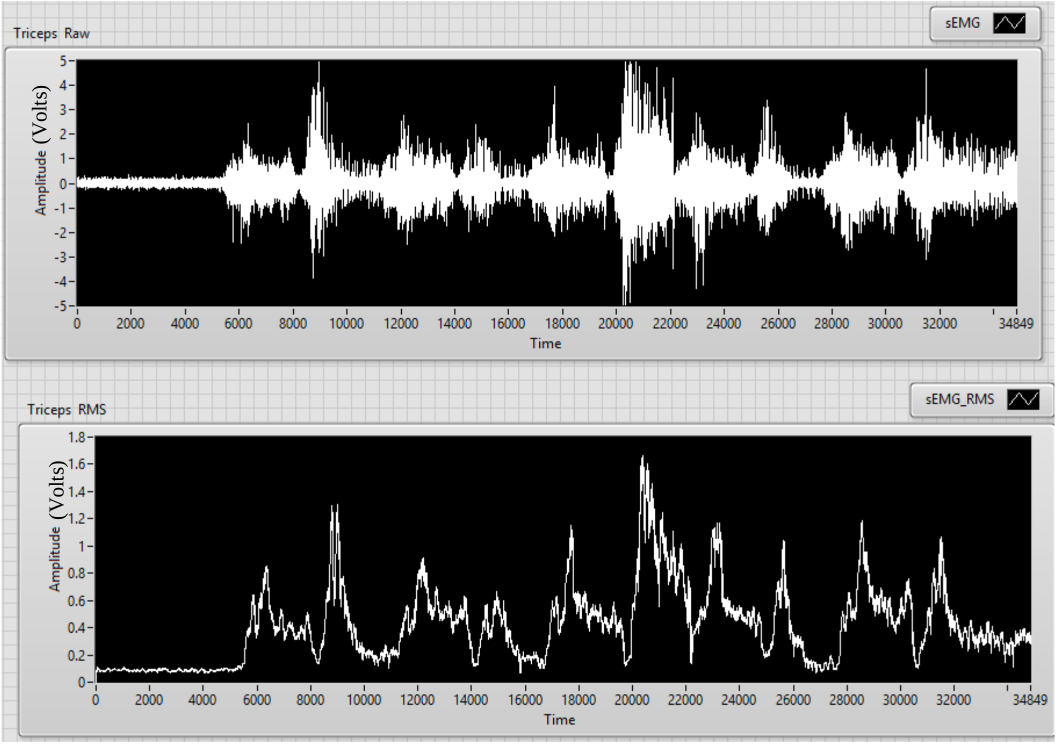


Figure (23): Triceps EMG signal and the Corresponding RMS

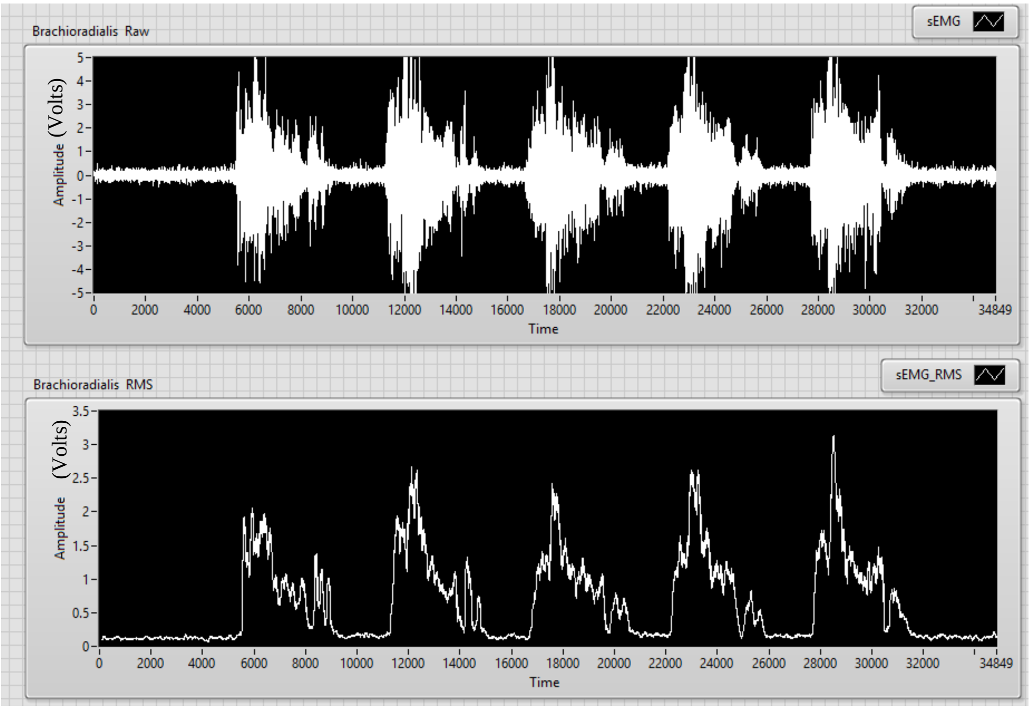


Figure (24): Brachioradialis EMG signal and the Corresponding RMS

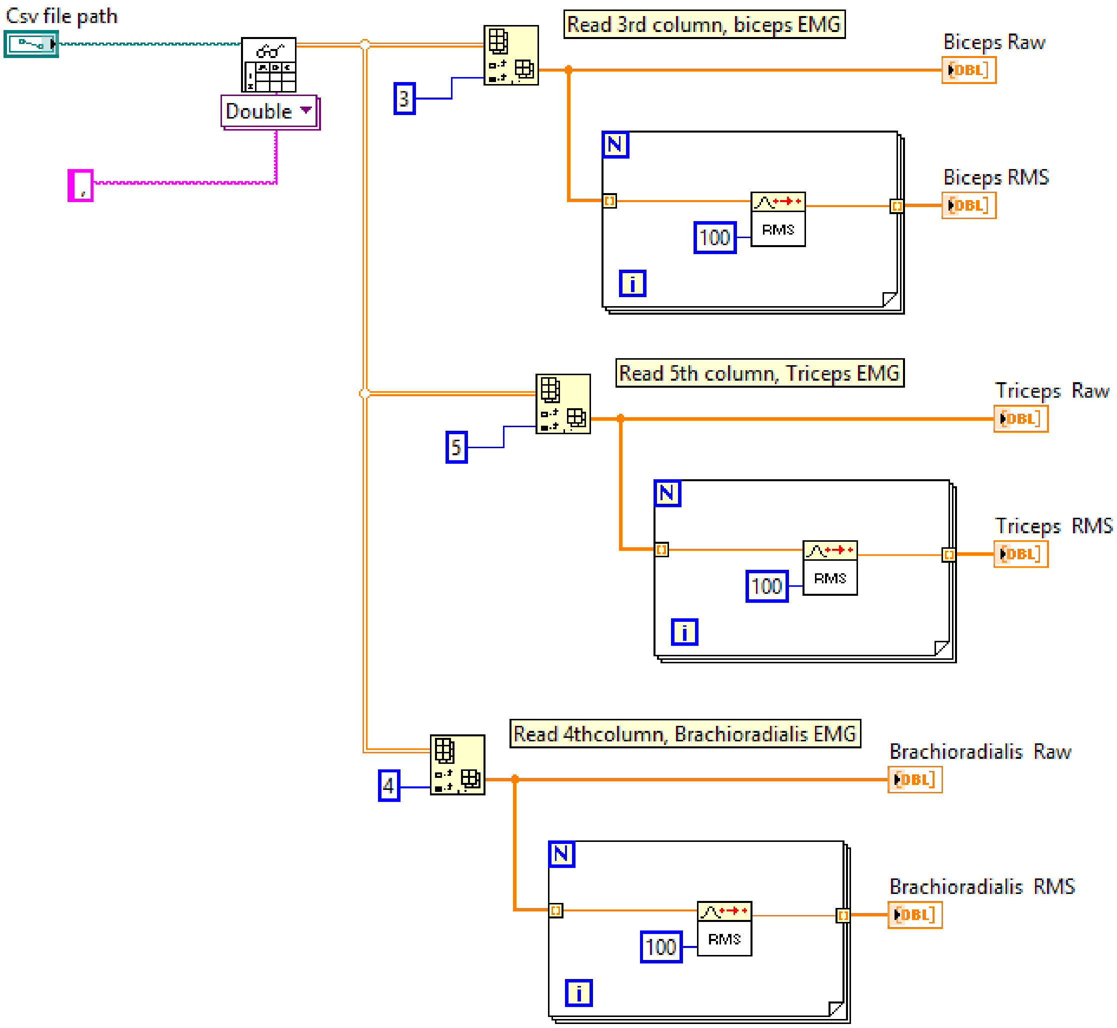


Figure (25): Acquiring data LabVIEW code

3.4 Fuzzy Logic Control System

Power assistance and augmentation devices track the control system based on human machine interface. Therefore, the control system should have capability to make an accurate response based on the sensory information. Furthermore, it is expected that the EMG signal levels differ from one person to another because it is influenced by many factors related to, for example, user's heath, electrodes placement and measurement quality. Based on these reasons and the facts mentioned in section 3.1, fuzzy logic control system was considered as the control methodology of the exoskeleton.

Fuzzy Approach to EMG Classification

Fuzzy system is a robust way to control an exoskeleton device and it has the potential in dealing with uncertainties which exist during the movement of the robotic arm. As a result, a rule based fuzzy logic method can be used to achieve the target of this project.

Before getting into the fuzzy system procedure performed to control the upper limb active exoskeleton, the main concepts and components of the fuzzy system should be discussed.

Fuzzy Logic System

Any fuzzy system has three main components: Fuzzifier, Inference rule base and Defuzzifier as seen in the following figure.

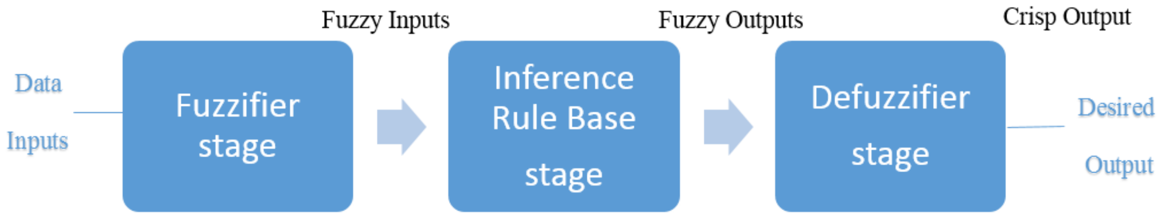


Figure (26): Fuzzy logic system

The inference engine is responsible of mapping each fuzzy input set into its corresponding fuzzy output set using rules and membership functions. These rules represent just an integral section of the fuzzy logic system. Furthermore, each of these rules is considered as a subsystem by itself with one or more membership function. It should be noted that the fuzzy rules only work when their corresponding input falls in the fuzzy variable span (Ajiboye, A.B. and Weir, R.F.,2005).

Originally, Fuzzy rules were just mapping structures resulting from the inputs to relate it with the desired outputs.

This procedure can be expressed mathematically as

$y = f(x)$ ………… *Equation (5)*

The number of rules, inputs and fuzzy sets for each of the input variables are the degrees of freedom which control the fuzzy system accuracy and determine its results. As a result, the membership function choice is based on assumptions of input kinds and the amount of noise. The membership function can be in different forms: triangle, trapezoid, sigmoid, singleton or goussian and it is symmetric about the average value. The high values of the membership functions mean that more noise is represented in the data (Ajiboye, A.B. and Weir, R.F.,2005).

In fact, the design of fuzzy logic system is based on various parameters that should be selected before getting into fuzzy logic design stage. This may look difficult to be established, but there are several methods to perform this using the input data and system training.

Fuzzy Rules for EMG Classification

The fuzzy system design methods determine the parameters values and corresponding membership functions according to original input data or the training dataset. To build a fuzzy logic system and establish the fuzzy rules, a specific number of input and output training pairs must be selected so that for every input x there is an output pair y (x,y). Then, the training dataset should be converted into a logical fuzzy rules set such as If-Then approach. The maximum rules number which represents the system is divided by the number of training pairs' basis system so that an optimal fitting can be established. The optimal system and the best fit of input output pars are then determined by tuning process which reduces the number of rules (Ahmad, S.A., Ishak, A.J., and Ali, S, 2010).

There are different ways to extract the fuzzy rules from data to be trained. One way is to obtain each fuzzy set center in the rule consequents and incidence. Another method is to assume the fuzzy sets for the consequential and antecedents and after that link the input data with the estimated fuzzy sets. In general, the fuzzy logic system is usually designed first and then the parameters can be optimized based on the training data (Ajiboye, A.B. and Weir, R.F., 2005).

Defuzzyfication

Defuzzification is simply converting the membership degrees of fuzzy system output variables into crisp absolute or numerical values based on the area under curves using one of the following methods (Ahmad, S.A., Ishak, A.J., and Ali, S,2010)..

- Centre of Area (CoA)
- Modified centre of Area
- Center of Maximum (CoM)
- Centre of Sum (CoS)

In this project, center of area (CoA) method is used for defuzzyfication. The concept behind this method is that the fuzzy logic system calculates the value of under membership function shape with respect to the output total range. The following equation is the standard equation to calculate the geometric COA (Ahmad, S.A., Ishak, A.J., and Ali, S,2010).

$$CoA = \frac{\int_{Xmin}^{Xmax} f(x) * x \, dx}{\int_{Xmin}^{Xmax} f(x) \, dx} \qquad \text{………… Equation (6)}$$

Where

x is the variable value

x_{min} and x_{max} are the fuzzy set range

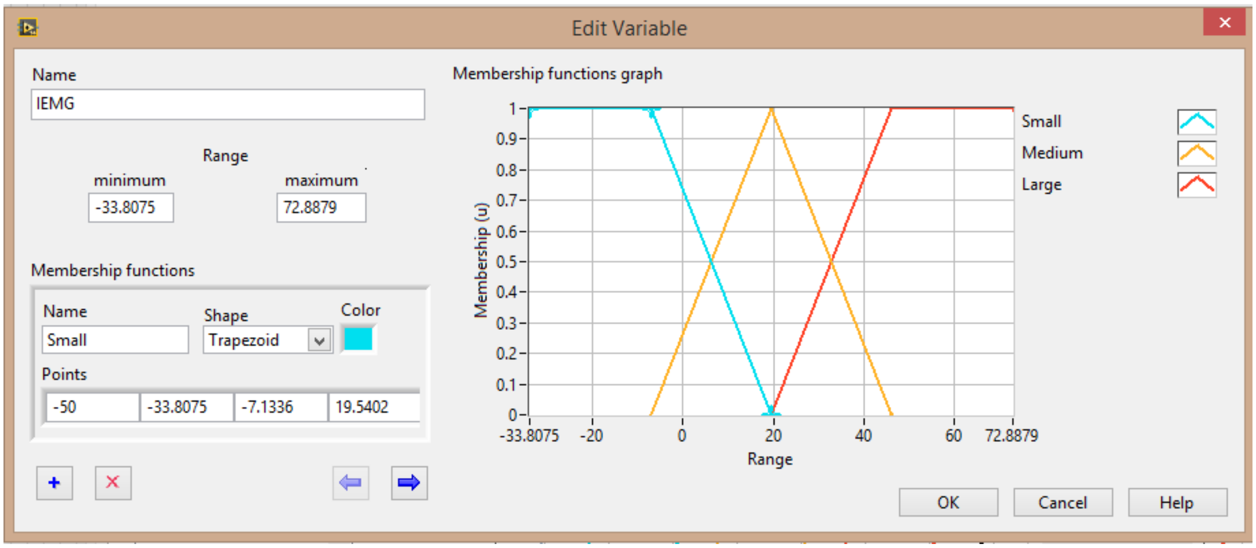
Design of Fuzzy Classifier in LabVIEW

There are different methods to control a motor (joint) based on EMG signals using fuzzy system. The rule-based fuzzy logic approach is a possible way to be performed using LabVIEW since a fuzzy logic designer toolkit is available.

First, the fuzzy system designer is opened from tools on the top of the project front panel of LabVIEW software. As seen in figure (29), the fuzzy system designer consists of three main components which are Variables, Rules and Test System.

Then, the input variables were selected as IEMG and RMS. Three membership functions were established for every input variable and a triangular and trapezoid shapes were selected. These memberships were normalized to a certain range from -33.8075 till 72.887 for IEMG and from 0.0343 till 3.149 for RMS based on the maximum and minimum value of the data and they were categorized (named) gradually as: Large, Medium, and Low as seen in figures (27) and (28).

On the other hand, the output was set to be the angle which should be ranged from about zero to 150 degrees approximately but it was ranged from 5.0025 till 170.887 based on the data minimum and maximum value and five membership functions were established with a tringle shape and categorized as: Very High, High, Medium, Low, Very low . These categories corresponds to the angle mode as seen in table (1). By this, both inputs and outputs variables were adjusted as seen in figure (29).



Edit Variable

Name: IEMG

Range

minimum: -33.8075

maximum: 72.8879

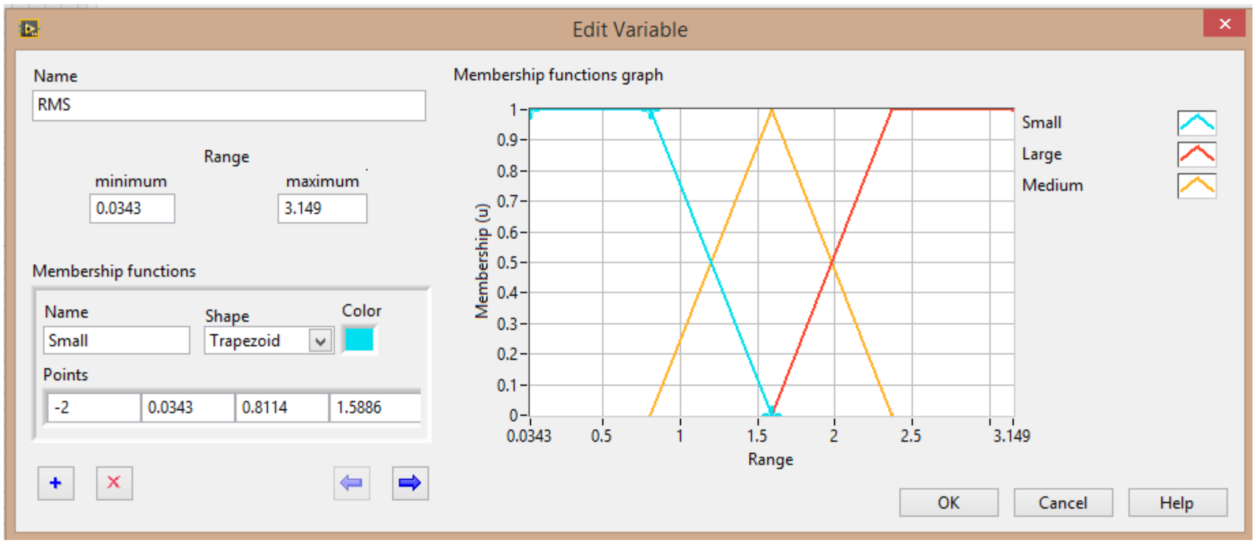
Membership functions

Name: Small

Shape: Trapezoid

Points: -50, -33.8075, -7.1336, 19.5402

Figure (27): IEMG input variable sitting



Name: RMS

Range: minimum 0.0343, maximum 3.149

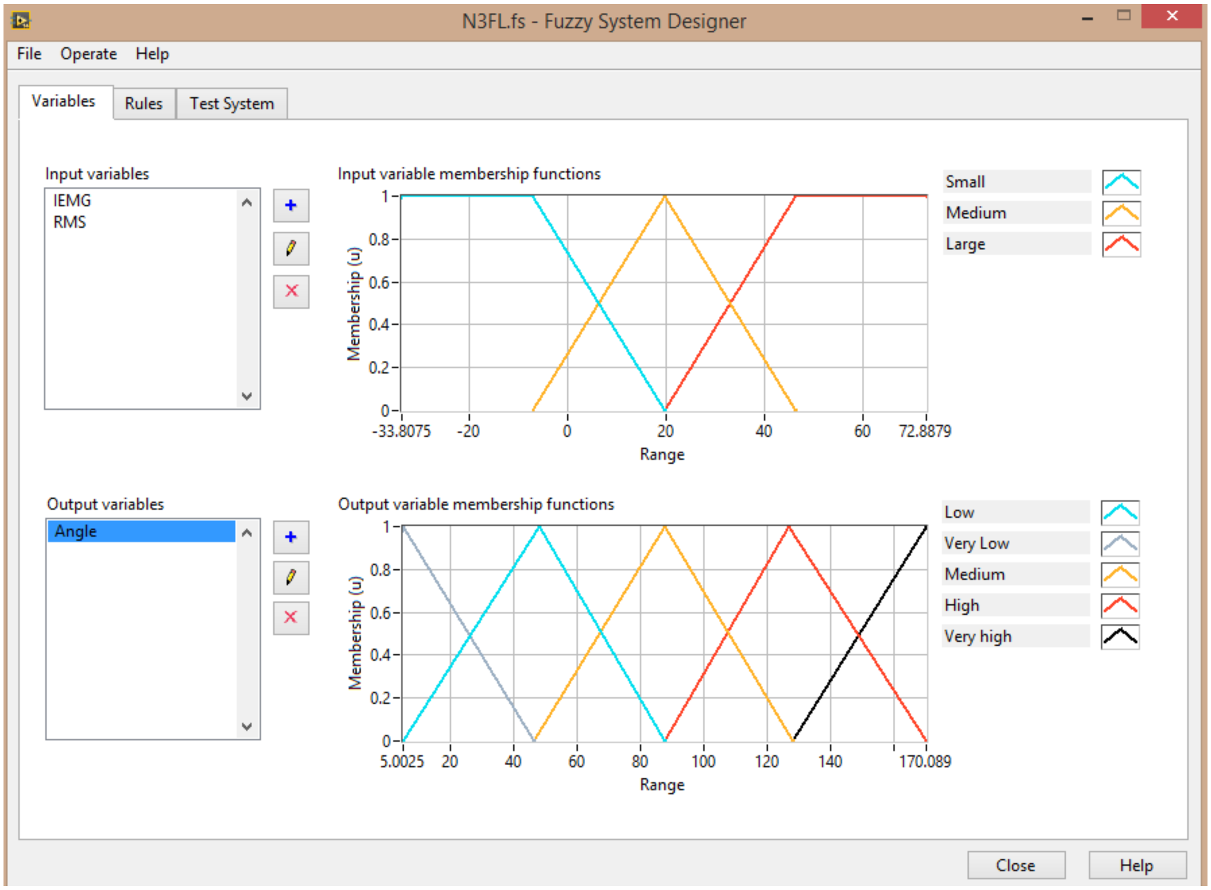
Membership functions

Name: Small

Shape: Trapezoid

Points: -2, 0.0343, 0.8114, 1.5886

Figure (28): RMS variable sitting



Input variables: IEMG, RMS

Output variables: Angle

Figure (29): Fuzzy Logic Designer tool in LabVIEW

Angle Category	Angle Mode	Angle Value (degrees)
Very High	Fully Flexed	170-136
High	Flexed	136-102
Medium	Right Angle	102-68
Low	Extended	68-34
Very Low	Fully Extended	34-0

Table (1): Angle modes and their corresponding value in degrees

After that, the rules were specified by taking a specific segment of RMS, IEMG and the calculated angle graphs at the same time range se figures (30) and (31). By comparing the changes in these signals the set of rules was developed. Since we have 4 membership functions, there should be (3*3) rules. Therefore, 9 rules were developed as listed in table (2). This rules implemented in the rules section of the Fuzzy System designer in LabVIEW and Center of Area (CoA) was selected as the defuzzification method, see figure (32).

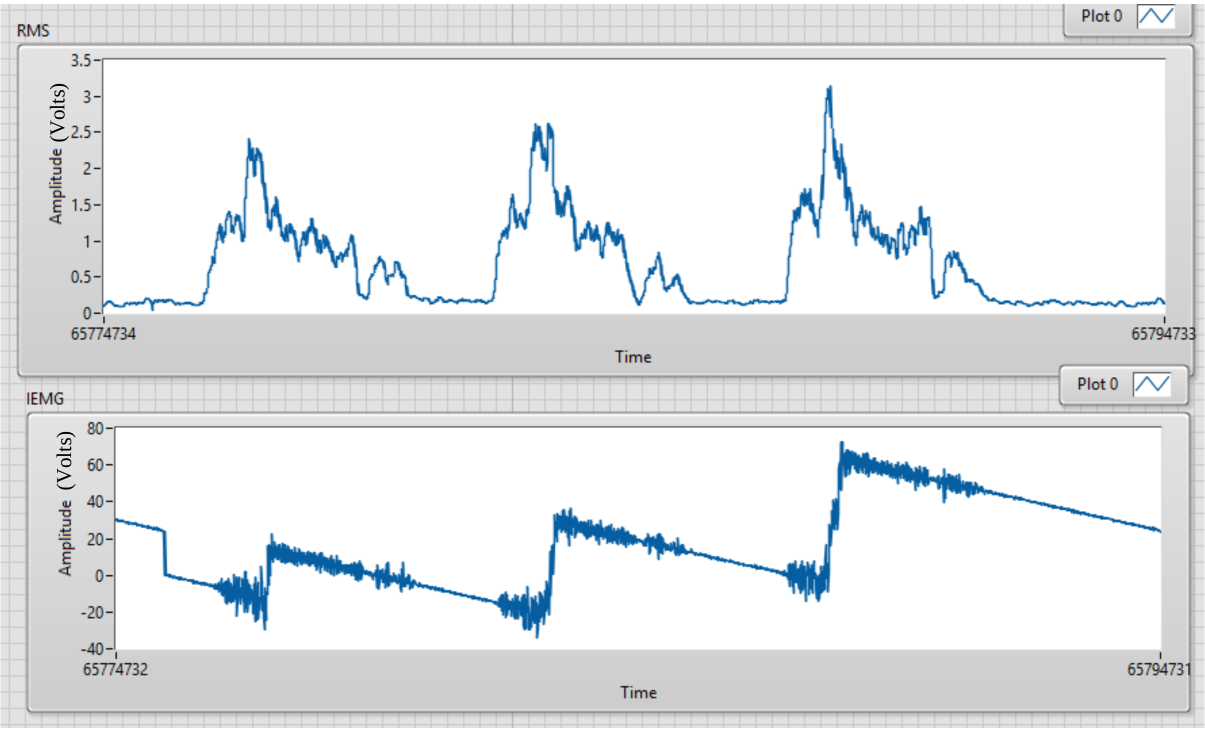


Figure (30): Fuzzy System Input Variables

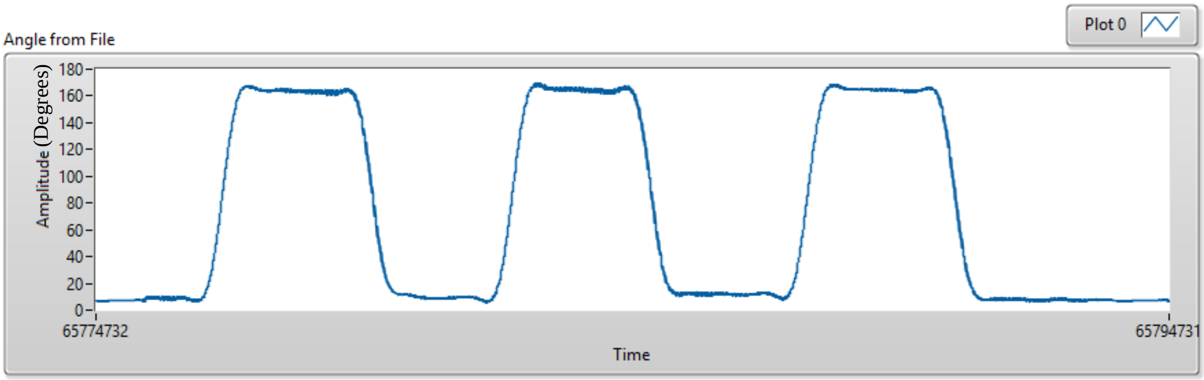
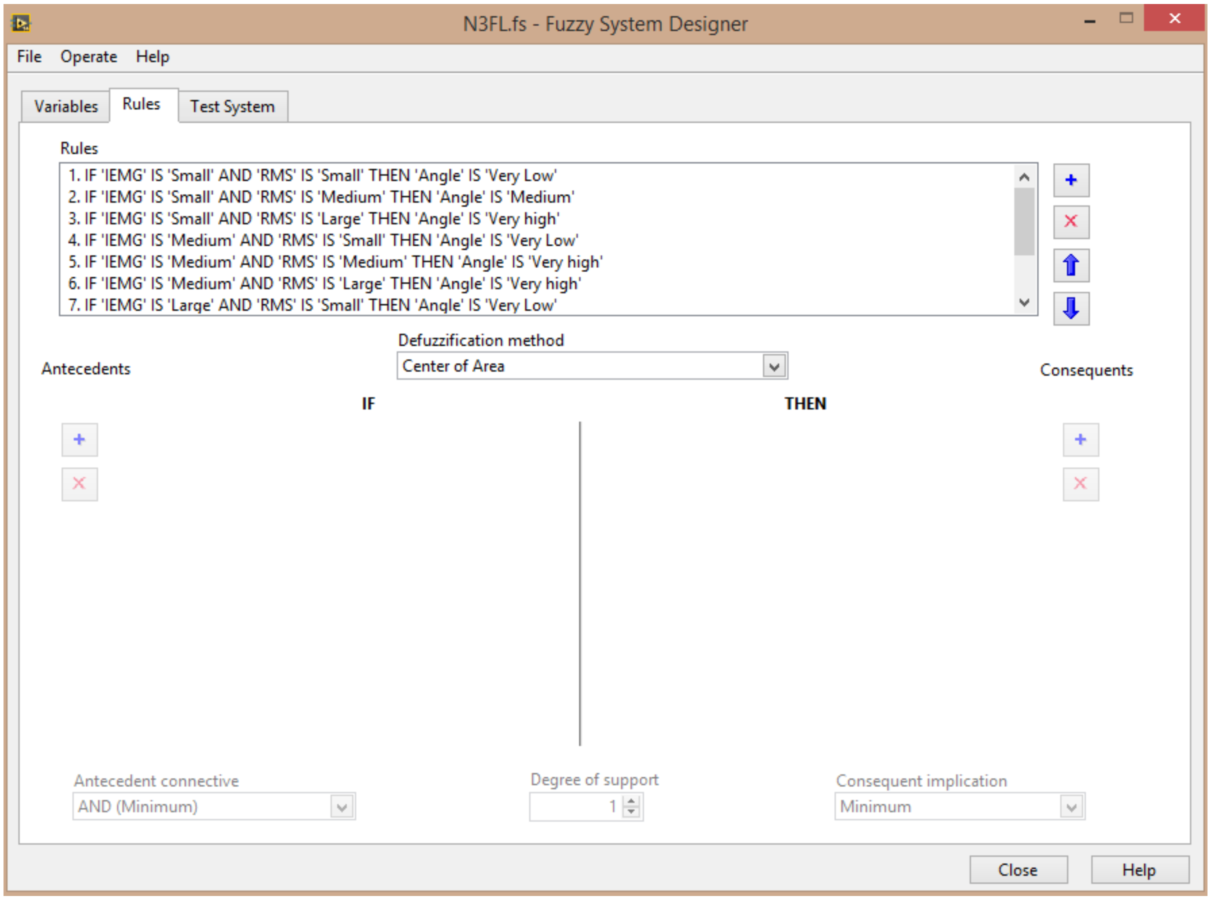


Figure (31): Fuzzy System Desired (Crisp) Output

Rule Number	IEMG	RMS	Angle	Angle Mode	Angle Value (degrees)
1	Small	Small	Very Low	Fully Extended	34-0
2	Small	Medium	Medium	Right Angle	102-68
3	Small	Low	High	Flexed	136-102
4	Medium	Small	Low	Extended	68-34
5	Medium	Medium	High	Flexed	136-102
6	Medium	Low	Very Low	Fully Extended	34-0
7	Large	Small	Very Low	Fully Extended	34-0
8	Large	Medium	Medium	Right Angle	102-68
9	Large	Low	High	Flexed	136-102

Table (2): Control System Fuzzy Rules



Rules

1. IF 'IEMG' IS 'Small' AND 'RMS' IS 'Small' THEN 'Angle' IS 'Very Low'
2. IF 'IEMG' IS 'Small' AND 'RMS' IS 'Medium' THEN 'Angle' IS 'Medium'
3. IF 'IEMG' IS 'Small' AND 'RMS' IS 'Large' THEN 'Angle' IS 'Very high'
4. IF 'IEMG' IS 'Medium' AND 'RMS' IS 'Small' THEN 'Angle' IS 'Very Low'
5. IF 'IEMG' IS 'Medium' AND 'RMS' IS 'Medium' THEN 'Angle' IS 'Very high'
6. IF 'IEMG' IS 'Medium' AND 'RMS' IS 'Large' THEN 'Angle' IS 'Very high'
7. IF 'IEMG' IS 'Large' AND 'RMS' IS 'Small' THEN 'Angle' IS 'Very Low'

Defuzzification method: Center of Area

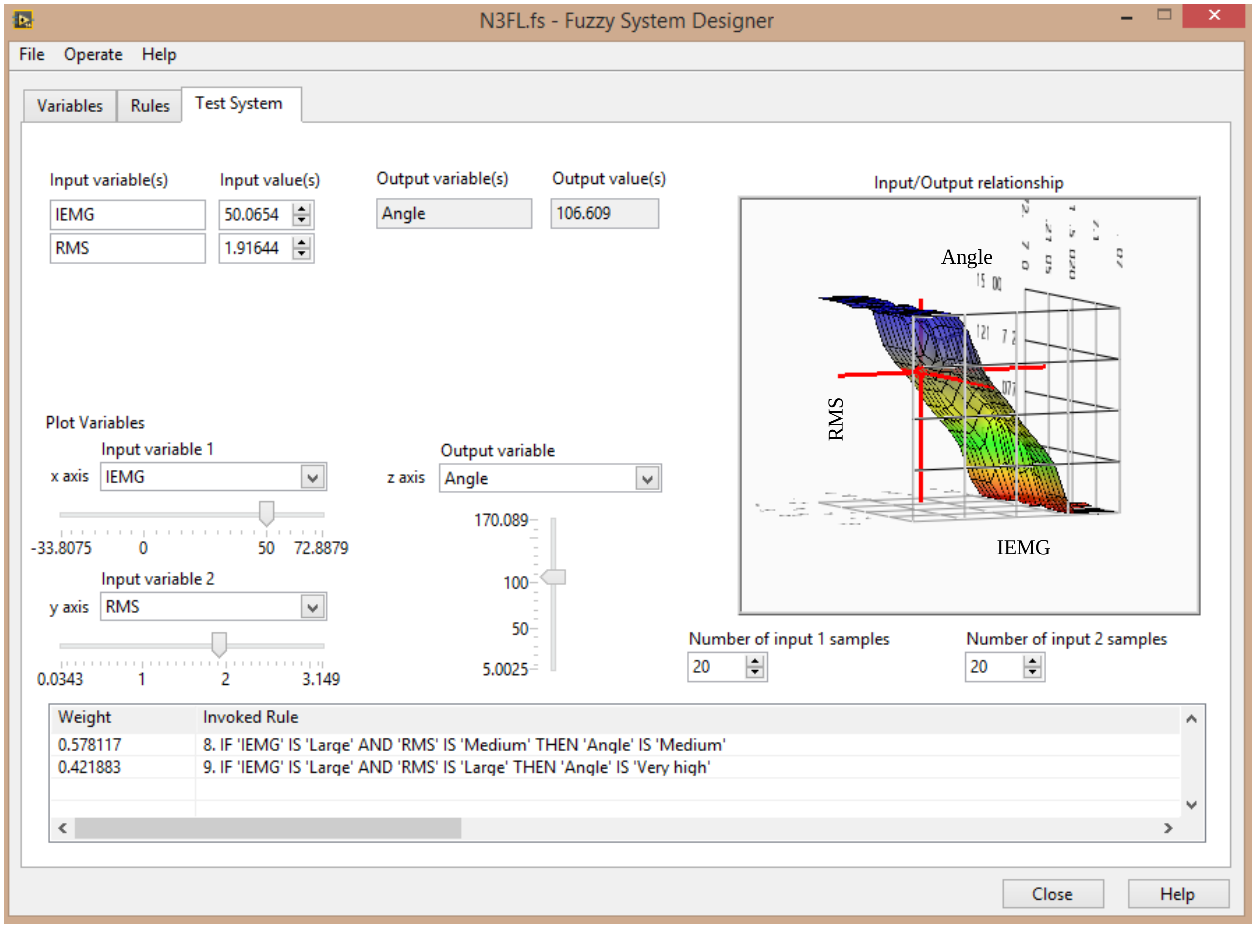
Antecedent connective: AND (Minimum)

Degree of support: 1

Consequent implication: Minimum

Figure (32): Rules Sittings in LabVIEW Fuzzy System Designer

Then, the model was tested for multiple values of input variables to check the corresponding angle, see figure (33). Then the model was saved and integrated in the LabVIEW code to see the results of estimated angle (crisp output) as seen in figure (34).



Input variable(s)	Input value(s)
IEMG	50.0654
RMS	1.91644

Output variable(s)	Output value(s)
Angle	106.609

Plot Variables

Input variable 1: x axis IEMG (-33.8075, 0, 50, 72.8879)

Input variable 2: y axis RMS (0.0343, 1, 2, 3.149)

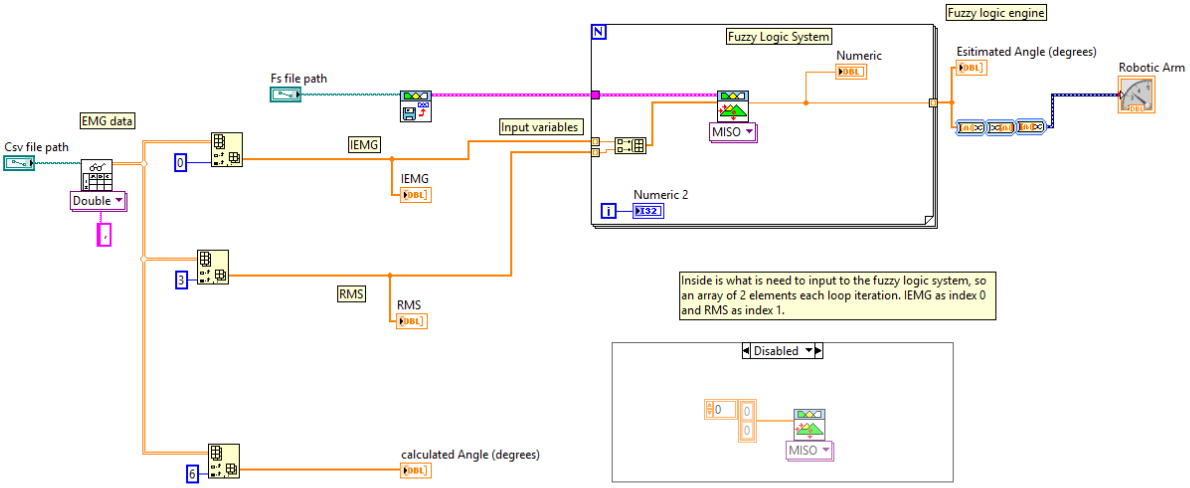
Output variable: z axis Angle (170.089, 100, 50, 5.0025)

Number of input 1 samples: 20

Number of input 2 samples: 20

Weight	Invoked Rule
0.578117	8. IF 'IEMG' IS 'Large' AND 'RMS' IS 'Medium' THEN 'Angle' IS 'Medium'
0.421883	9. IF 'IEMG' IS 'Large' AND 'RMS' IS 'Large' THEN 'Angle' IS 'Very high'

Figure (33): Test System in LabVIEW Fuzzy System Designer



Inside is what is need to input to the fuzzy logic system, so an array of 2 elements each loop iteration. IEMG as index 0 and RMS as index 1.

Figure (34): Control system LabVIEW code

4.Chapter 4: Results and Discussion

So far, the basic design and procedure of the exoskeleton control system has been discussed in details. A fuzzy logic approach was used to estimate the angle of elbow joint from sEMG signal during the dynamic flexing and extending of elbow joint. This was done by extracting two time domain EMG parameters like Integrated EMG (IEMG) and Root Mean Square (RMS) from raw EMG and input them to the If-then fuzzy logic rules which were obtained from the experimental findings. This chapter includes the analysis and outcomes of the control system and illustrates the estimated values of elbow joint angles resulted from the fuzzy logic system to compare them with the actual angle values. The results were obtained using the training data set which was previously recorded by the disposable electrodes while flexing and extending the elbow joint in five repeated cycles.

Results of Fuzzy Logic Control System

The output of fuzzy logic system represents the predicted angle of the elbow joint obtained during flexing an extending of elbow joint. To test the system, a series of trails were performed on the fuzzy logic system. After that, a consistent pattern was obtained.

The result of the fuzzy logic system is shown in figure (35). It can be observed that the estimated angle is looking similar to the targeted (actual) angle with a noticeable synchronization between them. Besides that, it can be seen that flexing gave much better results than extension in which the values from minimum to maximum on the left side of the cycles are closer to the actual values than the values which goes from maximum to minimum on the right side of the cycles. The maximum value of the estimated angle is equal to 156 degrees and it is a bit below the actual value which is at 170 degrees.

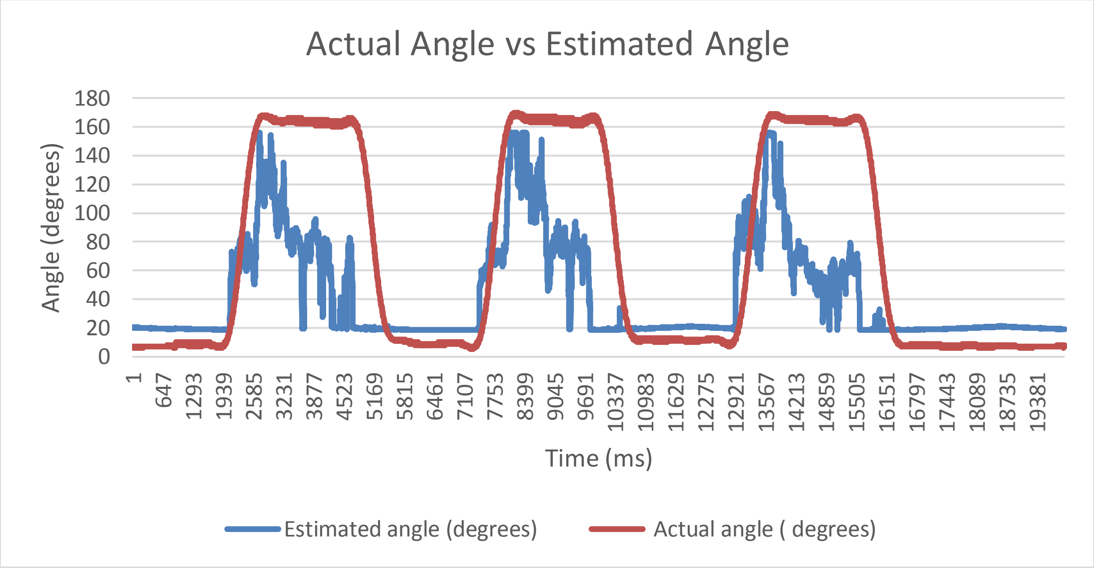


Figure (35): Actual Angle and Estimated Angle

The correlation coefficient between the actual and estimated angles was found by excel and it was equal to 0.707884. The output of the fuzzy system was fed as an input to the gauge design that represents the robotic arm in the front panel of LabVIEW, see figure (38). When the user’s arm is fully flexed the EMG value increase in proportion which means that there is a linear relationship between the angle and the EMG inputs, see figure (36). In fact, the high angle value indicates that more pronounced EMG activity occurred.

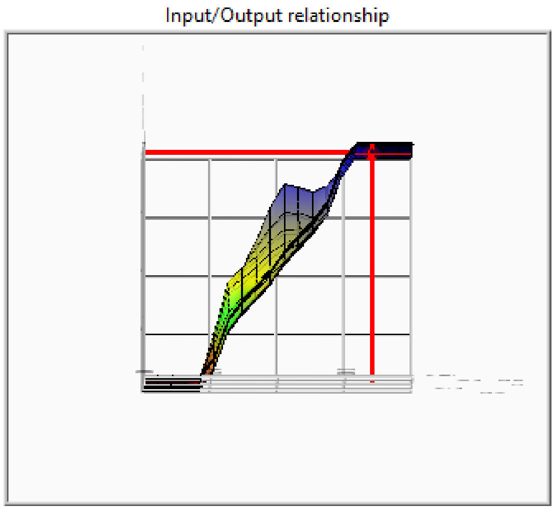
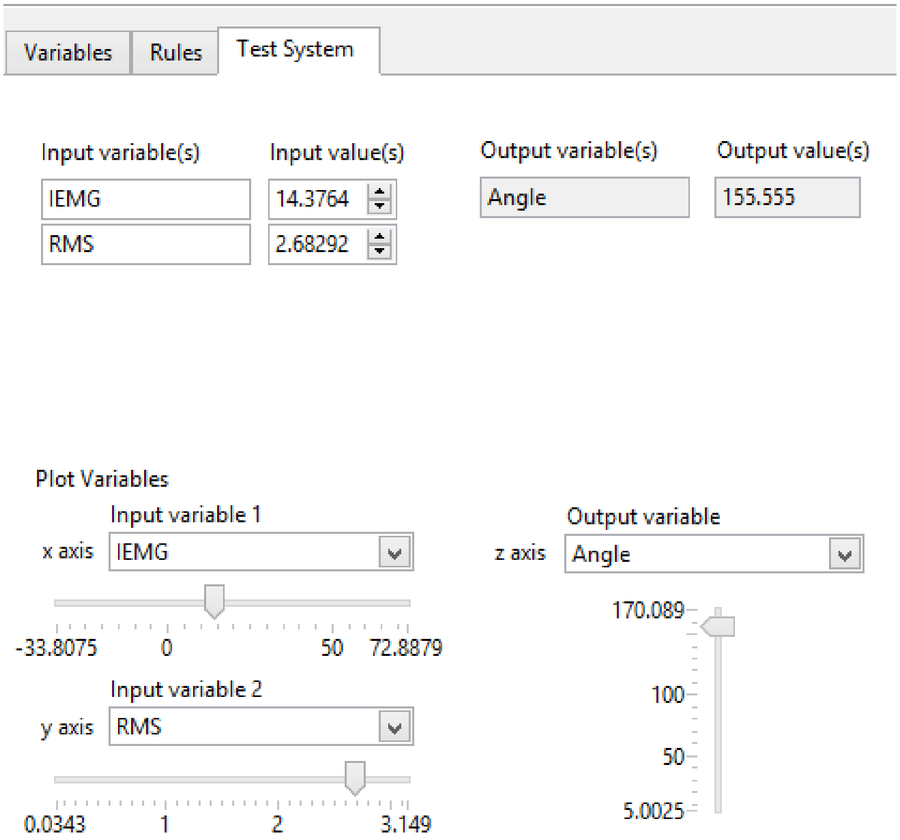


Figure (36): Fuzzy system Input/output relationship

In general, the result obtained shows that angle estimation can be performed using the time domain properties of EMG signal based on fuzzy logic system design. This also indicates that fuzzy logic technique doesn't require a lot of training compared with the other methods of position estimation such as artificial neural network. Therefore, linking the real time EMG signal with its corresponding angular component can be implemented in shorter time.



Input variable(s)	Input value(s)	Output variable(s)	Output value(s)
IEMG	14.3764	Angle	155.555
RMS	2.68292		

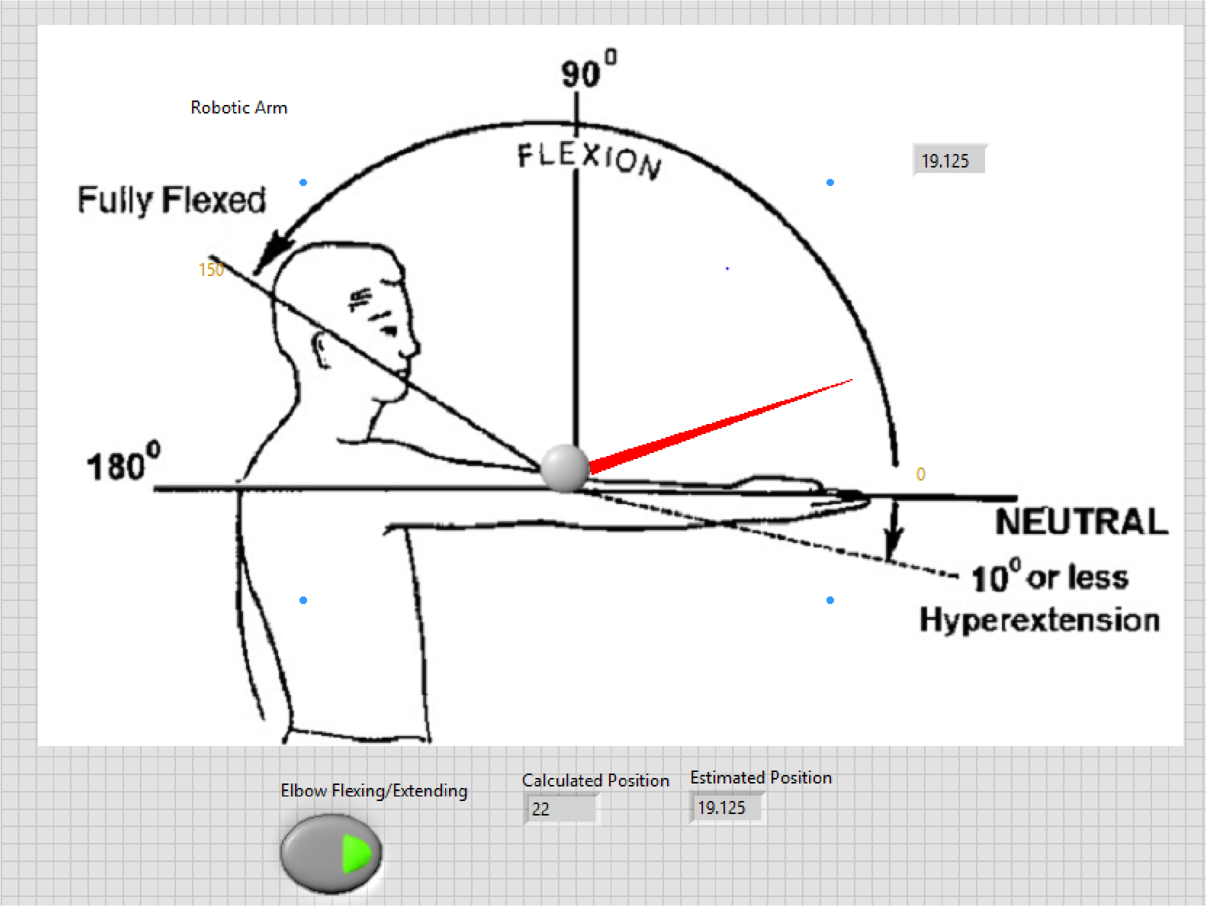
Input variable 1
x axis: IEMG

Input variable 2
y axis: RMS

Output variable
z axis: Angle

Figure (37): Fuzzy System Testing

The normal elbow motion range is between 0 and 150 degrees approximately and it can be varied from a person to another depending on the upper limb length and weight. However, the angular information obtained from the recorded data gave angles above 150 degrees. The simulation was performed based on that and the angle was between 5.0025 and 170.089 degrees referring to the maximum and minimum values of the calculated angles shown in figure (37).



Calculated Position 22

Estimated Position 19.125

Figure (38): Control system –LabVIEW front panel

Analysis results

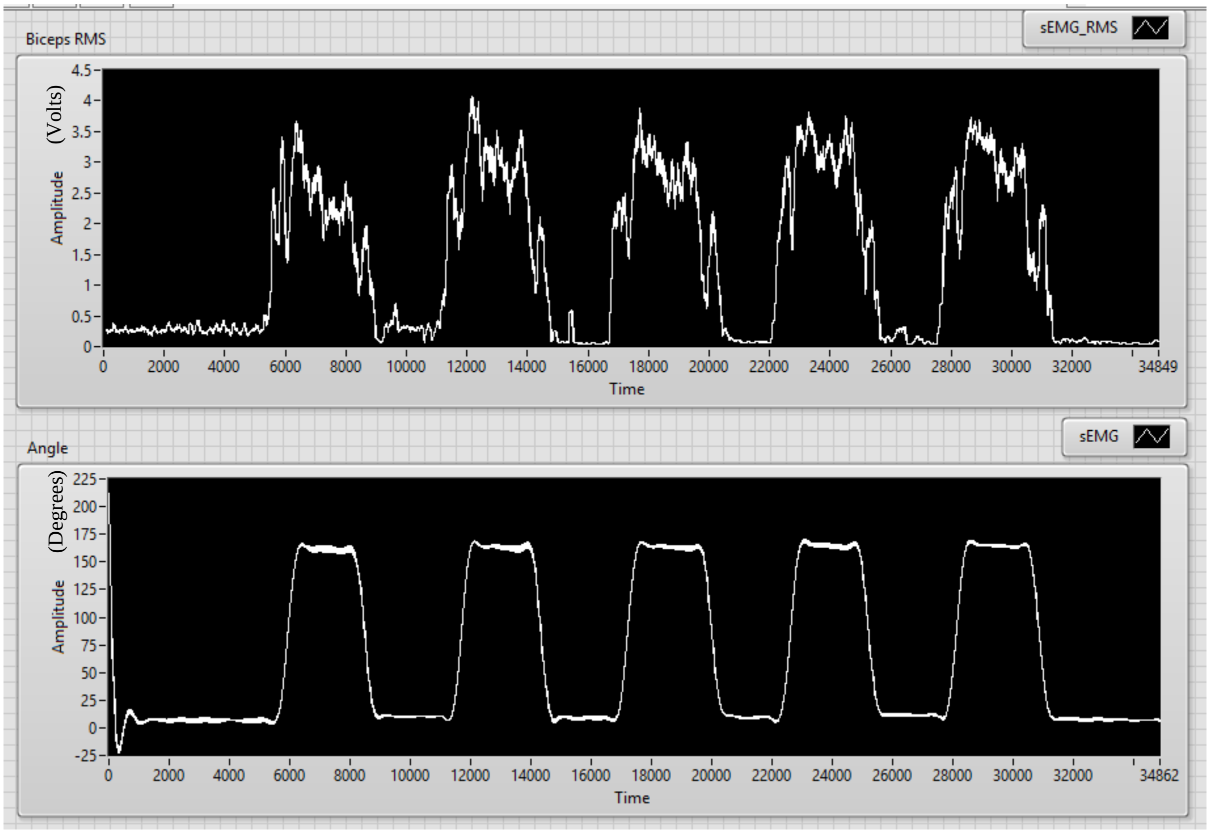


Figure (39): Synchronization of Angle and EMG

From figure (39) it is clear that the RMS of biceps signal is synchronized with the angle of movement. The angle graph shows that while flexing the angle increases from zero (Fully extended) till it reaches the maximum at 160 degrees approximately (Fully flexed). After that, the angle starts to decrease when the subject perform the extension movement till the angle goes back to zero.

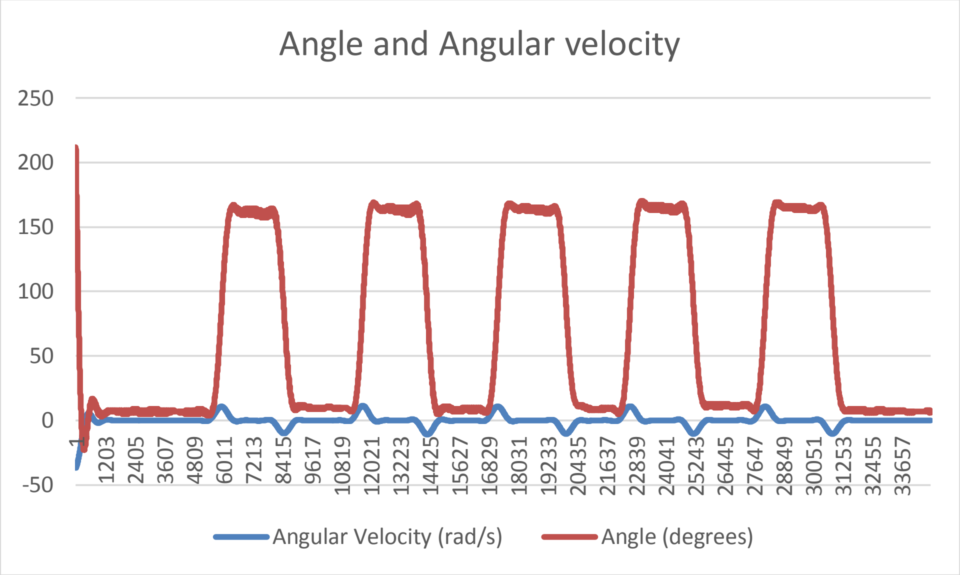


Figure (40): Angular Velocity and Angle Relationship

From figure (40), it can be observed that the angular velocity is positive while elbow flexing and negative while elbow extension.

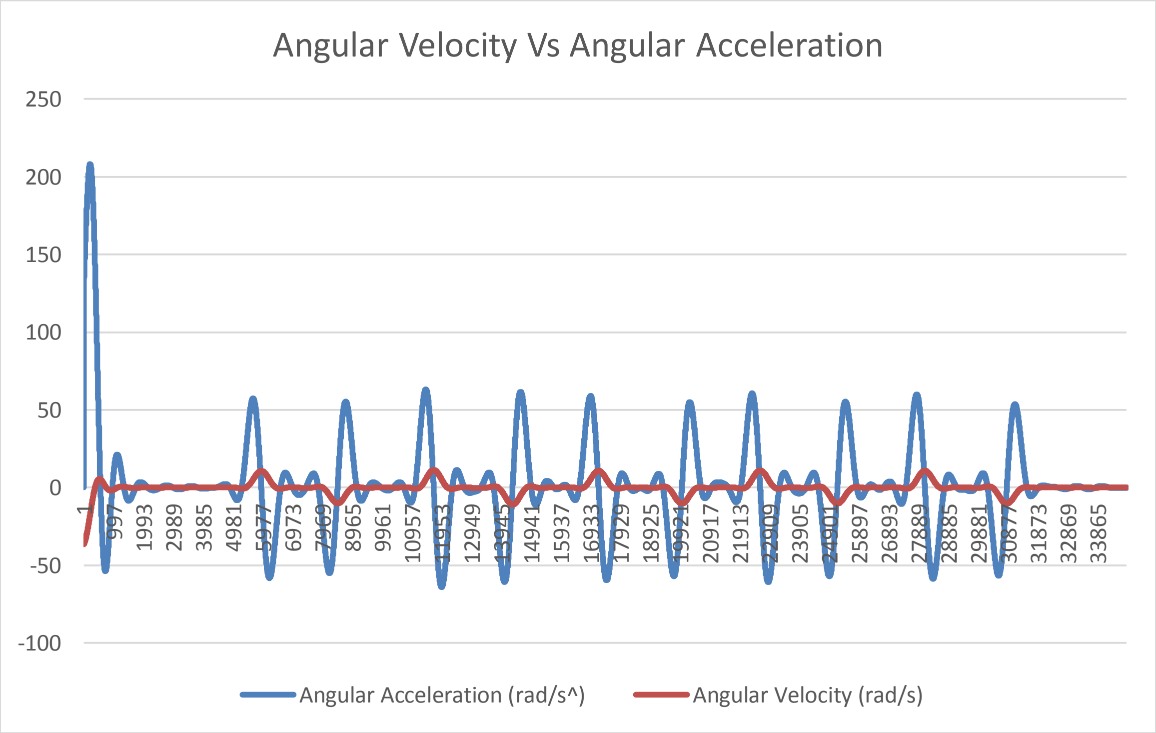


Figure (41): Angular Velocity and Angular acceleration Relationship

Another note is that no angular displacement when the angular velocity is equal to zero and that happens at the beginning and the end of the dynamic motion and when the movement direction changes from elbow flexing and extension and vice versa, see figure (41). Therefore, changing in movement direction happiness when there is a changing in the angular velocity sign. In fact, the angular acceleration depends on the force values that act on the system which generate the movements controlled by muscles responsible for elbow motion. That is why there are three phases in angular acceleration reflect the total muscular activity. During the first phase, the exoskeleton arm will accelerate in the extension direction while at the second phase the exoskeleton arm will accelerate in the flexing direction. The last phase indicates that the movement is about to finish in the extension direction as it started.

EMG-speed relationship

There is a strong relationship between the speed of motion and the EMG signal amplitude since the speed has an effect on muscles voluntary contractions during isometric/isotonic conditions. Research findings sate that the EMG amplitude is depending on the speed of motion with a linear relationship. In other words, higher signal amplitude leads to faster muscle contraction hence larger EMG amplitude, power and frequency. This concept was demonstrated on the EMG data recorded by **TrignoTM** wireless EMG system during different speeds of motion as seen the Appendix.

These results indicate that the speed control of the exoskeleton motor joint is operating by adjusting the contraction velocity with respect to the corresponding signal amplitude. This is expected to be performed in a way that the time of contraction is remaining approximately constant. Therefore, it can be noted that the speed control of exoskeleton is an important requirement to the muscle contraction synchrony.

Due to time limitation there was no simulation for the velocity parameter as planned.

Force/torque – EMG relationship

The main parameters required in applying EMG signal analysis in a robotic exoskeletons are force, frequency, angle and torque. Force and frequency relationship is easy to understand but this is not the case for the other parameters. As mentioned before, EMG signal is not easy to understand and a direct relationship between theses parameters is not a straight forward procedure. A good suggestion to study the frequency angle relationship is to find the Short Fourier Transform of the EMG signal and plot it versus time. Since force is related to frequency and angle of motion, the frequency of the EMG signal is also related with the angle of motion at a certain force. This concept is another way to relate the EMG signal to the angle (Kuriki et. al., 2012).

Torque is usually related to machine design. Since the project target is to control the position of motion for upper limb exoskeleton and there was no practical implementation in this project in addition to limited time, torque couldn’t be implemented on the software.

Therefore, analysing the power and torque amplitude is not striate forward and they cannot be easily extracted from the data used in this project. This can be done if weight was included during flexing and extending and force angle relationship can also be obtained by measuring the angle at different points of motion.

> It is important to point that the EMG signal is not necessarily reflecting the total torque or force generated by the muscle. That is because the motor units' number recorded by the EMG electrodes are always less than the number of the fired motor units during motion. When the motor unit is close enough to the EMG electrode, there will be an increase in the amplitude of EMG signal while if the motor unit is far from the EMG electrode, the EMG amplitude will not be changed although the force is expected to be increased. As a result, the relationship of EMG frequency or EMG firing rates and force is tend to be linear. However, EMG and force relationship is considered to be "linear" during isometric conditions of movement and non-linear during isotonic conditions of movement (Weir et al., 1992)

In terms of exoskeletons kinematics, applying EMG to measure the force requires a procedure of calibration parameters for each individual user. This standardized procedure should be done when accurate variables control is available. This is a challenging task with the complexity of the biological signals especially during dynamic movements. (Kuriki et. al., 2012)

Ch5: Conclusion and Future Work

CONCLUSION

The objective of this project was to design a simulated control system for an active upper limb exoskeleton with one DOF using fuzzy logic control approach and it has been achieved successfully. The sEMG signals were recorded from the biceps brachii and triceps muscles of the subject during flexion and extension of elbow. This was demonstrated by fuzzy logic control system to enable the user to control the robot motion based on their intention according to the biceps and triceps muscle activity (EMG signals). The control system contains decision making algorithm to drive a simulated motor unit that acts as an assistive elbow flexor and extensor.

The method used to achieve this target was based on extracting two time domain EMG parameters which are Integrated EMG (IEMG) and Root Mean Square (RMS) from raw EMG and integrate them with If-then fuzzy logic rules. The following were the main concluded learnings:

- The angle estimation can be performed using the time domain properties of EMG signal based on fuzzy logic system design.
- The maximum value of the estimated angle was equal to 156 degrees while the actual angle was 170 degrees.
- The estimated value of elbow joint angles was compared with the actual angle using fuzzy logic design in LabVIEW with approximately 70% correlation.
- The high angle value indicates that more pronounced EMG activity occurred
- The RMS of biceps signal is synchronized with the angle of movement.
- The angular velocity is positive with elbow flexing and negative with elbow extension.

Future Work:

This project was performed by simulating the exoskeleton control system based on software algorithms using LabVIEW and there was no practical or mechanical implantation involved. Therefore, the first thing that can be done to improve this project is to implement it practically.

Moreover, fuzzy logic control system was the control system in exoskeleton robot designed in this project and obtained prediction result can be improved by modifying the fuzzy rules to get better decision making abilities.

In addition, the design system has some drawbacks and limitations such as not responding to all patients. To overcome this problem and improve the performance of the system, a process of normalization should be used because it is important to have a system which works for different users to be able to compare the output across multiple patients.

Furthermore, patients differ in their physical geometry, length of muscles and movement patterns. This issue can be solved by normalizing the values of measurement versus the maximum value of effort. To do that, it is necessary to divide the sub-maximum values of effort by the maximum total effort value to get a smaller ratio of a normalized signal for future studies and comparisons.

Finally, there are other suggestions that can be added to enhance the general performance of the Exoskeleton robots and make their dynamic movements' to mimic human movements with no delay. These suggestions include:

- Modify a future plan to extend this project to high level stages with full implementation and use of practical experiments to generate more advance data benchmarked against commercial upper limb exoskeleton grades.
- Consultation of many research centers about the new generation of upper limb exoskeleton information, upper limb devices and upper limb exoskeleton commercial grades advantages and limitations.

- Review of all stages of this project, focusing on the problems will be valid starting point for future improvement studies with the ambition to use more updated methods and software.
- Sponsoring of new researchers in the field of robotic and rehabilitation will indeed have a positive impact on patients especially among vulnerable groups in developing countries.
- The collaboration between students from different field (biomedical, electrical, and mechanical) to have a joint research topic, covering the use of technology to improve the quality of robot to suit many patients.

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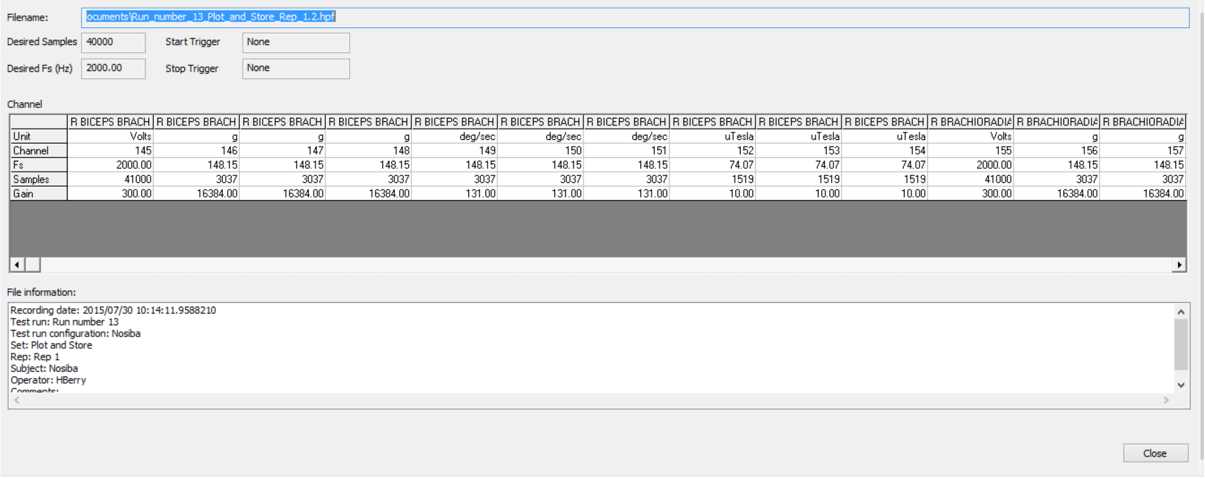
APPENDIX: RECORDED SIGNALS FOR SLOW, MEDIUM AND FAST SPEED MOTION

1) At slow speed motion:



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Channel

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Channel	145	146	147	148	149	150	151	152	153	154	155	156	157
Fs	2000.00	148.15	148.15	148.15	148.15	148.15	148.15	74.07	74.07	74.07	2000.00	148.15	148.15
Samples	41000	3037	3037	3037	3037	3037	3037	1519	1519	1519	41000	3037	3037
Gain	300.00	16384.00	16384.00	16384.00	131.00	131.00	131.00	10.00	10.00	10.00	300.00	16384.00	16384.00

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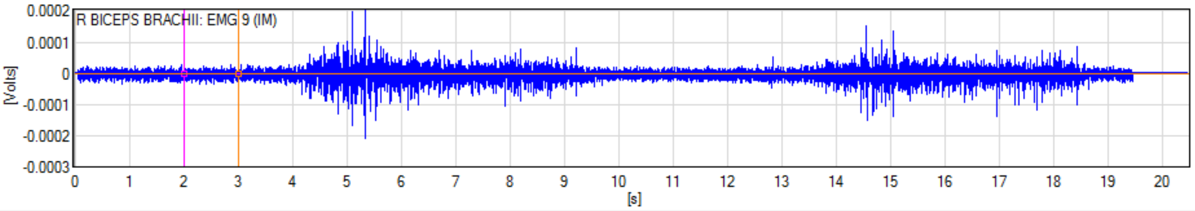
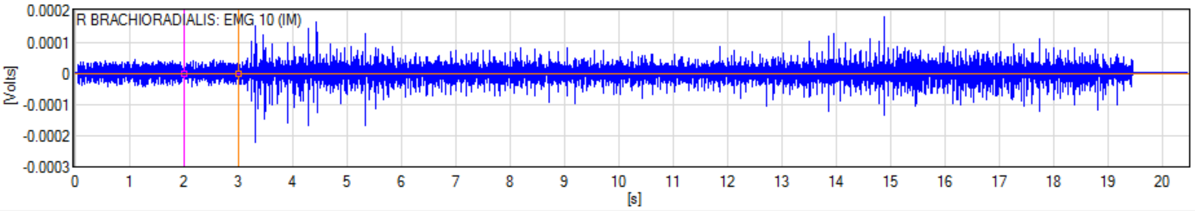
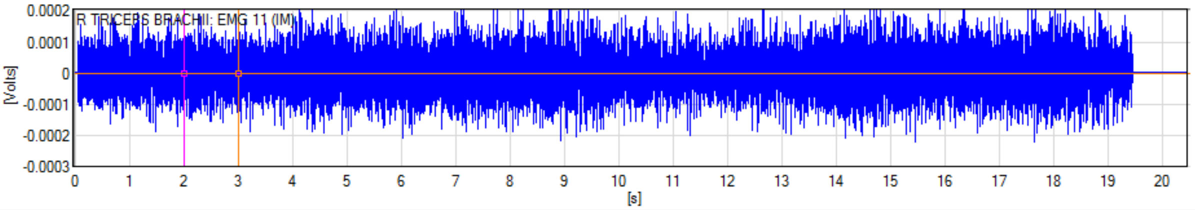






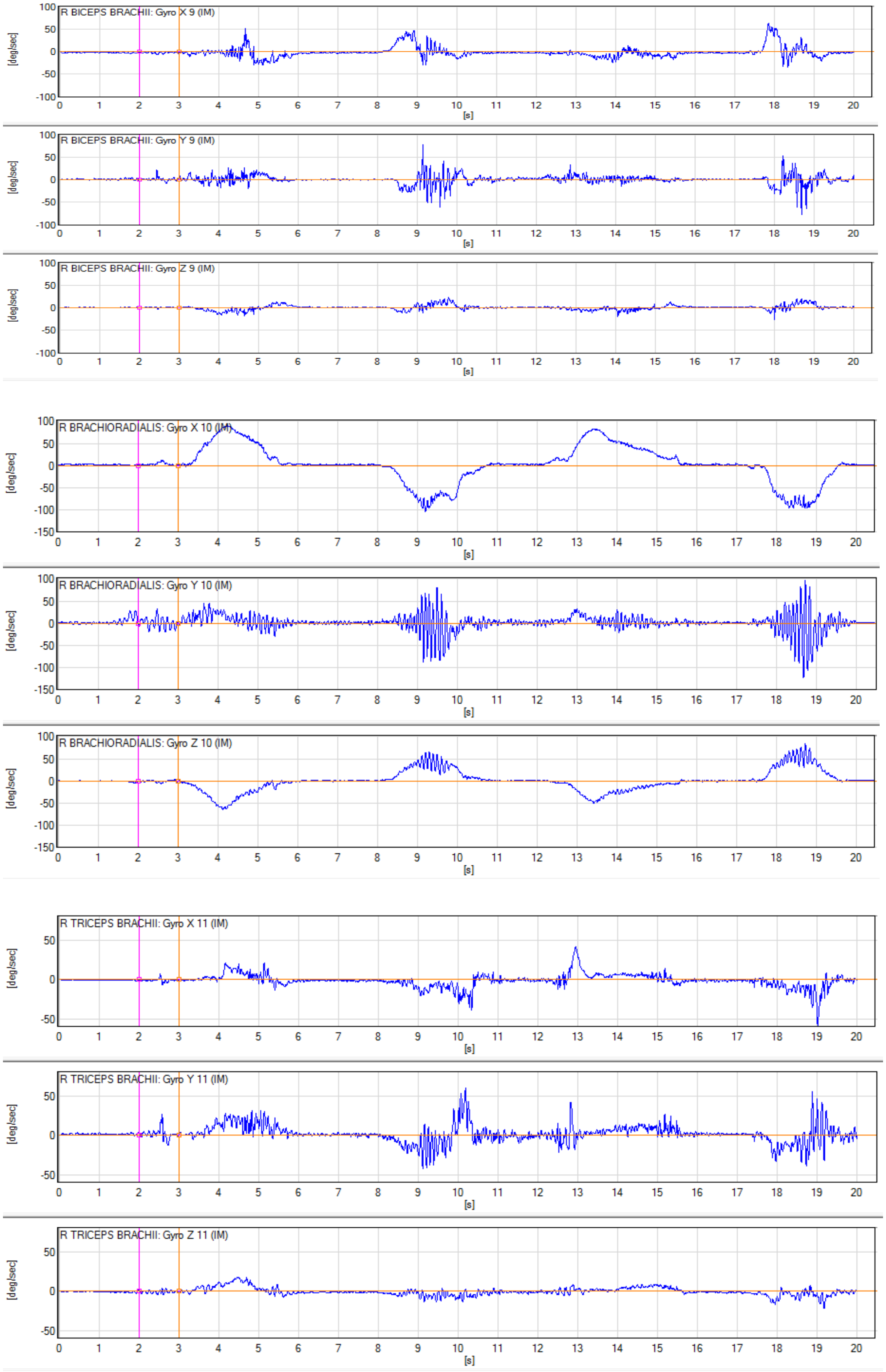
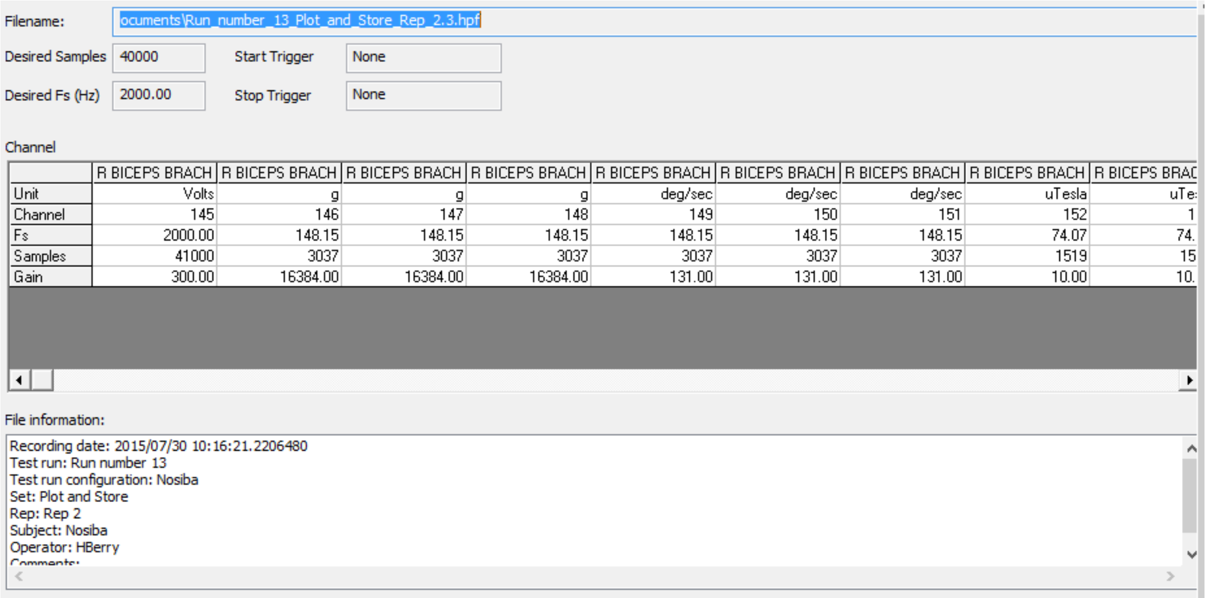


Figure (42): Recorded signal at slow speed motion

2) At medium speed motion



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Stop Trigger: None

Channel

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Unit	Volts	g	g	g	deg/sec	deg/sec	deg/sec	uTesla	uTe
Channel	145	146	147	148	149	150	151	152	1
Fs	2000.00	148.15	148.15	148.15	148.15	148.15	148.15	74.07	74.
Samples	41000	3037	3037	3037	3037	3037	3037	1519	15
Gain	300.00	16384.00	16384.00	16384.00	131.00	131.00	131.00	10.00	10.

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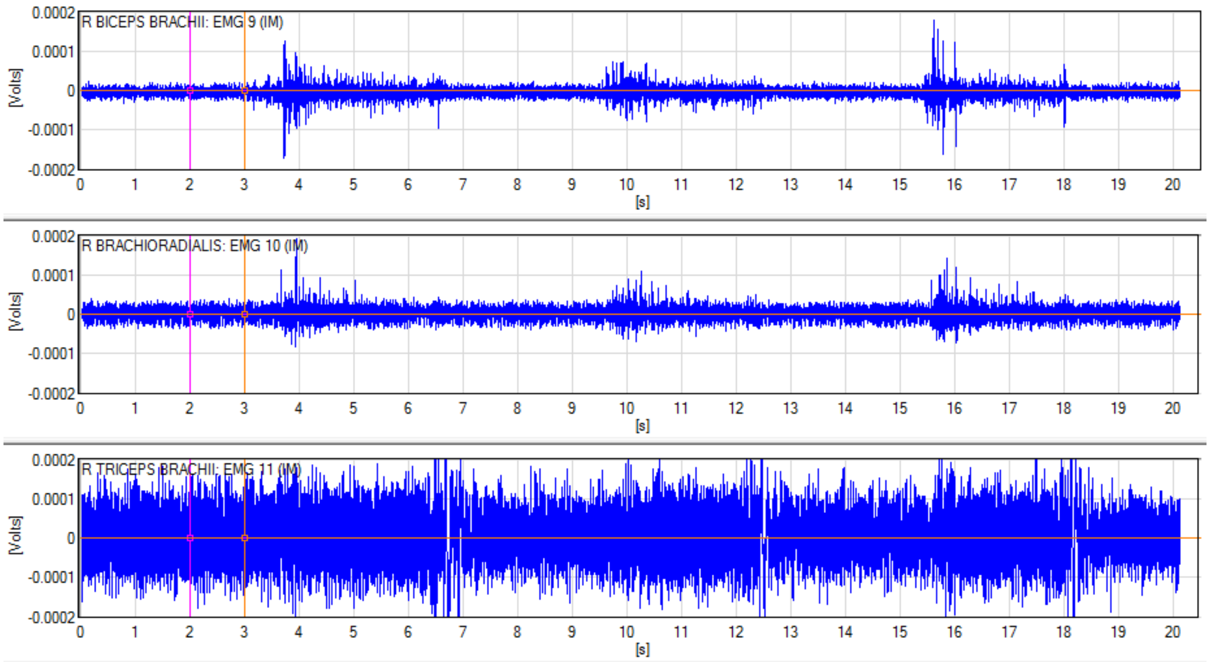
Subject: Nosiba
Operator: HBerry



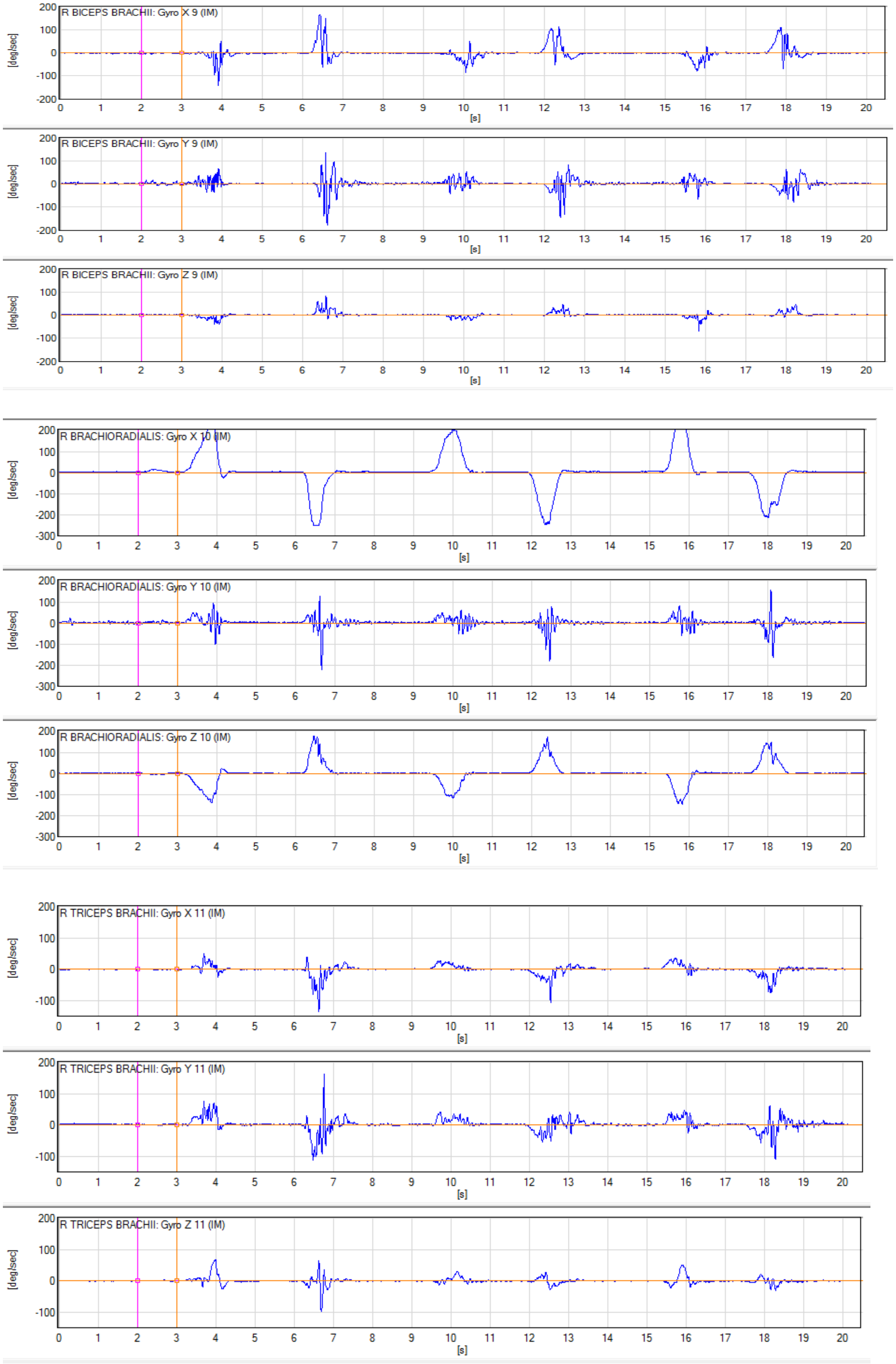
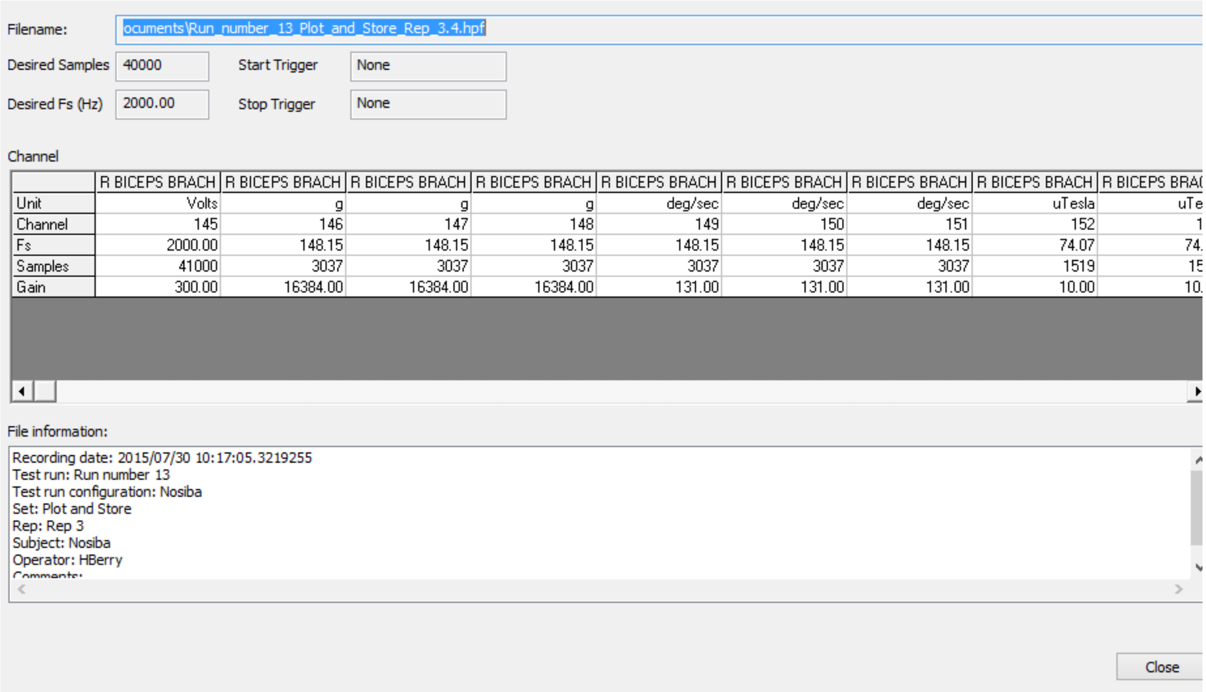


Figure (43): Recorded signal at medium speed motion

3) At fast speed motion



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Stop Trigger: None

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Unit	Volts	g	g	g	deg/sec	deg/sec	deg/sec	uTesla	uTe
Channel	145	146	147	148	149	150	151	152	1
Fs	2000.00	148.15	148.15	148.15	148.15	148.15	148.15	74.07	74.
Samples	41000	3037	3037	3037	3037	3037	3037	1519	15
Gain	300.00	16384.00	16384.00	16384.00	131.00	131.00	131.00	10.00	10.

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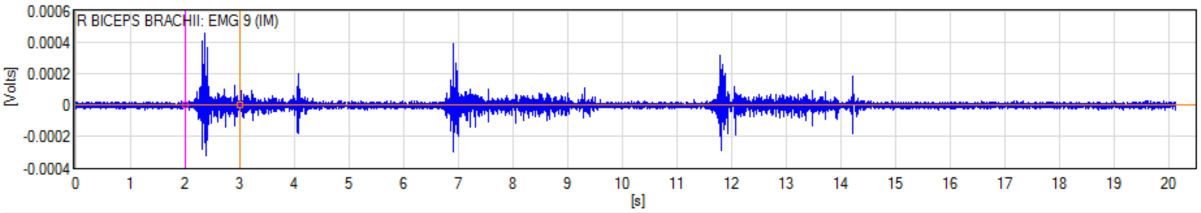

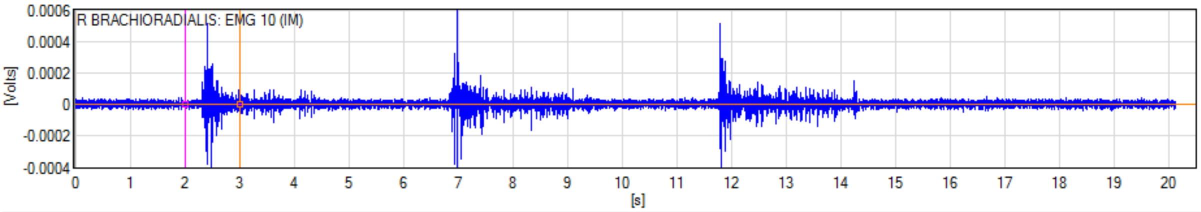

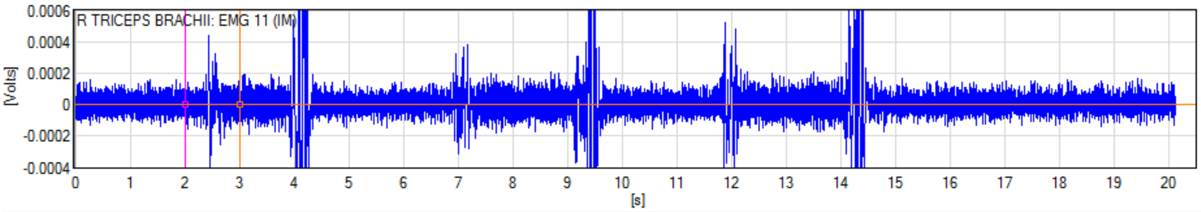

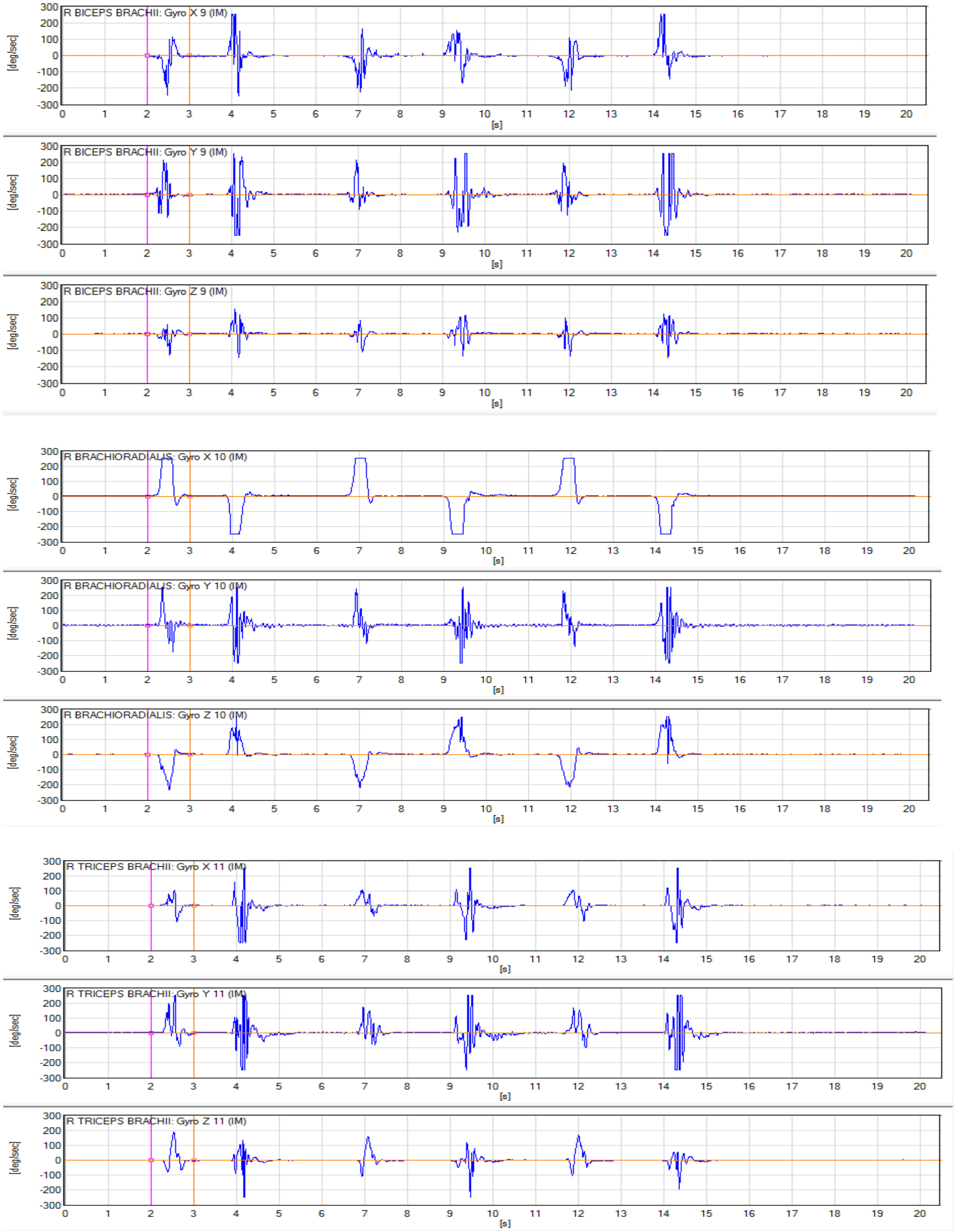

Figure (44): Recorded signal at fast speed motion